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Energy Master Planning toward Net Zero Energy Resilient Public Communities Guide

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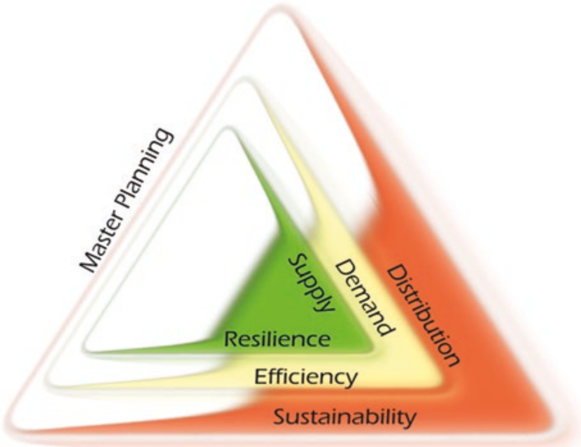
ISBN 978-3-030-95832-9 ISBN 978-3-030-95833-6 (eBook)
https://doi.org/10.1007/978-3-030-95833-6

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland


Master Planning
Supply
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Resilience
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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy program. A basic aim of the IEA is to foster international cooperation among the 30 IEA participating countries and to increase energy security through energy research, development, and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA coordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment toward more energy-efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies, and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high-priority research themes in the EBC Strategic Plan 2019–2024 are based on research drivers, national programs within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017, and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems, and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From these 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high-priority themes can be separated into two types, namely “Objectives” and “Means.” These two groups are distinguished for a better understanding of the different themes.

Objectives—The strategic objectives of the EBC TCP are as follows:

- Reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders, and promotion of co-benefits
- Improvement of planning, construction, and management processes to reduce the performance gap between design stage assessments and real-world operation
- The creation of “low-tech,” robust, and affordable technologies
- The further development of energy-efficient cooling in hot and humid or dry climates, avoiding mechanical cooling if possible
- The creation of holistic solution sets for district-level systems that consider energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications

Means—The strategic objectives of the EBC TCP will be achieved by the means listed below:

- The creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life-cycle analysis (LCA)
- Benefitting from “living labs” to provide experience of and overcome barriers to adoption of energy efficiency measures
- Improving smart control of building services technical installations, including occupant and operator interfaces
- Addressing data issues in buildings, including non-intrusive and secure data collection
- The development of building information modeling (BIM) as a game changer, from design and construction through to operations and maintenance

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the “Objectives” themes are final goals or solutions (or part of) for an energy-efficient built environment, while the “Means” themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019–2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Center
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behavior with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modeling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi-Zone Air Flow Modeling (COMIS) (*)
Annex 24: Heat, Air, and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy-Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low-Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)

Annex 35: Design of Energy-Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low-Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High-Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air, and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy-Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Toolkit on Energy-Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low-Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air-Conditioning (*)
Annex 49: Low-Exergy Systems for High-Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low-Energy Renovation of Residential Buildings (*)
Annex 51: Energy-Efficient Communities (*)
Annex 52: ☼ Toward Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy-Efficient Building Retrofitting—Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost-Effective Energy and CO2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO2-Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterization Based on Full-Scale Dynamic Measurements (*)
Annex 59: High-Temperature Cooling and Low-Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities—Optimized Performance of Energy Supply Systems with Exergy Principles (*)

Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy-Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low-Energy Residential Buildings
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low-Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life-Cycle-Related Environmental Impacts Caused by Buildings
Annex 73: Toward Net Zero Energy-Resilient Public Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: EBC Annex 76/SHC Task 59 Deep Renovation of Historic Buildings Toward Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: EBC Annex 77/SHC Task 61 Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling of Buildings
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy-Flexible Buildings Toward Resilient Low-Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
Annex 86: Energy-Efficient Indoor Air Quality Management in Residential Buildings
Working Group—Energy Efficiency in Educational Buildings (*)
Working Group—Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group—Annex 36 Extension: The Energy Concept Adviser (*)
Working Group—HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group—Cities and Communities
Working Group—Building Energy Codes

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Acknowledgments

The “Energy Master Planning toward Net Zero Energy Resilient Public Communities Guide” was developed within the IEA EBC Program Annex 73, as the result of a joint effort by researchers and practitioners from Australia, Austria, Denmark, Finland, Germany, Norway, the United Kingdom, and the United States. The authors express their appreciation for the many international contributors and organizations whose volunteer efforts made possible the development of this practical guide. Special gratitude is owed to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and its Technical Committee’s TC 7.6 “Building Energy Performance,” the US National Academies’ of Sciences and Medicine Federal Facilities Council, and the Environmental Security Technology Certification Program (ESTCP) for providing a platform for public discussion of the project’s progress and for the review of the document by its members. The authors would like to personally thank the members of the EBC Program Executive Committee Isabella Warisch, Republic of Austria Federal Ministry for Climate Action, Carlos Flores, National Australian Built Environment Rating System (NABERS), and the ESTCP Board member Paul Volkman, Office of the Assistant Secretary of the Army (Installations, Energy, & Environment) for providing direction, guidance, and support to the project and review of this Guide.

The authors gratefully acknowledge William J. Wolfe, Writer-Editor, SC-B Consulting, Inc., for his help in coordinating preparation of this document and Dr Ingo Leusbrock, AEE—Institute for Sustainable Technologies, Gleisdorf, Austria, for the cover artwork. The authors would like to acknowledge the financial and other support from the following organizations: the US Department of Defense Environmental Security Technology Certification Program; the office of the Assistant Secretary of the US Army for Installations, Energy, and Environment; the US Army Corps of Engineers; the US Department of Energy (Office of Building Technologies and Federal Energy Management Program); the EUDP-programme of the Danish Energy Agency; the Austrian Research Cooperation Programme (project number 864147); the Research Council of Norway through the research project ExPOSe (project number 268248) under the EnergiX program; ENOVA, the Norwegian energy efficiency agency, through the project comprehensive planning of nearly zero energy neighborhoods; the Department of Infrastructure Engineering at the University of Melbourne, Australia; and the Academy of Finland Strategic Research Council (SRC), Project: Smart Energy Transition (SET)—Realizing Its Potential for Sustainable Growth for Finland's Second Century, Decision No. 314325, the German Department of Economic Affairs and Energy in the context of the 6th Energy Research Program and by approval by the German Bundestag.

Executive Summary

Energy Master Planning and Community Planning

Buildings use about 40% of global energy, 25% of global water, and 40% of global resources; moreover, they generate approximately one-third of all greenhouse gas (GHG) emissions. Yet, buildings also offer the greatest potential for achieving significant GHG emission reductions, at least cost, in developed and developing countries. Furthermore, energy consumption in buildings can be reduced by 30–80% using proven and commercially available technologies (UNEP 2013). Different international, national, regional, local, and institutional sustainability development goals are aiming at using affordable, low-carbon, clean energy provided by resilient energy systems. Achieving these goals on the national or even on a large city level with the involvement of numerous users and stakeholders requires significant investments and coordination efforts. Nevertheless, the experience of public communities that have one owner (including Ministries of Defense, universities, and hospital campuses), where all buildings and the energy system are managed using one cost center, can serve as a model for larger and more complex communities.

Until recently, most planners of public communities in the United States and in several other countries have addressed energy systems for new facilities or for major renovation on an individual facility basis without consideration of community-wide goals with regard to energy sources, renewables, storage, or future energy generation needs. Because building retrofits of public buildings typically do not address energy needs beyond the minimum code requirements, it can be difficult if not impossible to achieve community-level targets on a building-by-building basis. In today's resource-constrained environment, public communities are looking for creative ways to drive additional efficiencies in energy use and reduce associated costs. For example, a synergistic approach to a diversified building cluster portfolio would allow for the storage and further use of a wide range of energy streams that would otherwise be wasted. Large coordinated efforts are needed to establish the needed synergy between different energy initiatives and future planned projects to minimize energy use and costs.

In most countries, community energy plans have been high-level strategy documents rather than planning documents (Singh et al. 2015). The synergy between community and energy planning becomes essential and critical for developing energy-efficient, sustainable, more resilient communities that provide incentives for the use of large-scale renewable energy sources and that encourage the use of community-scale generation, distribution, and energy storage technologies, which in turn results in increased resilience to natural and manmade threats to energy (thermal and electric) systems and boosts local economies.

Building-centric planning also falls short of delivering community-level resilience. For example, many building code requirements focus on hardening buildings to withstand specific threats, but a multi-building community may contain only a few mission-critical buildings that require such hardening. Furthermore, hardening is only one aspect of resilience. Recovery and adaptation should also be considered as effective energy resilience solutions. Over the past two decades, the frequency and duration of regional power outages from weather, manmade events, and aging infrastructure have increased. Major disruptions of electric and thermal energy have degraded critical mission capabilities and have caused significant economic impacts at military installations. There is a need to develop a highly resilient "backbone" of energy systems to maintain effective critical mission and service operations during such extended power outages over a range of emerging scenarios.

Best practices from around the world have proven that holistic Energy Master Planning can be the key to identifying cost-effective solutions of energy systems that depend on the climate zone, density of energy users, and local resources. The Energy Master Planning can be applied to different scales of communities, e.g., a group of buildings, a campus, a city, a region, or on the national scale. However, to benefit from synergies and to avoid suboptimization, successful energy master planning at the desired community scale should include an assessment of and considerations for the energy master plan at the given scale.

Energy Master Planning is especially valuable and critical when working with community- and campus-scale district energy systems that use a centralized plant to generate heating, cooling, and even power, and that distribute these utilities via a network to serve the aggregate heating, cooling, and power loads of multiple buildings. These district energy systems enable better sizing of generation capacity by leveraging the diversity of loads across different building types, and by taking advantage of economies of scale and increased energy efficiency relative to each building supporting its own local generation. The scale provided by district energy systems also enables the use of lower-carbon resources such as biomass and lake- and seawater cooling, which is not feasible at a building scale.

Some countries have a long tradition of city-level energy supply planning; in many European cities, public utilities are responsible for meeting the city's needs for electricity, gas, and heat. Experience also shows that countries and cities that set energy efficiency and climate targets find it important to work with community energy plans. The European Union (EU), for example, has established a legal framework (directives for energy efficiency, renewable energy, and buildings) for community energy planning; member states are required to implement the directives in national plans. This legislation builds on best practices from several EU countries where municipal energy planning has been driven by local publicly owned utilities harvesting local synergies and resources. In Sweden and Finland, this mainly involved district heating based on local biomass; in Norway, electric heating based on hydro power; and in Denmark, district heating based on maximal use of combined heat and power (CHP) and waste heat potential, combined with a new natural gas infrastructure connected to individual residential houses to reduce the dependency on imported oil. (Efforts in Denmark were undertaken to increase resilience at national level in reaction to the oil crises of 1973 and 1979.)

Although the integration of the energy master planning into the community master planning process may be a challenging task, it also provides significant opportunities to support energy efficiency and community resilience by increasing budgets for investments derived from energy savings, by providing more resilient and cost-effective systems, by increasing comfort and quality of life, and by stimulating local production, which boosts local economies.

This Guide is a result of research conducted under the IEA EBC Program Annex 73 (IEA 2021b) and the ESTCP EW18-5281 projects to support the planning of Low-Energy Resilient Public Communities that is easy to understand and execute.

Lessons Learned from Case Studies

Experience from the case studies (Appendix B and [IEA 2021b]) shows that Energy Master Planning that includes both demand and supply systems can cost-effectively increase energy efficiency on the national level by maximizing the use of combined heat and power and by recycling all heat from waste incineration. Case studies from North American universities have demonstrated the cost effectiveness of upgrading district steam and district cooling systems on the campus and building level by taking advantage of the fact that all renovation costs and operational benefits are attributed to a single university budget.

Energy master plans described in case studies have been formulated with a variety of different objectives, from such simple economic objectives as reducing operating costs, to improving the resilience of energy systems, to achieving net zero emissions at the building and campus level, to avoiding CO_2 taxes. Experience with the first energy-neutral town in the world showed that a transition to a 100% renewable energy supply (Güssing 2011) can triple tax incomes and thus boost the local economy within 15 years.

Analysis of case studies collected and summarized in Appendix B as a part of the Annex 73 project highlights the following observations:

- Typically, energy master plans allow total life-cycle costs to be minimized, support the decarbonization of the process of supplying energy to end users, and increase the resilience of thermal and power energy supply systems.

- In some cases, increases in the density of the built environment, the increased use of mechanical ventilation, and the implementation of new requirements for building cooling systems due to rising outdoor air temperatures and improved environmental quality standards can increase both energy costs and the community's energy use, resulting in a need for additional power generation and greater required heating and cooling capacity.
- The implementation of novel and more efficient end-use technologies, Building Energy Management Systems, and energy supply solutions, including thermal energy storage, Combined Heating, Cooling, and Power generation, reversible heat pumps, and broader use and integration of energy generation from renewable energy sources into distribution grids, can help to slow down or even reverse the increase in energy demand, can reduce the size of energy generation equipment by shaving peak loads (in particular the cooling peak in warm climates), and can make energy systems more resilient to the growing number of different natural and manmade threats and hazards. Existing thermal and power distribution networks can be expanded or combined to integrate existing energy generation equipment dedicated to individual buildings and building clusters; this results in improved operational efficiency, provides additional capacity required for peaking loads, and provides generation and distribution redundancy, which in turn results in the enhanced resilience of energy systems.
- Integrated energy systems can act as so-called virtual batteries; district heating can be provided by a CHP plant, heat pumps, electric boilers, and thermal energy storage (TES) units—measures that allow scheduling of equipment operation in response to not only daily but also weekly fluctuations of prices in the electricity market that can be affected by such factors as fluctuations in wind. A number of case studies (primarily from Germany and Denmark) illustrate current trends in replacement of old inefficient steam systems and superheated water by modern state-of-the-art district hot water systems. Such improvements reduce operating costs; increase overall system efficiency; integrate the use of waste heat from industry and renewable energy sources, both directly and via heat pumps; and generally improve system resilience. Measures such as these could be adapted to US campuses and military installations, where 95% of all campus heating systems are steam based. Note that this modernization and conversion would involve major capital outlays and business disruptions, particularly for converting buildings from steam to hot-water systems; such changes are often undertaken in a phased implementation based on the state of each system.
- Although water-based systems are currently lead district energy generation technologies due to their flexibility and lower temperature efficiencies, steam systems still represent viable and efficient methods for heating buildings. Some hospitals and laboratory buildings, for example, require access to the higher temperatures associated with steam for the purposes of sanitization. Steam is also highly pressurized, which allows it to use smaller distribution pipes and move heat in high-rise buildings better. Existing steam systems may also be paired with hot water as the system expands and adds new customers/users.

- Buildings configurations that include such improvements as well-insulated building envelopes; efficient Heating, Ventilating, and Air-Conditioning (HVAC) systems with large surface radiant heating and cooling technologies (e.g., floor- or ceiling-mounted heating and cooling); and the use of building core activation that can exploit smaller temperature differences between supply and return water used for heating and cooling all support the use of district systems with low-temperature heating and high-temperature cooling. This in turn enables the use of low-exergy sources, e.g., ground (geothermal), solar thermal, and groundwater, river or lake water, and heat from sewer systems. This also increases the resilience of building thermal energy systems, which can be decoupled from thermal energy sources for a relatively longer time.
- Case studies from Finland and Denmark show a trend toward the combination of heating and cooling. In highly efficient buildings, cooling may become a necessity where it may not have been before; the two thermal systems can be integrated to share the thermal energy in return water from the complementary heating/cooling system.
- On campuses where all buildings share a single owner, e.g., university campuses, medical centers, and military installations, energy efficiency measures made for individual buildings (e.g., building envelope renovation, replacing HVAC equipment and lighting systems with more efficient ones) can be used to reduce community-wide peak demand. When such projects are planned and scheduled as a part of a holistic Energy Master Plan, they can improve the cost effectiveness of the plan by improving building environmental conditions, better using resources, and enhancing system resilience. This approach requires collaboration between all stakeholders and strategic timing of different projects (HTF Stuttgart, Germany). In one instance, where the energy supply system was owned by the city (e.g., Case Study for Copenhagen, Denmark), the utility company was able to minimize energy cost to all consumers. Single-owner campuses are better situated for this use approach than are local communities with numerous building owners since single-owner campuses can optimally time the building renovation for all campus buildings.
- Emergency power backup solutions are typically limited to the use of emergency diesel or gas-fueled generators that are maintained for use only during power loss from the grid. Typically, they provide power to mission-critical operations and support life and safety needs. For example, some cost-effective micro grids implemented in the United States have connected critical users to gas-fueled CHP plants to provide energy assurance when power grid performance degrades.
- Similarly, peak boilers for the district heating system can be located close to critical consumers, e.g., a hospital, to ensure a more resilient heat supply (Vestforbrænding, Denmark).
- Micro grids are not common in European countries, where most power grids are reliable. However, in some cases (e.g., at the Technical University of Denmark) micro grids are used to avoid distribution tariffs since the costs of operating their own low-voltage grid are lower than the distribution tariff from the utility. In such cases, even large gas-driven CHP plants located on the campus are not connected to the campus grid but are rather connected to the utility grid and operated based on market energy prices.

Energy Planning as a Part of the Community Master Plan

For existing large areas, the planning process is complex, and includes consideration of future use and energy costs as well as maintenance and operation of existing infrastructure. Implementation plans for energy systems cover many years of actions to increase efficiency, resilience, and reliability. These plans are important to provide the scope, schedule, and security to projects funded either directly or using third-party financing.

The process of building efficient, sustainable, resilient communities requires careful coordination between stakeholders, including master planners, energy planners, and building designers. These stakeholders work at differing levels of detail and use different planning horizons, which may lead to suboptimal decisions for the community as a whole. Coordinating the myriad stakeholders involved in community planning can be a challenge.

Three levels of stakeholders can readily be identified. At the highest level of abstraction, master planners think in terms of long-term sustainability goals, including national energy strategy, community layout, transportation, and street design; in this stage, planners work to break down barriers between sectors and cities. To address sustainability, master planners must look at the society as a whole and extend the length of their view to 25 years or more (Case et al. 2015). Energy managers fall within the middle tier of abstraction; the focus of their work is on the local community or campus projects, which may vary between longer-term energy infrastructure projects, such as district energy systems, to medium- or near-term projects, such as building retrofits designed to meet community energy goals. Finally, the building (or infrastructure) designer's efforts occupy the most detailed level of abstraction. These engineers must create designs for a specific project that can be shown to be effective, buildable, biddable, and cost effective.

Integration of energy planning into community planning requires a holistic approach to the planning process and relies on new concepts, instruments, and tools, which must be made available to master planners, energy managers, decision-makers, and stakeholders. Energy master planning is a complex process that includes cultural, organizational, technical, legal, and financial aspects.

Energy Master Planning Concept

The objective of the community/installation Energy Plan is to produce a holistic roadmap that enables planners to work constructively toward various framing energy goals within defined community specific constraints. The Energy Master Planning concept described in this Guide differs from previously developed concepts (OASD 2016; Zhivov et al. 2014; IEA Annex 51) in that, in addition to meeting the community's framing energy goals, it integrates development of a highly resilient "backbone" of energy systems that allow communities to maintain critical missions and service operations effectively during extended outages over a range of

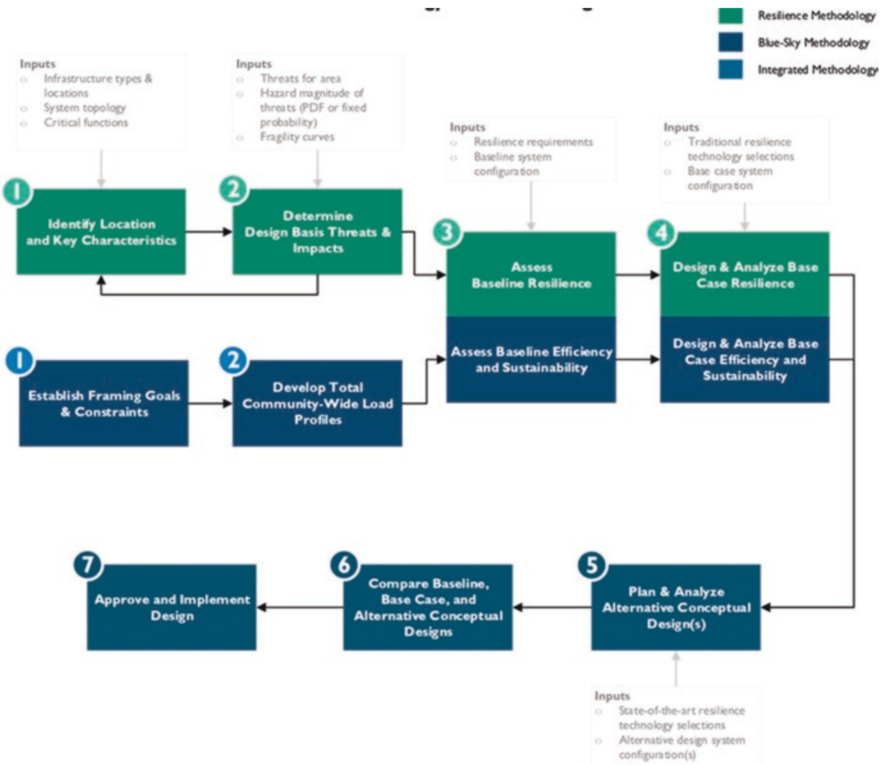


Fig. ES.1 Integration of energy systems resilience analysis into energy master plan

emergency scenarios, whether caused by weather, manmade events, or aging infrastructure (Fig. ES.1).

The integrated approach described in this Guide results in cost-effective operation of energy systems under normal (blue sky) conditions and in a less vulnerable, more secure, and more resilient energy supply to the community's critical mission functions during emergency (black sky) scenarios. It provides a framework for the planning process and outlines the main steps, which include: (1) establishment of energy framing goals and constraints, (2) assessment of a community's critical missions and functions, (3) assessment of community specific threats, (4) establishment of energy requirements for normal and mission-critical functions, (5) assessment of the current situation (baseline) to understand existing gaps against framing goals and constraints, and (6) development of future alternatives, including "business as usual" (base case) and more advanced alternatives of energy systems. Quantitative metrics should be used to compare baseline, base case, and future alternatives. "Blue sky" and "black sky" alternative architectures can be built upon the database of technologies and architectures summarized from internationally available best practices. Alternatives established under normal conditions (blue sky) consider energy goals, constraints, loads, and the operation of all buildings and systems. However, selection of architecture of different alternatives for energy systems during this phase of the planning process may already consider the implication of their characteristics and their function for the resilience of systems serving mission-critical facilities under emergency conditions.

The planning process for mission-critical buildings and functions addresses only critical loads under emergency (black sky) conditions. This part of the process includes steps that allow planners to narrow down the scope of buildings and operations and their loads to those that are mission-critical, that assess threats specific to locality and function of the installation and their impact on energy systems' degradation, and that calculate energy requirements for mission-critical functions. Planners will evaluate gaps in existing systems resilience, and develop future alternatives of systems that provide the required level of energy assurance to mission-critical functions, including "business as usual" (Base Case) and more advanced alternatives of energy systems, which will consider, but not be limited to, those developed under the "blue sky" scenario. At this point of analysis, there is an opportunity for iteration between alternatives developed under these two scenarios.

Final steps of the integrated Energy Master Planning process include the comparison of different alternatives against the framing goals established earlier using quantitative and qualitative metrics. At this point, iteration may be required to modify or create new alternatives if the goals were not met. Once decision-makers have selected a preferred alternative, they must prepare an implementation plan that includes an investment strategy and projects required to achieve the plan. Based on the situation at specific campuses, the breadth and depth of improvements under different alternatives may differ as a reflection of existing plans and timing for new construction, major and minor renovation of the building stock and utilities, criticality of their missions, and availability of resources. Also, the quality of the data available for development of the Baseline and the Base Case and energy requirements for mission-critical operations at specific installations may also vary. This may result in differences in the realization of the described concept at specific campuses.

Establishing Framing Goals and Constraints

It is important to clearly define energy-related requirements and long- and short-term energy goals, and important constraints and community priorities, at the beginning of a study.

Energy use requirements are typically established by a country, state, local authority, project team, building owner, or other stakeholder. Requirements are "must achieves" for the project design. In contrast, targets (or goals) are often desires (what one would like to achieve) and may or may not lead to requirements.

Energy goals that can be used in the comparison of alternatives may include:

- Energy use (site and primary)
- System resilience
- Use of renewables

- Environmental impact, e.g., greenhouse gas emissions
- System economics

Energy constraints that can be used for system architectures and technology database down-selection may include:

- Connection (or no connection, e.g., in remote or island locations) to outside community (which minimizes categories of system architectures)
- Existing or potential energy supply from outside the community boundaries (which minimizes categories of system architectures): power, hot water, steam, chilled water
- Fuel available: gas, coal, fuel oil, biomass, biogas
- Available renewable energy sources: solar thermal, solar photo voltaic (PV), geothermal, sea/river water cooling, geothermal
- Current energy systems on the campus: centralized or decentralized (no distribution lines available)
- Future energy systems that can be considered (centralized or decentralized)
- Operational and personnel constraints (consideration that some operators may not have skills to operate certain types of systems)
- Environmental constraints for using different types of technologies, e.g., water, emissions from CHP, etc.
- Building space constraints (no mechanical room for decentralized systems, thermal storage, etc.)
- Community space constraints (e.g., for seasonal storage, PV, or thermal solar panels array)
- Community layout constraints (e.g., for placing central heating or cooling system pipes)

Table ES.1 list examples of natural and imposed (manmade) constraints that impact selection of system architecture and technologies.

Long-term energy goals can be expressed as the reduction by a desired percentage of site or source energy use against a Baseline by a given year, or the achievement of a Net Zero site/source energy community within a given time frame. These goals lead to decision metrics that will be used to decide between alternative solutions. They help to focus the study and define “success.” It is entirely possible that the goals will turn out to be infeasible, in which case they can be adjusted once quantitative data are available. The most common energy requirements, goals, and constraints may be categorized as follows:

- Community, building cluster, and facility level
- Operational constraints
- Constraints based on natural threats
- Locational resources available: district chilled and hot water, steam, water, electricity grid, natural gas pipeline, liquid fuel
- Energy supply constraints: power supply limitations, gas supply limitations, availability of energy from renewable sources
- Requirements for energy systems resilience

Table ES.1 Constraints that narrow energy system architecture and technologies options

Natural constraints		Imposed constraints				
Category	Constraint	Category		Constraint	Category	Constraint
1. Locational threats	Regional or local air quality	**3. Energy and water distribution and storage systems**		Natural gas	**5. Indoor environment**	Air temperature
	Low-lying area (flooding)			electricity		Air humidity
	Extreme outside air temperatures			Fuel oil		Illumination level
	Extreme humidity			Chilled water		Indoor air quality
	High winds			Hot water		
	Fire			Steam		Radon
	Lightening			Water		
	Ground threats (volcano, mud slide, earthquake)	**4. Building related**	**Energy**	Energy use (site)	**6. Existing equipment in buildings and district systems**	Space heating
2. Local resources available	Solar			Energy use (primary)		Space cooling
				Energy Efficiency		Ventilation
	Wind		**Environmental**	Renewable energy		Humidity control
				Emissions		Water heating
	Biomass		**Operational**	Resilience		Food preparation
	Land or roof area available for renewable energy technologies installation			Financial/costs		Waste handling
	Natural gas			Maintenance		Electricity generation
	Electricity from the grid			Workforce limitations		District steam
	Liquid fuels					District hot water
	Hot water					District chilled water
	Chilled water			Other building owner limitations		

Energy System Resilience

The resilience of the energy system impacts the primary functionality of military installations, hospitals, and education campuses during disruptions. Throughout the history of energy systems, major disruptions of energy supply (both electrical and thermal) have degraded critical capabilities and caused significant social and economic impacts to private and public communities. Therefore, resilience must be an integral goal of the community-wide energy master planning process, and application of energy resilience principles is important during design of new and upgrade of existing energy systems. Best practices for resilient electric and thermal energy systems favor the use of installed energy sources rather than the use of emergency generation for short durations, and promote the use of multiple and diverse sources of energy, with an emphasis on favoring energy resources originating within the community (OUSD 2021).

Electric and thermal energy delivery may be visualized as having three delivery mechanisms or layers (Fig. ES.2). The first delivery mechanism is internal to the facility: it is the building-level power infrastructure for electric energy systems and building envelope and its mechanical systems for thermal energy supply. The second delivery mechanism is the emergency, or backup, energy systems directed to the facility from outside of the building but sourced from local infrastructure power and thermal energy generation. The third delivery mechanism is the full load delivered to the facility under normal operating conditions; this commonly comprises prime power or power delivery from an electric utility for electric systems, and steam, hot water, and/or chilled water delivered from the campus, building cluster, or some location outside the campus plant.

Two facility load levels are defined. The full electric and thermal power load is provided by the layer three system and serves the entire electrical/thermal load of the facility. The critical electrical load is provided by layers one and two, also referred to as backup power, and only serves the facility critical infrastructure. The facility critical infrastructure load results from the load shedding of all power-connected equipment that is not critical for the continuity of the mission or missions housed in the facility. Layer one power for a facility is the electrical backup power

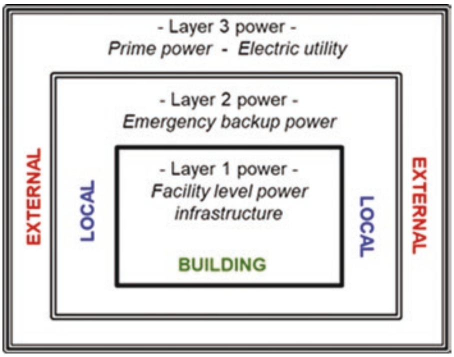


Fig. ES.2 Layers of power supply to mission-critical facilities that resides inside the facility. Common components are an uninterruptable power supply (UPS) and an automatic transfer switch (ATS). Layer one backup power is the shortest duration of electrical power capacity of the three layers. The power delivery capacity can typically be from several minutes to several hours.

Layer two power for a facility is the electrical backup power that resides outside of the facility, but that is, at a minimum, partially dedicated to supplying the facility. Common components are generator sets and renewable energy systems such as solar arrays. Layer two backup power is of variable duration. The electrical power delivery capacity can range from several hours to days in duration. The electrical power delivery capacity is limited only by factors such as fuel storage capacity and battery rectifier capacity. The layer two power can also be supplied for an installation-wide or campus microgrid system. In such a case, the facility power is supplied from a microgrid system that also provides power to other facilities that reside at the same location as the facility in question.

Layer three for a facility is the electrical power that resides in the infrastructure of the prime power utility. Common components of the utility that serve electrical power to the facility are substations and the medium voltage power distribution system. Layer three is the supplier of electrical power under normal conditions. Unlike layers one and two, layer three is not maintained or repaired by the facility. An exception would be when an installation or campus uses distributed power generation in conjunction with connection to the prime power utility; the primary goal is lower cost of the distributed power generation or opportunities to sell energy to the utility grid to achieve a positive cost differential. Failure at layer three requires a reliance on layers one and two for continuity of mission operations.

In the case of thermal energy systems, layer one can include the building envelope and the building-level thermal storage, while layer two may include an emergency boiler, a mobile boiler, or an electric backup thermal system.

A variety of energy system options can be used to supply power, heating, and cooling to campuses; these options vary by the architectures and technologies used, and by whether they apply to individual buildings, building clusters, campuses, or even entire communities. Design and evaluation of these system resilience measures should be based on requirements established by mission operators, which are currently not well understood.

The quantitative approach described in this Guide allows for evaluation of both the ability of a system to absorb the impact of a disruption (robustness), and its ability to recover from that disruption.

Critical missions may employ extensive redundancy and protect vital system components to ensure continuity of the mission, even when faced with a significant natural or manmade disaster. For such systems, mission success is very highly probable, but is still a probability. Consequently, the impact of an event can be considered to impact the probability of mission success. Some critical missions can withstand small disruptions as long as the system can recover quickly. In either case, the overall resilience of the system can be quantified as a deviation in mission availability from baseline operations to some degraded system state following a disturbance.

A quantitative approach to the resilience of a system supplying energy to the building proposed in the Guide can include (but is not limited to) the following metrics:

- Energy System Robustness (ER)
- Energy System Recovery Time or Maximum Time to Repair (MaxTTR)
- Energy Availability (EA)
- Energy Quality (EQ)

The first three parameters are critical for the selection of layers two and three energy supply system architecture, and for technologies it comprises, to satisfy requirements related to energy system resilience. Requirements for Energy Availability and Energy System Recovery Time depend on:

1. Criticality of the mission being served by the system
2. System repairability, which has significant dependence on the remoteness of the facility hosting the mission
3. Redundancy of facilities that can serve the same critical function and the layer one energy system capacity

Energy Quality is another important quantitative metric for the energy system that serves critical functions; energy quality should be considered as a design parameter for internal building (layer one) energy systems. Most of the mission-specific energy quality requirements, including limitation on short-term power interruptions, voltage and frequency variations, and harmonics, can be handled by the building-level energy systems. Building-level electric systems (nanogrids) generally include redundant or backup components and infrastructure for power supply, uninterruptible power supply, ATSs, data communications connections, and environmental controls (e.g., air-conditioning, fire suppression). Nanogrids also include various security devices that can be designed to provide power with a severe demand on the stability and level of the frequency, voltage, and waveform characteristics of the uninterruptable electrical power to mission-critical equipment, and that can operate in an islanded mode for between 15 minutes and several hours. It is important to account for the latter capability when requirements for maximum energy supply downtime are established.

Using the Energy Robustness metric, we can quantify the overall resilience of a system in two phases: absorption of the event and recovery (Fig. ES.3). Immediately after the event there is a sharp drop in the load available to the mission. For electric energy systems, the duration of phase one is much shorter than for thermal energy systems, unless thermal systems are used for processes using steam or hot water. This change from the Baseline to the degraded state represents the robustness of the system to that particular event. The time required to restore the system to its baseline state is referred to as recovery. The smaller the change in load available to the mission and the shorter the recovery time, the more robust the system.

The robustness, *R*, of the system to any particular event can be quantified using Eqs. ES.1a and ES.1b and is illustrated by the area between the line showing the baseline mission availability and the curve representing the actual mission

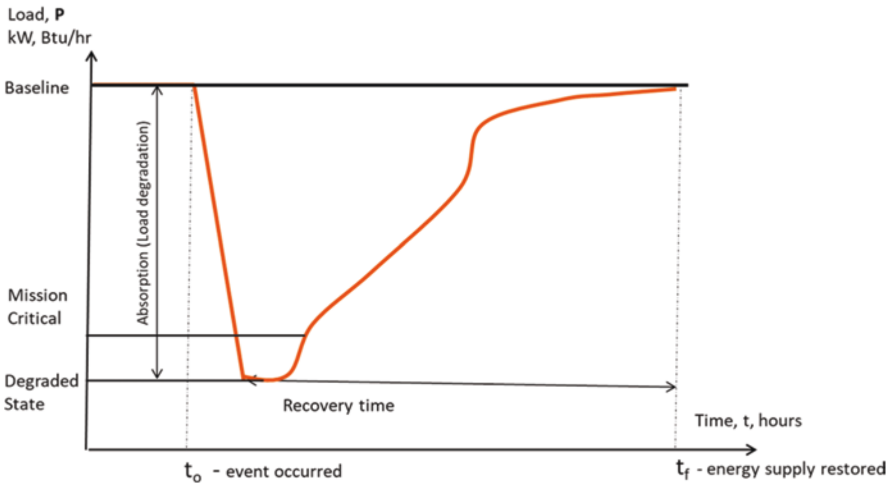


Fig. ES.3 System response to a disruptive event

performance over time. The smaller the area between the Baseline and the curve, the more resilient the system. Robustness will be measured on the scale between 0 and 1, where 1 is the most resilient system:

$$ER_{\text{m.c.}} = \frac{E_{\text{event}}}{E_{\text{m.c.}}} \tag{ES.1a}$$

$$R_{\text{baseline}} = \frac{E_{\text{event}}}{E_{\text{baseline}}} \tag{ES.1b}$$

where $R_{\text{m.c.}}$ and R_{baseline} are system robustness measured against the mission-critical load and the baseline load; $E_{\text{m.c.}}$ and E_{event} are energy supplied to the building during the period of time between t_o and e with the baseline load, mission-critical load and degraded due to even load:

$$\boldsymbol{E} = \int_{t_o}^{t_f} \boldsymbol{P}(t)\,dt \tag{ES.2}$$

Depending on mission needs, it may be more important to prioritize either absorption or recovery.

Energy Availability is a measure of the readiness of a system or component to perform its required function and is usually expressed as a function of equipment downtime as shown in Eq. ES.3.

$$\boldsymbol{EA} = \frac{\textbf{Uptime}}{\textbf{Uptime} + \textbf{Downtime}} \tag{ES.3}$$

Table ES.2 Determination of resilience requirements

Resilience metric requirement	Resilience phase	
	Availability	Recovery
Low	Criticality: **Low-Moderate** Remoteness: **Low** Facility Redundancy: **Yes**	Criticality: **Low** Remoteness: **Low-Moderate** Facility Redundancy: **Yes**
Moderate	Criticality: **Low-Mod** Remoteness: **Moderate-Significant** Facility Redundancy: **Yes**	Criticality: **Low-Mod** Remoteness: **Moderate** Facility Redundancy: **Yes**
Significant	Criticality: **Mod-High** Remoteness: **Significant-High** Facility Redundancy: **No**	Criticality: **Mod-Significant** Remoteness: **Significant-High** Facility Redundancy: **No**
High	Criticality: Significant-**High** Remoteness: **High** Facility Redundancy: **No**	Criticality: **High** Remoteness: **Significant-High** Facility Redundancy: **No**

This metric is used to evaluate the performance of the energy in terms of *percentage of time* it is available for the mission. For example, if an event occurs that reduces energy availability to 0.99, then the average expected weekly downtime of the mission is about 100 min. If the energy availability of a more resistant system is only reduced to 0.999, the expected weekly downtime for the mission is approximately 10 min. This essentially represents a tenfold difference in system performance.

The Guide offers a methodology that will help mission operators to determine requirements for Energy Availability and Recovery based on three factors: mission criticality, facility remoteness/repairability, and redundancy (Table ES.2).

The Resilience Requirement listed in Table ES.3 stratifies each Resilience Metric listed in Table ES.2. Each Resilience Metric is split into two levels of facilities, Primary and Secondary, which in turn have two levels of requirements for energy system resilience ranging from Low (0) to High (4). Such stratification of each Resilience Metric creates a more accurate scenario fitting the facility and mission requirement.

The availability of multiple categories will facilitate the ability of design teams to identify the most correct resiliency requirement for the project at hand. Tables ES.2 and ES.3 represent two category states for each of the four Resilience Metrics. Expansion of tiers for Resilience Metric Requirements improves the process by providing:

- An additional level of granularity that enhances the ability to more accurately select the most appropriate category of resiliency
- More flexibility for a project to identify the lowest Resilience Metric Requirement level that is appropriate (and to avoid inappropriate overdesign, which increases cost)

Table ES.3 Recommended resilience requirements for power systems serving mission-critical facilities

Resilience metric	Facility level	Resilience sub-metric	Category	Degraded state availability	Acceptable average weekly downtime (minutes)	Maximum single event downtime (minutes)
Low	Primary	Low	LP/1	0.92	806.4	2419
		Moderate	LP/1+	0.95	504	1500
	Secondary	Low	LS/0	0.9	1008	3024
		Moderate	LS/0+	0.92	806.4	2419
Moderate	Primary	Low	MP/2	0.99	100.8	302
		Moderate	MP/2+	0.995	50.4	150
	Secondary	Low	MS/1	0.95	504	1500
		Moderate	MS/1+	0.99	100.8	302
Significant	Primary	Moderate	SP/3	0.999	10.08	30
		Significant	SP/3+	0.9995	5.04	15
	Secondary	Moderate	MS/2	0.95	504	1500
		Significant	MS/2+	0.99	100.8	302
High	Primary	Significant	HP/4	0.9999	1.008	3
		High	HP/4+	0.99999	0.1008	0.3
	Secondary	Significant	HS/3	0.9995	5.04	15
		High	HS/3+	0.9999	1.008	3
P = Primary Facility/Mission					S = Secondary Facility/Mission	
L = Low Resilience Metric					M = Moderate Resilience Metric	
S = Significant Resilience Metric					H = High Resilience Metric	
+ = Highest 10% of a Specific Resilience Metric Range						
0 = Resilience Metric Range—Lowest Resilience Metric Range						
1 = Resilience Metric Range—Scaled 0 to 4, with 4 the highest level of resilience metric						
2 = Resilience Metric Range—Scaled 0 to 4, with 4 the highest level of resilience metric						
3 = Resilience Metric Range—Scaled 0 to 4, with 4 the highest level of resilience metric						
4 = Resilience Metric Range—Highest Resilience Metric Range						

- Assistance to a project team to resist the temptation to invent a resilience level not represented in less granular criteria, ensuring that sufficient levels are provided to fit a wide variety of projects

For thermal energy systems, the Maximum Single Event Downtime can be defined in terms of how long the process can be maintained or how long the building remains habitable (*habitability threshold*), or how long the thermal environment shall be maintained above the *sustainability threshold* level to protect the building against damage from freezing of water pipes, sewer, or fire suppression system; to protect sensitive content; or to prevent the start of mold growth during extended loss of energy supply with extreme weather events. Results of Temperature Decay Tests along with parametric studies of indoor air temperature decay using EnergyPlus-based building energy modeling presented in the Guide showed that high building mass contributes significantly to the thermal resilience of the building, as do greater building air tightness and higher thermal insulation (Table ES.4).

Table ES.4 Single event downtime for buildings with different mass, airtightness, and energy efficiency of the building's envelope

Building parameters	Temp ODB	Mass building			Frame building		
		Typical/post 1980	Low efficiency	High efficiency	Typical/post 1980	Low efficiency	High efficiency
Walls R-value, °F•ft²•h/Btu ([m²•K]/W)		20.5 (3.6)	40 (7.0)	50 (8.8)	20.5 (3.6)	40 (7.0)	50 (8.8)
Roof R-value, °F•ft²•h/Btu, ([m²•K]/W)		31.5 (5.5)	45 (7.9)	60 (10.6)	31.5 (5.5)	45 (7.9)	60 (10.6)
Air leakage, cfm/ft² at 0.3 in. w.g. (L/s.m² @75Pa)		0.4 (2)	0.25 (1.25)	0.15 (0.75)	0.4 (2)	0.25 (1.25)	0.15 (0.75)
Window (R-value, °F ft²•h/Btu, U value, W/(m²•K)		Double Pane; R = 1.78/U = 0.56	Double Pane; R = 3.34/U = 0.3	Triple Pane; R = 5.25/U = 0.19	Double Pane; R = 1.78/U = 0.56	Double Pane; R = 3.34/U = 0.3	Triple Pane; R = 5.25/U = 0.19
MaxSEDT Hab. (60 °F/15.6 °C)	−60 °F −51.1 °C	<1 h	2 h	5 h	<<1 h	1 h	2 h
MaxSEDT Sust. (40 °F/4.4 °C)		9 h	28 h	41 h	4 h	14 h	21 h
MaxSEDT Hab. (60 °F/15.6 °C)	−40 °F −40 °C	1 h	3 h	10 h	<1 h	2 h	4 h
MaxSEDT Sust. (40 °F/4.4 °C)		20 h	36 h	51 h	10 h	18 h	24 h
MaxSEDT Hab. (60 °F/15.6 °C)	−20 °F −28.9 °C	2 h	6 h	15 h	1 h	3 h	6 h
MaxSEDT Sust. (40 °F/4.4 °C)		31 h	46 h	60 h	15 h	22 h	28 h
MaxSEDT Hab. (60 °F/15.6 °C)	0 °F −17.8 °C	3 h	13 h	29 h	2 h	5 h	9 h
MaxSEDT Sust. (40 °F/4.4 °C)		43 h	59 h	90 h	1 h	28 h	33 h

(continued)

Table ES.4 (continued)

Building parameters	Temp ODB	Mass building			Frame building		
		Typical/post 1980	Low efficiency	High efficiency	Typical/post 1980	Low efficiency	High efficiency
MaxSEDT Hab. (60 °F/15.6 °C)	20 °F −6.7 °C	10 h	28 h	45 h	3 h	8 h	15 h
MaxSEDT Sust. (40 °F/4.4 °C)		60 h	78 h	95 h	28 h	35 h	40 h
MaxSEDT Hab. (60 °F/15.6 °C)	40 °F 4.4 °C	29 h	54 h	72 h	8 h	17 h	23 h
MaxSEDT Sust. (40 °F/4.4 °C)		93 h	112 h	123 h	41 h	47 h	50 h

Selection of Energy System Architecture and Technologies

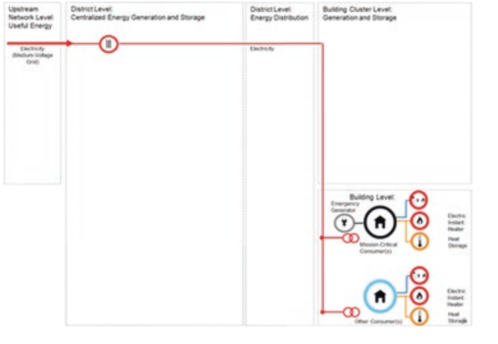
Selection of energy system architecture and types of technologies employed is important for detailed evaluation of the energy master plan baseline and of different alternatives, including the Base Case and more advanced concepts to be used in new development ("greenfield") and/or renovation/extension ("brownfield") projects. Different system options can be considered on the building level, building cluster level, or community level. Selection of these alternatives should consider the existing status of these systems, and the goals and objectives of the project, including improvement in systems resilience, local constraints, and economic and non-economic co-benefits.

The architecture and technologies used in a specific system may include components from several system generations to accommodate the end user needs, whether those components include new development (greenfield) projects, expansion of an existing system, or modernization and renewal of an aging system. For example, some critical hospital buildings and pharmaceutical facilities may need to provide steam to accommodate certain end users, while most other end users may be sufficiently served by hot water service.

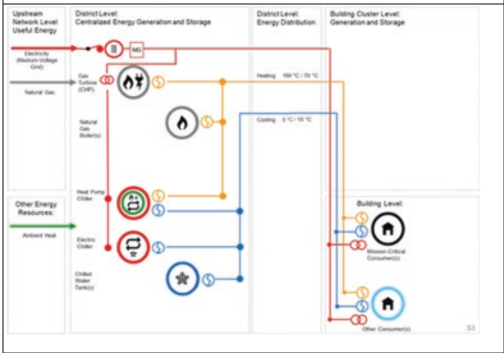
The Guide offers a library of more than 50 examples for energy system architectures generated based on experience gained from case studies and the Annex 73 team expertise, which cover centralized and decentralized, fossil-fuel-based, and renewable systems (see Fig. ES.4 for examples). The library includes general solutions as well as solutions for special situations like remote locations/islands or solutions with electrical enhancements and microgrids to allow islanding power systems from the main electric network. The library offers energy system designs for different climate zones or fuels, for densely populated communities and small, remote communities, and for communities with or without critical buildings. To assist the Energy Master Planning process, a library of system architecture templates includes a description of the application, and the advantages and disadvantages of each template.

Technologies for each system architecture can be selected from a technology database that includes information on technical, economic, and reliability characteristics of different technology archetypes along with a short technology description and application. Selection of technologies can be narrowed down by applying constraints related to the availability of different fuels and space available for installation-specific technologies and plants.

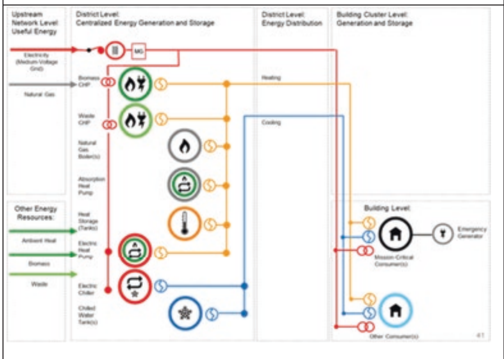
The technologies database was developed based on the information available from various sources. These included the NZP/System Master Planning (SMPL) tool, MIT LL Energy Resilience Analysis (ERA) tool, REOpt tool, US Department of Energy CHP factsheets, Danish Energy Agency Technology Catalogue, and information provided by the International District Energy Association (Danish Energy Agency 2019, 2020), EATON, Schneider Electric, TKDA, and GEF. The technology reliability data was provided by the US Army Corps of Engineers Power Reliability Enhancement Program (PREP). The database comprises multiple energy



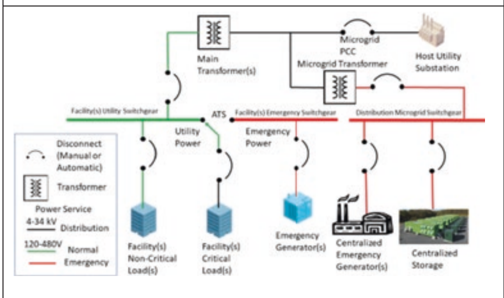
a. Generic power-only system with buildings heating and cooling using electric boilers and chillers



b. District heating, cooling and power systems (Case Study from UT Austin Medical Center)



c. Generic power, heating and cooling systems with CHP base-load generation seasonal storage, waste heat use, etc.



d. Notional microgrid with distribution-level centralized emergency generators and distribution-level centralized storage.

Fig. ES.4 Examples of energy systems architectures conversion, distribution, and storage technologies that can be integrated by energy planners into energy system architectures.

The MS Word® version of the database with fixed values of technology characteristics presented in this Guide is complemented by an Excel® version that is integrated into the Energy Master Planning tool. The Excel® database can be updated and adjusted based on specific fuel prices, currency, and national characteristics; it also includes text boxes and attachments for guidance. The MS Word® version is limited to fixed 2020 values regarding economic assumptions and does not include automatic calculations, e.g., the levelized cost of electricity (LCOE) calculation.

The database is structured (Fig. ES.5) to include the following categories:

- Electric systems
- Heat supply systems
- Chilled water systems
- Natural gas systems
- Miscellaneous

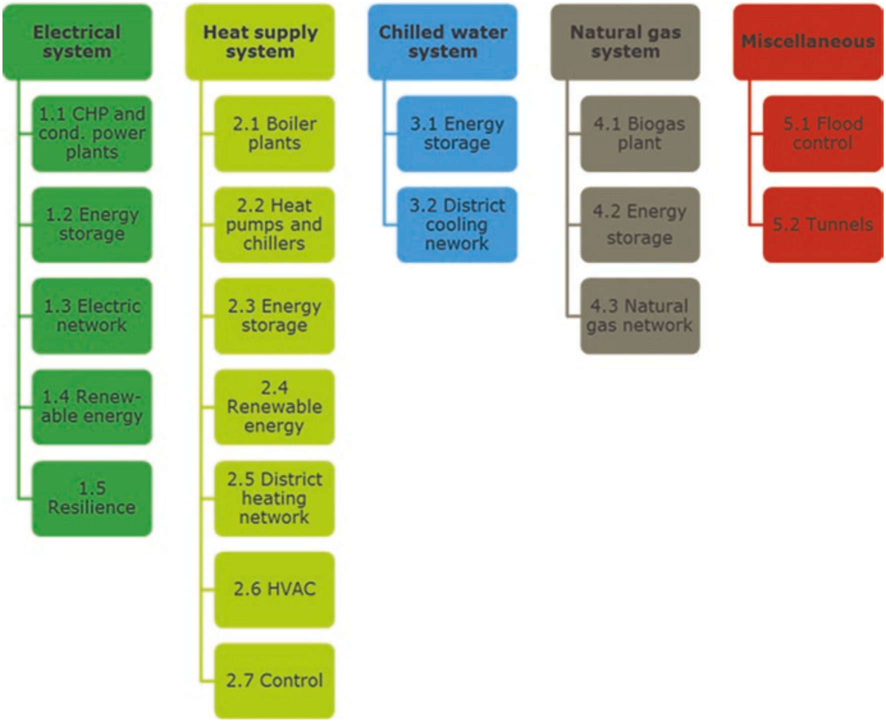


Fig. ES.5 Database structure

Energy Resilience of Interacting Networks (ERIN) Tool

The ERIN tool has been developed to support energy master planning processes that allow for the assessment of resilience of energy supply systems to various Design Basis Threats. The tool operates over networks that supply both individual buildings and districts. These networks comprise components (loads, generation, distribution/routing, storage, and transmission assets) and connections. These connections form the topology of the network—what is connected to what. Multiple flows of energy can be modeled: notably, both thermal (heating/cooling) and electrical flows and their interactions.

This network of components is subject to various scenarios that represent one or more ideal ("blue sky") cases as well as Design Basis Threats ("black sky" events). Each scenario has a probability of occurrence and zero or more intensities associated with it such as wind speed, vibration, and water inundation level. Fragility curves are used to relate the scenario's Design Basis Threat intensities to the percentage chance that a given component will fail to work under the duress of the scenario.

Examining the performance of the network while considering the possibility of failure due to various threats allows resilience metrics such as Energy Robustness (ER), Energy System Recovery Time (Maximum Single Event Downtime—MaxSEDT), or Energy Availability (EA) to be calculated. This can, in turn, help planners to see whether a proposed system or change to an existing system will meet their threat-based resilience goals.

Figure ES.6 shows the information flow and process for using the calculation tool. The goal of the process is to assist a planner in selecting appropriate architectures, configuring them for their local situation, and assessing them for their costs, energy usage, and resilience benefits versus relevant Design Basis Threats. This allows them to compare multiple architectures or different configurations of the same architecture (e.g., using different types or grades of equipment).

The process begins with the user's description of goals, site constraints, and available resources (Fig. ES.6). These criteria can be used to assist the user in selection (filtering out irrelevant choices and/or recommending especially relevant choices) and evaluation (tracking status of a design versus goals and/or constraints).

Next, the planner can proceed to architecture selection from a database of architectures. This selection can be guided based on site criteria. For example, if a user specifies that they have electrical and heating loads only (i.e., no cooling load), only those architectures with heating and electrical supply will be made available to browse from. An architecture is a pre-constructed template for how certain types of technologies are typically connected together. The architecture, once selected, must also be configured to match the user's unique situation. Configuration involves adjusting the selected architecture to better represent the desired situation by choosing specific equipment, specifying multiples, etc. Potential component technologies that fit with the architecture are looked up in a database of technologies. This results in the creation of an input file to be used by the resilience tool "engine."

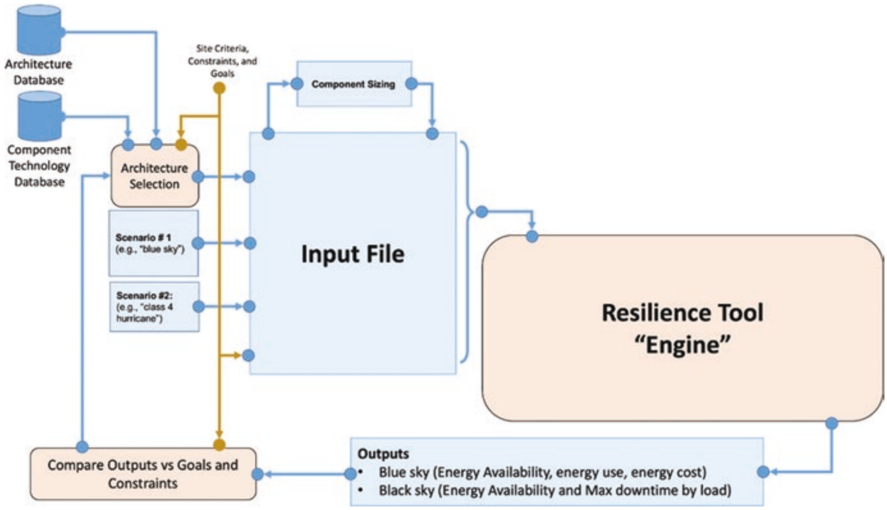


Fig. ES.6 Overall energy and resilience assessment process

Additional data needs include building load profiles for blue sky scenarios as well as black sky scenarios, along with the scenario descriptions themselves. Both blue sky and black sky are categories of scenarios. A blue sky scenario represents normal operating assumptions. In contrast, a black sky scenario involves consideration of Design Basis Threats. Load profiles represent the loads on the network over time for electrical, heating, and/or cooling needs. Load profiles correspond to a given building load or cluster of buildings under a given scenario.

Scenarios have an occurrence distribution, a duration, an optional maximum number of occurrences during the simulation, and, optionally, various Design Basis Threats intensities. Design Basis Threats intensities specify things like the wind speed during a hurricane, the inundation depth during a flood, and the Richter scale during an earthquake. A scenario can also specify whether normal reliability (failure and repair under typical conditions) should (or should not) be considered. Probability of occurrence can be based on actual data for an event.

A component technology database stores information about actual components that can be used by the tool. Components represent equipment on the network: chillers, boilers, backup generators, UPS systems, thermal energy storage tanks, fuel drums, etc. If the user has specific information about a given component, they can specify it. Otherwise, the information can be queried from the component technology database.

Once the architecture selection, configuration, and any sizing have been conducted, an input file can be written for the resilience tool "engine." The input file is parsed by the resilience tool "engine" and a simulation is initiated.

During network simulation, operational components process load requests as best they can. Power is routed according to the dispatch algorithm of the network. At the end of each scenario's simulation, statistics are calculated related to requested load, achieved load, energy availability, and maximum downtime.

When the entire simulation of all scenarios completes, energy robustness, energy recovery, energy availability, energy use, and energy cost can all be calculated for different loads during different Design Basis Threats. Energy system recovery time is represented by maximum downtime in the tool. These metrics can be compared to goals to identify gaps or progress toward a target (see bottom and bottom-left of Fig. ES.7). If sufficient progress has not been made, information from the last run can be used to enhance a subsequent architecture selection and configuration, and the process can continue.

The resilience tool engine and greater process are designed to allow for the assessment of a given network configuration with explicitly defined components and an explicit dispatch methodology. The ultimate audience for the tool and process will be master planners and energy managers. As such, we are trying to achieve a level of detail (fidelity) that is approachable by the target audience while also incorporating more depth and nuance than higher-level (i.e., less detailed) campus-level tools.

Multicriteria Analysis of Alternatives and Scenario Selection

Analysis of the Base Case and alternatives produces quantitative results that allow a determination of how close the users were able to come to achieving their goals and objectives, and a comparison of the Baseline, Base Case, and alternatives using defined criteria. There may be additional conflicting qualitative and quantitative criteria (e.g., risk, safety, comfort, fuel availability, etc.) that can support decisions in defining the roadmap to achieving ultimate framing goals.

The decision criteria are not usually equally important. To support the installation's decision process, users must elicit relative weights for the different criteria from decision-makers. This is not always an easy process, but it does encourage decision-makers to reflect on how they make their decisions.

Multicriteria Decision Analysis (MCDA) can be used to create weighted decision models and support traceable decision processes that integrate quantitative and qualitative factors. MCDA allows for the selection of a reduced set of good, non-dominating alternatives to be presented to decision-makers for final selection.

Implementation

The scope of the Energy Master Plan (EMP) can be broad; it may include new construction, demolition, and consolidation projects; energy supply; and energy distribution and energy storage components, including creative methods to build innovative site-to-grid arrangements that may provide grid stability or site resilience (Fig. ES.7). An EMP is not limited to energy-related projects; it may include a spectrum of non-energy-related projects, including new building construction and

Fig. ES.7 Scope of the Energy Master Plan

demolition, and utility modernization projects and non-energy-related measures to enhance the resilience of energy systems to Design-Based Threats, such as the elevation of energy equipment, construction of flood walls, or burying of cables.

In most cases, an EMP covers multiple interrelated projects (Fig. ES.8) where the outcome of one project or a group of projects influences one or more other projects (e.g., building efficiency improvements impact the size of required energy generation capacity; thermal energy supply to a new building requires installation of a pipe connection to an existing district system; connection of additional buildings to a hot water district system allows for an increase of CHP base load). Therefore, selection of alternatives for an EMP shall be based on the cost effectiveness of the entire EMP instead of individual projects that comprise the EMP. It is possible that some individual projects will not be cost effective when considered separately.

Life-Cycle Cost Analysis (LCCA)

One of the EMP alternatives, the Base Case, serves as a benchmark for LCCA of other alternatives. These alternatives might have different initial investment costs as well as different overall future cost savings, which could result in achieving better performance (e.g., greater energy use reduction, better environmental quality, and/or higher resilience of energy systems). LCCs typically include the following two cost categories: investment-related costs and capital expenditures (CAPEX) and operating expenditures (OPEX).

Investment costs describe total expenses of the investment as (1) buildings and (2) energy supply and distribution systems. These costs include the planning, modeling, design, and implementation of new materials; and the replacement and disposal costs of replaced materials, including both material and labor costs. The number and timing of capital replacements or future investments depend on the estimated life of a system and length of the service period. Sources for cost estimates for initial investments can be used to obtain estimates of replacement costs and expected service lives. A good starting point for estimating future replacement costs is to use initial investment costs along with price escalation factors related to comparable building construction and energy supply investment cost indices.

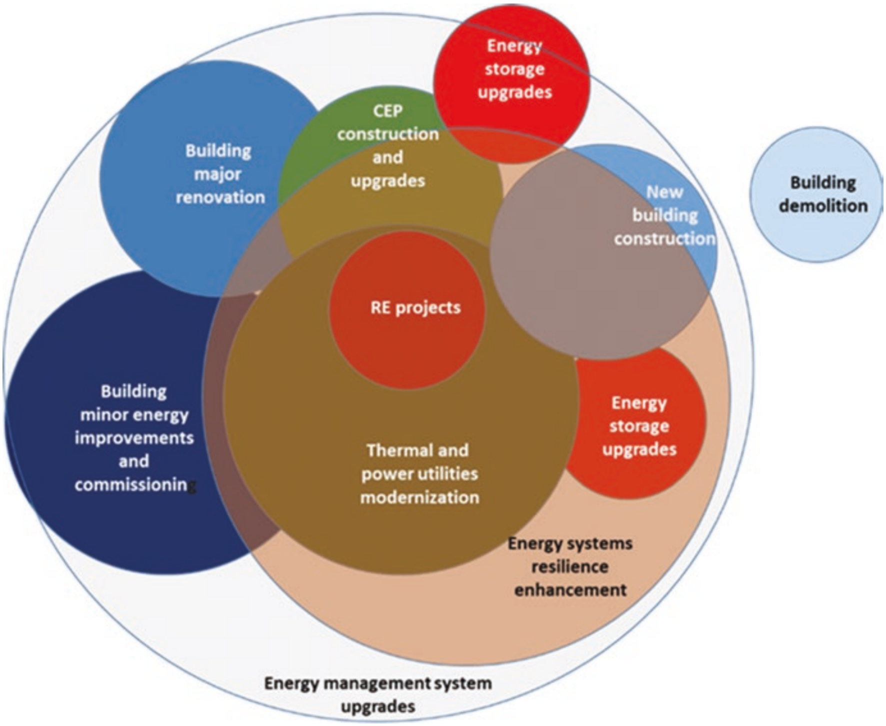


Fig. ES.8 Interrelation of projects under EMP

Synergetic Impacts The determination of the investment costs must consider synergetic impacts that can be obtained from a holistic EMP approach. For example, one approach could be to combine demand reduction on building and energy supply-level measures, which would in turn allow supply to be reduced as a result of the reduction in demand on the building level. Another approach could be to organize piping and cable configurations for thermal and electrical grids located in infrastructure trenches to reduce trenching costs, which, depending on underground conditions, can comprise over 50% of the total grid costs.

While a standard building LCCA broadly considers many operational costs, most cost-effectiveness calculations either on the building or the community level consider only energy cost benefits. However, ambitious energy investments often produce benefits beyond reduced energy consumption and peak demand shaving. Many of these additional benefits contribute to the objectives of organizations that implemented the projects and can have significant added value for those making investment decisions. Prior research (Lohse and Zhivov 2019; Zhivov 2020) has investigated such benefits as the impact of increased thermal comfort on the productivity of the building occupants, or the willingness to pay increased sales prices or rental rates for higher-performing buildings. Nevertheless, the monetization of non-energy benefits ("co-benefits") is still not broadly used on the building or building cluster level.

How to Calculate Risk and Resilience Costs and Benefits A long-duration power interruption and loss of thermal energy, especially in extreme climates, may significantly degrade regional and even national security (e.g., due to the loss of critical infrastructures or degraded critical missions at military bases). It can also affect the health and safety of a community and even result in a loss of human life (Viscusi and Aldy 2003).

While the cost of a given resilience measure is well understood (e.g., the costs of labor and materials to "underground" power lines), the resulting benefits are more difficult to assess, particularly because of a lack of supporting data (LaCommare et al. 2017). Although resilience has currently been acknowledged as a distinct benefit, it has not typically been quantified or valued.

National Renewable Energy Laboratory (NREL) authors Murphy et al. (2020) argue that the types of data that would support the benefits associated with resilience measures are difficult to collect because of the time and types of events needed to demonstrate the value of resilience investments (e.g., 100-year flood events happen so infrequently that the benefits of mitigation measures associated with these events are difficult to quantify in a realistic time frame). Moreover, even if the health, safety, and economic impacts of a threat could be quantified, it is very challenging to translate those impacts into financial consequences, which will ultimately indicate to a given stakeholder whether a change in investment or operations is warranted.

This Guide describes LCCA approaches to compare systems with different levels of energy systems resilience when the benefits of resilience can and cannot be assigned.

Key Risk Factors The decision-making process leading to EMP implementation is comparable to any other investment decision that requires variation analysis. The process assumes certain price, tax, and benefit value deviations. Analysis of a survey of project facilitators, Energy Service Companies (ESCOs), financiers, and insurance companies identified the following key risk factors: capital costs, energy, maintenance and other life-cycle costs, and energy savings. This Guide discusses how the design and execution of de-risking measures during different stages of the EMP development is crucial for the success of the EMP from the economic point of view. The de-risking measures detailed in the following paragraphs focus on the Key Risk Factors (investment and energy cost).

Business Models Table ES.5 lists the scope of different business models. For many public agencies and communities, it is important to reduce the number of parties involved to minimize both the effort required to manage these parties and the intersections between the different scopes that each party is willing to cover. Table ES.5 also lists the number of different parties involved in the process to illustrate the full spectrum of all six stages. Further explanation is provided in the respective descriptions of the different business models.

Table ES.5 Selection aide for business models in communities—comparison of EMP business models

Business model	Description	Pros	Cons
Appropriated funds	Funds appropriated by the governing agency as part of the yearly budgetary process; execution supervised by agency and subcontracting parties	Straight forward—follows the normal processes for capital improvement program Can be done incrementally for several years Manages resource to highest-priority areas	Subject to normal budget priorities Must be managed internally Follows normal design-build processes —no extended guarantees No energy performance guarantees No budget limitation guarantee
Fixed Payment	Funded by a utility. Paid back via fixed payments on the utility bill or on the property tax bill	Easily implemented Usually low interest rates Payment stays with the property in case property is sold	No energy guarantee Usually limited to small projects EMP implemented in pieces
ESPC	Energy Savings Performance Contact	Budget neutral Energy/operations savings pay for the upgraded systemsThird party manages the contract Energy savings are guaranteed, resulting in lowered financing rates Multiple technical updates can be built in	Not readily understood by many municipal officials Typically need a third-party expert to advocate for the customer Long approval cycles on final project/financing by customer Concerns by some decision makers on long-term debt
Utility Energy Service Contract (UESC)	Utility Energy Savings Contract	Budget neutral Energy/operations savings pay for the upgraded systemsThird party manages the contract Customer contracts with their utility—people they know Customer decides level of energy guarantee	Not readily understood by many municipal officials Typically need a third-party expert to advocate for the customer Long approval cycles on final project/financing Concerns by some decision makes on long-term debt Not all utilities offer this service

(continued)

Table ES.5 (continued)

Business model	Description	Pros	Cons
Blended Funding	Combining appropriated funding with ESPC/UESC	Same as ESPC/UESC Shorten financing term by injecting one-time or multiple cash payments Can get more energy conservation measures (ECMs) in the project	Same as ESPC/UESC Ensuring that the cash payments are available in the budget
PPA	Power Purchase Agreement—buy power from a non-utility partner or developer	Developer pays all costs Customer buys power at a price At the end of the contract period, customer can buy the equipment for fair market value or have it removed Developer may pay a lease payment to use customer land Consistency of long-term budget planning	Long-term procurement contract for customer—typically 20 years Energy prices may be fixed or escalated Locked in prices result in not being able to take advantage of potential future lower pricing
EUL	Enhanced Use Lease—customer leases underutilized land to a third party in exchange for resiliency	Developer pays all costs Lease payment is often "In Kind Consideration," which is often required or needed customer infrastructure updates If utility power is lost, the power being produced on the leased land is sent to the customer	Lease is 30–40 years Power from the leased land is sold to the utility grid or may be bought by the customer Land is unavailable for future customer expansion

Major Barriers for EMP Implementation Using ESPC and Utility Energy Savings Contract (UESC)

Operations and Maintenance Some savings opportunities can support many resilience projects without capturing operations and maintenance (O&M) savings; many others are only possible if they can capture those truly avoided costs that help finance a project. For example, many US Department of Defense (DoD) installations have several hundred backup generators, which are often inefficient, oversized, and expensive to maintain. Installing a microgrid that eliminates all standalone generators, or that maintains only a few configured into the microgrid, can produce significant O&M savings.

The DoD's current approach to the funding of standalone generators represents another major barrier to the implementation of microgrids. Although our cost analysis shows that microgrids can generate sufficient savings and revenue to make them attractive to Energy Savings Performing Contract (ESPC) and UESC vendors, the Services report that their proposed microgrid projects do not “pencil out” for private vendors. The difference relies on an accounting distinction: whereas our calculation considered all of the costs that standalone generators impose on a hypothetical base (capital, O&M, etc.), the DoD’s accounting system provides no such recognition; the costs of standalone generators on a base are paid out of multiple budget activities and by dozens of tenants. For third-party financing to “pencil out,” the DoD needs to recognize the costs that it already pays for energy security (Marqusee et al. 2017).

Military Construction Projects A significant majority of ESPC projects combine appropriations with private financing, per 42 U.S.C. § 8287(a)(2)(E), which provides funding options. In carrying out a contract under this subchapter, a Federal agency may use any combination of appropriated funds and private financing under an energy savings performance contract.

UESCs may be fully funded or may include any combination of appropriations and financing. The DoD has determined that it is prohibited from using Military Construction (MILCON) funds in conjunction with an ESPC or UESC. Even ERCIP (Energy Resilience and Conservation Investment Program) funds are off-limits because MILCON is the source of ERCIP funds. Where MILCON or ERCIP funds are available for resilience projects, more comprehensive, coordinated projects could be carried out more quickly and more seamlessly if those funds could be combined with ESPC or UESC. Additionally, such a funding combination could guarantee or assure more savings and those savings could be leveraged for even more investment than the total investment of separate projects—some privately financed and others funded with appropriations.

Utilities Privatization in DoD In resilience planning, consideration should be given to the status of utilities at a given DoD installation. In particular, where utilities privatization has occurred, there will be a need to coordinate with the utilities privatization contractor to ensure that resilience capabilities are at the ready. According to the Office of the Assistant Secretary of Defense for Sustainment (https://www.acq.osd.mil/eie/IE/FEP_Utilities.html), maintaining access to reliable, resilient, and cyber-secure energy resources, generation assets, distribution infrastructure, and facility-related controls and data is critical to the execution of DoD missions. Alternative Financing Mechanisms (AFMs) leverage commercial sources of capital to finance near-term enhancements to DoD utility infrastructure.

As part of a comprehensive Installation Energy Plan (IEP), AFMs can provide material benefits to DoD Components by providing cost-effective access to capital that might not otherwise have been obtainable through traditional methods. AFMs require DoD Components, however, to also use contractual mechanisms to ensure compliance with energy security, energy resilience, and cybersecurity requirements. Utilities privatization is one of several AFMs that a Military Department may use to finance utility improvements in support of the DoD’s energy reliability, energy resilience, and cybersecurity goals. In the privatization process, military installations shift from the role of owner/operator to that of smart utility service customer. Privatized systems continue, however, to function as Defense Critical Infrastructure (DCI) such that a DoD Component's decision to pursue utilities privatization must be consistent with prioritized mission assurance requirements (10 U.S.C. 2688), applicable DoD instructions and guidance, and the affected installation's IEP.

Structure of the Guide

This Guide has been developed to provide a deeper understanding of the Energy Master Planning process through the lens of best practices and lessons learned from case studies from across the globe. It helps to establish objectives and constraints for energy planning, and to give a better understanding of available technologies and energy system architectures that combine to comprise a diverse set of local energy supply and demand considerations. The Guide introduces concepts and metrics of energy system resilience methodologies and discusses business and financial models for Energy Master Plans implementation.

Based on the architectures and an extensive technology database that includes prime movers, network distribution components, and auxiliary equipment needed in a system, a tool has been developed to help inform energy planners, energy engineers, system and building developers, political leaders, building owners, and city planners to better analyze and address their own local circumstances. The tool conducts a multicriteria analysis of alternatives and scenario selection that integrates economic, energy, and resiliency targets.

The Guide is organized into the following chapters and appendices.

- Chapter 1 is an introduction to the Guide.
- Chapter 2 focuses on the integration of energy planning into community planning.
- Chapter 3 details the methodology of Energy Master Planning and the process of integration of Energy Systems Resilience Analysis into the Energy Master Plan.
- Chapter 4 is devoted to establishing energy goals and constraints.
- Chapter 5 provides an understanding of the data required for Energy Master Planning and resilience analysis.
- Chapter 6 focuses on defining, measuring, and assigning resilience requirements.
- Chapter 7 provides a methodology for the selection of energy system architecture and technologies.
- Chapter 8 describes a tool that supports analysis of the Baseline and different energy alternatives.
- Chapter 9 delves into the multicriteria analysis of alternatives and scenario selection: integrating economic, energy, and resiliency targets.
- Chapter 10 describes economic and business aspects of Energy Master Planning.

The Guide is also accompanied by a separate book of Case Studies.

References

Case, M., R. Liesen, M. Swanson, J. Yu, and A. Zhivov. 2015. Integration of master planning and energy planning: From detailed to conceptual analysis. *ASHRAE Transactions* 121 (1): 133–140.

Danish Energy Agency, The. 2019. *Socio-economic analysis methodology and assumptions*. Copenhagen: Danish Ministry of Climate, Energy, and Utilities. https://ens.dk/service/fremskrivninger-analyser-modeler/samfundsoekonomiske-analysemetoder.

———. 2020. *Technology data*. Copenhagen: Danish Ministry of Climate, Energy and Utilities. https://ens.dk/en/our-services/projections-and-models/technology-data.

Güssing, Borough of. 2011. *Case study: The European Centre for renewable energy (EEE) in Güssing as an example of how synergies can be realized*. http://www.guessing.co.at/.

IEA. 2021b. *Annex 73. Energy master planning for resilient public communities – Case studies*, ed. Anna Maria Fulterer and Ingo Leusbrock. Paris: International Energy Agency, Energy in Buildings and Communities (IEA-ECB), Annex 73. https://annex73.iea-ebc.org/.

LaCommare, Kristina, Peter Larsen, and Joseph Eto. 2017. *Evaluating proposed investments in power system reliability and resilience: Preliminary results from interviews with public utility commission staff*, LBNL-1006971. Berkeley: Lawrence Berkeley National Laboratory. https://doi.org/10.2172/1342947.

Lohse, R., and A. Zhivov. 2019. *Deep energy retrofit guide for public buildings – Business and financial models*. Basel: Springer.

Marqusee, Jeffrey, Craig Schultz, and Dorothy Robyn Noblis. 2017. *Power begins at home: Assured energy for U.S. military bases*, 24. Reston: Noblis, Inc. https://www.pewtrusts.org/~/media/assets/2017/01/ce_power_begins_at_home_assured_energy_for_us_military_bases.pdf.

Murphy, Caitlin, Eliza Hotchkiss, Kate Anderson, Clayton Barrows, Stuart Cohen, Sourabh Dalvi, Nick Laws, Jeff Maguire, Gord Stephen, and Eric Wilson. 2020. *Adapting existing energy planning, simulation, and operational models for resilience analysis*, NREL/TP-6A20-74241. Golden: NREL. https://www.nrel.gov/docs/fy20osti/74241.pdf.

OASD (Office of the Assistant Secretary of Defense). 2016. *Memorandum. Subject: Installation energy plans*. Washington, DC: OSD. https://www.acq.osd.mil/eie/Downloads/IE/Signed%20Installation%20Energy%20Plan.pdf.

OUSD (Office of the Under Secretary of Defense). 2021. *Memorandum. Subject: Metrics and standards for energy resilience at military installations*. Washington, DC: OUSD. https://www.acq.osd.mil/eie/Downloads/IE/Metrics%20and%20Standards%20for%20Energy%20Resilience%2020%20May%202021.pdf.

Singh, Birendra (Rob), Pallavi Roy, Thierry Spiess, Bala Venkatesh. 2015. *Sustainable integrated urban and energy planning, the evolving electrical grid and urban energy transition*. Toronto: Ryerson University, Centre for Urban Energy. https://www.ryerson.ca/content/dam/cue/pdfs/White%20Paper%20-%20Urban%20and%20Energy%20Planning.pdf.

UNEP (United Nations Environment Programme). 2013. *Energy efficiency for buildings*. Paris: UNEP. www.studiocollantin.eu/pdf/UNEP%20Info%20sheet%20-%20EE%20Buildings.pdf.

Viscusi, W. Kip, and Joseph E. Aldy. 2003. The value of a statistical life: A critical review of market estimates throughout the world. *Journal of Risk and Uncertainity* 27 (1): 5–76.

Zhivov, Alexander M., Michael Case, Richard Liesen, Jacques Kimman, and Wendy Broers. 2014. Energy master planning towards net zero energy communities/campuses. *ASHRAE Transactions* 119 (1): 325. NY-14-010. New York: ASHRAE winter conference.

Zhivov, Michael. 2020. Enhanced life-cycle cost analysis of sustainable office buildings. *ASHRAE Transactions* 126 (1): 691–712.

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Chapter 1
Introduction

Abstract Best practices from around the world have proven that holistic Energy Master Planning can be the key to identifying cost-effective solutions of energy systems that depend on the climate zone, the density of energy users, and local resources. The Energy Master Planning can be applied to different scales of communities, for example, a group of buildings, a campus, a city, a region, or on the national scale. However, to benefit from synergies and to avoid suboptimization, successful Energy Master Planning at the desired community scale should include an assessment of and considerations for the Energy Master Plan at the given scale. This chapter provides an overview of the guide that has been developed to provide a deeper understanding of the Energy Master Planning process through the lens of best practices and lessons learned from case studies from across the globe. It helps in establshing energy goals, objectives, and constraints for energy planning and gives a better understanding of technologies available and energy system architectures to represent a diverse set of local energy supply and demand considerations. The guide introduces concepts and metrics of energy system resilience methodologies and discusses business and financial models for Energy Master Plans implementation.

1.1 Energy Master Planning and Community Planning

Until recently, community energy plans in most countries have been high-level strategy documents rather than planning documents (Singh et al. 2015). The synergy between community and energy planning becomes an essential component that is critical for:

- Developing energy-efficient, sustainable, more resilient communities
- Providing incentives in using large-scale renewable energy sources
- Encouraging the use of community-scale generation, distribution, and energy storage technologies that increase resilience to natural and man-made threats to energy systems (both thermal and electric) and that boost local economies.

Some countries have had a long tradition for city-level energy supply planning. In many European cities, particularly, a public utility is responsible for serving the

A. Zhivov, *Energy Master Planning toward Net Zero Energy Resilient Public Communities Guide*, https://doi.org/10.1007/978-3-030-95833-6_1

city with electricity, gas, and heat. Experience in these areas reveals that countries and cities that set up energy efficiency and climate targets find it important to work with community energy plans. The European Union (EU), for example, has established a legal framework (directives for energy efficiency, renewable energy, and buildings) for community energy planning and requires member states to implement the directives in national plans. This legislation builds on best practice from several EU countries where municipal energy planning has been driven by local publically owned utilities that harvest local synergies and resources. In Sweden and Finland, this has mainly involved district heating based on local biomass; in Norway, electric heating based on hydropower; and in Denmark, district heating based on maximal use of combined heat and power (CHP) and waste heat potential, combined with a new natural gas infrastructure connected to individual residential houses to reduce the dependency on imported oil. (Efforts in Denmark were undertaken to increase resilience at national level in reaction to the oil crises of 1973 and 1979.)

Energy Master Planning is especially valuable and critical when working with community- and campus-scale district energy systems that use a centralized plant for generating heating, cooling, and even power and for distributing these utilities via a network to serve the aggregate heating, cooling, and power loads of multiple buildings. Such planning enables these district energy systems to better size generation capacity by leveraging the diversity of loads across different building types, to enhance economies of scale, and to increase energy efficiency relative to each building by supporting its own local generation. The scale provided by district energy systems also enables the use of lower carbon resources such as biomass and lake and seawater cooling, which is not feasible at a building scale.

While the integration of the Energy Master Planning into Community Master Planning process has its challenges, it also provides significant opportunities to support energy-efficient and resilient community concepts, including increased budgets for investments derived from energy savings, more resilient and cost-effective systems, increased comfort and quality of life, and local production that boosts local economies.

1.2 Lessons Learned from Case Studies

Experiences from the case studies (Appendix B and [IEA 2021]) show that the Energy Master Planning that includes both demand and supply systems cost-effectively increases energy efficiency improvement on the national level by maximizing use of combined heat and power and recycling all heat from waste incineration. Case studies from North American universities demonstrated the cost-effectiveness of upgrading district steam and district cooling systems on the campus and building levels by taking advantage of the fact that all renovation costs and operational benefits are attributed to a single university budget. The Energy Master Plans described in the case studies were conducted with a variety of different objectives, ranging from the simple desire to improve the economic “bottom line” by reducing operating costs; to improving the energy system’s resilience; to achieving net-zero greenhouse gas emissions at the building and campus levels, thereby avoiding greenhouse gas taxes. Experience with the first energy-neutral town in the world showed that a transition to a 100% renewable energy supply (Güssing 2011) can triple tax incomes and thus boost the local economy within 15 years.

An analysis of case studies collected and summarized in Appendix B as a part of the Annex 73 project supports the following observations:

- Typically, Energy Master Plans help to minimize total life-cycle costs, support decarbonization of energy supply to end users, and increase the resilience of thermal and power energy supply systems.
- In some cases, an increase in the density of built environment, combined with the increased use of mechanical ventilation and new requirements for building cooling systems due to rising outdoor air temperatures and improved environmental quality standards, results in an increase in the community’s energy use and a corresponding increase in energy cost. This can also result in a need for additional power generation and an increase in required heating and cooling capacity.
- The use of novel and more efficient end-use technologies and Building Energy Management Systems and energy supply solutions, including thermal energy storage; combined heating, cooling, and power generation; and reversible heat pumps, and the broader use and integration of energy generation from renewable energy sources into distribution grids can all help to slow or even reverse the increase in energy demand, to reduce the size of energy generation equipment by shaving peak loads (in particular the cooling peak in warm climates), and to make energy systems more resilient to the growing number of different natural and man-made threats and hazards. Existing thermal and power distribution networks can be expanded or combined to integrate existing energy generation equipment dedicated to individual buildings and building clusters, which results in improved operational efficiency, provides additional capacity required for peaking loads, and provides generation and distribution redundancy resulting in enhanced resilience of energy systems.
- Integrated energy systems can act as a “virtual battery” (see Chap. 7); district heating can be provided by a CHP plant, heat pumps, electric boilers, and thermal energy storage (TES) units, which allow equipment operation to be scheduled in response to daily (and weekly) fluctuations in electricity market prices caused by the wind variations. A number of case studies (primarily from Germany and Denmark) illustrate current trends in replacement of old inefficient steam systems and superheated water by modern state-of-the-art district hot water systems, which resulted in reduced operating costs, increased overall system efficiency, an integration of waste heat from the industry and from renewable energy sources directly and via heat pumps, and improved system resilience. This experience can be valuable for US campuses and military installations as 95% of all campus heating systems are steam based. This modernization and conversion involves major capital outlays and can disrupt normal business activities, particu-

larly when converting buildings from steam to hot water systems, and is therefore often undertaken as a phased implementation based on the state of each system.

- While water-based systems are the current vanguard of district energy due to the flexibility of generation technology and lower temperature efficiencies, steam systems are still a viable and efficient method for heating buildings. For example, some buildings, such as hospitals and laboratories, need access to the higher temperatures associated with steam for the purposes of sanitization. Steam is also highly pressurized, which allows it to use smaller distribution pipes and to better move heat in high-rise buildings. Existing steam systems may also be paired with hot water as the system expands and adds new customers/users.
- Well-insulated building envelopes; efficient heating, ventilating, and air-conditioning (HVAC) systems with large surface radiant heating and cooling technologies (e.g., floor- or ceiling-mounted heating and cooling); and the use of building core activation that can use smaller temperature difference between supply and return water used for heating and cooling allow for the use of district systems with low-temperature heating and high-temperature cooling. This in turn enables the use of low exergy sources, i.e., ground (geothermal), solar thermal and groundwater, river or lake water, heat from sewer systems, etc. This also increases the buildings' thermal energy system resilience, as they can be decoupled from thermal energy sources for a longer time.
- Case studies from Finland and Denmark show a trend toward the combination of heating and cooling. In highly efficient buildings, cooling may become a necessity where it may not have been before; the two thermal systems can be integrated to share the thermal energy in return water from the complementary heating/cooling system.
- In campuses where all buildings share a single owner, e.g., university campuses, medical centers, and military installations, energy efficiency measures made to individual buildings (e.g., building envelope renovation, replacing HVAC equipment and lighting systems with more efficient ones) can be used to reduce community-wide peak demand. When such projects are planned and scheduled as a part of a holistic Energy Master Plan, they can improve the cost-effectiveness of the plan by improving building environmental conditions, better using resources, and enhancing system resilience. This approach requires collaboration between all stakeholders and strategic timing of different projects (HTF Stuttgart, Germany). In one instance, where the energy supply system was owned by the city (e.g., case study for Copenhagen, Denmark), the utility company was able to minimize energy cost to all consumers. Single-owner campuses are better situated to this use approach than are local communities with numerous building owners since single-owner campuses can optimally time the building renovation for all campus buildings.
- Emergency power backup solutions are typically limited to the use of emergency diesel or gas-fueled generators that are maintained for use only during power loss from the grid. Typically, they provide power to mission-critical operations and support life and safety needs. For example, some cost-effective microgrids

implemented in the United States have connected critical users to gas-fueled CHP plants to provide energy assurance when power grid performance degrades.

- Similarly, peak boilers for the district heating system can be located close to critical consumers, e.g., a hospital, to ensure a more resilient heat supply (Vestforbrænding, Denmark).
- Microgrids are not common in European countries, where most of power grids are reliable. However, in some cases (e.g., at the Technical University of Denmark), microgrids are used to avoid distribution tariffs since the costs of operating their own low-voltage grid are lower than the distribution tariff from the utility. In such cases, even large gas-driven CHP plants located on the campus are not connected to the campus grid but are rather connected to the utility grid and operated based on market energy prices.

For existing large areas, the planning process is complex and includes consideration of future use and energy costs as well as maintenance and operation of existing infrastructure. Implementation plans for energy systems cover many years of actions to increase efficiency, resilience, and reliability. These plans are important to provide the scope, schedule, and security to projects funded either directly or using a third-party financing.

1.3 Structure of the Guide

This guide has been developed to provide a deeper understanding of the Energy Master Planning process through the lens of best practices and lessons learned from case studies from across the globe. It helps in establishing objectives and constraints for energy planning and gives a better understanding of technologies available and energy system architectures to represent a diverse set of local energy supply and demand considerations. The guide introduces concepts and metrics of energy system resilience methodologies and discusses business and financial models for Energy Master Plans' implementation.

Based on the architectures and on an extensive technology database that includes prime movers, network distribution components, and auxiliary equipment needed in a system, a tool has been developed to help inform energy planners, energy engineers, system and building developers, political leaders, building owners, and city planners to better analyze and address their own local circumstances. The tool conducts a multicriteria analysis of alternatives and scenario selection: integrating economic, energy, and resiliency targets.

The guide is organized into several chapters and appendices:

- Chapter 2 focuses on the integration of energy planning into community planning.
- Chapter 3 details the methodology of Energy Master Planning and the process of integration of Energy Systems Resilience Analysis into the Energy Master Plan.
- Chapter 4 is devoted to establishing energy goals and constraints.

- Chapter 5 provides an understanding of the data required for Energy Master Planning and resilience analysis.
- Chapter 6 focuses on defining, measuring, and assigning resilience requirements.
- Chapter 7 provides a methodology for the selection of energy system architecture and technologies.
- Chapter 8 describes a tool that supports analysis of the Baseline and different energy alternatives.
- Chapter 9 delves into the multicriteria analysis of alternatives and scenario selection: integrating economic, energy, and resiliency targets.
- Chapter 10 describes economic and business aspects of Energy Master Planning.

The guide is also accompanied by a separate book of case studies.

References

Güssing, Borough of. 2011. *Case study: The European Centre for renewable energy (EEE) in Güssing as an example of how synergies can be realized*. http://www.guessing.co.at/.

IEA (International Energy Agency). 2021. *Annex 73. Energy master planning for resilient public communities – Case studies*, ed. Anna Maria Fulterer and Ingo Leusbrock. Paris: International Energy Agency, Energy in Buildings and Communities (IEA-ECB), Annex 73. https://annex73.iea-ebc.org/.

Singh, Birendra (Rob), Pallavi Roy, Thierry Spiess, Bala Venkatesh. 2015. *Sustainable integrated urban and energy planning, the evolving electrical grid and urban energy transition*. Toronto: Ryerson University, Centre for Urban Energy. https://www.ryerson.ca/content/dam/cue/pdfs/White%20Paper%20-%20Urban%20and%20Energy%20Planning.pdf.

Chapter 2
Energy Planning as a Part of the Community Master Plan

Abstract For existing large areas, the planning process is complex and includes consideration of future use and energy costs as well as of maintenance and operation of existing infrastructure. Implementation plans for energy systems cover many years of actions to increase efficiency, resilience, and reliability. These plans are important to provide the scope, schedule, and security to projects funded either directly or using third-party financing.

The process of building efficient, sustainable, resilient communities requires careful coordination between stakeholders, including master planners, energy planners, and building designers. These stakeholders work at differing levels of detail and use different planning horizons, which may lead to suboptimal decisions for the community as a whole.

The process of building efficient, sustainable, and resilient communities requires careful coordination between a number of stakeholders, including master planners, energy planners, and building designers. These stakeholders work at differing levels of detail and use different planning horizons, which may lead to suboptimal decisions for the community as a whole. Coordinating the myriad stakeholders involved in community planning is daunting.

Three levels of stakeholders can readily be identified. At the highest level of abstraction, master planners think in terms of long-term sustainability goals, including national energy strategy, community layout, transportation, and street design; in this planning activity, planners break down barriers between sectors and cities. To address sustainability, master planners have to look at the society as a whole and extend the length of their view to 25 or more years (Case et al. 2015). Energy managers fall within the middle tier of abstraction; their work, which focuses on the local community or campus, may vary between longer-term energy infrastructure projects, such as district energy systems, and medium- or near-term projects, such as building retrofits designed to meet community energy goals. Finally, the building (or infrastructure) designer falls into the most detailed level of abstraction. These engineers must create designs for a specific project that can be shown to be effective, buildable, biddable, and cost-effective.

A. Zhivov, *Energy Master Planning toward Net Zero Energy Resilient Public Communities Guide*, https://doi.org/10.1007/978-3-030-95833-6_2

Similarly, energy planners who plan the national level or city level should recognize the opportunities at campus or building level. Instead of planning new power capacity at locations far from the cities, integrated planning could prove that it would be more efficient to locate the plant on the city outskirts and to combine it with the development of a district heating system that would allow all buildings to be connected and renovated to use a lower-temperature heating system. For example, the Danish Electricity Supply Act of 1976 gave the Minister the power to approve new power capacity and to combine it with the local city-level heat supply planning; as a result, all the CHP potential is now used. The EU directive for energy efficiency has a similar requirement, although it is not binding for the member states. Energy legislation in the EU, in particular the Energy Efficiency directives and the Renewable Energy directive, sets the legal framework for community energy planning in which member states and communities shall consider the option of district heating and cooling to transfer renewable and surplus energy to the buildings in the spatial planning. In Denmark, such a legal framework was established in 1979 specifically to reduce the dependency on imported oil and to cost-effectively increase the energy efficiency for communities by combining district heating based on the CHP potential and to use the waste heat from large buildings with a new natural gas infrastructure to heat small buildings.

In all cases, the creation of higher-level master plans should consider and incorporate the long-term goals formulated on the regional or state level. Development and implementation of Energy Master Plans require that there be effective communication and coordination between these three stakeholders. For instance, the use of compact development in an area development plan (part of a master plan) may lead to more efficient use of district energy systems and may result in lower source energy use. To this end, the master planner and energy manager should work together to consider energy options across the community. Similarly, attainment of sustainability goals may require that buildings not exceed particular energy budgets or that they connect to district thermal or electrical systems. The overall goals and their rationale need to be factored into individual building design goals. There are numerous examples of projects in which building designers were not aware of the benefits of connecting buildings to a nearby heating and cooling loop that had excess capacity and more efficient and environmentally friendly sources, such that they were consequently required to purchase unnecessary additional equipment. In other examples, requirements for condensate collection from HVAC systems were met, but the condensate ended up being disposed of in a sanitary sewer system because there was no provision for using the recovered condensate.

Case et al. (2015) described a multi-tier process of real property master planning. The process generally starts with a 25-year sustainability plan that lays out overarching goals for the installation community. These goals typically include a vision, support for the installation's mission, energy, water, waste, natural resources, and other topics. The master planner produces a real property master plan (RPMP) that may contain the following subsections or sub-plans (AFCESA 2020):

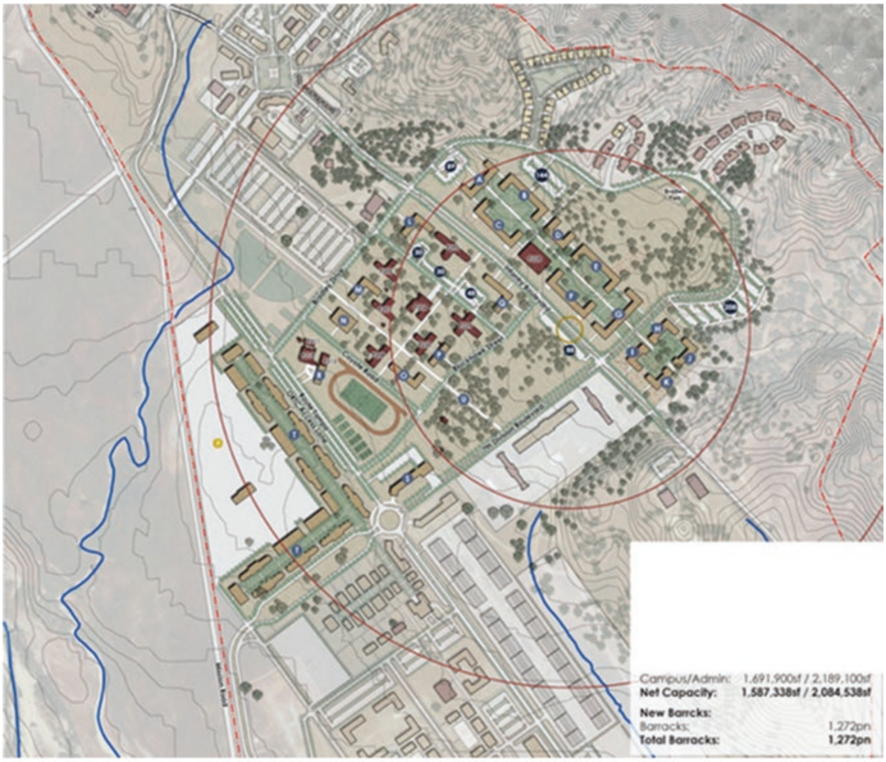
- Master plan
- Vision plan
- Framework plan (which subdivides the community into planning districts and identifies key planning concepts to guide the district planning effort)
- Constraints and opportunities map
- Community development plan
- Area development plans
- Regulative plan
- Illustrative plan
- Implementation plan
- Network plans
- Overall regulation plan
- Transportation plan
- Pedestrian plan
- Open space plan
- Community planning standards
- Community design guide.

The vision plan contains notes about assumptions for energy and environmental conditions over at least 50 years and conceivably over 100 years. The overall regulation plan may require a section on water use limitations. The community planning standards and design guide contain explicit instructions about design conditions.

The area development plan (ADP) breaks the overall community into areas, each of which is planned separately. Figure 2.1 shows an example of an overall illustrative plan for one of military installations. The ADP documents the envisioned future state for the listed area of the community, including a description of existing buildings that will be retained (and possibly renovated), buildings that will be demolished, and buildings to be built.

Using information presented in the ADP, the planner can develop necessary components of the Energy Master Plan: the Baseline and the Base Case. Adopting the terminology from Zhivov et al. (2014), the Baseline represents current energy use for the ADP; the Base Case represents the future state (existing buildings—demolished buildings + planned buildings); and other alternatives represent the Base Case with modifications. In planning such alternatives, it is important to consider the integration of supply and demand, which leads to optimized solutions.

Integration of energy planning into community planning requires a holistic approach to the planning process and the availability of new concepts, instruments, and tools to master planners, energy managers, decision-makers, and stakeholders. Energy Master Planning is a complex process that includes cultural, organizational, technical, legal, and financial aspects. The following chapters of the guide describe Energy Master Planning concepts and tools that focus primarily on technical and financial aspects of this process.



Source: Case et al. (2014a,b).

Fig. 2.1 Example of illustrative plan for a military installation. (Source: Case et al. 2014a, b)

References

Air Force Civil Engineer Support Agency (AFCESA). 2020. *Installation master planning*, Unified Facilities Criteria (UFC) 2-100-01. Washington, DC: Headquarters, U.S. Army Corps of Engineers (HQUSACE), Naval Facilities Engineering Command (NAVFAC), and AFCESA (Preparing Agency).

Case, M., R. Liesen, A. Zhivov, M. Swanson, B. Barnes, and J. Stinson. 2014a. A computational framework for low-energy community analysis and optimization. *ASHRAE Transactions* 120: 130–144.

Case, Michael, Richard J. Liesen, Alexander Zhivov, Matthew Swanson, Benjamin Barnes, and James Stinson. 2014b. *A computational framework for low energy community analysis and optimization*, NY-14-011, 283. New York: ASHRAE Winter Conference.

Case, M., R. Liesen, M. Swanson, J. Yu, and A. Zhivov. 2015. Integration of master planning and energy planning: From detailed to conceptual analysis. *ASHRAE Transactions* 121 (1): 133–140.

Zhivov, Alexander M., Michael Case, Richard Liesen, Jacques Kimman, and Wendy Broers. 2014. Energy master planning towards net zero energy communities/campuses. *ASHRAE Transactions* 119 (1): 325. NY-14-010. New York: ASHRAE winter conference.

Chapter 3
Methodology of Energy Planning Process

Abstract The objective of the community/installation energy plan is to produce a holistic roadmap that enables planners to work constructively toward various framing energy goals within defined community-specific constraints. The Energy Master Planning concept described in this guide differs from previously developed concepts in such a way, that in addition to meeting the community's framing energy goals, it integrates the development of a highly resilient "backbone" of energy systems that allow communities to maintain critical missions and service operations effectively during extended outages over a range of emergency scenarios, whether caused by weather, manmade events or aging infrastructure.

The integrated approach described in this chapter results in the cost-effective operation of energy systems under normal (*blue sky*) conditions and in a less vulnerable, more secure, and more resilient energy supply to the community's critical mission functions during emergency (*black sky*) scenarios. It provides a framework for the planning process and outlines the main steps. These steps include (1) establishment of energy framing goals and constraints, (2) assessment of a community's critical missions and functions, (3) assessment of community-specific threats, (4) establishing energy requirements for normal and mission-critical functions; (5) assessment of the current situation (baseline) to understand existing gaps against framing goals and constraints, and (6) development of future alternatives, including "business as usual" (base case) and more advanced alternatives of energy systems.

3.1 Concept

The objective of the community/installation energy plan is to produce a holistic roadmap that helps the community/installation to work constructively to meet its various framing energy goals within defined community-specific constraints. Different public and private communities have mission-critical and life and safety needs. Over the past two decades, major disruptions of electrical and thermal energy supply have degraded critical mission capabilities and caused significant economic impacts on private and public communities.

A. Zhivov, *Energy Master Planning toward Net Zero Energy Resilient Public Communities Guide*, https://doi.org/10.1007/978-3-030-95833-6_3

The concept of Energy Master Planning described in this guide differs from previously developed definitions (OSD 2016; Zhivov et al. 2014; IEA Annex 51) in that, in addition to meeting a community's framing energy goals, it also integrates the development of a highly resilient "backbone" of energy systems that allows the community to maintain its critical missions and service operations effectively during extended outages over a range of emergency scenarios, whether caused by weather, man-made events, or aging infrastructure.

The integrated approach described in this section (Fig. 3.1) results in cost-effective operation of energy systems under normal (*blue sky*) conditions and in a less vulnerable, more secure, and more resilient energy supply to the community's critical mission functions during emergency (*black sky*) scenarios. It provides a framework for the planning process and outlines the main steps. These steps include (1) establishment of energy framing goals and constraints, (2) assessment of a community's critical missions and functions, (3) assessment of community-specific threats, (4) establishing energy requirements for normal and mission-critical functions, (5) assessment of the current situation (Baseline) to understand existing gaps against framing goals and constraints, and (6) development of future alternatives, including "business as usual" (Base Case) and more advanced alternatives of energy

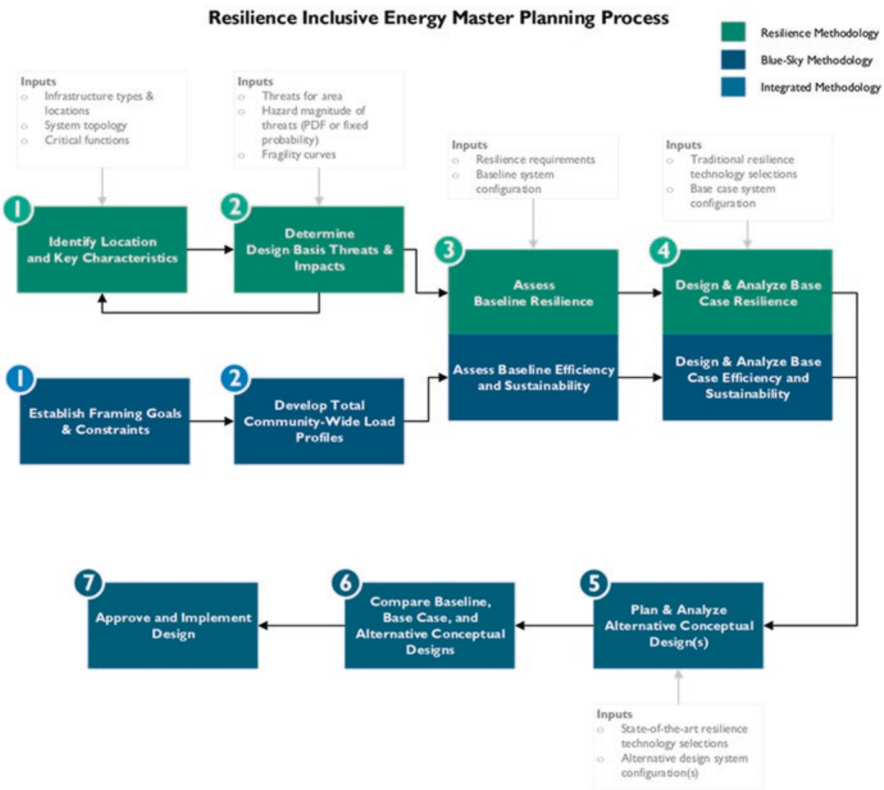


Fig. 3.1 Integration of Energy Systems Resilience Analysis into Energy Master Plan

systems. Quantitative metrics should be used to compare Baseline, Base Case, and future alternatives. *Blue sky* and *black sky* alternative architectures can be built upon the database of technologies and architectures summarized from internationally available best practices (Chap. 7).

Steps presented in Fig. 3.1 within blue shaded boxes outline the part of the Energy Master Planning process that considers energy goals, constraints, loads, and operation of all buildings and systems included into the scope under normal (*blue sky*) conditions. However, selection of architecture of different alternatives for energy systems may already consider implication of their characteristics and function on resilience of systems serving mission-critical facilities under emergency conditions.

Steps illustrated using black shaded boxes show the planning process for mission-critical buildings and functions that address only critical loads under emergency (*black sky*) conditions. This part of the process includes steps that allow a narrowing of the scope of buildings and operations and their loads to those that are mission critical, which supports the assessment of threats specific to locality and function of the installation and their impact on energy systems' degradation and the calculation of energy requirements for mission-critical functions.

Planners will evaluate gaps in existing system resilience and develop future alternatives of systems providing required level of energy assurance to mission-critical functions, including "business as usual" (Base Case) and more advanced alternatives of energy systems with consideration of, but not limited to, those developed under the *blue sky* scenario. At this point of analysis, there is an opportunity for iteration between alternatives developed under these two scenarios.

Final steps of the integrated Energy Master Planning process include the comparison of different alternatives against the framing goals established earlier using quantitative and qualitative metrics. At this point, it may be required to perform the process iteratively to modify or create new alternatives if the goals were not met. Once a preferred alternative has been selected by decision-makers, an implementation plan is prepared that includes an investment strategy and projects that will be required to achieve the plan. More details regarding each of these steps are provided in subsections below. Based on the situation at specific installations, the breadth and depth of improvements under different alternatives may differ to reflect existing plans and timing for new construction, major and minor renovation of the building stock and utilities, criticality of their missions, and availability of resources. Also, the quality of the data available for development of the Baseline and the Base Case and energy requirements for mission-critical operations at specific installations vary. This may result in differences in the realization of the described concept at specific installations. Though the integrating process described above is evolving and undergoing pilot demonstration at several military installations, its elements (especially for the "blue sky" scenario) have been implemented in multiple Energy Master Plans at DoD installations (Zhivov et al. 2014).

The following subsections provide more details of each of these steps.

3.2 Establishing Boundaries of the Analysis

During the initial step of the EMP, the project team meets with the stakeholders to develop the vision, goals, constraints, requirements and expected outputs, and the development timeline. Energy and environmental performance and security goals shall be based on the national, regional, and community energy and sustainability policies and shall meet resilience requirements that support the energy systems' ability to provide mission-critical functions. This step is critical since it provides a framework for the rest of EMP development.

Care should be taken to ensure the stakeholders' group is small enough to be productive, but large enough to bring the right balance of perspectives and expertise. The stakeholders' group should include the largest energy-consuming tenants and community planners. This step is also an opportunity to obtain top-level support for the plan and to educate leadership on its importance to achieve community's critical mission objectives and energy goals.

The **scope** of the Energy Master Planning effort can include residential, commercial, and public buildings; community-based infrastructure; industrial energy users; community-owned and transit transportation and other energy-consuming users; or any combination of those. Also, it can be limited to include only mission-critical facilities. When defining the scope, it is important to understand the energy users that the community can control. A common scope of Energy Master Planning will include community building stock, industrial processes, and community-based infrastructure but may or may not extend to community-owned private and public vehicles.

A community can have fixed boundaries defined either by physical limitations (e.g., an island-based community) or political or administrative boundaries (Fig. 3.2). For example, a military installation or university campus may be a contiguous area or may be comprised of separate areas. Such community boundaries

Fig. 3.2 Examples of community boundaries: (**a**) defined by building clusters; (**b**) defined by physical limitations. (Zhivov et al. 2015)

define its real estate but may also suggest the possibility for interface with other communities via electrical or thermal (district heating/cooling) networks. An analysis of community boundaries may also reveal how communities can best meet their energy needs (e.g., by purchasing power, hot water, steam, chilled water, or other utilities from networks and/or by capturing waste heat from processes). The same analysis can determine the feasibility of exporting power, heat, and cooling energy from cogenerated sources to other buildings within the community.

3.3 Establishing Framing Goals and Constraints

It is important to clearly define long- and short-term **energy goals** at the beginning of a study, as well as important **constraints and community priorities**. Long-term energy goals can be expressed as the reduction by a desired percentage of site or source energy use against a Baseline in a given year or the achievement of a net-zero site/source energy community within a given time frame. These goals lead to decision metrics that will be used to decide between alternative solutions, described later. They help to focus the study and define "success." It is entirely possible that the goals will turn out not to be feasible, in which case the goals can be adjusted once quantitative data are available. The most common energy goals and constraints are described in Chap. 4 and may include the following groups:

- Building and facility level
- Operational constraints
- Constraints based on natural threats
- Locational resources available: district chilled and hot water, steam, water, electricity grid, natural gas pipeline, liquid fuel
- Energy supply constraints: power supply limitations, gas supply limitations, availability of energy from renewable sources
- Requirements to energy system resilience.

Other "Core Values" After defining the community energy goals and energy-related constraints, it is important to connect these goals to the existing community's "core values."

Though very important to mission-critical operations, public community leaders commonly find it a struggle to place a quantified value on the enhanced energy security provided by energy systems. In the private sector, energy security can be monetized by analyzing the reduction in insurance premiums or by evaluating the loss of goods, business, or research results or damage to property or goods. When a direct connection between energy assurance and the value of a jeopardized mission cannot be made, it is useful to do an analysis to determine which features that contribute to the energy system's resilience during its operation mode in the emergency situation will result in a reduction in its first or operating costs during normal "blue sky" operation.

Arguments can be made to articulate different co-benefits of reduced environmental effect and resource consumption with selected energy alternatives. Examples may include (Annex 51):

- Increased energy supply security
- Reduced economic disruptions caused by volatile energy prices
- Realization of local economic advantages by capitalizing on local/regional investments in energy conservation or renewables
- Improvement and modernization of local infrastructure, etc.

Installation/community leaders, decision-makers, and end users and businesses can help to define core area values and to connect them with the planned installation/community development.

3.4 Establishing Baseline

An important step in community energy planning and energy system optimization is establishment of current site and source energy use and cost profiles and associated greenhouse gas (GHG) emissions. The Baseline is defined as the current energy consumption profile. It is essential that the Baseline capture the quantity and type of energy used (transformed) by the community/installation (Fig. 3.3) such as grid electricity, natural gas, propane, and energy generated from renewable sources (e.g., solar, wind, hydro, etc.). It is also important to understand how the energy is used, whether for heating, cooling, plug loads, or industrial processes (Fig. 3.4).

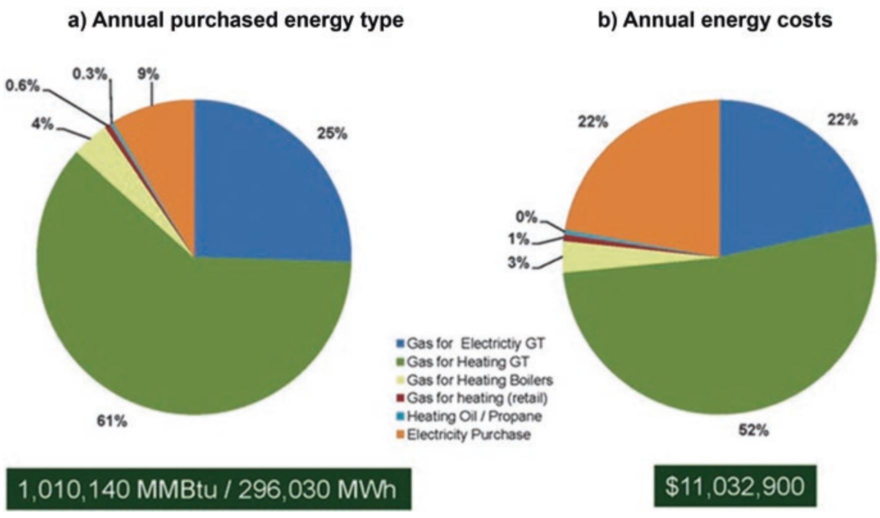


Fig. 3.3 Example of energy use and cost for a military community. (Zhivov et al. 2015)

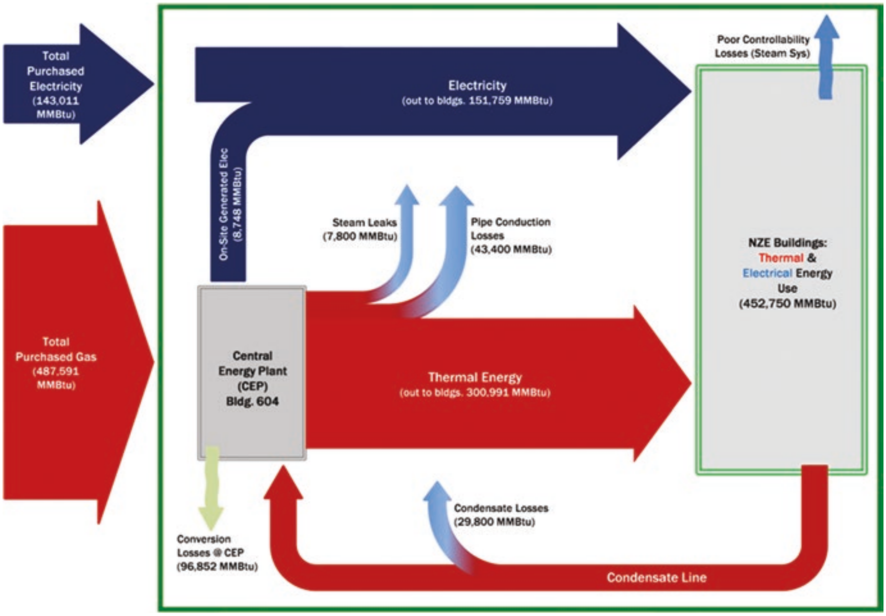


Fig. 3.4 Schematic of Baseline energy uses and wastes at a net-zero energy (NZE) area of one military installation. (Zhivov et al. 2015)

The Baseline is a snapshot of a point in time and can be derived from a reference year or from consumption data averaged over a number of years to even out climatic variations. The total energy use in the community can be grouped by different users, losses in generation, conversion, and transmission using the following categories:

1. End Uses
   (a) Building functions
   (b) Industrial processes
   (c) Central services—compressed air/water/sewer
2. Distribution losses
   (a) Hot water, chilled water, and steam network
   (b) Onsite electrical
3. Onsite conversion losses
   (a) Turbines
   (b) Boilers
   (c) Engines
4. Offsite conversion and distribution losses
   (a) Purchased natural gas
   (b) Purchased electricity.

The site energy use is comprised of energy uses and losses under categories 1, 2, and 3. The source energy use is derived from the energy uses and losses under categories 1–4. Different data sources and estimation approaches can be used in this analysis.

Data Collection The data required to develop the community-wide Baseline for normal operation (blue sky) include information on existing facilities, utility data, rate schedules, annual to monthly consumption, and meter data at the building level, if available. Information on existing infrastructure such as central plants, heating and cooling loops, and the electrical grid is usually required as well. There is usually a "data cleaning" step to ensure that the used data are complete and accurate. Trained subject matter experts (SMEs) are required for this step. They will conduct a walk-through of representative existing facilities and may need to look at building plans to determine methods and materials of construction, HVAC equipment, and other energy-related parameters. The data required for resilience analysis of energy systems serving mission-critical functions under *black sky* (emergency) scenario include the information on total energy use by each mission-critical facility/function and, when available, the data on:

- Priority loads of the mission-critical areas of these buildings.
- Loads of dedicated HVAC and electrical systems serving these areas.
- Loads of HVAC systems and electrical systems serving non-critical facility areas, if these areas can be hibernated during the "black sky" operation.

In addition to load profiles for mission-critical operations, information on maximum downtime of energy systems serving mission-critical operations and information on thermal and electrical energy quality required by these operations need to be collected from mission operators.

Some of this information can be obtained by approximation of capacities of existing emergency generators, boilers, and chillers. Caveats are that this information may be outdated or that existing equipment can be oversized.

The amount of information needed depends greatly on the level of analysis. More detailed information on the required information is listed in Chap. 2.

To describe Baseline end uses, models are usually developed for individual facilities included in the analysis or for facilities with similar physical features, which can be modeled as one facility group (Case et al. 2014). The models are calibrated to metered data by comparing energy use intensities calculated by the models against measured data.

Military installations often only have meter data for the entire installation or district heating/cooling/power plants. In this case, energy use of the facilities is apportioned by comparing the aggregate modeled usage against the installation-wide usage. However, individual metered data that can be used to calibrate the models more accurately are increasingly available. In fact, to achieve any optimization of end user's energy performances, it is absolutely necessary to log energy consumption data in a more detailed manner than it was common in the past.

During this step, team compares the Baseline analysis results against the installation's vision and goals. The analysis should quantify gaps for energy systems against community framing goals.

3.5 Establishing the Base Case

Baseline data can be used to project a Base Case scenario for energy use given the availability of information on an increase or decrease of energy use due to new construction, consolidation and demolishing processes, building repurposing and change of mission or new requirements to thermal comfort and indoor air quality, use of new and existing utility contracts, and dates when known contracts will expire.

The Base Case is defined as a future "business as usual" alternative that includes all existing and already planned facilities. Facilities marked for demolition in the Baseline are not included. The Baseline models of buildings and energy systems shall be adjusted to reflect all planned modifications. The Base Case shall include the data on site and primary energy use and energy cost with categories similar to the ones used for the Baseline. It is important to present the data showing the cost of implementation of the Base Case as well as changes in site and source energy use, energy cost, and GHG compared to the Baseline.

During this step, team compares the Base Case analysis results against the installation's vision and goals. The analysis should assess implementation costs and quantify gaps for energy systems against community framing goals. The Base Case will serve as a benchmark for LCCA of alternative systems.

3.6 Establishing Energy System Alternatives

Once the Baseline and Base Case have been established, energy planners can start exploring options or alternatives. A handful of alternatives shall be selected that will be analyzed in depth. Electrical and thermal energy systems consist of four major elements: energy generation, energy distribution, energy storage, and energy demand (Güssing 2011) (Fig. 3.5). The goal is to find the optimum balance of these elements for the entire energy system, where each element is considered in the calculation of the amount of energy delivered and lost, in various forms, by the energy systems (Loorbach 2007) and by its impact on energy system resilience.

Alternatives can explore different levels and scopes of building stock renovation and energy supply strategies. Building stock renovation scenarios can include scopes as broad as renovation of the whole-building stock, including an analysis of different energy efficiency levels (from light renovation using only cost-effective measures to a deep energy renovation or only a deep energy renovation of buildings with a potential to undergo major renovation during the timeline of the study). Supply strategies can include, but not be limited to, decentralized energy supply,

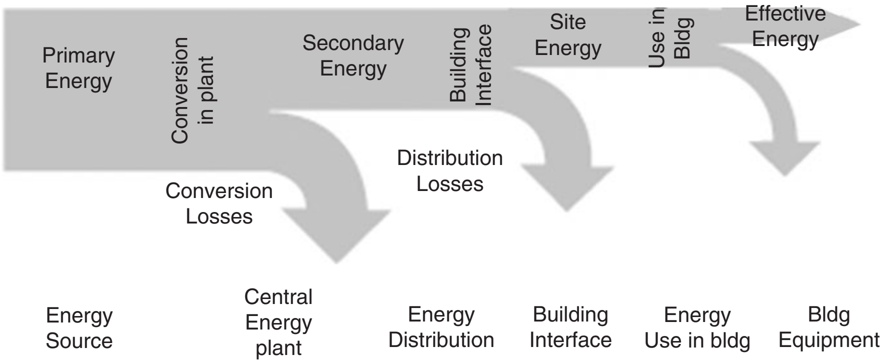


Fig. 3.5 Energy supply chain from primary energy to its use inside a building. (Zhivov et al. 2015)

steam-to-hot-water district system conversion, energy supply using only renewable energy sources, short-term and seasonal thermal energy storages, batteries, etc. Distribution strategies can include 100% centralized energy supply solutions, completely decentralized solutions, or a combination of clusters of buildings connected to several central energy plants (heating, cooling, and cogeneration) and buildings having individual (decentralized) energy systems. Since energy and cost analysis of each scenario is a time-consuming process that depends on tools and expertise used, it is recommended to preselect and agree on alternatives during the initial steps of the project. Some architectures of thermal and electrical systems, their preferable applications, and pros and cons are presented in Appendix E. A case studies book accompanying this guide provides a diverse set of examples and best practices.

For each alternative, it is important to present the data that shows the cost of its implementation and changes in site and source energy use, energy cost, GHG, and harmful emissions compared to the Baseline and the Base Case (the cost of emissions can be included in the cost-benefit analysis).

3.7 Mission Criticality Assessment

Mission-critical facilities are defined as facilities that are vital to the continuation of operations of the organization or agency. In addition to core critical facilities and operations, there are critical facilities that, if not maintained, impact the safety of the public and its property during and after a disaster. The latter typically include police stations, fire stations, hospitals and clinics, sewer lifts and water treatment plants, electric generating facilities, and facilities that store hazardous materials. The priority of each critical mission function and corresponding facility asset shall be identified by tenants and customers and documented and approved by the community leadership. Criticality of the function/asset is prioritized based on the consequences of its loss. These assets should include existing mission essential vulnerable area (MEVA) lists, high risk targets (HRTs), and assets that are critical to tenants/organizations in the community. The criticality assessment is important to downselect the list of facilities for resilience analysis of energy systems providing energy to these facilities during the black sky scenarios. Also, understanding mission criticality helps mission operators in selecting requirements for the resilience of energy systems that serve facilities supporting this mission. This chapter and Appendix C describe methodologies for assessing criticality and establishing requirements for energy system resilience.

3.8 Threat Assessment

Threats may come in the form of natural disasters, accidents, and man-made threats. Threats that the community has chosen to incorporate within the EMP are called design basis threats. Energy system resilience will be analyzed against this limited number of design basis threats. It is important to include the threats that occur with low frequency but pose a potentially high consequence. Design basis threats should be evaluated individually but may also be evaluated in combinations depending on anticipated impacts to the given area. This chapter describes threat assessment methodology.

3.9 Mission-Critical Loads and Energy Resiliency Matrix

For a community/campus/military installation to be resilient, it must serve the energy demands that will be present during the disruption scenarios. The planner must understand the dynamic demand of each asset or building in the disruption scenarios and scale up to demand for each critical function to plan, develop, and evaluate resilient designs. This contrasts with standard Energy Master Planning process that uses historic data or models to calculate energy demands for a blue sky day. The characteristics of the critical energy load can vary significantly between functions. For example, a communications function may require a large but steady supply of power to meet its equipment and conditioning needs. A shelter, on the other hand, may have little to no critical power demand but have a large but variable heating demand to protect occupants from environmental conditions.

Figure 3.6a gives an overview of how critical and non-critical loads are broken out within buildings, while Fig. 3.6b illustrates 24-h load profiles for the disruption scenario. Profiles for blue sky scenarios could be drastically different.

A load analysis should be conducted to classify each load as to the type of power that it should have and to determine the loads within the facility that need to continue to function following a loss of the normal source of energy. This analysis allows evaluation of the loads that must be uninterruptible, those to which power must be restored to perform an essential function (essential), or those that are not

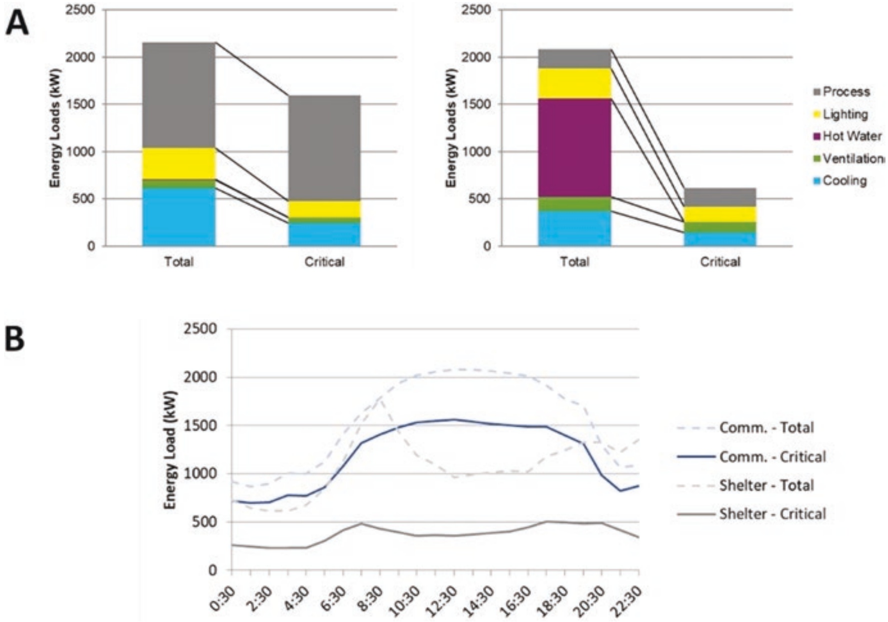


Fig. 3.6 Total and critical electrical demands: (**a**) total and critical electrical demand load for a data center (left) and a dormitory (right) and (**b**) critical electrical demand hourly profiles for communications and shelter over a 24-h period

required for the facility/mission to function if the normal power source is interrupted (nonessential). Furthermore, each load needs to be evaluated for energy quality requirements (e.g., electrical equipment performance classes, thermal system energy requirements: steam, chilled water, low- or high-temperature hot water). For more information, see Appendix Y.

3.10 Resiliency Analysis and Gap Evaluation

Baseline Thermal and electrical Energy Availability and maximum allowable outage duration are calculated for each mission-critical facility and compared to requirements set by mission operators (see notional example in Table 3.1). Values in the table are notional and for illustration purposes only. For more details, see this chapter.

Comparing the values for both Energy Availability and maximum outage duration allows the planner to see where gaps exist between the Baseline values and the requirements. The example summarized in Table 3.1 shows a Baseline system configuration that already meets the Energy Availability requirement for Facility 2 and

Table 3.1 Resilience metrics for notional system Baseline (Avelar 2007)

Critical facilities	Required		Baseline	
	Energy Availability	Max allowable outage duration (minutes)	Energy Availability	Max observed outage duration (minutes)
Facility 1	95.0%	120	94.0%	180
Facility 2	80.0%	60	80.0%	80
Facility 3	99.0%	26	98.0%	26
Facility 4	95.0%	120	90.0%	140
Facility 5	99.995%	26	99.0%	30

Facility 4. All other metrics exhibit a gap that must be addressed in alternative system designs.

Gaps between required resilience levels to design basis threats and Baseline resilience levels should be addressed by planners through investments in the system. Proposed changes are captured in conceptual designs that can then be compared to the Baseline and each other. The Base Case design is the first conceptual design developed to improve resilience and includes the most basic and common ways of improving the system.

Base Case The Base Case design for mission-critical energy systems only targets elimination of the resilience metric gap and does not consider blue sky metrics for efficiency or sustainability. Base Case design options include only traditional technologies (see Chap. 4). These technologies are placed by the planner throughout the system to improve the energy resilience to loads within critical facility categories that have a resilience gap discussed earlier. The planner may have to run the system model iteratively while selecting and parameterizing the Base Case design to ensure that systems are not under- or over-built but meet the resilience metric requirements as closely as possible.

Once this is complete, the planner should compute the total capital cost for the Base Case design, based on localized cost guidance for each technology selected. This Base Case design is only concerned with meeting the required resilience of the critical functions. It does not take advantage of the layout of the system or the potential to network buildings into microgrids. It does not take advantage of mutually beneficial designs for resilience, efficiency, and sustainability.

The data listed in Table 3.2 illustrate the Base Case system configuration that meets or exceeds energy resilience requirements.

The purpose of the Base Case design is to serve as a cost savings comparison for the alternative designs. Though the Base Case conceptual design will satisfy resilience requirements, it may not be the most cost-effective way to achieve increased resilience and will not improve blue sky metrics. A cost analysis for both total load under blue sky conditions and critical load under design basis threats should be performed for Base Case and alternative conceptual designs.

Alternative Designs The alternative conceptual designs discussed in Sect. 3.5 are the primary integration point for traditional EMP. These designs should integrate

Table 3.2 Resilience metrics for notional system Base Case design

Critical facilities	Required		Base Case	
	Energy Availability	Max allowable outage duration (minutes)	Energy Availability	Max observed outage duration (minutes)
Facility 1	95.0%	120	95.0%	120
Facility 2	80.0%	60	83.0%	60
Facility 3	99.0%	26	99.0%	26
Facility 4	95.0%	120	95.0%	105
Facility 5	99.995%	26	99.995%	26

blue sky goals with resilience goals such that performance is co-optimized for the planner. These designs should explore additional technologies beyond the Base Case conceptual design and should also consider alternative system configurations. It is important to review and consider enhancement of the building-level electric nanogrids with regard to equipment redundancy and storage capacity and with regard to improvements in the building envelope resilience in terms of thermal and air barrier efficiency and increase in the building mass (see Appendix C for details). These measures can allow downscaling of requirements to resilience of electrical and thermal energy supply systems. Alternative designs shall consider an increase in redundancy and reliability of energy generation, distribution, and storage components as well as protection of this equipment from predominant threats using such measures as elevating equipment, erecting flood walls, installing underground cables, etc. For all selected alternatives, thermal and electrical Energy Availability and maximum allowable outage duration are calculated for each mission-critical facility and compared to requirements set by mission operators (see notional example in Table 3.3). Values in the table are notional and for illustration purposes only. For more details, see this chapter.

Chapter 4 further details the Base Case and alternative designs architecture and technologies to satisfy the “black sky” scenario.

3.11 Comparing Alternatives

For each alternative, it is important to present the data showing the cost of its implementation, operating costs, life-cycle costs, and changes in site and source energy use, energy cost, GHG and harmful emissions, system resilience compared to the Baseline and Base Case, and energy requirements and constraints described in Chap. 4.

This information will allow to find the optimum solution for the entire community energy system and for those servicing mission-critical facilities that will meet the established energy and resiliency goals at the lowest life-cycle cost. The selection of the best alternative is highly dependent on climate conditions and local drivers, such as energy demand densities, existing networks, building system

Table 3.3 Comparison of resilience of Alternative 1 designs

	Required		Alternative 1		Alternative 2		Alternative 3	
Critical function	Energy Availability	Max allowable outage duration (minutes)	Energy Availability	Max observed outage duration (minutes)	Energy Availability	Max observed outage duration (minutes)	Energy Availability	Max observed outage duration (minutes)
Facility 1	95.0%	120	97.0%	110	95.0%	120	96.0%	105
Facility 2	80.0%	60	82.0%	55	85.0%	58	81.0%	60
Facility 3	99.0%	26	99.99%	26	99.99%	26	99.0%	26
Facility 4	95.0%	120	95.0%	115	95.0%	120	97.0%	90
Facility 5	99.995%	26	99.995%	26	99.995%	26	99.999%	26

configurations, etc. In addition, the selection can also be highly dependent on critical operations/mission assurance needs.

At the end of this phase, the team and stakeholders should have a strategic view of available alternatives and their pros and cons compared to the Baseline and Base Case, including their costs and gaps between their end results and energy goals. Based on analysis of this information, the community/installation leadership and stakeholders' group should decide on a preferred alternative.

3.12 Multicriteria Decision Analysis

Quantitative data from the Baseline, Base Case, and alternative design analysis is used to compare them against framing goals formulated at the beginning of the Energy Master Planning process and to determine how close the planners were able to come to achieving their goals. The level of achieving different goals will vary for different alternatives. A multicriteria decision analysis (MCDA) tool can be used to create weighted decision models and support traceable decision processes that integrate quantitative and qualitative factors. It is usually the case that the decision criteria are not equally important to each other. To support the community's decision process, the users apply elicit weights for the different criteria from decision-makers. This is not always an easy process, but it does encourage decision-makers to reflect on how they make their decisions. For more information about MCDA, see Chap. 2.

3.13 Developing Implementation Strategy

As part of the implementation strategy, long-term goals are transitioned into medium-term goals (milestones) and short-term projects, which must have tangible results. It is important to recognize that many decision-makers (e.g., installation commanders, etc.) have limited-term assignments or duties and will more likely commit to projects that can be realized during their tenure. Furthermore, short-term projects satisfy the short-term (1–5 years) planning process. It is important to get commitment from both decision-makers and funding agencies since they play key roles in achieving the long-term goal. The main restriction is that 100% of the short-term projects fit on the roadmap toward the long-term goals.

The transition process is described in terms of the definition and implementation of a roadmap to NZE communities. As soon as the long-term goal is set, one can apply backcasting and forecasting techniques to define the process leading toward energy neutrality (Zhivov et al. 2014; Annex 51 (2014); Kimman et al. 2010).

Backcasting (Fig. 3.7) denotes the process of defining milestones (mid-term goals) and determining the necessary steps to reach the final goal. Backcasting answers the fundamental question: "If we want to attain a certain goal, what actions must be taken to get there?" Using backcasting, concrete actions in the short term

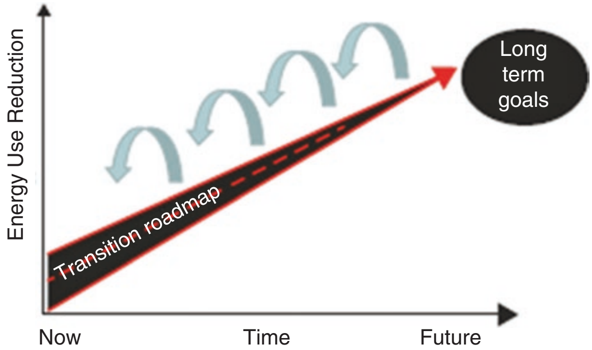


Fig. 3.7 Backcasting: formulate concrete actions from the long-term goals. (Zhivov et al. 2014)

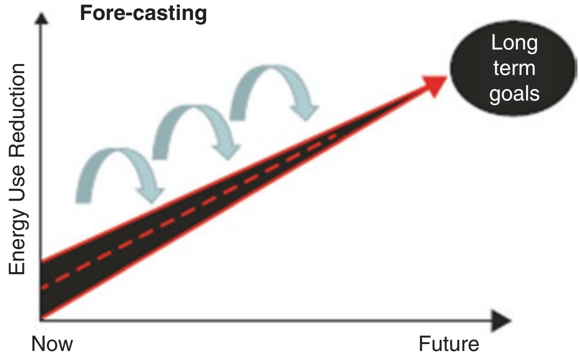


Fig. 3.8 Forecasting: formulate concrete actions from core area values and test them with the long-term values. (Zhivov et al. 2014)

can be formulated from the long-term goals. For instance, a goal of an energy-neutral built environment in 2050 could be supported by requiring that all new houses built after 2015 (for instance) be energy-neutral.

Forecasting (Fig. 3.8) refers to planning projects to meet milestones defined through the backcasting process, i.e., setting project requirements, and optimizing and designing projects and sets of projects in a holistic way that is geared to meeting each milestone. The feasibility of the projects can be learned from a review of best practices and the frontrunners.

Backcasting and forecasting approach the challenge of discussing the future from opposite directions. Backcasting and forecasting processes are both necessary to determine the transition path and to make the roadmap as concrete as possible. Both backcasting and forecasting can be used for monitoring the transition process to the long-term goals.

The Base Case and alternatives may vary by systems' architecture and its component (to include a variety of energy conversion, storage, and distribution technologies) and by implementation strategies and projects prioritizing and sequencing. They may result in partially unattainable goals or exceed them in a cost-effective way. The concept of community Energy Master Planning described in this section allows planners to seize the opportunity to think strategically about individual projects and programs.

3.14 Assembling, Reviewing, and Finalizing Document

In this step, the team documents the analysis in the form of the EMP. The narrative should be clear and concise and readable by a range of audiences and include an executive summary. Supporting documentation and detailed technical information should be contained in appendices. The project execution plan should comprise the majority of the document and institute a feedback process to absorb lessons learned as projects and other activities are executed. The document should also include communications and coordination plans that establish roles, responsibilities, and accountability, thereby leveraging the stakeholder group to ensure the smooth implementation of projects. The document should also include technical guidance and procedures to ensure the appropriate operations, maintenance, and testing (OM&T) is conducted on energy systems that align to mission requirements. Throughout the lifetime of the EMP, there will be multiple changes in community missions and functions, new energy requirements will be issued, and new technologies will be developed. Therefore, the EMP should be considered as a living document, and the team should continue to meet with the stakeholder group and community leadership regularly to keep them informed and actively involved. So, the document can be updated on the regular bases.

References

Annex 51. 2014. *Energy efficient communities*. https://www.iea-ebc.org/Data/publications/EBC_PSR_Annex51.pdf.

Avelar, Victor. 2007. *Guidelines for specifying data center criticality/tier levels*, APC White paper 122. Schneider Electric Data Center Science Center. https://download.schneider-electric.com/files?p_Doc_Ref=SPD_VAVR-6PHPBU_EN.

Case, M., R. Liesen, A. Zhivov, M. Swanson, B. Barnes, and J. Stinson. 2014. A computational framework for low-energy community analysis and optimization. *ASHRAE Transactions* 120: 130–144.

Güssing, Borough of. 2011. *Case study: The European Centre for renewable energy (EEE) in Güssing as an example of how synergies can be realized*. http://www.guessing.co.at/.

Kimman, J., R. Rovers, and R. Ravesloot. 2010. *Toward 0-impact buildings and built environments*. Amsterdam: Techne Press. ISBN:978-90-8594-028-9.

Loorbach, D. 2007. *Transition management*. Utrecht: International Books.

OASD (Office of the Assistant Secretary of Defense). 2016. *Memorandum. Subject: Installation energy plans*. Washington, DC: OSD. https://www.acq.osd.mil/eie/Downloads/IE/Signed%20Installation%20Energy%20Plan.pdf.

Zhivov, Alexander M., Michael Case, Richard Liesen, Jacques Kimman, and Wendy Broers. 2014. Energy master planning towards net zero energy communities/campuses. *ASHRAE Transactions* 119 (1): 325. NY-14-010. New York: ASHRAE winter conference.

Zhivov, A., M. Case, R. Liesen, and M. Swanson. 2015. *Demonstrate energy component of the installation master plan using net zero installation virtual testbed*, Final Report. ESTCP Project EW-201240. https://apps.dtic.mil/sti/pdfs/AD1024263.pdf.

Chapter 4
Establishing Energy Use-Related Goals and Design Constraints

Abstract This chapter discusses how to establish framing goals and constraints for building and community energy projects that must be considered when Energy Master Planning is conducted. They may include energy use, emissions, sustainability, resilience, regulations and directives, regional and local limitations such as available energy types, local conditions, costs of energy supply to the community and stakeholders, and individual project requirements.

Before jumping into any discussion about project goals and constraints related to EMP or any other planning initiative, it is important to revisit terminology to ensure that stakeholders clearly understand the nuances in terminology and use consistent, understandable language in communicating project objectives. Goals, objectives, and targets are easily interpreted as desirable or optional endpoints and not rigid design requirements. On the other hand, requirements and constraints must be met (they are rigid). It is important that both optional and rigid criteria are clearly communicated to the design team to ensure that all parties have a clear understanding of the firm constraints to which a project is being designed.

The systematic approach to identifying and classifying project goals presented in Chap. 2 can be used to ensure that the EMP team has a clear understanding of higher-level design requirements driven by project goals. If this approach is taken early in the process, it can positively impact multiple steps of the EMP, e.g., in architecture selection (if campus or community modeling is done), in technology selection, and in scenario analysis.

4.1 How to Establish Energy Use Requirements and Targets

Energy use requirements are typically established by a country, a state, a local authority, the project team, a building owner, or other stakeholders. Requirements are "must achieves" for the project design. In contrast, targets (or goals) are often desires (what one would like to achieve) and may or may not lead to requirements.

A. Zhivov, *Energy Master Planning toward Net Zero Energy Resilient Public Communities Guide*, https://doi.org/10.1007/978-3-030-95833-6_4

Table 4.1 European Union (EU) and US federal government energy-related goals and directives

Policy or directive	Goal, law, or regulation	
EU-EPBD[a]	Goal	EU reduce GHG emissions 20% below 1990 levels (Dir. 2010/31/EU)
		20% of EU energy use from renewable sources by 2020 (Dir. 2010/31/EU)
		New buildings nearly zero-energy by 2020; public buildings by 2018 (Dir. 2018/884/EU)
		Countries do national plans to increase number of NZEBs (Dir. 2018/884/EU)
EU-EC[b]		Energy efficiency target for the EU
		Renewable energy target for the EU
U.S.-EPACT 2005[a]	Law	Federal facilities be designed a minimum of 30% better than IECC or ASHRAE codes
		Renewable energy use by federal government be at least 7.5% of total by 2013
U.S.-EISA 2007[a]		Federal government eliminate fossil fuel use in new and renovated facilities by 2030
		Federal government reduce energy use of facilities by 30% by 2015
		New and renovated federal government buildings reduce use of fossil-fuel-generated energy by 55% (2010), 80% (2020), and 100% (2030).
		At least 30% of hot water demand in federal buildings to be met by solar heating.
U.S.-10CFR433	Regulation	Federal facilities be designed to meet ASHRAE 90.1-2013
		Federal facilities designed a minimum of 30% below ASHRAE Baseline Building 2013.

[a]EPBD (2018), EPAct (2005), EISA (2007) and US 10CFR-433 (2013)
[b]EC (2019, 2020, 2021) and European Environment Agency (2014)

Table 4.1 provides some examples of goals and requirements imposed at the highest levels. One is the EU Energy Performance in Buildings Directive (EPBD 2018), which sets a goal of all new buildings being near-zero energy use by 2020. This goal becomes a requirement if it is adopted as such by a participating European country into their building code. Until then, it is a desire. A second is the US Energy Independence and Security Act of 2007 (EISA 2007), which requires energy use reductions of 30% below a building energy performance standard in newly designed facilities owned by the federal government.

At a lower level and related to energy targets is the energy efficiency standard ANSI/ASHRAE/IES Standard 100 (ASHRAE 2018) for existing buildings. This standard establishes energy use targets for buildings as an indicator of building energy efficiency. When this standard is adopted as a requirement by a state (e.g., the State of Washington (2019) is developing building code requirements that parallel Standard 100) or a community, the targets in it can become a requirement. Other examples of energy use-related targets and goals could be NZE use, a percent renewable energy use, or an energy-related emissions maximum. If any of these were mandated, they would, of course, become a requirement.

4.1.1 Identifying Existing Energy Use Requirements

Energy use or energy use-related requirements can be established at any level. We will focus on the national or federal level as state and local requirements are too numerous and diverse to address in this guide.

Most countries, and especially those at the forefront of climate change efforts, have high-level goals in place that have led to mandated requirements for buildings at lower levels, typically for new buildings but often for existing buildings as well. Building codes officials and building designers are two sources that can help you easily identify the energy-related building requirements that would apply to your project. Today, requirements seem to be changing rapidly, so it is important to stay abreast of them in any master planning effort.

The typical building energy use-related requirements that have been in use for many years in most countries are either prescriptive or performance-based (either energy use or energy cost). Country or city requirements are often those outlined in a recent version of ANSI/ASHRAE/IES Standard 90.1 (ASHRAE 2016) or the International Energy Conservation Code (IECC 2018) or requirements that are like them. The prescriptive requirements mandate minimum efficiencies of building equipment and minimum performance levels for building components or the structure as a whole. The performance-based requirements mandate that an improved total building energy use or energy cost level be achieved.

Many countries have already gone (or are starting to go) beyond these requirements to assure a minimum level of energy performance for every building at the whole-building level. Several European countries have recently established single numerical energy use targets for new buildings that have been adopted as requirements. Outside of the military, the United States has not yet established required numerical energy use targets for new buildings. The United States has, however, established single numerical energy use targets for 53 existing building types in an energy standard, which is now being considered for adoption by local jurisdictions (ASHRAE 2018). Appendix A Tables A.1 and A.2 provide some of these US targets, which have been established for 16 different climate zones within the United States to reflect the impact of differing climates and construction practices. Table 4.2 lists existing US and European (i.e., for several European countries) energy use requirements and targets for prevalent building types. Note that, when you compare countries, many climate zones in the table are similar, base years vary somewhat, the type of energy use that is the basis for each requirement/target is the same for some and different for others, and the maximum energy use values have some interesting differences.

Table 4.2 lists energy use maximums for a limited number of building types that are common across each country. The number of building types with targets available varies widely by country. US targets address 53 building types, Finland's maximums address nine types, and Norway's maximums address 13 types. Denmark uses two equations to calculate targets for at least six building types; Austria does not segregate by building type but focuses only on heating energy use and uses

Table 4.2 Building energy use maximums and targets by country[a]

Country	United States	Australia	Austria	Denmark	Finland	Norway
Basis year	**2012**	**2019**	**2015**	**2018**	**2017**	**2017**
Climate zone	**5A, 6A, 7**		**5A and 6A**	**5A**	**6A and 7**	**6A and 7**
	Building maximum energy use (kBtu/ft² per year)					
General building type	**Total primary energy use**[b]	**Heating and cooling energy use**[c]	**Heating energy use**	**Total primary energy use**	**Total primary energy use**	**Total net energy use**
Office[d]	91–109	NA	15.1	13.0	31.7	36.5
School	80–136	NA	15.1	13.0	31.7	34.9
Apartment[d] **(5+ units)**	99–129	3.4–35.8	17.2	9.5	28.5–33.3	30.1
Dormitory	123–160	NA	17.2	9.5	NA	NA
Hotel	108–122	NA	15.1	9.5	50.7	53.9
	Building maximum energy use (MJ/m² per year)[e]					
Office[d]	1033–1235	NA	171.4	147.6	360.0	414.0
School	904–1544	NA	171.4	147.6	360.0	396.0
Apartment[d] **(5+ units)**	1127–1462	39–407	195.8	108.0	324–378	342.0
Dormitory	1400–1818	NA	195.8	108.0	NA	NA
Hotel	1231–1382	NA	171.4	108.0	576.0	612.0

[a]Values for more building types can be found in Appendix A. The United States has values for 53 different building types (Table I.1). Finland has values for nine building types (Table A.6). Norway has values for 13 building types (Table A.7). Denmark distinguishes buildings only by whether they have residential use (dwellings, dormitories, hotels, etc.) or not (Table A.5). And Austria does not appear to distinguish by building type (Table I.4)

[b]Ranges are shown for the general building types because the United States has values for 53 different building types and 16 climate zones excluding zone 5C (Table I.1 and Table A.2). US primary energy use values are much higher than European values partly due to the use of much higher site to primary (source) energy use multipliers in the United States

[c]Australia values vary widely due to widely different climate zones within the country (Table A.3)

[d]In some countries, the office building type is referred to as administration, and the apartment type is referred to as dwelling, community houses, block of flats, or building block

[e]The sources of maximum and target values for each country are:

Australia—National Construction Code based on minimum required NatHERS rating; 39–406 MJ/m²-yr (3.4–35.8 kBtu/ft²-yr)

Austria: Guidelines of the Austrian Institute of Building Technology 2015. Page 4, table in section 4.2.2

Denmark: Energy Requirements of BR18 (Danish Building Regulations 2018), calculated using Fig. 4, Pg. 6

Finland: National Building Code of Finland, 1010/2017 Decree of the Ministry of the Environment on the Energy Performance of New Buildings, p. 3

Norway: Regulations on technical requirements for construction works (Building Technical Regulations—TEK17), July 2017. Page 47

United States: ASHRAE Standard 100 (2018) “Energy Efficiency in Existing Buildings,” derived from Table 7.2a simple equations to calculate different maximums for new versus renovated buildings. Australia only has maximums for residential building types. Appendix A includes country-specific references for the sources of the energy use maximums and targets listed in Table 4.2.

4.1.2 *Developing Your Own Energy Use Requirements or Targets*

Several options could be examined if building energy use limits do not exist in your area, do not exist for your building type, or are built on a basis that may not apply well to your location. These include:

1. Using maximums or targets that exist in your region. Note that maximums or targets specific to similar building types, similar climates, and the typical building constructions in your location will be more reliable for your buildings. For example, note the similarity between values in Table 4.2 for neighbors Finland and Norway, which are in the same climate zone.
2. Creating a target based on the energy use of similar, neighboring buildings. This can be done by gathering a random sample of buildings of your type and looking at the distribution of their energy use intensities and picking a target value from the distribution to achieve. You could pick the sample average, median, a distance from the average or median, or other distributional value as a target. This is similar to what was done in Standard 100 with the top quartile performance value in the distribution for each of the 53 building types chosen as the energy target (Sharp 2015). Note that Standard 100 also offers an operating hour adjustment when evaluating a building against one of its targets since operating hours sometimes vary considerably within a building type.
3. Using an energy simulation-based method to estimate a representative energy use maximum (this approach was used to establish several of the required values in Table 4.2 for European countries).
4. In the United States, you could:

   (a) Adopt the energy targets or alternative (less stringent) energy targets by building type and climate zone in Standard 100.
   (b) Set a target based on the building energy use performance metrics published in the *ASHRAE HVAC Applications Handbook* (ASHRAE Handbook: HVAC Applications [ASHRAE 2019]; see chapter 37). A summary of the targets in this handbook is provided in Appendix A, Tables A.8 and A.9. The average, median, top quartile, and top 10% performance values by building type for around 50 building types are readily available there.
   (c) Use the Energy Star (USEPA 2020) qualification threshold value as a target (which is a performance score based on the energy use data of similar buildings and, like Standard 100, corresponds to performance in the top quartile of buildings). A significant limitation of this approach is that Energy Star

will only provide threshold values for a few building types (note, however, that they are the most prominent building types in the United States). The Energy Star scoring capability is built from measured data on US buildings only, so it cannot be used as a reliable indicator of building performance outside the United States.

One US study (Frankel and Turner 2008) indicates that many new buildings designed using a performance-based approach that relies on energy modeling will perform below model predictions and thus not meet their projected energy cost budget. A more recent UK study (van Dronkelaar et al. 2016) indicates a similar finding. This is expected, as pointed out in the Frankel study, because energy simulation should not be expected to be a reliable predictor of actual energy use when a building is placed in service. The Frankel study indicated that, for the sample of buildings as a whole, actual performance was nearly predicted, but on an individual building basis, about 50% of the buildings fell short of predictions with many performing far short of predicted use. The van Dronkelaar study showed a more intense issue, with well more than half of the sample falling below predicted energy use (actual use was higher than predicted). For the many falling way below predictions, one wonders if the resulting design of some of these buildings was as efficient as intended.

In contrast, if you set a representative, single numerical energy target for a building and require ten buildings of that type being constructed to meet it as built (i.e., based on the measured energy use of each building when occupied) and there are consequences or fixes in the event of underperformance, then building owners and/or designers will be more accountable, and the prevalence of buildings falling short, as seen in these studies, should be reduced. Just getting the substantial percent of new buildings that fall short of their expected performance up to expected performance would dramatically improve the performance of the population of new buildings constructed annually. The concept of setting whole-building measured energy use targets for new buildings is getting traction in the United States (the City of Seattle, Washington (Seattle.gov 2018), has adopted them on a small scale, the State of California has work underway toward this end, and the City of New York (NYC 2019) has gone to the next level, beyond energy use targets, and recently succeeded in requiring energy use-related emissions maximums at the building level). US states and cities are realizing that continuing to design buildings via reliance on a modeling-only approach is not advancing the performance of their building population fast enough to meet their environmental (or energy use) goals.

4.1.3 Identifying Energy Use Targets for Communities (vs. Individual Buildings)

Energy use maximums and targets are almost always established at the building level. With that case, how do you establish a target for a community? Since communities or military installations are essentially groups of buildings, one could envision identifying the maximums or targets for the individual buildings of the community and summing them to produce a community-level maximum or target. Energy use targets, like those in Standard 100 for the United States, are ideal for this (see US building energy use targets in Appendix A, Tables A.1 and A.2). Energy use for energy-using systems external to buildings would have to be added if energy use were measured at the community level (such as for the energy use for pumping for the distribution of potable water within the community or the energy used for street lighting). Or it could be ignored if measurements were made at the building level.

Figure 4.1 shows a simplified example of this. The individual target energy use of each building is calculated using an energy use intensity (EUI) target for that building type multiplied by the floor area of the building. The campus totals of building floor area and target energy use are calculated and used to calculate a campus target EUI. The same can be done with the metered energy use from each building on the campus to calculate the campus actual EUI for comparison to the target.

As an example, at a minimum, one would expect any community where energy efficiency was a priority would be better than average. In the United States, one could use the averages (mean values) from the *ASHRAE HVAC Applications Handbook* (ASHRAE 2019) or Appendix A, Table A.8, in the methodology (shown in Fig. 4.1), and compare the result to measured data from the community of buildings in question, to easily and quickly determine if this is true.

Campus Statistics by Building Type

Building Type	Building Target EUI	Building Size (sq m)	Target Energy Use
Office 1	356	2000	712,000
Office 2	356	1000	356,000
Clinic	490	500	245,000
Distribution Center	181	5000	905,000
Motel/Inn	517	2000	1,034,000
Vehicle service/repair	246	400	98,400

Campus Totals

Building Floor Area	Target Energy Use
10900	3,350,400

Campus Target EUI
307

(a)

Campus Statistics by Building Type

Building Type	Building Target EUI (kBtu/sf-yr)	Building Floor Area (sf)	Target Energy Use (kBtu/yr)
Office 1	36	100,000	3,600,000
Office 2	36	60,000	2,160,000
Clinic	53	50,000	2,650,000
Distribution center	18	100,000	1,800,000
Dormitory	54	150,000	8,100,000
Vehicle service	24	20,000	480,000
			18,790,000

Campus Totals

Building Floor Area (sf)	Target Energy Use (kBtu/yr)
480,000	18,790,000

Campus Target EUI
39

(b)

Fig. 4.1 Example of determination of an energy use target for a campus. (**a**) Systeme Internationale (SI) units. (**b**) IP units

4.1.4 Establishing Targets via Modeling Versus a Measured Data Approach

The traditional way of developing energy targets for multiple building types has been through energy modeling. This traditional way has several limitations that challenge both the developer and the user. These include (1) limited targets by building type (due to modeling expense, targets for only a few building types have been developed), (2) limited configurations for each building type (prototypical building constructions are often chosen by the modeler to represent an entire building type where constructions and building systems may vary widely), (3) user assumptions that the model and its results are representative of the building or buildings they are attempting to address, and (4) the reliability of model-based predictions (it is well known that modeling results are often quite different from the actual measured performance of buildings). The most prominent prototypical building models readily available to support building energy modeling appear to be the models available at the US Department of Energy (USDOE) Building Energy Codes Program website.[1] Many of the European building energy use maximums for new buildings have been developed using a model-based approach.

An alternative way of developing energy targets that is beginning to be used and gaining attention in the United States is to build them using measured energy use data from a population of existing buildings (Sharp 2015). An example of this is the energy targets in ANSI/ASHRAE/IEES Standard 100 (ASHRAE 2018). In these, the distribution of EUIs for existing buildings by building type is evaluated, and a minimum performance level for each building type is selected based on the distributions. A major advantage of this approach is that ultimately the target chosen is grounded to reality as it is based on the measured performance of existing buildings. The challenge with this approach is that it requires a significant, random sample of buildings for every building type where a target is to be identified. While there are millions of existing buildings available to support this approach, the widespread availability of measured building energy use data on a significant scale is rare. Standard 100 leverages a national, publicly available database produced by the US government, i.e., the US Commercial Buildings Energy Consumption Survey (EIA 2012).

4.2 Establishing Energy-Related Sustainability Goals and Requirements

Sustainability is an organizing principle that leads to specific approaches that inform the design of new systems, modernization or expansion of existing systems, choice of fuel options, operations and maintenance (O&M) strategies, and pathways to aging system modernization. Sustainability needs to be made part of the

[1] https://www.energycodes.gov/development/commercial/prototype_models

organizational culture to enable the required short-term response during emergencies and to continue to incorporate longer-term risk mitigation resilience toward unplanned outages. It is critical that sustainability criteria are integrated into the energy planning and decision-making processes from the very outset.

Sustainability can cover a broad array of topics. It could be argued that Energy Master Planning is a part of sustainability planning as many topics often covered under the sustainability umbrella go well beyond those related to Energy Master Planning. Sustainability areas such as recycling and reuse, water management, and landscaping and land use may have little relation to energy availability or use. In contrast, sustainability areas such as energy supply, renewable energy, energy efficiency, emissions, and resilience are strongly tied to energy availability and use. This guide focuses on the latter.

Sustainability goals and requirements are typically established by government agencies, executive leadership, project teams, or other stakeholders. Sustainability guidance and assessment or rating systems are available from industry associations (e.g., Leadership in Energy and Environmental Design (USGBC 2020) from the US Green Building Council and BREEAM (2020) from the Building Research Establishment). These sources can be tapped to identify the many different topic areas where sustainability can be addressed, sustainability requirements, best practices, and methodologies and tools that help assess sustainability performance.

The following sections describe key sustainability criteria that address technical, economic, and environmental sustainability related to energy use.

4.2.1 Reliability of Energy Supply

Reliability refers to the ability for systems to continue operating through a disturbance, uncontrolled events, or cascading failures. This includes tolerating disruptions from outside the system, as well as recovering unanticipated failure of any system elements.

Alternatives explored in EMPs should include energy supply options that are designed for reliable performance and are supported by skilled operators trained in good operational and maintenance processes to ensure high levels of system availability.

The reliability of energy-using systems, such as heating and cooling systems, is also important. Energy systems' reliability is discussed in Chap. 3.

4.2.2 Economic Viability of Energy Options

Economic viability and the prioritization of objectives from multiple stakeholders play an important role in the decision process used to evaluate the various alternatives proposed in the EMP. An LCCA will lead to more sustainable decisions.

Minimizing costs in a way that maximizes total value provides long-term financial benefits and allows for flexibility in making decisions.

4.2.3 Environmental Impact

Sustainability goals are closely linked with objectives to minimize carbon and carbon-equivalent emissions associated with energy supply and delivery. District energy systems provide the scale that enables multiple fuel choices and fuel switching options in support of carbon reduction goals. It is important, when possible, that environmental impact is accounted for through economics. As an example, the Danish Heat Supply Act (Ministry of Environment and Energy 2000) makes reduction of GHG emissions profitable by imposing a "cost to the environment" through environmental (fuel) taxes enacted by the national authorities.

4.2.4 Resiliency of Energy Systems

Increasingly frequent extreme events, such as natural disasters, amplified by increasing urbanization and impacts from climate change, are resulting in severe and costly damage to systems, people, and communities.

Resiliency refers to the ability of the energy systems to adapt to changing conditions, withstand disruption, and recover quickly. Building resilience into the design and operations of systems can help address economic disruption and speed up recovery while adding to system health and longevity.

A detailed, quantitative approach to evaluating energy system resilience that also touches on facility resilience is provided in Chap. 3.

At the building, facility, and community levels, the US Green Building Council (USGBC) formally adopted RELi (USGBC 2020), the resilience consensus standard to develop buildings and communities that offer greater adaptability and resilience to weather and natural disasters.

Incorporation of resilience into sustainability addresses not only capability to withstand natural and man-made impacts on the building stock and infrastructure but make them healthier and improve their longevity. The critical factors that enable resiliency include:

- System Design
  Resiliency requires anticipating risk and providing the necessary redundancy as well as design features that mitigate specific local risks to resiliency. Design considerations for backup power with onsite CHP-based microgrids or diesel generators are needed to address black sky days. TES can serve as a thermal battery to support critical thermal loads during an outage.

- O&M Processes
  The everyday running of a well-designed system requires the availability of good system documentation and O&M procedures. Clear documentation is critical in promoting a thorough understanding of the practices and procedures that must be implemented during blue sky and black sky days.
- Personnel
  Highly critical to resiliency are trained staff with the skills needed to operate and maintain systems. In addition, provisions must be made to ensure that the required staff are available and present to support resiliency.

4.3 Establishing Energy-Related Resilience Goals and Requirements

Energy-related resilience goals and requirements, like those for sustainability, are typically established by government agencies, executive leadership, project teams, or other stakeholders. These sources can be tapped to identify both energy supply and energy system resilience requirements where they currently exist. Typical resilience requirements related to energy supply are backup generators for electricity, uninterruptable power supplies for data centers, equipment with dual-fuel capability, and onsite fuel or energy storage. Typical resilience requirements related to energy systems are backup or supplemental chillers, boilers, and pumps associated with space conditioning systems.

Resilience requirements are usually tied to mission-critical facilities—those facilities that must operate continuously with no or minimal disruption. Military installations and public or private campuses or communities serve a range of missions, some of which are more critical than others. In a perfect world, designers would be able to protect assets for all levels of critical missions from the effects of any possible threats that come in the form of natural disasters, accidents, and man-made threats. Where funding and design constraints exist, however, some mission-related assets must be prioritized over others, and "design basis threats" that the community has chosen to account for in the EMP must be identified. Some missions, deemed essential, must be performed without interruption during and after a disaster. In addition to core mission-critical facilities and operations, there are critical facilities that impact the safety of the public and property during and after a disaster if not maintained. The priority of each critical mission function and corresponding facility asset shall be identified by responsible parties and documented and approved by installation/campus/community leadership. A methodology for mission criticality analysis and prioritization at facilities is presented in Chap. 3. A methodology for threat analysis and ranking is presented in Appendix D.

Recommended resilience requirements for power systems serving mission-critical facilities are discussed in Chap. 2 and listed in Table 5.11. Recommended resilience requirements for thermal energy systems are specified in Sect. 5.3.2 and in Appendix D.

4.4 Identifying and Assessing Your EMP Design Constraints

It is important to identify and apply your design constraints early in the EMP process. Doing so can bring efficiency to the process and better focus the EMP team. If the assessment of constraints is not performed early or is only marginally addressed, the EMP team may later find that it has spent time and resources on design options that are not feasible.

4.4.1 Identifying Your EMP Design Constraints

Many requirements and existing conditions will constrain your design options when working to reach a solution through an EMP process. Sharp et al. (2020) recently attempted to identify and organize them to help those undertaking EMP. Table 4.3 lists the natural and imposed (man-made) constraints adapted from that work that impact EMP. While the data in Table 4.3 may not be totally comprehensive relative to a specific project, it does provide a great starting point for getting EMP stakeholders to think about potential constraints and their impacts early in EMP to hopefully add some efficiency to their EMP efforts.

4.4.2 Energy Master Planning Framing Constraints

Some of the constraints identified in Table 4.3 will provide boundaries for a representative campus or community architecture if you are modeling a design and/or limiting your technology options. As a result, it is important to understand those boundaries and how they may impact your design, as discussed in this section. Once understood, the systematic methods of characterizing local resources and constraints presented in this chapter can help the planner with both architecture selection or specification and technology screening (see Sects. 7.7.5 and 7.7.6). Systematic approaches such as these can provide key input for automated EMP scenario analysis (see Chap. 1).

In contrast to the other constraint categories, locational threats typically do not eliminate energy system or technology options but simply affect the way they are installed (e.g., hardened in the case of high winds or earthquakes, elevated or bermed in the case of flooding, etc.). Other constraint categories often eliminate system or technology options. For example, limited locational resources such as insufficient wind or solar insolation can eliminate design options and specific renewable energy technologies. Limited locational resources can usually not be overcome to enable a solution or technology, so these are classified as “hard” constraints.

Existing distribution capability or distribution systems can limit technology options as well. But they can sometimes be overcome (constraints that can be

Table 4.3 Natural and imposed (man-made) constraints that impact EMP

Natural constraints		Imposed constraints				
Constraint category	Constraint[a]	Constraint category		Constraint[a]	Constraint category	Constraint[a]
1. Locational threats	Regional or local air quality	*3. Energy & water distribution & storage systems*		Natural gas	*5. Indoor environment*	Space temperature
	Low-lying area (flooding)			Electricity		Humidity
	Extreme temperatures			Fuel oil		Illumination levels
	Extreme humidities			Chilled water		Radon
	High winds			Hot water/steam		Ventilation
	Fire			Water		
	Lightning					
	Ground threats (volcano, mud, sinkhole, earthquake)	*4. Building and facility*	*4a. Energy use*	Energy use (site)	*6. Equipment in buildings and district systems*	Space heating
				Energy use (primary)		Space cooling
2. Locational resources	Solar insolation			Energy efficiency		Ventilation
	Wind		*4b. Environmental*	Renewables		Humidity control
	Biomass			Emissions		Water heating
	Land area		*4c. Operational*	Resilience		Food preparation
	Roof area			Reliability		Waste handling
	Interior area (space)			Financial/cost		Control systems
	Natural gas			Maintenance limits (e.g., simple, low cost)		Electric generation
	Electricity			Work force limitations		District steam
	Liquid fuels (oil, LPG, etc.)					District hot water
	Chilled water			Critical facility		District chilled water
	Hot water/steam			Islanding		
	Water			Other planner/building owner limiting factor		
	Heat sources/sinks					

[a]Constraint that could limit technology selection

overcome are referred to as “soft” constraints). An example would be the installation of a new CHP plant that requires either a natural gas or fuel oil supply that does not exist or is too small in its current capacity. These would be considered soft constraints if a new gas line or additional fuel oil supply or storage could be built into the project to overcome them.

Each constraint in Table 4.3 will have a limit or limits. For example, land area may be available for a photovoltaic array, but how much land is available (the limit of the constraint)? Natural gas may be available to a campus, but if a CHP plant is to be erected, what is the current distribution limit (capacity) of natural gas to the campus? Is that capacity fixed (a hard limit), or can it be increased to support a new plant? So, to complete the assessment of constraints in Table 4.3 and their impact on technology selection, it is necessary to identify and quantify the limits for each constraint and then overlay them on candidate technologies for the site or facility. These limits frequently impact technology selection during EMP. Although not fully quantified in many cases, an example of summary of constraint limits assembled for many of the design constraints in Table 4.3 can be found in Appendix A, Table A.10. More detail on EMP constraints, existing constraint limits, and assessing their impacts on design options is available in the article by Sharp et al. (2020). An extensive list of references for Table A.10 is available in that article.

In the sections that follow, the constraints in Table 4.3 are discussed in terms of their application, i.e., their potential to impact technology selections, along with examples.

4.5 Natural Constraints: Locational Threats

Locational threats usually do not influence technology selections. Threats such as flooding, high winds, lightning, storms, and earthquakes typically influence the way a technology is installed (e.g., hardened) and not the downselection of technology options. Some locational threats do have the potential to affect technology selection and should, therefore, be evaluated to narrow solution options. Local air quality conditions and their limits may eliminate the use of combustion-based heating or power generation systems especially in more urban areas. Other examples are extreme cold temperatures, which can eliminate the use of air-to-air heat pumps, and areas with significant humidity, which can constrain or eliminate evaporative-type cooling systems.

4.6 Natural Constraints: Locational Resources

Resource limits can profoundly affect technology selection. Low solar insolation, wind, biomass, and space resources can quickly eliminate many renewable technologies from consideration. If certain fuels are not available or limited, some fuel-fired technologies may get eliminated, and this may be even more pronounced if there is a dual-fuel capability desired for resilience. The lack of district chilled or hot water or steam resources may limit you to building-level energy systems unless there is an option to increase the scope of your project.

4.7 Energy and Water Distribution and Storage Systems Constraints

Limitations in existing distribution and energy storage systems will certainly influence technology selection. Electric feeders and local transformers and conductors limit the capacity to distribute electricity. There may also be limitations on connecting renewable energy sources to existing distribution lines. Local gas lines, if they exist, have fixed sizes and distribution pressures that limit the amount of gas that can be distributed. And onsite fuel storage systems have limited capacities. While all of these can limit technology selection, most of these are soft constraints (they can be overcome, either by adding larger or additional distribution components or more storage). So, one should be careful not to eliminate technologies before a hard/soft constraint limit analysis, discussed later in this paper, is performed.

4.8 Building and Facility Constraints

A common building-level constraint is an energy use limit. More common in EU countries, these limits are usually based on a maximum energy use per unit of floor area (EUI) by building type. While robust energy use targets have been recently developed for climate zones in the United States, they have not been adopted on a significant scale to date in local energy codes to turn them into constraints.

Generally, energy use limits push you to select more efficient versions of a technology but do not eliminate technologies. But if the limit is based on building site energy use (the energy use as measured at the building as opposed to a source or primary energy use basis, which accounts for the energy consumed in energy generation and distribution), an energy use limit can much more profoundly affect technology selection. For example, if energy use is measured on a site-energy basis, a heat pump can deliver two to four units of energy for every unit they consume in contrast to a gas furnace, which will deliver approximately one unit for every unit consumed. As a result, the heat pump will use far less energy on a site-energy basis than the furnace. However, the cost per unit of energy for electricity may be 3–8 times that for natural gas on a site-energy basis (partly because of power generation and distribution losses). On this basis, the heat pump may reduce your energy use but will likely push up your annual energy bill.

Another example is a fossil-fueled CHP plant. While these can provide major electricity cost savings, they dramatically boost total energy use as measured on a site-energy-use basis (additional discussion on this can be found in Zhivov et al. 2014). In both cases, site-energy-use-based constraints without consideration of energy costs may push the planner to a significantly lower EUI but at a higher annual operational energy cost. A primary or source energy use basis for measurement does not have this extreme energy use variance relative to technology selection and thus does not tend to eliminate technologies as an energy limit. Planners/designers should pay considerable attention to this if an energy use constraint is specified since competing technologies could be eliminated just because of the basis of the energy use measurement.

Building energy efficiency requirements usually do not exist at the whole-building or facility level. They usually exist at the system (e.g., attics or windows) or equipment (chiller or heating system) levels, which would be covered under Building Equipment and District Systems Constraints in Table 4.3. Some energy codes require a new building to be a specific percentage better than a standard or Baseline design. If that percentage is based on an EUI change and the EUIs are measured on a site-energy-use basis, technology selection could be impacted simply from the chosen basis for the EUI as discussed in the previous paragraph.

Environment-related, building-level constraints could easily impact technology selection. A renewable energy use requirement would affect technology selection if the renewable energy is generated onsite. An emissions-related constraint at the building level is rare but could affect technology selection if it exists. Primarily, it is local air quality threat or building equipment constraints on emissions that affect technology selection.

The other type of building- and facility-level constraints in Table 4.3 is operational constraints. Resilience and critical facility constraints are usually related and may affect technology selection. Examples would be a requirement for local (at the building) backup electrical power or for full islanding capability. Either case could drive you toward fuel-fired generator sets, renewable technologies, and/or energy storage systems. Other operational constraints are financial and workforce related. Fixed construction or tight annual operating budgets may mandate technology trade-offs. Workforce limitations (either manpower or expertise or both) may exist and influence technology selection.

4.9 Indoor Environment Constraints

Compared with other constraints in Table 4.3, indoor environment constraints mainly address the thermal comfort of building occupants from the aspect of personal needs. It aims at providing more comfortable indoor conditions to improve health benefits and work productivity. Indoor environment is a complex concept that involves a variety of factors that can influence environmental quality and energy use. Based on the national conditions, each country sets its own requirements and constraints on the indoor temperature, humidity, lighting illumination levels, radon, and ventilation. Thereby, energy use can vary due to the different demand.

4.10 Equipment in Buildings and District Systems Constraints

Most equipment constraints are minimum equipment efficiencies by system type. Minimum equipment efficiencies exist to ensure that efficient equipment is installed and also to ensure that equipment efficiencies by themselves do not eliminate competing technologies. Equipment efficiency when combined with fuel cost, emissions, or other factor considerations may eliminate a technology, but equipment efficiency alone generally will not. Some additional constraints that may affect equipment selection are equipment emissions and noise. These should also be considered when reducing candidate technologies early in master planning.

4.10.1 Assessing the Limits of Natural Constraints

4.10.1.1 Assessing Natural Constraints

As the data in Table 4.3 show, natural constraints can typically be categorized into locational threats and resources. Locational resources enable you to use different technologies; locational threats primarily influence how an individual technology is installed, and they do not influence the technology selection.

4.10.1.2 Assessing Limits for Locational Threats

As mentioned earlier, a few locational threats may affect technology selection and should be evaluated to narrow solution options. Limitations on local air quality conditions may eliminate the use of combustion-based heating or power generation systems especially in more urban areas. Extreme cold temperatures may eliminate the use of air-to-air heat pumps, while areas with significant humidity may constrain the use of evaporative-type cooling systems.

4.10.1.3 Assessing Limits for Resource Constraints

Identifying and assessing the limits for some natural resource constraints can be challenging, but there are many resources available to help the master planner. Assessing the availability and amounts of energy available to the building or community is a logical first step. This may not be a significant concern for an existing building or community if the master planning effort reduces current energy use. However, if the demand on an existing energy resource increases, especially substantially as in the case of adding a CHP plant, energy demand could significantly increase and strain the current energy resource and/or distribution capability.

Electricity availability and distribution limitations can be identified through your local provider. The availability of electricity is usually not an issue, but the existing distribution capacity for electricity can be a limitation.

Fuel and water resource limits can also be identified via local utility providers. These are likely available in quantities needed, but distribution systems could be a constraint. These could also be soft constraint limits, as options for overcoming constrained distribution systems could be increasing distribution pressure (to increase volume), adding new piping, or increasing pipe size to eliminate the constraint.

Chilled water, hot water, and steam resource limits can be identified via the capacity of the local central plants that supply them. Note these resource limits must be considered in light of the resource demand from any users currently on the district system outside the building or campus under consideration.

The availability of insolation, wind, and biomass resources can be challenging, but there are often tools available that will help in this evaluation. Before the availability of these resources is evaluated, however, it is sometimes worthwhile to look at the availability of land and roof areas to support these systems. If there is insufficient area for technology installation, resource availability does not matter. Constraints associated with available land and roof areas to support the installation of energy generation systems such as solar or wind can of course be quantified via campus maps, building drawings, or simple measurements.

Solar insolation maps like that shown in Fig. 4.2 can be used to quantify the local insolation resource. Unless solar insolation is quite low year-round, the annual quantities alone are not enough to eliminate solar-based technologies. Higher energy prices in areas of low insolation or low energy prices in areas of high insolation can change the economics of solar energy-based renewable energy systems. An economic evaluation that compares the cost of grid energy displaced relative to the first and operational cost of the solar-based system is required to screen technologies.

The US National Renewable Energy Laboratory (NREL) developed the Renewable Energy Optimization (REOpt) tool (https://reopt.nrel.gov/) to perform the economic analysis of renewable energy options based on local site conditions and system costs. This tool is publicly available and can be used by novices to make a "go/no-go" decision on renewable energy technologies. If a "go" decision is made, NREL recommends that a skilled REOpt user perform the analysis to produce the final, more accurate economic analysis results. In Europe, the Photovoltaic Geographical Information System (PVGIS) provides solar radiation maps and the ability to evaluate the performance of grid-connected PV systems (https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html).

Wind resource maps like that shown in Fig. 4.3 are often available and can be used to quantify wind availability. In some cases, quantifying the wind resource

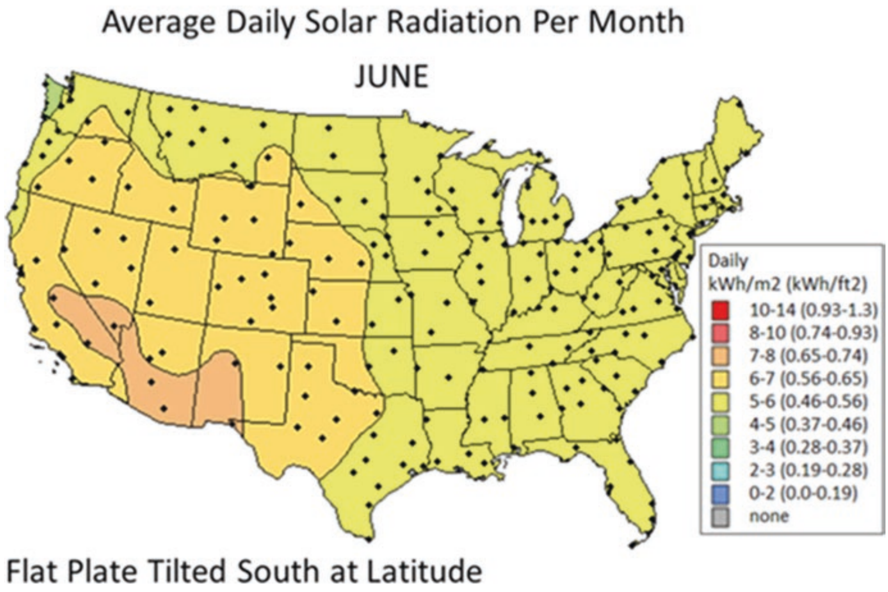


Fig. 4.2 Solar radiation intensity map of the United States. (Source: Sengupta et al. 2018)

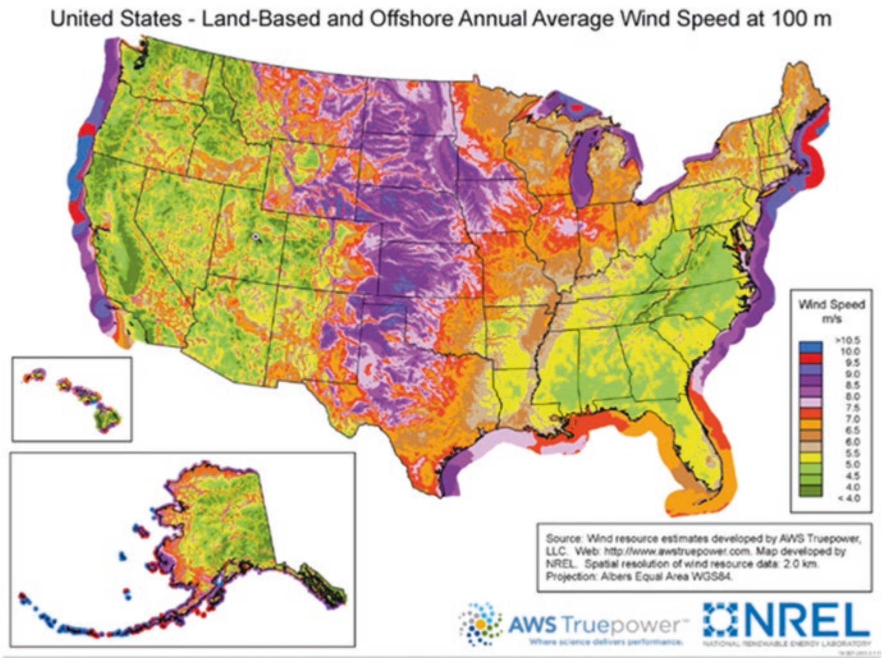


Fig. 4.3 Average wind speed map of the United States. (Source: Draxl et al. 2015)

may be sufficient to inform the user of the viability of wind-based technologies without an economic analysis. A wind resource normally has to be quite abundant for wind-based energy systems to be economical. As with insolation, local energy prices and distribution infrastructure costs (if located remotely) can influence the viability of wind-based technologies. NREL's REOpt tool can also assist in the go/no-go decision for wind technologies.

Biomass resource maps showing tons/year like that shown in Fig. 4.4 can be used to estimate your local biomass resource. In addition to ample local availability, material quality (material type and moisture content) can be significant influences on the practicality of a biomass-based system. The REOpt tool can again be used for analyzing the go/no-go economic analysis for biomass-based systems. Unlike solar and wind technologies, biomass-based systems can involve material handling equipment and biomass storage and can be labor intensive. Costs associated with these factors should not be overlooked in the economic analysis. Another very important factor that drives biomass-based system economics is the long-term cost stability of the biomass fuel. If local demand for biomass changes rapidly, costs can increase rapidly, which can be a major impact on the economic viability of a biomass-based system. These important (and numerous) factors, which are easy to miss in a simple economic analysis, should be considered very carefully if a system of this type is considered.

If enough renewable energy resources are available, the evaluation of roof or land areas to support a renewable energy system is also needed. Solar-, wind-, and

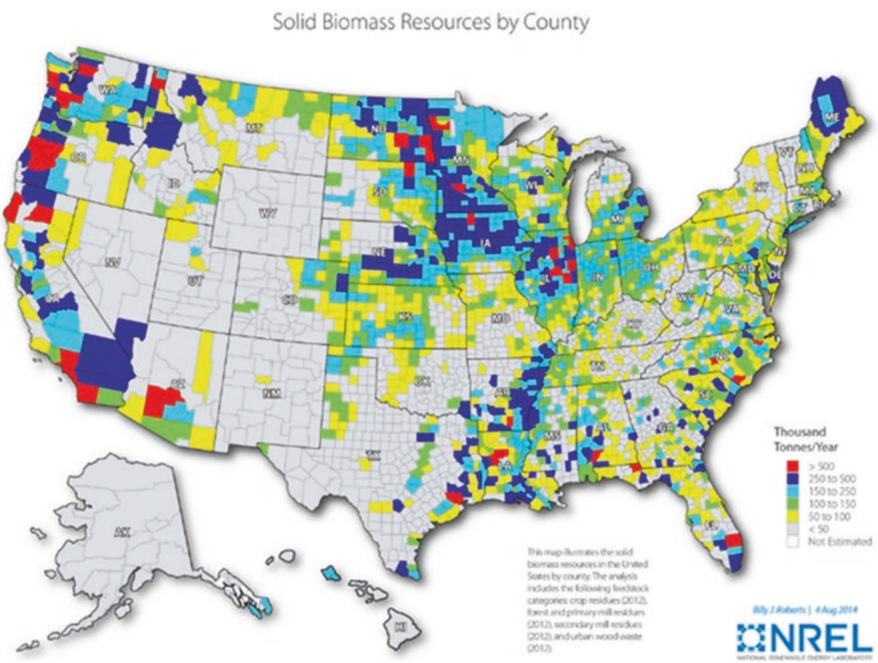


Fig. 4.4 Biomass resource map of the United States. (Source: Milbrandt 2005)

biomass-based systems require space. Urban settings or the lack of control over land or roof space can take onsite renewable energy options out of consideration. Approximately 1076 ft^2 (100 m^2) is needed for every 20 kW of solar panel capacity. (Note that efficiencies are improving, which reduces the area needed.) Wind turbines and biomass plants can have large footprints. All these resource constraints can affect technology selection, so their area requirements are worth evaluating early in the process to downselect the options you evaluate.

4.10.2 Applying Framing Constraint Limits

The Energy Master Planning process is carried out in at least three stages starting with the concept phase, the first planning stage, and subsequent iterations. Interactions between EMP and other construction planning must be set up from day 1 to avoid costly iterations.

4.10.3 Decision-Making to Reach Design Options

In the first stage of EMP (the concept phase), more holistic and even generic constraints resulting from mission-related framing goals and spatial planning must be considered. These may affect technology selections. The second stage adds the assessment of constraints and their limits on both technology selection and component levels.

4.10.4 The Hierarchy of Applying Constraints

Figure 4.5 shows the process of applying and evaluating constraint limits. Once a comprehensive list of constraints is identified (as in Table 4.3) and their limits are quantified for the first step of Fig. 4.5, the next step is to perform an analysis of the rigidity of each constraint limit (Step 2, the hard/soft limit analysis). The EMP planner/evaluator needs to assure that any constraint limit used in the final scoping down of technology options is a hard limit. Hard limits go directly to Step 4. In many cases, identified limits will be soft limits, in which case there is usually flexibility to overcome the limits (see related discussion in the next section). The planner/evaluator needs to assure they do not eliminate technologies based on soft limits. Soft limits move to Step 3, where options for overcoming each soft limit are evaluated to identify the real, hard limit for the constraint in question. These move to Step 4 with the others to produce the complete set of hard limits. With these in hand, the EMP planner/evaluator can begin the orderly application of constrain limits to narrow

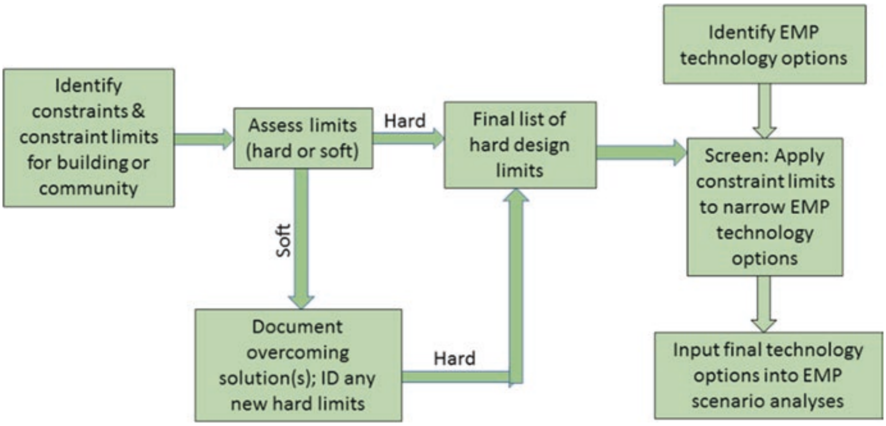


Fig. 4.5 Workflow for scoping down technology options to optimize EMP scenario analysis

down the many technology options to those that will satisfy their final project objectives.

4.10.5 Identifying Soft and Hard Constraint Limits

A “soft limit” is defined here as an existing constraint limit that can be overcome by a less restrictive limit. As illustrated in Fig. 4.5, after the comprehensive list of constraint limits is assembled, the EMP team should assess if any of the limits are “soft” and, if so, identify the hard limits related to them to arrive at the final list of hard constraint limits. A “hard limit” is quite the opposite; it is defined here as a constraint limit that is not flexible or negotiable and that cannot be overcome by a less restrictive limit. To illustrate these concepts to the planner/evaluator, some examples of soft and hard limits follow:

1. Soft locational resource constraint limit—lack of local roof and land area. Lack of local mounting area for PV systems does not necessarily eliminate this technology. PV systems can be in space remote to a building or main campus, tied to the local grid, and supplied to feed the building or campus. This is a common practice with the US military but note that tying into a local grid may not be easy or without significant cost.
2. Soft locational resource constraint limit—district chilled water is unavailable because the existing system is at capacity. Options that may relax or eliminate this limit could be adding a new chiller to the central plant or perhaps building a new district chiller plant if the project scope is large.
3. Soft distribution system and storage constraint limit—gas is not piped to the campus or building, or local lines are at capacity. Because they typically do not account for a major percentage increase in project cost, new gas lines are

commonly installed in both large- and small-scale projects. If current lines are at capacity, some more flexible possibilities are to increase gas line pressures (increasing flow volume) and installing additional or larger lines.

4. Soft building constraint limit—limited manpower or skill set of in-house maintenance. This limitation may affect larger, more complex technologies such as CHP systems or other energy generation technologies. Outsourcing operations and maintenance is perhaps an option, and for highly cost-effective technologies, the additional cost may easily be covered by cost savings resulting from the technology.

While all of these soft constraint limits have the potential to eliminate candidate technologies, in most cases, they would be considered soft constraints that can be overcome in whole or in part and, in doing so, avoid the elimination of what could be desirable technologies for an EMP solution. As a result, the planner/evaluator should be careful about assuming that a limit is hard and using it to eliminate technologies before the hard or soft constraint limit analysis is performed.

Examples of hard constraint limits are more easily understood; they include such things as rigid local air quality limits, other laws and imposed constraint limits that are inflexible, and low amounts of local solar radiation or wind.

4.10.6 Applying the Constraint Limits to Reach EMP Solution Options

The first step in preparing to apply constraints is to identify the optimum hierarchy for applying them. Applying constraints should normally flow as indicated by the data in Table 4.3, beginning with the application of natural constraints, either locational threats or resources. Assessing locational threats relative to eliminating technologies is usually easier and faster as they are easy to assess and few of them are significant enough to rule out technologies. Three that may quickly eliminate some technologies are (1) extreme cold temperatures and (2) high humidity (the potential technology impacts of these two are discussed in Sect. 4.5 "Natural Constraints: Locational Threats") and (3) air quality threats. Air quality threats are often present in or near population-dense cities. In the United States, this could mean a campus or city in a non-attainment area where air quality is worse than current air quality standards or in an area with air quality near non-attainment status. This scenario can easily constrain or eliminate combustion-based technologies from consideration.

The assessment of natural resource constraints is recommended next as many are relatively easy to assess, and for those that are more difficult, there are data and tools available that can help the evaluator in their assessment (see Sect. 4.10.1.3 "Assessing the Limits for Resource Constraints" for this discussion and some available tools).

Moving closer to and within the boundary of the community or facility, energy distribution systems and energy storage constraints are the next logical constraints to apply. Design specifications and capabilities of these systems are typically available. If district chilled or hot water or steam plants are unavailable, this quickly narrows choices for the planner to building-specific heating and cooling technologies unless there is enough budget and project scope to build a district plant.

Within the community or facility, building and facility constraints are recommended as the next area for the evaluation of constraint limits. At this point, several technologies may have already been taken off the EMP evaluation plate as a result of other applied constraints. Constraint limits may eliminate additional technologies but also may push you toward specific technologies. For example, a limitation requiring the use of renewable energy will force the use of renewable energy systems; one requiring the continuous operation of critical facilities would require the implementation of backup generation or energy storage systems or both.

Limits for indoor environment and equipment in building and district systems constraints should have the lowest evaluation priority since they typically do not impact technology selection. If this is the case, the application of constraint limitations to narrow the scope of the many technology options for EMP may result in the application of building and facility constraints.

References

10CFR-433. 2013. *U.S. Code of Federal Regulations Part 433*. https://www.govinfo.gov/app/details/CFR-2013-title10-vol3/CFR-2013-title10-vol3-part433.

ASHRAE. 2016. *Energy standard for buildings except low-rise residential buildings*, ASHRAE Std. 90.1-2016. Atlanta: ASHRAE. https://www.ashrae.org/technical-resources/bookstore/standard-90-1.

———. 2018. *Energy standard for buildings except low-rise residential buildings*, ASHRAE Std. 90.1-2016. Atlanta: ASHRAE.

———. 2019. *HVAC applications. ASHRAE handbook*. Atlanta: ASHRAE. https://www.techstreet.com/ashrae/ashrae_handbook.htmlhttps://www.ashrae.org/about/news/2019/ashrae-releases-new-hvac-applications-handbook.

Draxl, C., B.M. Hodge, A. Clifton, and J. McCaa. 2015. *Overview and meteorological validation of the wind integration National Dataset Toolkit*, Technical Report NREL/TP-5000-61740. Golden: National Renewable Energy Laboratory. https://www.nrel.gov/gis/wind-resource-maps.html.

EC (European Commission). 2019. *Clean energy for all Europeans package*. Brussels: EC. https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en.

———. 2020. *The renewable energy directive*. https://ec.europa.eu/energy/topics/renewable-energy/renewable-energy-directive_en.

———. 2021. *The energy efficiency directive*. https://ec.europa.eu/energy/topics/energy-efficiency/targets-directive-and-rules/energy-efficiency-directive_en.

EIA (Energy Information Administration). 2012. *Commercial Buildings Energy Consumption Survey (CBECS)*. Washington, DC: EIA. https://www.eia.gov/consumption/commercial/.

EISA (U.S. Energy Independence and Security Act of 2007). 2007. *Energy Independence and Security Act of 2007*. https://www.govinfo.gov/content/pkg/PLAW-110publ140/pdf/PLAW-110publ140.pdf.

EPAct (Energy Policy Act). 2005. *Energy Policy Act of 2005*. https://www.govinfo.gov/content/pkg/PLAW-109publ58/pdf/PLAW-109publ58.pdf.

EPBD (Energy Performance of Buildings Directive). 2018. *(EU) Directive 2018/844 Amending Directive 2010/31/EU on the Energy Performance of Buildings*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.156.01.0075.01.ENG.

European Environmental Agency, The. 2014. *Costs of air pollution from European industrial facilities*. Copenhagen: European Environmental Agency. https://www.eea.europa.eu/publications/costs-of-air-pollution-2008-2012.

Frankel, Mark, and Cathy Turner. 2008. *Energy performance of LEED® for new construction buildings*. Vancouver: New Buildings Institute. https://newbuildings.org/sites/default/files/Energy_Performance_of_LEED-NC_Buildings-Final_3-4-08b.pdf.

IECC (International Energy Conservation Code). 2018. Energy efficiency and carbon reduction. In *Leading the way to energy efficiency*. Washington, DC: IECC. https://www.iccsafe.org/products-and-services/i-codes/2018-i-codes/iecc/.

Milbrandt, A. 2005. *A geographic perspective on the current biomass resource availability in the United States*, Technical report NREL/TP-560-39181.

Ministry of Environment and Energy (Denmark). 2000. *Danish Heat Supply Act*. Copenhagen: Ministry of Environment and Energy. https://www.energybrokers.co.uk/news/resources/danish-heat-supply-act#:~:text=Article%201.,the%20energy%20system%20on%20oil.

NYC (City of New York). 2019. *Climate mobilization act*. New York: New York City Council. https://council.nyc.gov/data/green/.

Seattle.gov. 2018. *Energy compliance through the target performance or total building performance paths*, SDCI Tip #423. Seattle: Seattle Department of Construction & Inspections (SDCI). http://www.seattle.gov/DPD/Publications/CAM/Tip423.pdf.

Sengupta, M., Y. Xie, A. Lopez, A. Habte, G. Maclaurin, and J. Shelby. 2018. The National Solar Radiation Data Base (NSRDB). *Renewable and Sustainable Energy Reviews* 89 (June): 51–60. https://www.nrel.gov/gis/solar-resource-maps.html.

Sharp, Terry. 2015. *Derivation of building energy use intensity targets for ASHRAE Standard 100*, ORNL/TM-2014/215. Oak Ridge, TN: Oak Ridge National Laboratory. https://info.ornl.gov/sites/publications/files/Pub49965.pdf.

Sharp, Terry R., Alexander Zhivov, Matthias Haase, and Joergen Rose. 2020. *Energy master planning: Identifying framing constraints that scope your technology options*. ASHRAE Winter Meeting, Atlanta, February 2020.

State of Washington. 2019. *Senate Bill 5116*. http://lawfilesext.leg.wa.gov/biennium/2019-20/Pdf/Bills/Senate%20Bills/5116.pdf.

USEPA (U.S. Environmental Protection Agency). 2020. *U.S. Environmental Protection Agency Energy Star Program*. https://www.energystar.gov/.

USGBC (U.S. Green Building Council). 2020. *LEED: Leadership in Energy and Environmental Design*. Web page. http://leed.usgbc.org/leed.html.

van Dronkelaar, Chris, Mark Dowson, E. Burman, Catalina Spataru, and Dejan Mumovic. 2016. A review of the energy performance gap and its underlying causes in non-domestic buildings. *Frontiers in Mechanical Engineering*. https://doi.org/10.3389/fmech.2015.00017.

Zhivov, Alexander M., Michael Case, Richard Liesen, Jacques Kimman, and Wendy Broers. 2014. Energy master planning towards net zero energy communities/campuses. *ASHRAE Transactions* 119 (1): 325. NY-14-010. New York: ASHRAE winter conference.

Chapter 5
Defining, Measuring, and Assigning Resilience Requirements

Abstract Major disruptions of energy supply (both electrical and thermal) have degraded critical capabilities and caused significant social and economic impacts to private and public communities. Therefore, resilience must be an integral goal of the community-wide Energy Master Planning process since the application of energy resilience principles is important during the design of new and upgrades of existing energy systems. Best practices for resilient electric and thermal energy systems favor the use of installed energy sources rather than the use of emergency generation for short durations; best practices also promote the use of multiple, diverse sources of energy, with an emphasis on favoring energy resources that originate within the community. The energy system options that can be used for power supply, heating, and cooling of campuses vary by their architectures and technologies used, including for individual buildings, building clusters, the campus-wide level, and the community level. Design and evaluation of system resilience should be based on requirements established by mission operators, which are currently not well understood. This chapter addresses requirements to resilience for both electric and thermal systems comprising energy conversion, distribution, and storage components.

5.1 Introduction

Resilience of the energy system impacts the primary functionality of military installations, hospitals, and education campuses during disruptions. Throughout the history of energy systems, major disruptions of energy supply (both electrical and thermal) have degraded critical capabilities and caused significant social and economic impacts to private and public communities. Therefore, resilience must be an integral goal of the community-wide Energy Master Planning process since application of energy resilience principles is important during design of new and upgrade of existing energy systems. Best practices for resilient electrical and thermal energy systems favor the use of installed energy sources rather than the use of emergency generation for short durations; best practices also promote the use of multiple, diverse sources of energy, with an emphasis on favoring energy resources that originate within the community (DoD 2020). Examples of best practices of such

A. Zhivov, *Energy Master Planning toward Net Zero Energy Resilient Public Communities Guide*, https://doi.org/10.1007/978-3-030-95833-6_5

systems implementation can be found in the Annex 73 case studies book (summarized in Appendix B).

The energy system options that can be used for power supply, heating, and cooling of campuses vary by their architectures and technologies used, including for individual buildings, building clusters, the campus-wide level, and the community level. Design and evaluation of system resilience should be based on requirements established by mission operators, which are currently not well understood.

Metrics for energy resilience fall into two broad categories: attribute-based and performance-based (Vugrin et al. 2017; Roege et al. 2014). Attribute-based metrics can be counted or populated via checklists or surveys. They often describe the characteristics that make a system resilient, such as robustness or reliability (NIAC 2009). However, these metrics are difficult to integrate into the EMP process because they are not easily compared with performance-based metrics in other categories, such as cost-effectiveness (e.g., overall net present value of the energy system) or sustainability (e.g., kg of CO_2 equivalent emissions) (Jeffers et al. 2020).

A resilient energy system (electrical or thermal) is one that can prepare for and adapt to changing conditions and that can recover rapidly from such disruptions as deliberate attacks, accidents, and naturally occurring threats (White House 2013; ES2 [HQDA 2015]). This chapter provides a definition of resilience, outlines metrics that can be used in the resilience inclusive EMP process described in Chap. 3, and describes quantitative methods for evaluating the resilience of existing or proposed designs.

Concepts of reliability and resilience of energy systems are often confused. The primary difference between reliability-focused planning and resilience-focused planning is the type of events included in the process and the methods used to quantify the impact of the events. Reliability-focused planning limits itself to high-probability events with relatively low consequences (USDOE 2017). System reliability is the desired level of system performance. Commonly used indices to measure electrical system reliability are the Customer Average Interruption Duration Index (CAIDI), which gives the average outage duration that any given customer would experience or the average restoration time, and System Average Interruption Duration Index (SAIDI) (IEEE 1366 [2012]). For resilience-focused planning, in addition to the information on statistical system element failure, system reliability should be adjusted for expected low-probability, high-consequence threats and hazards expected for the locality of interest, which are called design basis threats. Therefore, resilience of energy systems is threat-informed rather than threat agnostic, as systems that are resilient to one threat type may not be resilient to another threat type. For example, an area that is exposed to high winds and earthquakes would not be considered resilient if the energy system were only hardened to wind but not to ground acceleration.

While there have been more discussions and research related to resilience of electrical energy systems, resilience of thermal energy systems is also important, especially for extreme climate locations. This chapter addresses requirements to resilience for both electrical and thermal systems comprised of energy conversion, distribution, and storage components.

5.2 Quantifying Energy System Resilience

The quantitative approach described in this chapter supports the DoD memorandum that outlines the metrics and standards for energy resilience at military installations (DoD 2020) and allows for evaluation of both the ability of a system to absorb the impact of a disruption (robustness) and its ability to recover. Critical missions may employ extensive redundancy and protect vital system components to ensure continuity of the mission, even when faced with a significant natural or man-made disaster. For such systems, mission success is very highly probable but is still a probability. Consequently, the impact of an event can be considered to impact the probability of mission success. Some critical missions can withstand small disruptions (see, e.g., Uptime Institute requirements tiers in Appendix C) as long as the system can recover quickly. In either case, overall resilience of the system can be quantified as a deviation in mission availability from Baseline operations to some degraded system state following a disturbance.

A comprehensive literature review of energy system resilience conducted by Willis and Loa (2015) identified 154 metrics currently used by the energy industry. Ayyrub (2015) also conducted a comprehensive review of resilience definitions and the metrics relevant to energy systems and buildings. These practical and simplified proposed metrics capture the entire attribute set in the resilience definition.

A quantitative approach to resilience of system supplying energy to the building can include (but is not limited to) the following metrics:

- Energy System Robustness (ER)
- Energy System Recovery Time
- Maximum Time to Repair (MaxTTR)
- Energy Availability (EA)
- Energy Quality (EQ)

The first three parameters are critical for selection of the energy supply system architecture and technologies that comprise it, to satisfy requirements related to energy system resilience. As discussed in Sect. 5.3.1, requirements for Energy Availability and Energy System Recovery Time depend on:

1. Criticality of the mission being served by the system
2. System repairability, which has significant dependence on remoteness of the facility hosting the mission
3. Redundancy of facilities that can serve the same critical function

Requirements for **Energy Robustness** depend on a load that is critical to the mission and that can be measured as the percentage of the load that is available to mission essential loads from the total mission essential load requirements (1); it can also be related to the overall building energy load under normal (blue sky) conditions (2). These loads are illustrated using the notional example shown in Fig. 5.1.

Energy Quality is another important quantitative metric for the energy system that serves critical functions; energy quality should be considered as a design parameter for internal building energy systems. Most of the mission-specific energy

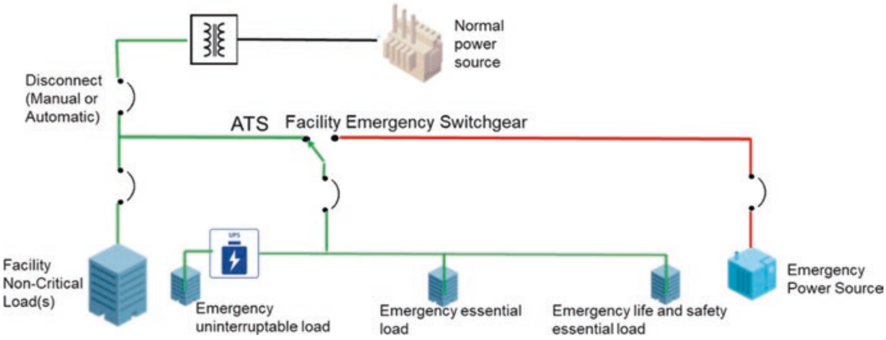


Fig. 5.1 Schematic of the one-line diagram for a notional facility

quality requirements, including limitation on short-term power interruptions, voltage and frequency variations, harmonics, etc. (see Performance Class Transient Limits in Unified Facilities Criteria (UFC) 3-540-01 [NAVFAC 2019]), can be handled by the building-level energy systems. Building-level electrical systems (nanogrids) generally include redundant or backup components and infrastructure for power supply, uninterruptible power supply, automatic transfer switches (ATSs), data communications connections, and environmental controls (e.g., air-conditioning, fire suppression). Nanogrids also include various security devices that can be designed to provide power with severe demands on the stability and level of the frequency and voltage and with waveform characteristics of the uninterruptable electrical power to mission-critical equipment and that can operate in an islanded mode between 15 min and several hours (Fig. 5.2). It is important to account for the latter capability when requirements for maximum energy supply downtime are established.

Planning for a resilient thermal energy system should consider that a well-insulated and airtight building envelope of the massive building can maintain habitable indoor air temperature for several hours after heat or cooling supply to the building is interrupted (see Sect. 5.3.2).

Internal electrical and thermal systems are designed based on the type (class or tier) of facility. Requirements for Energy Availability, Energy Recovery Time, and Energy Quality to be specified for energy systems that provide energy to a typical building will differ from those required by a building that houses critical equipment and personnel.

5.2.1 Energy System Robustness

5.2.1.1 Defining Energy System Robustness

Robustness is defined as "the ability to absorb shocks and continue operating" (NERC 2018). In many critical facilities, there may be many mission assets that are considered uninterruptible, critical but interruptible, and life- and safety-related.

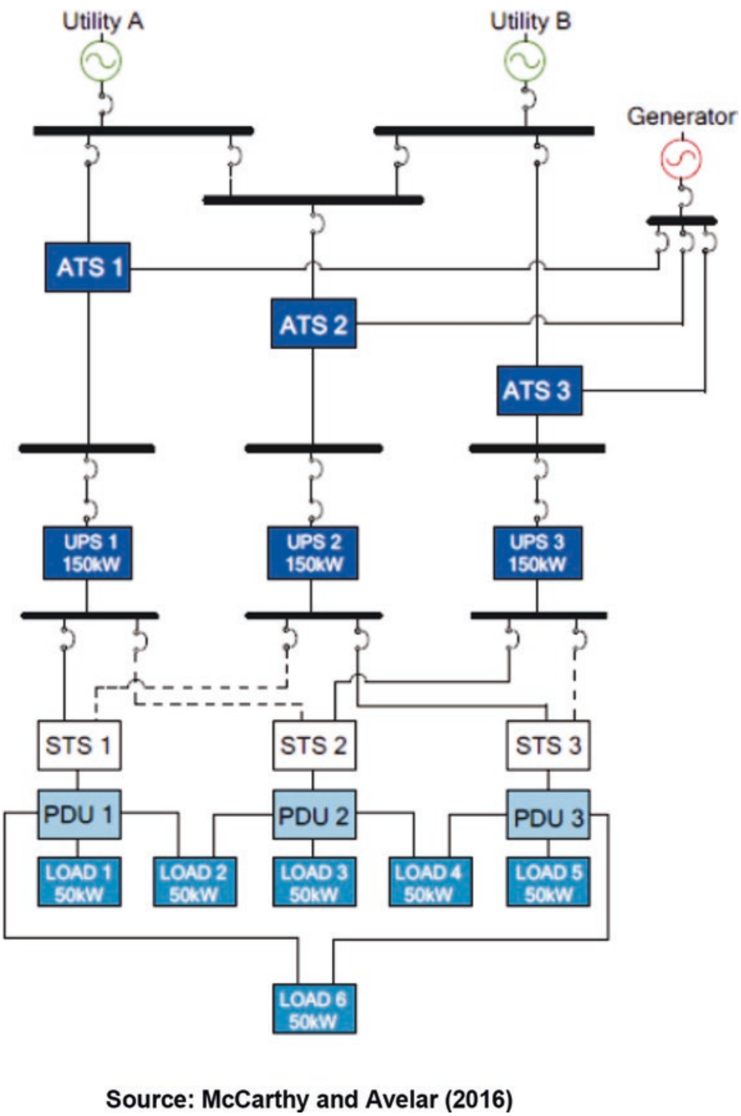


Fig. 5.2 Example of the building-level electrical grid (nanogrid). (Source: McCarthy and Avelar 2016)

Since it is imperative to the mission that these assets remain online, any undelivered load to such facilities or assets would be considered a mission failure. Energy Robustness is a metric that shows power availability, P (in kW and/or kBtu/hr), to satisfy critical mission loads over a period of time immediately following the event, measured as a fraction of the mission-critical requirement or as a fraction of the Baseline energy requirement.

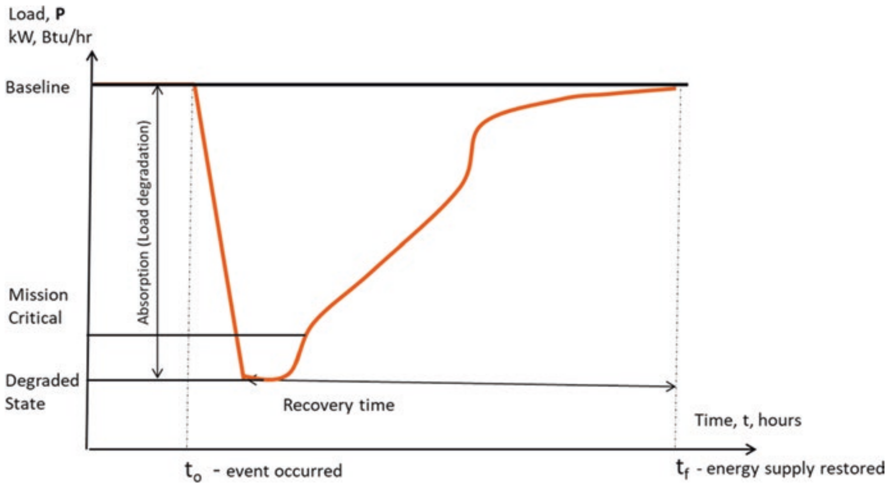


Fig. 5.3 System response to a disruptive event

Using the Energy Robustness metric, we can quantify the overall resilience of a system in two phases: absorption of the event and recovery. Consider an event occurring as shown in Fig. 5.3. Immediately following the event, there is a sharp drop in the load available to mission. For electrical energy systems, duration of phase one is much shorter than for thermal energy systems, unless thermal systems are used for processes using steam or hot water. This change from the Baseline to the degraded state represents the robustness of the system to that particular event. The time required to restore the system to its Baseline state is referred to as recovery. The smaller the change in load available to mission and the shorter the recovery time, the more robust the system.

The Energy Robustness, *ER*, of the system to any particular event can be quantified using Eq. 5.1a and 5.1b and is illustrated in Fig. 5.3 by the area between the line showing the Baseline mission availability and the curve representing the actual mission performance over time. The smaller the area between the Baseline and the curve, the more resilient the system. Energy Robustness will be measured on the scale between 0 and 1, where 1 is the most resilient system:

$$ER_{\text{m.c.}} = \frac{E_{\text{event}}}{E_{\text{m.c.}}} \tag{5.1a}$$

$$ER_{\text{baseline}} = \frac{E_{\text{event}}}{E_{\text{baseline}}} \tag{5.1b}$$

where $R_{\text{m.c.}}$ and $R_{\text{ baseline}}$ are system robustness measured against the mission-critical load and the Baseline load and E_{event}, $E_{\text{m.c.}}$, and E_{event} are energy supplied to the

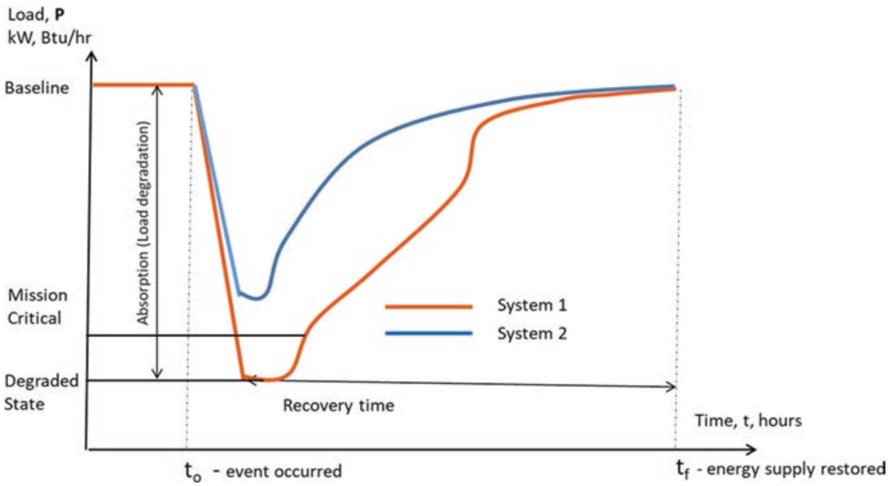


Fig. 5.4 Two systems with different absorption

building during the period of time between t_o and t_f with the Baseline load and mission-critical load and degraded due to even load:

$$E = \int_{t_f}^{t_o} P(t)\,dt \tag{5.2}$$

Depending on mission needs, it may be more important to prioritize either absorption or recovery. For example, Fig. 5.4 shows two systems with different levels of absorption. The two systems have the same recovery time, but System 2 has a lower initial decrease in power available to the building. System 2 is more resistant to the postulated event and is more robust than System 1 despite the fact that the two systems have the same recovery time.

In other cases, it may be more important to prioritize recovery from an event than to prioritize absorption. Figure 5.5 shows two systems with similar absorption to an event but different recovery times. Although both systems have the same ability to absorb the shock from the event, the shorter recovery time for System 2 yields larger area under the curve. Accordingly, System 2 can be said to be more resilient than System 1.

5.2.1.2 Energy System Recovery

In the recovery phase, the system is stabilized, and no further damage or degradation is expected. The system may be operating in alternate or emergency modes with a reduced load. At the beginning of this phase, energy may be provided to

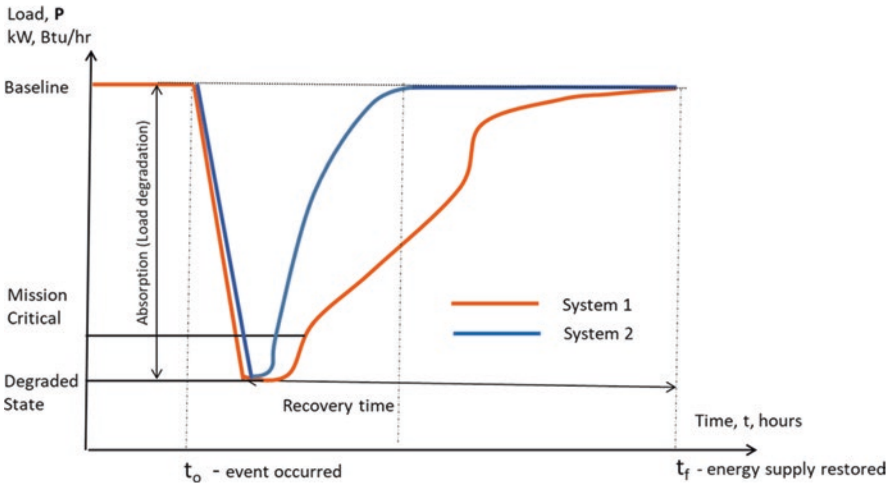


Fig. 5.5 Two systems with different recovery times

critical systems using internal building system with the power storage capacity followed by standby generators, emergency boilers, alternate utility feeds, or distributed energy resources. In this phase, the emphasis is on restoring the system to its Baseline operation.

As previously discussed, the shorter the recovery time, the more robust the system. Recovery time is determined by the average length of time required to return damaged components to service. In general, the availability energy for the mission increases as assets are recovered. For large or complex systems, availability during the recovery phase may change continuously. For smaller systems, or where fewer redundant paths exist, it can be more useful to consider the change in availability during the recovery phase as a step function. That is, there are discrete step changes in availability as components or success paths are returned to service.

Figure 5.6 provides an example of this concept. In this example, an event has disabled both the onsite generation and one of the two redundant utility feeders. The onsite generators are quickly returned to service, resulting in a large step increase in availability to support mission-critical loads. During generator unavailability, power to mission-critical assets is provided by UPSs integrated into the nanogrid. After some time, the redundant utility feed is returned to service, resulting in a second step increase in availability. It is important to note that for a single success path to be restored, all series components must be fully restored before improvements in availability are realized. For example, if an event disables a backup generator, its associated fuel tank, and fuel lines, then all of these assets must be repaired before that feed is considered back online.

If one considers the step-change model shown in Fig. 5.6, it becomes apparent that the recovery time for the system can be approximated using the mean time to repair (MTTR) for the various affected components. However, designers, planners, and facility managers must use caution when using MTTR to anticipate recovery

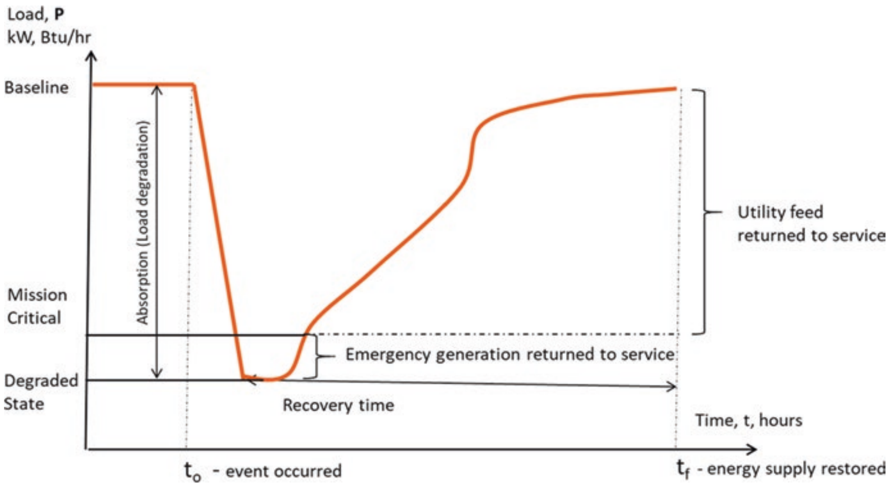


Fig. 5.6 Stepped recovery of power system assets

time following a contingency event. MTTR data is typically based on failure modes that occur during normal operation. Contingency events may cause different failures to occur, and additional logistical delays must be considered based on the nature of the event and the location of the site. To determine the recovery time for a system, MTTR data should be used as an input to a valuation of the disaster recovery plan.

Following a contingency event, the facility or site should have a plan in place to quickly adapt to and recover from the effects of the event. Due to limitations of personnel, resources, and logistics, repairs for all components cannot occur simultaneously. Some assets may also need to be restored in sequence. Priority must be given to restoring power to the level satisfying needs of mission-critical loads. In this case, **MTTR** of the system providing mission-critical load shall be smaller than **maximum single event allowable downtime** or a **Maximum Time to Repair (MaxTTR)** assigned based on the configuration and a storage capacity of nanogrid.

The following steps should be considered when developing a recovery plan:

Step 1. Identify the Components That Are Likely to Have Failed
This step may already have been completed as part of evaluating system robustness. Fragility curves and unique factors such as site geography are used to identify those components and also to identify success paths that may be inoperable following the event.

Step 2. Evaluate Repair Priorities
Using the reliability block diagram, we can evaluate the effectiveness of individual repair activities based on the effect that they have on mission availability and the time it takes to execute the repair. For example, when comparing two repair activities that have similar execution times, the activity that results in a larger improvement in mission availability should be prioritized. Typical MTTR values can be used as an input to the evaluation of the time requirements for each activity, but

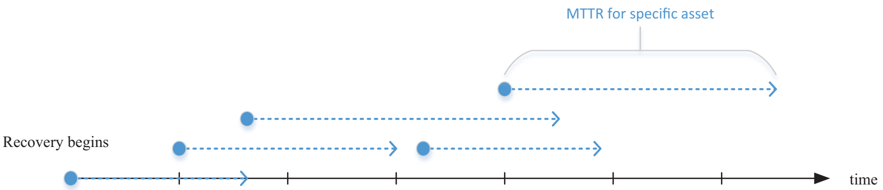


Fig. 5.7 Sample recovery timeline

event-specific failure modes and additional logistical delays should also be evaluated. In this step, it is important to consider any repairs that, due to operational or resource limitations, may need to be executed in sequence.

Step 3. Determine the Overall Time to Return to Baseline Operations
Once the overall structure of the recovery plan is in place, the timeline for recovery should be evaluated. The result should be a site-specific and event-specific number representing the required execution time for the planned series of repair activities. The result should be evaluated against operational limitations such as fuel reserves to determine whether the recovery time is adequate. Figure 5.7 shows an example of how the timeline for a typical recovery plan may look. Each arrow represents the repair time for a specific asset. Note that individual repair events are staggered to optimize personnel and equipment resources throughout the recovery phase.

5.2.2 Energy Availability

5.2.2.1 Defining Energy Availability (EA)

Energy Availability is a measure of the readiness of a system or component to perform its required function and is usually expressed as a function of equipment downtime as shown in Eq. 5.3.

$$EA = \frac{\text{Uptime}}{\text{Uptime} + \text{Downtime}} \tag{5.3}$$

This metric is used to evaluate the performance of the energy in terms of **percentage of time** it is available for the mission. For example, if an event occurs that reduces energy availability to 0.99, then the average expected weekly downtime of the mission is about 100 min. If a more resistant system has only reduced energy availability to 0.999, the expected weekly downtime for the mission is approximately 10 min. This essentially represents a tenfold difference in system performance.

There are two principal measures of availability: inherent availability (A_i) and operational availability (A_o).

Inherent availability: when only reliability and corrective maintenance or repair (i.e., design) effects are considered, we are dealing with inherent availability. Inherent availability is calculated based on the failure rate and MTTR for system components, without considering any logistical delays or preventative maintenance factors. This level of availability is solely a function of the inherent design characteristics of the system.

Operational availability: real-world consideration of repair times, etc. requires that availability be determined not only by reliability and repair but also by other factors related to preventative maintenance and logistics. When these effects of preventative maintenance and logistics are included, we are dealing with operational availability. Operational availability is a "real-world" measure of availability and accounts for delays such as those incurred when spares or maintenance personnel are not immediately on hand to support maintenance.

System operational considerations and the nature of events to be considered may dictate the preferred measure of availability for evaluating a given event. For example, hurricanes are often closely tracked and forecasted, allowing for several days or even weeks of advance notice before arrival. This can provide workers with time to perform routine checks on backup systems and to delay or back out of more invasive maintenance tasks. In this situation, the availability of the system is more representative of its inherent availability. For disturbances that occur without warning such as seismic events, it may be more useful to consider operational availability as this is more representative of normal day-to-day operations. In practice, it is important to consider the impact of an event on both the inherent and operational availabilities of the system. For the purposes of this discussion, the following examples will refer to operational availability. US Army Technical Manual (TM) 5-698-1 (HQDA 2007) provides additional information on basic availability concepts and definitions.

Traditional reliability and availability analysis methods, such as reliability block diagrams, state-space modeling, or Monte Carlo simulations, may be used to evaluate mission availability during Base Case and contingency operations. Additional information on each of these methods, as well as general availability concepts, can be found in US Army TM 5-698-1 (HQDA 2007).

Reliability is concerned with the probability and frequency of failures (or, more correctly, the lack of failures). A commonly used measure of reliability for repairable systems is the mean time between failures (MTBF). The equivalent measure for non-repairable items is mean time to failure (MTTF). Reliability is more accurately expressed as a probability of success over a given duration of time, cycles, etc. For example, the reliability of a power plant might be stated as 95% probability of no failure over a 1000-h operating period while generating a certain level of power.

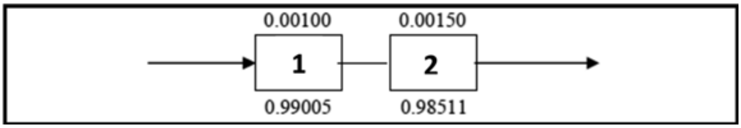


Fig. 5.8 Block diagram illustration of reliability of components installed in series

5.2.2.2 Evaluating Energy Reliability

According to TM 5-698-1 (HQDA 2007), reliability of the system with components installed in series can be calculated using Eq. 5.4:

$$R_s = R_1 \times R_2 \times \ldots \times R_i .. \times Rn, \tag{5.4}$$

where Ri is reliability of component i.

Figure 5.8 shows example of calculation reliability of the system with two components installed in series.

The number above each block in Fig. 5.8 is the failure rate in failures per million operating hours. The number below each block is the component reliability. The system reliability may then be calculated as

$$R_s = R_1 \times R_2 = 0.99005 \times 0.98511 = 0.9753.$$

Reliability with Redundancy The system shown in Fig. 5.9 has the same components (1 and 2) in series denoted by one block labeled "1&2," but two of each component are used in a configuration referred to as redundant or parallel. Two paths of operation are possible.

Each block in Fig. 5.9 represents the series configuration of components 1 and 2. The number below is the reliability calculated using Eq. 5.4. The paths are (top) 1&2 and (bottom) 1&2. If either of two paths is intact, the system can operate. The reliability of the system is most easily calculated as

$$R = 1 - (1 - R_s) \times (1 - R_s) = 0.9994 \tag{5.5}$$

where R_s is reliability of the system of components 1 and 2 installed in series. Adding a component in parallel, i.e., redundancy, improves the system's ability to perform its function.

For the purposes of evaluating resilience, the following discussion will focus on the reliability block diagram/Boolean algebra methodology.

Constructing a reliability block diagram requires translating the system topology into a set of discrete elements and logic gates. Items connected in series are typically combined with AND operators; parallel objects and strings are typically combined with OR operators. Each element in the block diagram has an associated availability statistic, which is derived from statistical data collected from similar

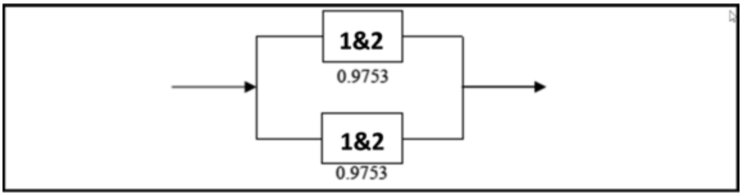


Fig. 5.9 Block diagram illustration of reliability of components installed in parallel

components. Figure 5.10 shows an example of a typical utility system translated into a reliability block diagram. Note that combining redundant paths with an OR operator significantly increases the mission availability.

Incorporating contingency event data into availability modeling allows for a quantifiable difference in performance between Base Case and contingency operations. This can be accomplished using deterministic approach, similar to traditional failure mode, effects, and criticality analysis (FMECA). This method assumes that an event of a certain magnitude has occurred and evaluates the effect that the event has on overall system availability.

5.2.2.3 Evaluating Energy System Robustness

The following steps can be used in the deterministic method for robustness evaluation of a typical distribution system illustrated by Fig. 5.10.

Step 1. Determine Events for Which the Energy Availability Should Be Assessed

Threats and Hazards

The all-threat/all-hazard assessment is conducted for the area of interest with identified critical assets. Threats may come in the form of natural disasters, accidents, and man-made threats, the most common of which are listed in the Table 5.1.

Threats and hazards to be addressed in the resiliency analysis integrated into the EMP are called design basis threats. It is important to include the threats that occur with low frequency but pose a potentially high consequence. Design basis threats should be evaluated individually but may also be evaluated in combinations depending on anticipated impacts to the given area. While the area of interest may not be directly affected by a threat or hazard, the secondary or tertiary effects caused by events elsewhere may prove impactful to the mission at some level and therefore must be considered during the threat analysis.

Methodology of threat/all-hazard assessment developed by US Army North (ARNORTH) includes the following criteria: operational capability, intentions/likelihood, and whether the activity and operating environment was designed primarily to assess man-made threats and is not applicable to address other types of threats and hazards. The CARVER method is another well-documented method that has been applied to several domains. This methodology focuses on the following six

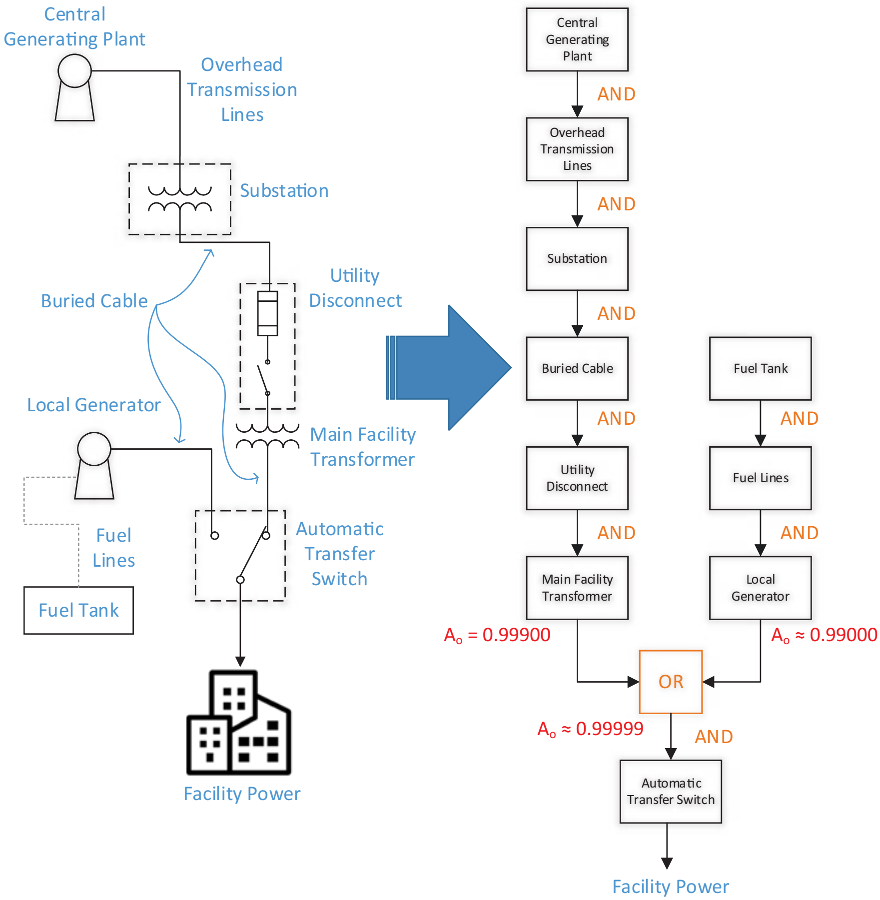


Fig. 5.10 Reliability block diagram for a typical distribution system

metrics: **C**riticality of the asset, **A**ccessibility of the target to the adversary, **R**ecoverability time to repair/replace the asset, **V**ulnerability of the asset to attack, **E**ffects the threat would have on the area, and **R**ecognizability of the target in different weather conditions and distances. Similar to the ARNORTH method, it addresses a combination of threat and its impact on the asset and was designed primarily to address man-made threats. It seems like the most applicable to prioritization of different threats for a given locality is a modification of the above methodologies developed at Fort Bragg in combination with the All-Hazard Threat Assessment (ATHA) methodology (DoD 2017). This site-specific threat matrix ranks different threats (Table 5.2) based on a combination of Threat Probability and Threat Severity as follows:

Table 5.1 Typical threats and hazards

Natural	Unintentional and technological	Man-made
Hurricane and tropical storms	Unintentional spill of hazardous materials	Conventional bomb/IED
Landslides and debris flow	Nuclear power plant failure	Biological agent
Thunderstorms and lighting	Failure of supervisory control and data acquisition system	Chemical agent
Tornados	Explosion	Nuclear bomb
Tsunami	Workplace fire	Radiological agent
Wildfire	Industrial accident	Arson/incendiary attack
Water and ice storms		Armed attack
Sinkholes		Cyberterrorism
Earthquakes		Hazardous material release (intentional)
Extreme heat		
Floods and flash floods		
Hail		
Damaging winds		
Droughts		

Table 5.2 Ranking threats

Threat	Threat probability	Threat severity	Threat rating	Threat rank

$$\text{Threat Rating} = \text{Threat Probability} \times \text{Threat Severity}$$

There are four categories of threat and hazard probability ratings (low, medium, critical, and high). The threat and hazard probability ratings can be found in the Mission Assurance Assessment Standalone Tool (MAAST). The use of these ratings and definitions will facilitate the uniform assessment of the likelihood or probability of any individual threat or hazard occurring. Probability is defined as the estimate of the likelihood that a threat will cause an impact to the mission or a hazard within the area of interest.

Table 5.3 aligns the threat/hazard likelihood ratings with terms used by the intelligence community (IC) credibility probability ratings.

For typical hazards and threats, numerical probability rating based on frequency of occurrence is listed in enclosure to DoD (2017). The information is based on authoritative data sources for Continental United States (CONUS) locations.

Table 5.3 Threat and hazard metrics

Linguistic value	Low	Medium	Critical	High
Description	Indicates little or no credible evidence of a threat to the asset or the immediate area where the asset is located For the identified threat, there is little or no credible evidence of capability or intent and no demonstrated history of occurrence against the asset or similar assets. For the identified hazard, there is a rare history, or no documented history, of occurrence in the immediate area or region where the asset is located	Indicates a potential threat to the asset or the immediate area where the asset is located. Also indicates there is a significant capability with low or no current intent, which may change under specific conditions, and there is low or no demonstrated history. For the identified threat, there is some evidence of intent. There is little evidence of a current capability or history of occurrence, but there is some evidence that the threat could obtain the capability through alternate sources. Alternatively, the identified threat evidences a significant capability, but there is little evidence of current intent and little or no demonstrated history. The identified hazard has a demonstrated history of occurring on an infrequent basis in the immediate area or region where the asset is located	Indicates a credible threat against the asset or the immediate area where the asset is located. The identified threat has both the capability and intent, and there is a history that the asset or similar assets are, or have been, targeted on an occasional basis The identified hazard has a demonstrated history of occurring on an occasional basis in the immediate area or region where the asset is located	Indicates an imminent threat against the asset or the immediate area where the asset is located The identified threat has both the capability and intent, and there is a history that the asset or similar assets are being targeted on a frequent or recurring basis The identified hazard has a demonstrated history of occurring on a frequent basis in the immediate area or region where the asset is located
Numerical rating	0.1–0.25	0.26–0.50	0.51–0.75	0.76–1.00

Other threat data for the analysis can be obtained from various open-source databases, the most common of which for the United States are:

- Federal Emergency Management Agency (FEMA, https://www.fema.gov)
- National Oceanic and Atmospheric Administration (NOAA, https://www.ncdc.noaa.gov)
- US Geological Survey (USGS, https://www.usgs.gov/natural-hazards)

Additionally, countries or agencies may have their own threat databases and maps that can be used for certain areas.

5.2.2.4 Threat Severity

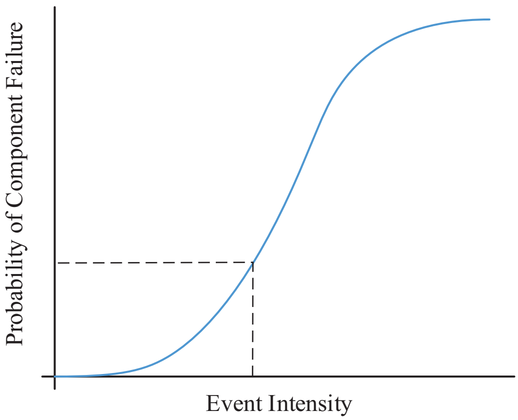
Threat or hazard severity may be similar to the term "consequence." When assessing a potential threat or hazard, you are asking "what would be the psychological, economic, sociological, or military impact if this hazard were to occur?" Since the severity of a threat or hazard can be very difficult to assess, we suggest applying the Effect Metrics used for criticality assessment listed in Table 5.4.

For selected design basis threats, the higher intensity events have a greater risk of causing energy system component failure, but they occur less frequently. This can be seen in the graph in Fig. 5.11. The bounded area of the graph on the left shows the fragility curve for a particular component; this shows the probability of component failure according to the intensity of an event. The unbounded area of the graph on the right shows the probability density function for a particular event, based on event intensity.

Table 5.4 Threat Severity metric

Numerical value	0–4	5–8	9–12	13–16	17–20
Linguistic value	Negligible	Minor	Very high	Extreme	Catastrophic

Fig. 5.11 Fragility curves for the notional event



From the probability of failure determined from fragility curves for a design-based threat (event), the resulting probability of component failure (given the event occurrence is above the threshold) indicates that the reliability of the system for that event should therefore be evaluated.

For other events, the severity of risk may be more subjective. For contingencies such as wildlife damage, cyberattacks, or terrorist attacks, the probability of occurrence may be unknown or is subject to change. Consequently, a threshold value for conditional probability of failure may not exist, and a different means of event selection is warranted.

Step 2. Determine What Components Are Likely to Fail as a Result of the Event

All components in a system are uniquely vulnerable to a set of events. For example, exterior generators may be vulnerable to flooding, whereas supervisory control and data acquisition (SCADA)-controlled switchgear may be more vulnerable to cyberattacks. If fragility curves for individual components are available, then the probability of component failure associated with an event can be incorporated into the system availability model. However, in many cases, it may be more practical to consider certain key components as having failed due to the event. For the deterministic approach, this clearly identifies single points of failure or areas that require additional hardening measures.

Step 3. Analyze the Degraded System State

As previously mentioned, functionality for critical missions that are considered uninterruptible must be maintained. In these cases, the change in system performance can be measured by the change in mission availability from the Baseline state. In other words, a contingency event is considered to affect mission availability, not overall mission success. For example, in the postulated power system shown in Fig. 5.12, a wind event disables only overhead transmission lines. Since backup power can be immediately supplied by emergency generators, mission loads can continue to operate. However, until the transmission lines are restored, the likelihood of failure is significantly increased.

Similar methods can be used to evaluate the degraded mission availability for other alternatives using reliability block diagrams, Monte Carlo method, etc. However, the input data must be modified to reflect the impact of the event being considered. The simplest method is to consider failed components as having an availability of zero. If equipment fragility curves are available, the resulting equipment reliability can be incorporated into the existing availability model.

5.3 Power and Thermal Energy Requirements for Resilience Metrics

Power and thermal requirements for resilience metrics can vary from site to site and depend on a multitude of factors. As previously discussed, certain sites may want to prioritize either robustness or recovery depending on their specific needs.

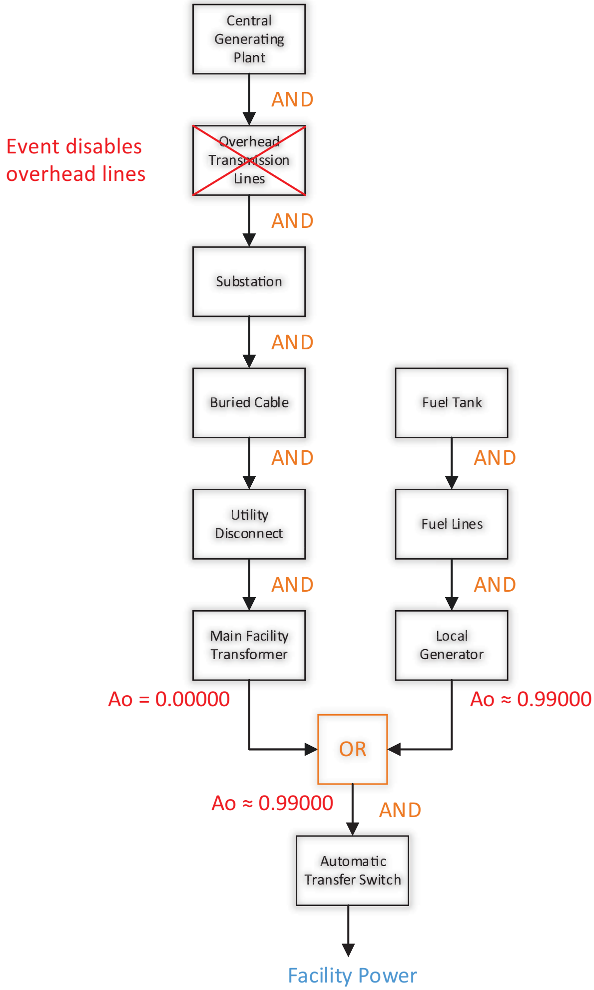


Fig. 5.12 Distribution system model in degraded state

5.3.1 Power Systems

To evaluate requirements to the energy system availability, it is important to apply a realistic time scale to the Baseline and degraded availability states. Typically, availability is related to equipment downtime on a yearly scale; a "six nines" system relates to about 30 s of downtime per year.

When assessing the minimum acceptable level of degraded state availability, it is also important to consider the site-specific requirements for availability, as well as requirements for system topology. For example, a Baseline availability requirement of six nines (0.999999) can be achieved using an N + 2 redundant arrangement of three elements each with an availability of 0.99 or an N + 1 redundant arrangement

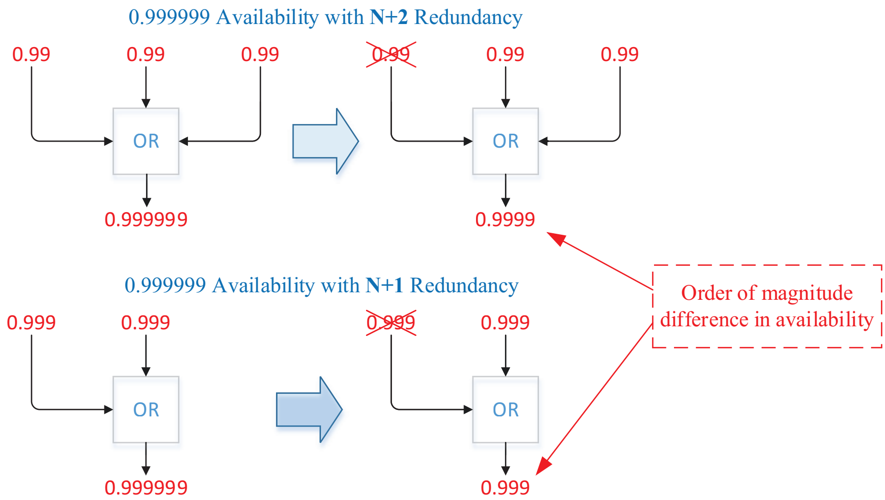


Fig. 5.13 N + 2 vs. N + 1 system resilience

of two elements each with an availability of 0.999. If an event occurs that incapacitates only one feed, the N + 2 system will have a degraded state availability a full order of magnitude higher than the N + 1 system. Naturally, systems with a higher level of required redundancy should have more stringent requirements for resilience than those with less design redundancy. This is shown in Fig. 5.13.

Site-specific requirements for resilience should also be decided by weighing several major factors. Ultimately, the required level of resilience is based on the level of mission criticality, the remoteness of the site, and whether the mission is duplicated and can be executed at any other sites.

5.3.1.1 Criticality

Many government agencies (including DoD installations) and public and private enterprises serve a range of missions, some of which are more critical than others. In a perfect world, designers would be able to protect all levels of critical missions from the effects of any possible event. However, due to funding and design constraints, some assets must be prioritized over others.

Critical mission function is defined as a function that is vital to the continuation of operations of the organization or agency (HQDA 2008). These functions include those required by statute or executive order and other functions deemed essential by the head of each organization and must be performed without interruption to execute critical missions including during and after a disaster. In addition to core critical facilities and operations, there are critical facilities that, if not maintained, impact the safety of the public and its property during and after a disaster. The priority of each critical mission function and corresponding facility asset shall be identified by tenants and customers and shall be documented and approved by the community leadership. Methodology of criticality analysis used in this chapter uses a modified version of the metrics from “USARNORTH Risk Management Process” (USARNORTH 2019) where “importance” is the sum of all of the following metrics: Effect, Recoverability, Substitutability, Mission Functionality, and Repairability. Based on this methodology, facility criticality can be classified as Low, Moderate, Significant, or High. In many cases, specific details related to the level of criticality of a mission may be classified.

5.3.1.2 Remoteness (System Repairability)

Critical facilities and other critical assets exist in a variety of locations. This can have a significant effect on the time of recovery for a mission following an extreme event in the case of limited availability of a qualified repair crew on site and the access to spare parts. Remoteness is primarily related to the geographical location of a facility or installation but can be further influenced by other accessibility factors. Topographic features such as bodies of water or mountainous terrain as well as the number and condition of access roads can also impact the remoteness of a site. For example, if a site can only be accessed via a single bridge, it would be considered as more remote than a similar site with several access points. Similar to the level of criticality, the remoteness of a site can be categorized in relative terms. For the purposes of resilience planning, sites should be considered to have Low, Moderate, Significant, or High remoteness (Table 5.5).

Typically, more remote sites should prioritize the robustness phase of resilience as recovery may be limited by physical constraints. This maximizes overall resilience by prioritizing the ride-through ability for these missions. Major factors affecting system repairability are availability of spare parts and personnel having specified skill levels required for prescribed level of energy system maintenance and repair. A commonly used measure of a system repairability is the MTTR.

Table 5.5 Remoteness/repairability metric

Numerical rating	Low (0–6)	Moderate (7–12)	Significant (13–160)	High (17–20)
Description	Immediate/low cost or short-term/moderate cost to repair (0–72 h)	Mid-term repair/significant cost to repair (more than 72 h, less than 7 days)	Long-term/high cost to repair (more than 7 days, less than 30 days)	More than 30 days or no repair possible

5.3.1.3 Facility Redundancy

Some missions can be carried out at geographically diverse sites such that a contingency event at one is unlikely to affect mission success at any of the other sites. Also, at the same site, buildings can provide different levels of service to different mission functions. This creates additional mission redundancy and can reduce resilience requirements at an individual site.

Multiple functions may be served by a single asset, and multiple assets can all serve a single function. To allocate different assets to different mission-critical functions, stakeholder input is helpful, especially when assets operate differently in day-to-day scenarios as opposed to emergency situations. Functions and their criticality may change during emergencies as infrastructure is used in different ways from normal operations. Emergency plans should be consulted to understand how infrastructure asset uses are expected to change during a disruptive event.

Infrastructure assets can be buildings (e.g., a cafeteria), system components (e.g., water pumps, pipes, and valves), or loads within buildings (e.g., computing resources). In addition to buildings, assets may also be point loads such as communications towers or networks such as water distribution systems. When functions are provided by networks—a potable water system or a communications network, for example—the critical function performance is a complex function of asset performance that should be calculated using a system model. However, when functions are provided by collections of point assets, estimating the fraction of necessary critical function that the asset can provide is sufficient.

The output of this step is a matrix that associates infrastructure assets with critical functions (Jeffers et al. 2020). Table 5.6 lists the elements of a generic asset to function mapping matrix. Planners should fill out Table 5.6 for all assets and buildings that provide or enable critical functions and map them based on the relative capability of providing their functions. For instance, if Asset 1 is able to provide 100% of Function A's requirements, it would score 1.0. Similarly; if Asset 2 and Asset 3 are each capable of providing 50% of Function B to the area of interest (AOI), they would each score 0.5. It is not necessary for the rows to add to 1.0. Some critical functions have redundant assets—for instance, Asset 1 and Asset 3 could each have capability of providing 0.75 of the requirements for Function C.

Using the notional system, Fig. 5.14 shows that each of the four buildings provides different services to five critical functions. Building A is a dormitory with a dining facility. Building B is a student center with a bank, convenience store, small coffee shops/cafes (assumed to be closed during emergencies), and a basement that

Table 5.6 Building to critical function mapping matrix

	Assets and buildings			
Critical function	Asset 1	Asset 2	Asset 3	…
Function A				
Function B				
Function C				

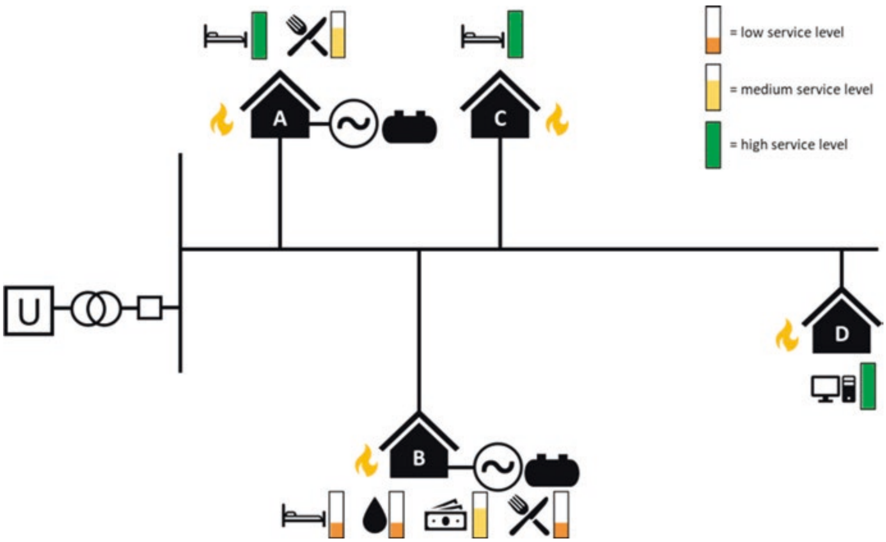


Fig. 5.14 Critical functions and their service levels applied to the notional system. (Jeffers et al. 2020)

Table 5.7 Mapping of buildings to functions for notional system

Critical function	Building A	Building B	Building C	Building D	Redundancy
Shelter	1.0	0.5	1.0		150%
Food	0.75	0.25			0%
Finance		0.5			0%
Water		0.25			0%
IT and data				1.0	0%

can serve as a storm shelter. Building C is a second dormitory. Building D is a data center with servers for research labs and campus administration files.

The data in Table 5.7 maps each asset to the community and mission functions it provides. Building A can provide 100% of the required shelter since it already serves as housing and can provide 75% of the required food if the dining facility stays open. Food may be limited to supplies on hand and will naturally decline the longer the emergency lasts. Building B is providing food and bottled water at a low level to those who can purchase items at the convenience store and cannot support by itself the needs of the entire campus for these functions, especially for extended disruption durations. The bank in Building B can provide financial services at a medium level through branch services and an ATM, but not enough to serve the entire campus. During an extended event, some individuals will need to rely on off-campus financial services even if Building B is operational. Building C is another dormitory, providing shelter at a high level with no additional functions. Building D serves as a data center for the campus.

Table 5.8 Facility redundancy metric

High (0–6)	Significant (7–12)	Moderate (13–16)	Low (17–20)
Not difficult to accomplish mission using facilities providing similar capabilities (redundancy >150%)	Difficult to accomplish mission using facilities providing similar capabilities (redundancy 60–150%)	Very difficult to accomplish mission using facilities providing similar capabilities (redundancy 35–55%)	Limited substitutes for facilities providing similar capabilities are available (redundancy <30%)

If it is important to evaluate the practical considerations in mission duplication, several questions must be answered. Will the mission be transferred to an alternate site automatically? Will personnel be available at the alternate site to process the mission? Can the mission be transferred in anticipation of a foreseen event? In the interest of simplicity, the ability of a mission to be carried out at alternate sites should be considered as a simple yes or no. This information will help to select the facility redundancy score from Table 5.8.

5.3.1.4 Categories for Energy Availability and Recovery

Once these three factors (mission criticality and facility remoteness/repairability and redundancy) have been evaluated, the results can be used to determine the requirement categories for both Availability and Recovery (Table 5.9). As previously discussed, these two aspects of resilience should be considered independently due to the unique needs of individual sites. Using the data in Table 5.9, the three factors can be applied to place a mission or asset in prioritized categories for both Robustness and Recovery. The result is a low-moderate-significant-high index for each resilience phase. For example, a mission with moderate criticality, significant remoteness, and moderate facility redundancy would have a Significant robustness requirement and a Medium recovery requirement.

Note: The process of assigning resilience requirements is based on three factors—mission criticality and facility remoteness/repairability and redundancy. This process needs to be executed by mission operators, not energy planners. This process may include information classified as Secret or Top Secret if the asset or supporting infrastructure were classified. Typically, installation critical assets are For Official Use Only (FOUO) and not classified unless they are designated as Defense Critical Assets (DCAs), Task Critical Assets (TCAs), or supporting infrastructure for DCAs or TCAs. In any case, this process can be executed internally, and results can be kept for internal use as backup information. Based on this process, operators will identify requirements to energy systems, which can be provided to energy planners (without any background information).

Table 5.10 provides examples of facilities that can be affiliated with different levels of requirements to energy system resilience for low remoteness and low redundancy factors.

Table 5.9 Determination of resilience requirements

Resilience metric requirement	Resilience phase	
	Availability	Recovery
Low	Criticality: **Low-Mod** Remoteness: **Low** Facility redundancy: **Yes**	Criticality: **Low** Remoteness: **Low-Moderate** Facility redundancy: **Yes**
Moderate	Criticality: **Low-Mod** Remoteness: **Moderate-Significant** Facility redundancy: **Yes**	Criticality: **Low-Mod** Remoteness: **Moderate** Facility redundancy: **Yes**
Significant	Criticality: **Mod-High** Remoteness: **Significant-High** Facility redundancy: **No**	Criticality: **Mod-Significant** Remoteness: **Significant-High** Facility redundancy: **No**
High	Criticality: **Significant-High** Remoteness: **High** Facility redundancy: **No**	Criticality: **High** Remoteness: **Significant-High** Facility redundancy: **No**

Table 5.10 Examples of allocation of different facilities to mission-based resilience requirement categories (may be different at a particular site)

Resilience metric requirement			
Low	Medium	Significant	High
Offices, administrative, housing, recreation facilities, etc.	Intelligence processing, district office buildings, etc.	Medical centers, logistics warehouses, etc.	Warfighting facilities, IC, hospitals, continuity of government operations, critical communications facilities, nuclear command and control, etc.

The following section provides recommendations to mission operators on how to select energy requirements for their mission-critical facilities based on metrics presented in Table 5.9.

5.3.1.5 Recommended Requirements for Energy Availability (EA) and Maximum Single Event Downtime (MaxSEDT)

The resilience requirements listed in Table 5.11 stratify each Resilience Metric listed in Table 5.9. Each Resilience Metric in Table 5.9 is split into two levels of facilities, Primary and Secondary, which in turn have two levels of requirements to energy system resilience ranging from Low (0) to High (4). Such stratification of each Resilience Metric creates more accurate scenario fitting to the facility and mission requirement.

The availability of multiple categories will facilitate the ability of design teams to identify the most correct resiliency requirement for the project at hand. The tables represent two category states for each of the four Resilience Metric requirements

Table 5.11 Recommended resilience requirements to power systems serving mission-critical facilities

Resilience metric	Facility level	Resilience sub-metric	Category	Degraded state availability	Acceptable average weekly downtime (minutes)	Maximum single event downtime (minutes)
Low	Primary	Low	LP/1	0.92	806.4	2419
		Moderate	LP/1+	0.95	504	1500
	Secondary	Low	LS/0	0.9	1008	3024
		Moderate	LS/0+	0.92	806.4	2419
Moderate	Primary	Low	MP/2	0.99	100.8	302
		Moderate	MP/2+	0.995	50.4	150
	Secondary	Low	MS/1	0.95	504	1500
		Moderate	MS/1+	0.99	100.8	302
Significant	Primary	Moderate	SP/3	0.999	10.08	30
		Significant	SP/3+	0.9995	5.04	15
	Secondary	Moderate	MS/2	0.95	504	1500
		Significant	MS/2+	0.99	100.8	302
High	Primary	Significant	HP/4	0.9999	1.008	3
		High	HP/4+	0.99999	0.1008	0.3
	Secondary	Significant	HS/3	0.9995	5.04	15
		High	HS/3+	0.9999	1.008	3

P = Primary facility/mission, S = Secondary facility/mission, L = Low resilience metric, M = Moderate resilience metric, S = Significant resilience metric, H = High resilience metric
+ = highest 10% of a specific resilience metric range, 0 = resilience metric range—lowest resilience metric range, 1 = resilience metric range—scaled 0 to 4, with 4 the highest level of resilience metric, 2 = resilience metric range—scaled 0 to 4, with 4 the highest level of resilience metric, 3 = resilience metric range—scaled 0 to 4, with 4 the highest level of resilience metric, 4 = resilience metric range—highest resilience metric range

listed in Table 5.9. Expansions of tiers for Resilience Metric requirements create the process three needed properties:

- An additional level of granularity for more accurate direction as to the most appropriate category of resiliency, which assists in the ability to select the most appropriate category.
- More flexibility for a project to identify the lowest Resilience Metric requirement level that is appropriate; this helps to avoid overdesign beyond appropriate levels, which increases cost.
- Assistance to the project team so they will not feel a need to invent a resilience level not represented in the less granular criteria, thereby ensuring that the project team has sufficient levels to fit a wide variety of project needs.

The Primary Facility Level category in each Resilience Metric is dedicated to those facilities that have the higher level of resilience requirement within the main Resilience Metric category, while the Secondary Facility Level category is for those facilities that have the lower level of requirements for resilience within the main Resilience Metric category and that do not require all of the design features for energy system resiliency that a Primary Facility requires.

The differentiator between a Primary Facility/Mission and a Secondary Facility/Mission within a given Resilience Metric is the level of criticality split into two potential choices, i.e., a stricter requirement and a less strict requirement.

The plus (+) differentiator is used to identify the highest 10% of resilience for a level of Resilience Metric. This allows for identification of the highest resilience Category within a Resilience Metric without the necessity of elevating into the next higher Facility Level. In installations with grouping of buildings, a common Resilience Metric may be appropriate with stratification by Categories for resilience priority among buildings and missions. The numerical indicators (0, 1, 2, 3, 4) function as a guide in stepping through the sub-table levels of Resilience Metric. This creates the stratification choices in identifying the most correct level of facility resilience.

Over the four category ranges that make up a Resilience Metric requirement Category, the resilience variables increase with progression through the ranges. Improvement in Degraded State Availability and MaxSEDT will also yield improvement across the Primary and Secondary categories dependent on the metric of Low-Moderate-Significant or High. The MaxSEDT also improves throughout the Primary and Secondary categories; this is the one variable that is unique in every category. This results in the MaxSEDT being the differentiating variable when there is overlap in the Degraded State Availability and Average Weekly Downtime variables.

Power delivery can be thought to have three delivery mechanisms. The first delivery mechanism resides internal to the facility; it is the building-level power infrastructure. The second delivery mechanism is the emergency, or backup, power directed to the facility from outside of the building but sourced from local infrastructure power generation. The third delivery mechanism is the full power load delivered to the facility under normal operating conditions; this is commonly prime power or power delivery from an electric utility.

Power from the first delivery mechanism will be referred to as layer one power. Power from the second and third delivery mechanisms will be referred to as layers two and three, respectively.

Two facility load levels are defined. The full electrical power load is provided by layer three power and serves the entire electrical load of the facility. The critical electrical power load is provided by layers one and two, also referred to as backup power, and only serves the facility critical infrastructure. The facility critical infrastructure load results from the load shedding of all power connected equipment that is not critical for the continuity of the mission or missions housed in the facility.

Layer one power for a facility is the electrical backup power that resides inside of the facility. Common components are a UPS and an ATS. Layer one backup power is the shortest duration of electrical power capacity of the three layers. The power delivery capacity can typically be from several minutes to several hours.

Layer two power for a facility is the electrical backup power that resides outside of the facility but at a minimum is partially dedicated to supplying the facility.

Common components are generator sets and renewable energy systems such as solar arrays. Layer two backup power is of variable duration. The electrical power delivery capacity can be several hours to days in duration. The limit of electrical power delivery capacity is only limited by factors such as fuel storage capacity, battery rectifier capacity, etc. The layer two power can also be supplied for an installation-wide or campus microgrid system. In such a case, the facility power is supplied from a microgrid system that also provides power to other facilities that reside at the same location as the facility in question.

Layer three for a facility is the electrical power that resides in the infrastructure of the prime power utility. Common components the utility serves electrical power to the facility are substations and the medium voltage power distribution system. Layer three is supplier of electrical power under normal conditions. Unlike layers one and two, layer three is not maintained and repaired by the facility. An exception is use of installation or campus distributed power generation in conjunction with connection to the prime power utility; the primary goal is lower cost of the distributed power generation or opportunities to sell into the utility grid for a positive cost differential. Failure at layer three requires relying on layers one and two for continuity of mission operations.

MaxSEDT is presented as a more critical metric for design parameters than MTTR. MTTR is a mean, or average, of the total repair time of the mean value of all single event repair times. For a normal distribution curve, this results in one-half of all single event repair times less than the MTTR and one-half of the single event repair times greater than the MTTR. Every single event downtime will vary in severity. While some incidents will require days to repair, others will take minutes.

MaxSEDT is a more appropriate critical metric in the design of a mission-critical facility. Long repair time is not desirable for mission-critical facilities. Mission-critical facilities have a limit of the maximum time the mission can endure an interruption of electrical power. MaxSEDT is an important metric because it tells you how efficiently you can respond to and repair the worst-case downtime event. Ideally, the electrical power system will be designed to achieve the mission requirement for MaxSEDT.

Commonly, the MaxSEDT will increase from layer one to layer three. The concept of a larger, more complex, electrical power system that has the capacity to supply larger amounts of power will generally require longer time to repair a MaxSEDT event.

A project has resilience variables in relation to Resilience Metric, Facility Level, Resilience Sub-Metric, and Category. These are Degraded State Availability, Average Weekly Downtime, and **Maximum Single Event Downtime**. A project may choose one of these variables or a combination to best fit the facility and mission requirements.

This methodology is used to drive the MaxSEDT as the deciding variable when choosing a Resilience Metric for a facility, and downtime has flexibility in the variable range. This provides a means of identifying a Resilience Metric level when Average Weekly Downtime is not the most critical variable.

Facilities and missions may value the time for repair and return to normal operating conditions more than the downtime experienced on a yearly basis. In other words, the mission requirement that has greater importance is how long the facility is down, compared to how often a downtime event might occur. This creates greater emphasis on the maximum duration of a downtime event than on statistical long-term averages or means.

The calculation of MaxSEDT is based on four standard deviations from the mean on the positive side of a normal distribution function. Four standard deviations of a normal distribution is 99.9% of incidents. This represents virtually the maximum downtime occurrence of the possible incidents. A normal distribution is also represented by a *Z* distribution. Four standard deviations of the normal distribution is also a *Z* score of four for a *Z* distribution. A *Z* score formula is used to arrive at the maximum single event downtime, as

$$x = \left(z \times \sigma\right) + \mu \tag{5.6}$$

where x is the incident value, z number of z states, σ standard deviation value, and μ mean value.

For a normal statistical curve, standard normal distribution, the number of data points that fall within two standard deviations on the positive side of the curve is 95% of positive incidents. Due to the inherent uncertainty in the range of incidents, the standard deviation will use the range rule, and the Average Weekly Downtime value will be divided by 2.

For the calculation, the standard deviation value is 50% of the mean value. The number of z states is four or four standard deviations. The mean value is the Average Weekly Downtime.

5.3.2 Thermal Systems

Thermal energy systems are composed of both demand and supply sides (Fig. 5.15). The demand side is comprised of mission-related active and passive systems including thermal demand by the process, HVAC systems maintaining required environmental conditions for the process and comfort for people, and a shelter/building that houses them. Requirements for thermal or environmental conditions in the building or in any part that houses critical mission-related processes and people include criteria for thermal comfort and health, process needs, and criteria preventing mold/mildew and other damage to the building materials or furnishings. These requirements for normal (blue sky) and emergency (black sky) operations are described in detail in Appendix D, which specifies requirements for building thermal conditions under normal and emergency operations for occupied and temporarily unoccupied spaces. Thermal comfort conditions in the mission-critical facility during normal operations differ from cold stress threshold limits or heat stress threshold limits

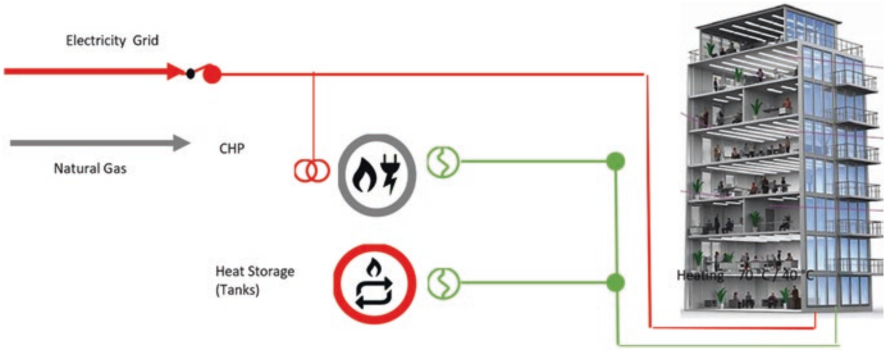


Fig. 5.15 Component of the notional thermal system

applicable for mission operators to conduct mission-critical tasks. That is to say, the total heating or cooling loads during normal operations differ from critical loads during emergency operations. This affects requirements to EA provided by the supply system. The time to restore the system to its Baseline state is another requirement to the energy supply system. EA and maximum single event downtime are two critical metrics of the thermal system characteristics of any asset affected by the event and may be affected by several factors including site remoteness, event severity, and environmental condition.

5.3.2.1 Maximum Single Event Downtime of Thermal System

Maximum downtime for a thermal system can be defined in terms of how long the process can be maintained or how long the building remains habitable (**habitability threshold**) or how long the thermal environment shall be maintained above the **sustainability threshold** level to protect the building against damage from freezing of water pipes, sewer, and fire suppression system, to protect sensitive content, or to prevent the start of mold growth during extended loss of energy supply with extreme weather events (e.g., 40 °F [4.4 °C]). Zhivov et al. (2021) defines the threshold limit value for building habitability for the heating season as a condition in which the room air temperature is above 60 °F (16 °C) and for the cooling season as a condition in which wet bulb global temperature (WBGT) accounts for a combination of room air temperature and relative humidity below 88 °F (31 °C). Mission operators may select different thresholds based on age, health, or level of training of inhabitants.

A building's total heat consumption per unit of time can be calculated using Eq. 5.7:

$$Q_{\text{tot}} = Q_{\text{loss tr}} + Q_{\text{inf}} + Q_{\text{vent}} - Q_{int} \tag{5.7}$$

where $Q_{\text{loss tr}}$ is the heat flow to compensate for thermal losses due to heat transfer by conduction, Q_{inf} heat flow to heat outside air due to infiltration, Q_{vent} heat flow to heat ventilation air, and Q_{int} internal heat flow from people and internal processes.

$$Q_{\text{loss tr}} = U\,A\left(T_{\text{out}} - T_{\text{in}}\right), \tag{5.8}$$

where U is the overall coefficient of heat transfer, A total building surface area, and ($T_{\text{out}} - T_{\text{in}}$) a difference between inside and outside air temperatures.

$$Q_{\text{inf}} = AL\,A\,C_p\left(T_{\text{out}} - T_{\text{in}}\right), \tag{5.9}$$

where AL is the air leakage rate and C_p specific heat of air.

$$Q_{\text{vent}} = L\,C_p\left(T_{\text{out}} - T_{\text{in}}\right), \tag{5.10}$$

where L is the outside air ventilation rate.

Based on these simplified equations, the major factors affecting the heat flow rate and therefore the time when the internal temperature reaches threshold based on building habitability/survivability or sustainment include difference between inside and outside air temperature; building envelope leakage rate; building envelope insulation properties, including insulation levels of its components; and thermal bridging and internal thermal load (people and appliances/equipment connected to electric power).

Also, thermal mass of the building structures composed of concrete, masonry, or stone materials that constitute a high level of embodied energy enables the building to absorb and store heat to provide "inertia" against temperature fluctuation. The amount of heat that can be absorbed by the building mass can be calculated using the following equation:

$$Q_{\text{storage}} = M\,Cp\,\Delta T, \tag{5.11}$$

where Q_{storage} is the amount of energy that can be stored by the building mass, M is the building mass, C_p is the specific heat of the building material, and ΔT is the allowable change in the room air temperature.

Figure 5.16 shows how these factors will influence the time when the building reaches its habitability (t_h) and sustainment (t_s) thresholds. For more details regarding temperature decay in buildings during emergency situations, see Appendix C.

A "first of its kind" thermal decay study attempted to address thermal decay in cold environments (Oberg et al. 2021) was conducted at Fort Wainwright, AK, and Fort Greely, AK. These tests occurred with outside air temperatures ranging between −20 and −40 °F (−28.9 °C and −40 °C), which allowed researchers to obtain the building-specific data on temperature change in different building areas and different surfaces of tested buildings to identify critical areas with significant temperature degradation compared to other building areas. These tests found that air temperature

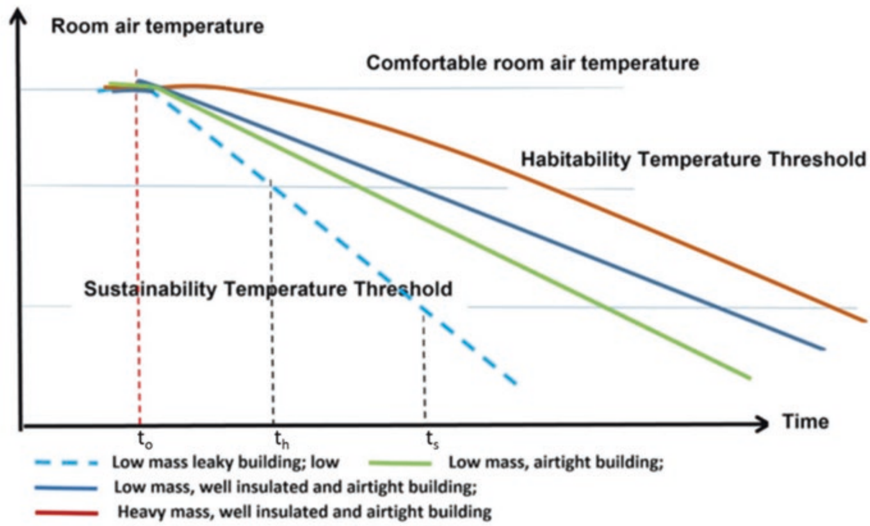


Fig. 5.16 Notional example of temperature decay rate for different types of building envelope

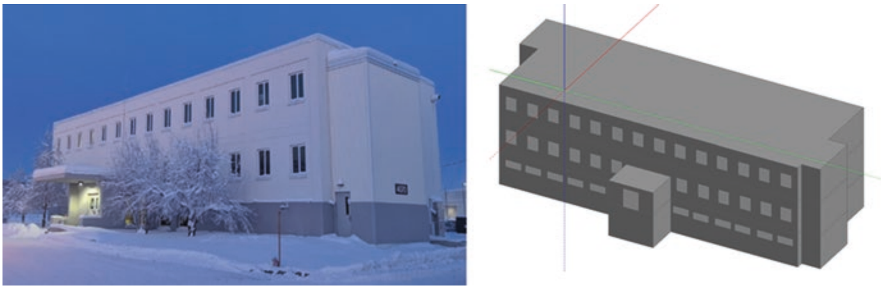


Fig. 5.17 Studied building photo and model representation. (Liesen et al. 2021)

in mechanical rooms located in the basement, in a semi-basement, or on the first floor having an opening for makeup air, fenestration, or a large open stairway column located nearby deteriorated more quickly than that in other parts of the building; therefore, mechanical rooms can be used as representative locations for identifying the time when a building reaches sustainability thresholds. Typically, the longest time to reach the habitability threshold occurs on the middle floors; these locations are recommended for hosting mission-critical operations and therefore have been used as representative locations for this purpose. EnergyPlus-based building energy modeling was used in this study, combined with the weather data corresponding to the test locations and dates. This allowed the building models to be calibrated for use in parametric studies of representative buildings.

The parametric studies (Liesen et al. 2021) of indoor air temperature decay were conducted using the geometry of one of the studied buildings (Fig. 5.17), which has two floors and a basement and houses office and meeting spaces, medical examination facilities, and medical laboratories.

The following parameters were changed in the study:

- ***Building mass***: high mass building (CMU and poured concrete slabs) (1) and light frame buildings (2).
- ***Thermal envelope characteristics***: ranging from pre-1980 code construction (1), current minimum energy efficiency requirements (lower efficiency) (2), and the state-of-the-art energy efficient building characteristics (high efficiency) (3) for the buildings constructed in the USDOE climate zone 8. Table 5.12 lists specific characteristics for these three building categories.
- ***Outside dry bulb air temperature (ODB)***: −60 °F (−51.1 °C), −40 °F (−40 °C), −20 °F (−28.9 °C), 0 °F (−17.8°C), 20 °F (−6.7°C), and 40 °F (4.4°C) TMY3 weather files used in the parametric study have been adjusted to steady-state temperature files.

Results of these studies presented in Table 5.12 clearly showed that high building mass contributes significantly to the thermal resilience of the building, along with the higher building air tightness and a higher thermal insulation. Figure 5.18 illustrates the case of simulated interruption of the mechanical heating supply during outside temperature conditions of −40 °F (40 °C). In a building with a mass structure and a more energy efficient building envelope design, the indoor air temperature approached the habitability level of 60 °F (16 °C) 7 h later than for a similar building with a less energy efficient building envelope and 6 h later compared to a similar arrangement with a framed (i.e., lower thermal mass) building structure. Intersection of the indoor air temperature decay line with the building sustainability threshold of 40 °F (4 °C) occurs 31 h and 27 h later, respectively, for the same scenarios. When mass high performance buildings are compared to buildings built using pre-1980 code (i.e., the majority of existing buildings), the difference in the maximum time to repair calculated till the building air temperature reaches habitability and sustainability threshold values much more significant (Fig. 5.19).

5.3.2.2 Blue Sky and Emergency Energy Demands

During a normal (blue sky) scenario, energy generated onsite or imported from outside the AOI can be consumed by ALL end uses (mission-critical and non-mission-critical building functions, industrial processes, central services—compressed air/water/sewer, etc.). This quantity of energy will also include distribution losses (hot water, chilled water, and steam network, onsite electrical) and onsite conversion losses (turbines, boilers, engines).

During emergency scenarios, some generation, distribution, and thermal storage system components may be compromised, e.g., components may be out of order, or fuel supply to the campus can be limited. To maintain critical functions, the need for energy by both critical and non-critical functions can be reduced by shedding non-critical thermal loads. To do this, loads must be prioritized (to denote where and

Table 5.12 Parametric study results for the maximum single event downtime

Building parameters	Temp ODB	Mass building			Frame building		
		Typical/post-1980	Low efficiency	High efficiency	Typical/post-1980	Low efficiency	High efficiency
Walls *R*-value, °F·ft^2·h/Btu ([m2·K]/W)		20.5 (3.6)	40 (7.0)	50 (8.8)	20.5 (3.6)	40 (7.0)	50 (8.8)
Roof *R*-value, °F·ft^2·h/Btu ([m2·K]/W)		31.5 (5.5)	45 (7.9)	60 (10.6)	31.5 (5.5)	45 (7.9)	60 (10.6)
Air leakage, cfm/ft^2 at 0.3 in. w.g. (L/s. m2 at 75 pa)		0.4 (2)	0.25 (1.25)	0.15 (0.75)	0.4 (2)	0.25 (1.25)	0.15 (0.75)
Window (*R*-value, °F ft^2·h/Btu; *U* value, W/(m2·K))		Double pane; $R = 1.78/U = 0.56$	Double pane; $R = 3.34/U = 0.3$	Triple pane; $R = 5.25/U = 0.19$	Double pane; $R = 1.78/U = 0.56$	Double pane; $R = 3.34/U = 0.3$	Triple pane; $R = 5.25/U = 0.19$
MaxSEDT Hab. (60°F/15.6°C)	-60 °F −51.1 °C	<1 h	2 h	5 h	<<1 h	1 h	2 h
MaxSEDT Sust. (40°F/4.4°C)		9 h	28 h	41 h	4 h	14 h	21 h
MaxSEDT Hab. (60°F/15.6°C)	−40 °F −40 °C	1 h	3 h	10 h	<1 h	2 h	4 h
MaxSEDT Sust. (40°F/4.4°C)		20 h	36 h	51 h	10 h	18 h	24 h
MaxSEDT Hab. (60°F/15.6°C)	−20 °F −28.9 °C	2 h	6 h	15 h	1 h	3 h	6 h
MaxSEDT Sust. (40°F/4.4°C)		31 h	46 h	60 h	15 h	22 h	28 h
MaxSEDT Hab. (60°F/15.6°C)	0 °F −17.8°C	3 h	13 h	29 h	2 h	5 h	9 h
MaxSEDT Sust. (40°F/4.4°C)		43 h	59 h	90 h	21 h	28 h	33 h

MaxSEDT Hab. (60°F/15.6°C)	20 °F −6.7°C	10 h	28 h	45 h	3 h	8 h	15 h
MaxSEDT Sust. (40°F/4.4°C)		60 h	78 h	95 h	28 h	35 h	40 h
MaxSEDT Hab. (60°F/15.6°C)	40 °F 4.4°C	29 h	54 h	72 h	8 h	17 h	23 h
MaxSEDT Sust. (40°F/4.4°C)		93 h	112 h	123 h	41 h	47 h	50 h

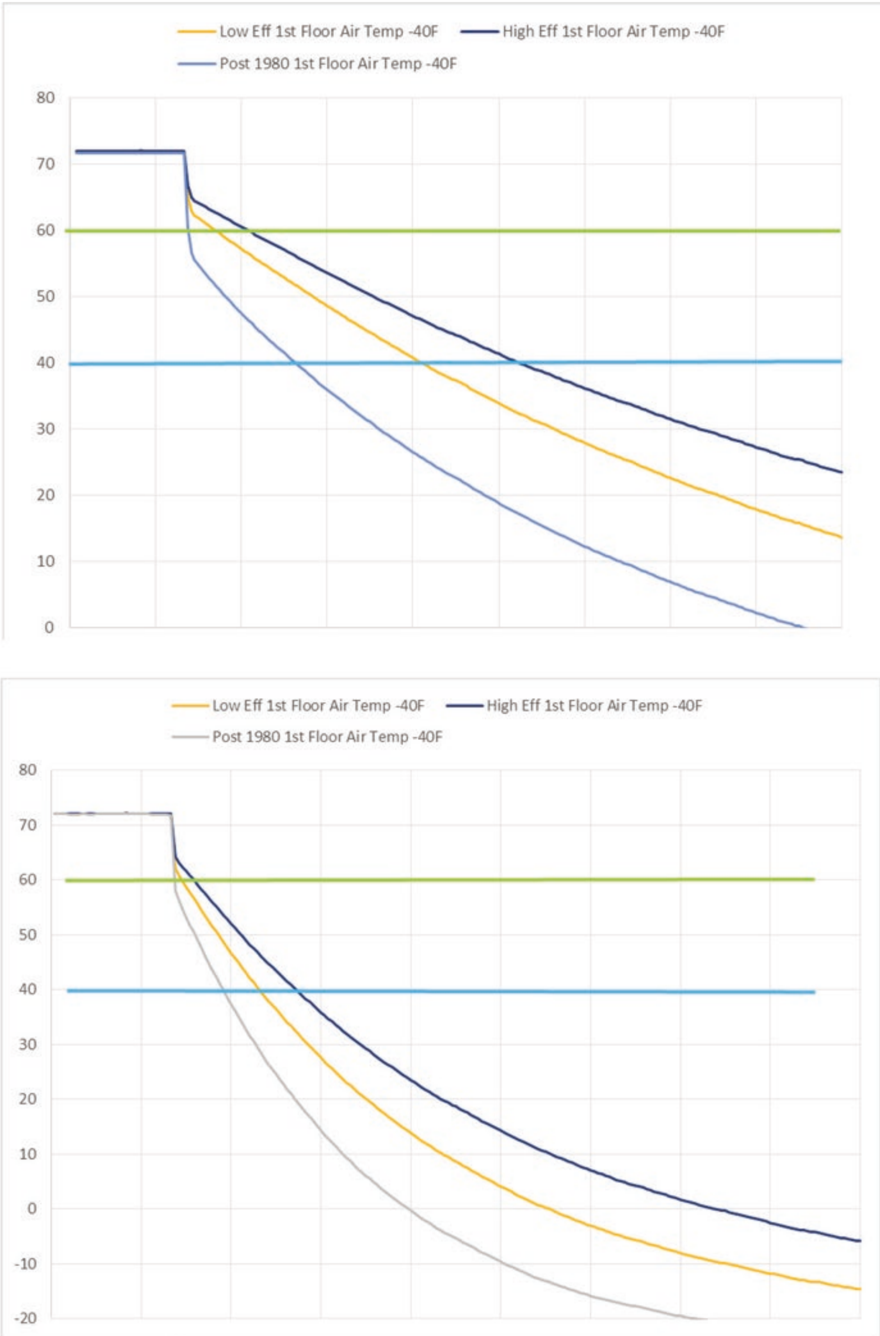


Fig. 5.18 Indoor air temperature decay in high-efficiency, low-efficiency, and post-1980 buildings with a heating system failure at outdoor air temperature of −40 °F (−40 °C): (**a**) mass building, (**b**) frame building

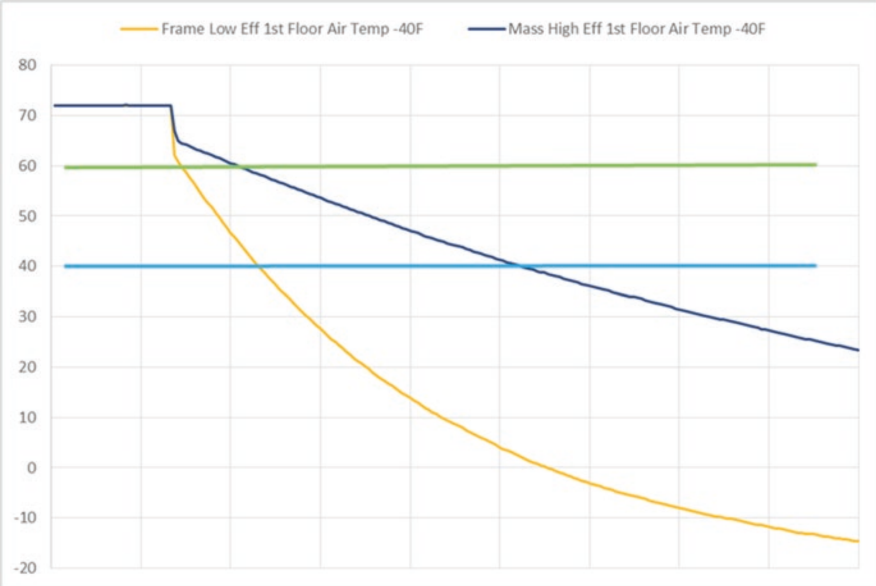


Fig. 5.19 Comparison of indoor air temperature decay in low-efficiency frame building vs. high-efficiency mass building with a heating system failure at outdoor air temperature of −40 °F (−40 °C)

how energy will be used). Priority for energy supply must be given to buildings and their areas with mission-critical uninterruptable or interruptible processes. These mission-critical areas may include the whole building or, in some cases, as little as 5–10% of the total building area. For example, using this strategy, a data center would keep computer room air conditioners (CRACs) online, but would shut down some office-only area air-conditioning. This example reduces the demand on backup supplies of generator fuel enabling longer run times for onsite supplied power.

The amount of thermal energy to be supplied to non-critical areas of a building or to non-critical buildings can be significantly reduced by using direct digital control (DDC) to control space temperature (or by using manual controls) to extend the use of limited resources without jeopardizing mission-critical, life, or safety functions or building sustainability. Figure 5.20 shows that, while the room air temperature in the mission-critical area of the building must be maintained close to the normal temperature, air temperature in surrounding areas can be reduced to the level of survivability. Air temperature in non-mission-critical facilities can be temporarily dropped to the level above the sustainability threshold. If possible, ventilation systems shall be designed and adjusted to accommodate zonal control to reduce airflow rate in non-mission-critical zones to the level required for building pressurization. In occupied areas that have ventilation reduced, care must be given to not violate air change per hour requirements of codes. When outside environmental conditions warrant, systems such as economizers may be used to maintain indoor air

Fig. 5.20 Temperature reduction concept in mission-critical and non-mission-critical areas/buildings

temperature. Nevertheless, due to their specific use in emergency scenarios, some buildings may use more energy (e.g., shelters, dining facilities, etc.).

5.4 Conclusions

Power and thermal energy delivery can be thought to have three delivery mechanisms. The first delivery mechanism resides internal to the facility; it is the building-level power infrastructure for electrical energy systems and building envelope and its mechanical systems for thermal energy supply. The second delivery mechanism is the emergency, or backup, energy systems directed to the facility from outside of the building but sourced from local infrastructure power and thermal energy generation. The third delivery mechanism is that which delivers the full load to the facility under normal operating conditions; this is commonly prime power or power delivery from an electric utility for electrical systems and steam, hot water, and chilled water delivered from the campus, building cluster, or outside the campus plant.

Two facility load levels are defined. The full electrical and thermal energy load is provided by layer three energy source and serves the entire electrical and thermal load of the facility. The critical electrical and thermal energy load is provided by layers one and two, also referred to as backup power, and only serves the facility critical infrastructure. The facility critical infrastructure load results from the load shedding of all power connected equipment and thermal energy serving areas that are not critical for the continuity of the mission or missions housed in the facility.

This chapter introduces a quantitative approach to resilience of electrical and thermal energy systems supplying energy to the building mission-critical areas that includes the following metrics: Energy System Robustness (ER), Energy System Recovery time (ER), Energy Availability (EA), and Energy Quality (EQ).

The first three parameters are critical for selection of the energy supply system architecture and technologies of which it is comprised to satisfy requirements related to energy system resilience. Energy Availability and Energy System Recovery Time depend on (1) criticality of the mission being served by the system; (2) system repairability, which has significant dependence on remoteness of the facility hosting the mission; and (3) redundancy of facilities that can serve the same critical function.

Requirements for Energy Robustness depend on a load that is critical to the mission and can be measured as the percentage of the load that is available to mission essential loads from the total mission essential load requirements (1); it can also be related to the overall building energy load under normal (blue sky) conditions (2). Energy Quality is another important quantitative metric for the energy system serving critical functions and should be considered as a design parameter for level one building energy systems.

The characteristics of the critical energy load can vary significantly between functions. For example, a communications function may require a large but steady supply of power to meet its equipment and conditioning needs. A shelter, on the other hand, may have little to no critical power demand but may have a large but variable heating demand to protect occupants from environmental conditions.

To prevent significant damage to non-critical buildings, minimum thermal requirements (in cold climate) and air humidity above the dew point (in hot and humid climates) shall be maintained in these buildings that will require thermal energy to these buildings, but at significantly reduced rate.

There are also large variations in energy demand profiles based on the function's location. For example, the acceptable system disruption period will be significantly shorter for a heating system coping with an Alaskan winter than for one in the relatively temperate climate of Seattle, WA.

These variations in type, magnitude, and schedule of critical energy requirements are essential considerations when developing resilience system performance metrics such as energy availability and MaxSEDT. This paper provides information on MaxSEDT that can be used to select thermal energy systems serving buildings with different levels of building envelope efficiency and mass located in cold and arctic climates and outside air temperature ranging between −60 and 30 °F (–51 and –1 °C).

References

Ayyrub, B. 2015. Practical resilience metrics for planning, design, and decision making. *ACME Journal of Risk and Uncertainty in Engineering Systems, Part A. Civil Engineering* 1 (3): 04015008.

DoD (U.S. Department of Defense). 2017. *DoD Emergency Management (EM) Program*, DoD Instruction (DODI) 6055.17. Washington, DC: DoD. https://irp.fas.org/doddir/dod/i6055_17.pdf.

DoD. 2020. *Memorandum on metrics and standards for energy resilience at military installations. Metrics and standards for assessment of energy resilience, supporting policy and guidance and associated reporting requirements*. Washington, DC: U.S. Department of Defense.

HQDA (Headquarters, Department of the Army). 2007. *Reliability/availability of electrical & mechanical command, control, communications, computer, intelligence, surveillance and reconnaissance (C4ISR) facilities*, Army technical manual (TM) 5-698-1. Washington, DC: HQDA. https://www.wbdg.org/FFC/ARMYCOE/COETM/ARCHIVES/tm_5_698_1_2003.pdf.

———. 2008. *U.S. Army continuity of operations (COOP) program policy and planning*, Army regulation 500–3. Washington, DC: HQDA.

———. 2015. *Energy security and sustainability (ES2) strategy*. Washington, DC: HQDA. https://www.hsdl.org/?view&did=766353.

IEEE. 2012 [1366]. *IEEE Guide for electric power distribution reliability indices*. Piscataway, NJ: Institute of Electrical and Electronics Engineers.

Jeffers, Robert F., Amanda M. Wachtel, Alexander M. Zhivov, Calum B. Thompson, Avinash Srivastava, and Patrick W. Daniels. 2020. Integration of resilience goals into energy master planning framework for communities. *ASHRAE Transactions* 126 (1): 803–823.

Liesen, Richard J., Brianna Morton, Brandy Diggs-McGee, and Alexander M. Zhivov. 2021. Thermal energy system resilience: Thermal Decay Test (TDT) in Cold/Arctic Climates, Part II modeling. *ASHRAE Transactions* 127 (1).

McCarthy, Kevin, and Victor Avelar. 2016. *Comparing UPS system design configurations*, White Paper 75. Rev. 4. Schneider Electric. Schneider Electric's Data Center Science Center DCSC@ Schneider-Electric.com.

NAVFAC (Naval Facilities Engineering Command). 2019. *Engine-driven generator systems for prime and standby power applications*, UFC 3-540-01. Washington, DC: Headquarters, U.S. Army Corps of Engineers (HQUSACE), NAVFAC (Preparing Agency), and U.S. Air Force Civil Engineer Center (AFCEC). https://www.wbdg.org/FFC/DOD/UFC/ufc_3_540_01_2014_c2.pdf.

NERC (North American Electric Reliability Corporation). 2018. *Reliability issues steering committee report on resilience*. Atlanta: NERC. https://www.nerc.com/comm/RISC/Related%20Files%20DL/RISC%20Resilience%20Report_Approved_RISC_Committee_November_8_2018_Board_Accepted.pdf.

NIAC (National Infrastructure Advisory Council). 2009. *Critical infrastructure resilience: Final report and recommendations*. Washington, DC: NIAC. https://www.cisa.gov/sites/default/files/publications/niac-critical-infrastructure-resilience-final-report-09-08-09-508.pdf.

Oberg, Bjorn K., Angela Urban, Emmet Leffel, Jonathan Goebel, Matt Perry, Dragos Vas, Dayne Broderson, Richard Liesen, and Alexander Zhivov. 2021. Thermal energy system resilience: Thermal decay test (TDT) in cold/arctic climates, Part I data collection and protocol. *ASHRAE Transactions* 127 (1).

Roege, P., Z.A. Collier, J. Mancillas, J.A. McDonagh, and I. Linkov. 2014. Metrics for energy resilience. *Energy Policy* 72: 249–256.

USARNORTH (U.S. Army North). 2019. *Risk management process*, 210-221-0494. San Antonio: USARNORTH.

USDOE (U.S. Department of Energy). 2017. Ensuring electricity system reliability, security, and resilience. Ch. 4. In *Transforming the nation's electricity sector: The second installment of the QER*. DOE/EPSA-0008. Washington, DC: USDOE. https://www.energy.gov/sites/prod/files/2017/02/f34/Quadrennial%20Energy%20Review%2D%2DSecond%20Installment%20%28Full%20Report%29.pdf.

Vugrin, E., A. Castillo, and C. Silva-Monroy. 2017. *Resilience metrics for the electric power system: A performance-based approach*, SAND2017-1493. Albuquerque: Sandia National Laboratories. https://doi.org/10.2172/1367499.

White House, The. 2013. *Presidential policy directive 21: Critical infrastructure security and resilience*, PPD-21. Washington, DC: The White House. https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil.

Willis, Henry H., and Kathleen Loa. 2015. *Measuring the resilience of energy distribution systems*. Santa Monica: RAND Corporation. https://www.rand.org/pubs/research_reports/RR883.html.

Zhivov, Alexander, William Rose, Raymond Patenaude, and William Warren. 2021. Requirements for building thermal conditions under normal and emergency operations in extreme climates. *ASHRAE Transactions* 127 (1).

Chapter 6
Data Required for Energy Master Planning and Resilience Analysis

Abstract Preparation of the Energy Master Plans requires information that can include general information, campus and building-level information, information on building archetypes and topology, HVAC systems, energy generation systems and existing distribution systems, basic fuel availability and potentials, and possible synergies along with the information required for unique building modeling and resilience analysis. The chapter describes specific types of information required and potential sources of information from which it can be obtained.

Preparation of the EMP requires information that can be divided in the following categories:

- General information
- Campus- and building-level information
- Information on building archetypes and topology
- HVAC systems
- Energy generation systems
- Existing distribution systems
- Basic fuel availability and potentials
- Possible synergies
- Information required for unique building modeling
- Information required for resilience analysis

General information can be obtained from energy manager, utilities manager, engineering department, and master planner and can be finalized during the kick-off meeting. Among the main questions to be answered under this category of information gathering are:

- What are the boundaries of the area to be studied?
- What are installation's framing energy goals (source, site, renewable energy [RE], etc.)?
- What are energy supply limitations (power, gas, biomass, wind, area available for solar photovoltaic (PV) and solar thermal panels)?
- What is the time frame for meeting the ultimate goal?

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- Is it a phased approach? If yes, which are these phases?
- Is there any preliminary plan developed to achieve the goal?
- Which other goals installation wants to accomplish along with energy use reduction (e.g., repair buildings, repair and upgrade utilities, accommodate mission changes, improvement of the campus, architectural improvement, improve comfort or indoor air quality [IAQ], etc.)?
- What other priorities should be considered?
- What are desired economic characteristics (boundaries), e.g., minimum first costs and life-cycle cost (LCC)?
- Is there any budget allocated for this project or parts of this project?
- Project structure (organization chart): project manager, decision-makers, stakeholders, project team (national labs, ESCOs, other contractors), and external reviewers?

Table 6.1 lists the framing goals and constraints to be used in evaluation of the Baseline, Base Case, and different alternatives against each other and the Base Case. This table has active macros available in the tool described in Chap. 4.

Campus and building information can be collected from the master planner, engineering department, and energy manager and includes:

- Map and boundaries of the area under consideration, preferably in digital format
- The existing buildings that will be demolished and that will be built. Please add this information to the abovementioned Excel® spreadsheet
- The buildings that are planned for retrofit under a sustainment, restoration, and modernization (SRM) program and the current scopes of these projects
- Geographic information system (GIS) data for the site (ESRI electronic format if possible. Best is “file geodatabase” [*.gdb], followed by “personal geodatabase” [*.mdb], and then shape files)
  - Real Property Inventory (RPI) data with detailed characteristics for each building
  - List of planned facilities’ electrical distribution systems (GIS and single line drawings)

    Hot water/steam distribution system
    Cold water distribution system

  - Potable water distribution system
  - Storm drainage system
  - Wastewater system (sewers)
  - Natural gas distribution system
  - Petroleum, oils, and lubricants (POL—fuel oil tanks, lines, pumps)
  - Community boundary
  - List of existing backup generators
  - Transportation network (roads)
  - SCADA systems
  - AEWRS data (1 year required, 3 years preferred)
  - SWARS report (1 year required, 3 years preferred)

Table 6.1 Project framing goals and objectives

Energy Master Planning objective	Classification of objective		Value	Value (units)	Examples of entries		
	Goal (Y/N)	Requirement (Y/N)			Goal (Y/N)	Requirement (Y/N)	Values
System economics, return on investment (ROI)				%		Y	20%
System economics, net present value (NPV)							
Environmental impact (% reduction in GHG)				%			
Reduce source energy use (% reduction)				%			
Reduce site energy use (% reduction)				%			
Reduce water use (% reduction)				%			
Meet or exceed an energy use standard (specify standard)				%		Y	30% better
Renewable energy use (quantity)				MMBtu/yr			
Renewable energy use (% of total source energy use)				%			
Renewable energy use (% of total site energy use)				%			
Renewable energy generation (% of electricity use)				%			
Renewable energy generation (% of heating energy use)				%			
Renewable energy generation (% of total source energy use)				%			
Renewable energy generation (% of total site energy use)				%			
Fossil fuel-based energy use (% reduction)				%	Y		50%

(continued)

Table 6.1 (continued)

Energy Master Planning objective	Classification of objective		Value	Value (units)	Examples of entries		
	Goal (Y/N)	Requirement (Y/N)			Goal (Y/N)	Requirement (Y/N)	Values
Hot water (% generated from renewable energy)				%	Y		100%
Backup/redundant systems for electric generation						Y	N + 1
Backup/redundant systems for space cooling						Y	N + 1
Backup/redundant systems for space heating						Y	N + 1
Grid-independent capability for mission-critical operations							
System availability for mission-critical buildings* (uptime as % of total run time)				%		Y	99.99%
System reliability for mission-critical buildings* (number of days – MTBF)				Days		Y	400 days
System resilience for mission-critical buildings* (number of hours – MTTR)				Hours		Y	7 h
Water use limit				kgal/day			
Particulate emissions limit				ppm			
Maximum project cost				$k			$50,000 k
Lowest LCC							
Minimum first cost							
Minimum operational cost							
Ease of maintenance (e.g., simple, low cost, minimal labor, serviceable via existing skill set)						Y	

(continued)

Table 6.1 (continued)

Energy Master Planning objective	Classification of objective		Value	Value (units)	Examples of entries		
	Goal (Y/N)	Requirement (Y/N)			Goal (Y/N)	Requirement (Y/N)	Values
User-added Objective 1: (specify)							
User-added Objective 2: (specify)							
User-added Objective 3: (specify)							
User-added Objective 4: (specify)							
User-added Objective 5: (specify)							

- Additional information (preferred, but not required):
  - Prior installation reports/audits/analysis
  - Energy bills (gas, electricity, etc.)
  - Water bills
  - Waste collection bills
  - Building-specific energy metering data
  - Building-specific water metering data

Building typology information can be requested from the master planner and engineering department:

- Building type, e.g., barracks (UEPH), office, instruction (GIB), dining (DFAC), training barracks, brigade HQ (BdHQ), battalion HQ (BNHQ), company operations (COF), data center (InfoSys), Army reserve (ARC), warehouse (GPW), equipment maintenance (TEMF), commercial/retail, religious, physical fitness (PFF), outpatient health (OHC), school-primary, school-secondary, youth center (FMWR), child development (CDC), single-family home, townhouse, lodging (hotel), and others (please explain).
- Building era, e.g., mid-century, pre-1980, post-1980, ASHRAE (based on construction completion date).
- Facility use: unusual use (relative to facility type) and unusual equipment (based on facility type and era).

HVAC systems information can be obtained from the energy manager and engineering department. This needs to include all systems with the basic characteristics (location, power output, max. and average airflow, age, electricity consumption, combination with air condition, air heat recovery).

Energy generation systems (all of them, big ones and small ones) information can be requested from electrical engineer, utilities manager, and energy manager and includes:

- List of all heating/cooling/domestic hot water (DHW) plants, boilers, and chillers with their basic characteristics (location, power output, covered buildings, fuel, annual consumption, age, condition, estimated efficiency, need for maintenance and repair, etc.)
- List of all power generating/converting facilities with their basic characteristics (location, power output, covered buildings, fuel, annual fuel consumption, age, condition, estimated efficiency, need for maintenance and repair, etc.)
- Emergency power generation as described above

Distribution systems information can be requested from Directorate of Public Works (DPW) electrical engineer, utilities manager, and energy manager and includes:

- Map of existing gas network with piping diameters and connection points
- Map of existing district heating steam network with piping diameters, connection points, and buildings interfaces; describe condition of pipes, insulation qualities, and utility tunnels
- Map of existing district heating hot water network with piping diameters, connection points, and buildings interfaces; describe condition of pipes, insulation qualities, and utility tunnels
- Map of existing district cooling network with piping diameters and connection points; describe condition of pipes, insulation qualities, and utility tunnels
- Map of existing power distribution lines and substations

Basic fuel potentials information can be requested from DPW energy manager and includes:

- The fuels that are available on site
- Available roof/ground area for solar power/hot water generation
- Groundwater characteristics (depth, temperature, flowing speed)
- Whether it is allowed to use the river, lake, or ocean water for heating or cooling purposes directly or indirectly. (This question aims for compliance with the legal framework)
- Monthly average wind speed and wind direction
- Whether there is a significant potential of forest in the region so wood chips for heating/cogeneration can be considered

Possible synergies information should be requested from energy manager and from the production/facilities managers, if applicable. In this category, the following questions can be asked:

- Are there facilities located close to each other with a simultaneous demand for heating/DHW and cooling? If yes, what are they?
- Is there waste heat available from on site or nearby from manufacturing process or power generation that can be considered as a potential heat source?

Information required for building modeling. There might be unique buildings to be built or undergo major renovation on the campus for which none of existing generic models is applicable. These unique buildings are probably listed in the "others" category. To include these buildings in the analysis, the following information can be requested from the engineering department, master planner, and/or energy manager:

- CAD drawings with plan and elevation views with material sections for walls, roofs, floors, windows, etc. with enough details to model the buildings, including drawings of HVAC systems with specifications of as-built equipment
- Plan view of the building with the major function areas colored in to indicate, e.g., office spaces, classrooms, barracks, etc., would be helpful. This can be electronic or paper. For each functional area, include schedules and loads for occupants, lights, equipment, etc.
- Current and projected utility rates and bills, as detailed as possible
- GIS shape files

Information required for resilience analysis can be requested from the commander, energy manager, DPTMS manager, and/or major tenants' operation personnel and includes the following:

- Does the installation have the emergency plan?
- What is the time frame for which the plan has been developed?
- Which buildings are mission-critical based on operations (results from criticality analysis)?
- Which buildings and operations are mission-critical based on life and safety (e.g., hospitals, dining facilities, day care, electrical power systems, thermal energy systems, water systems for cooling, sanitary sewage disposal, firefighting systems, industrial and potable water uses, bulk fuel storage and refueling, emergency generators, and UPS, HVAC systems, EMP protection system, etc.)?
- What is the total load, electrical and thermal (provided by external electrical and thermal grids), and onsite generation?
- What are priority loads provided by reduced capacity of external grid and from onsite generation and/or storage?
- What are critical loads when supply from onsite generation and/or storage is limited? How do they differ when energy supply from external grids is interrupted for less than an hour (several hours, a day, 2–3 days, a week, 14 days)?
- What is the allowable downtime of electrical and thermal systems for mission-critical and life and safety operations (none, 60 s, 10 min, 20 min, 30 min, 4 h, 8 h, etc.)?

- What are electrical and thermal energy requirements for mission-critical operations and life and safety operations (e.g., frequency range, voltage range, steam, temperature of hot or chilled water, etc.)?
- What are mandatory requirements for energy systems (redundancy, efficiency, reliability, and resilience), and to which threats do these requirements pertain?
- What are the major natural threats to the locality of community/installation (e.g., earthquake, wildfire, floods, tornados, etc.), based on threat assessment provided by DPTMS?
- Have any risk analysis studies been conducted to assess impacts of different threats on specific buildings, infrastructure, and energy systems? What were their results?
- Were (are) there any past, current, or planned efforts to harden buildings, infrastructure, or energy systems and distribution lines based on results of studies listed in Appendix B?
- Is there any documented evidence on how long buildings were able to survive without heating, cooling, or humidity control before they began to experience sustainability problems requiring costly repairs (e.g., frozen pipes, water damage, mold and mildew, etc.)?
- Can you provide a list of onsite generation and energy storage equipment and its characteristics, expected life and age, conditions, maintenance level, fuel type, and storage capacity? Which buildings/parts of building/operations this equipment can serve? Does this equipment operate only in emergency situations or is a part of the general operation? Location of this equipment and architecture of distribution systems (when connected to the grid).

References

ASHRAE. 2007. *Energy standard for buildings except low-rise residential buildings*, ASHRAE Std. 90.1-2007. Atlanta: ASHRAE.

———. 2020. *Standard for the design of high-performance green buildings*, Standard 189.1-2020. Atlanta: ASHRAE.

Chapter 7
Selection of Energy System Architecture and Technologies

Abstract This chapter offers a list of power and thermal energy system architectures technologies and technologies they employ. These system architectures and technologies have been categorized and documented with their characteristics (cost and performance), application, pros, and cons described. This information can be used for detailed analysis of the Energy Master Plan baseline and of different alternatives including the base case and more advanced concepts to be considered in new development ("greenfield") and/or renovation/extension ("brownfield") projects. Different system options can be considered on the building level, building cluster level, or community level. Selection of these alternatives should consider the existing status of these systems, the goals and objectives of the project, including improvement in systems resilience, local constraints, and economic and non-economic co-benefits.

7.1 Introduction

Selection of energy system architectures and types of technologies employed for use in new development ("greenfield") and/or renovation/extension ("brownfield") projects is usually based on the following master planning considerations:

- **Baseline**: The current status of buildings and existing systems. It is important to know the existing status to better plan and design scenarios to improve energy usage and resilience.
- **Base Case** (business as usual): Local and national energy efficiency and environmental codes, adopted standards, and institutional mandates prescribing minimum requirements to buildings and energy systems are incorporated into the analysis to create the "business as usual" scenario. This case provides a reference point for comparison, which assumes that no significant changes outside of planned projects will be implemented within the study period.
- **Cost**: The total investment and operating (including energy, maintenance, and replacement) costs for each alternative. Ultimately, the lowest LCC considering environmental benefits is the key priority for any campus owner. The economic

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assessment, which is normally based on the Net Present Value Method and a project period of (for example) 20 years, considers residual value of assets with long lifetime such as building envelope and energy networks. It is important to include all incremental costs (and not average costs) of the alternatives compared to the base case, in particular for analyzing complicated interactions between the energy carriers, e.g., the interactions between CHP and heat pumps.

- **Alternatives**: When selecting alternatives it is important to consider relevant alternatives for planning at one level (building, campus, local community); it is always a good idea to start with a screening of the options at one or two levels above. A project at the building level shall, for example, be compared with options at the campus or community level to not miss better options.
- **Resilience**: Mission-critical facilities along with safety- and health-related facilities may have special requirements to energy system resilience to different threats and hazards specific to the locality of interest. The "do nothing" energy system solution may jeopardize critical mission. Costs associated with the business-as-usual solutions can be significant and may exceed the ordinary cost of energy systems designed without resilience requirements in mind.
- **Local environment**: Energy system design and performance have an impact on the local environment. The negative impact of energy system performance on the local environment can significantly reduce campus livability and the value of surrounding private property (e.g., local building-level coal boilers are harmful for the air quality, noise created by wind turbines reduces the value of private property, and chillers installed outside of buildings emit noise and heat).
- **Climate change**: Energy generation based on fossil fuels is the main source of greenhouse gas emissions resulting in climate change. Use of energy from renewable sources in the most cost-effective way shall be among the priorities for community energy master planning.
- **Sustainable Development Goals** (SDGs): An increasing number of local governments, cities, and campus owners pay attention to the SDGs, which address all the abovementioned priority factors, and even go beyond them to create a more long-term livable society. These international energy policy objectives should also be recognized by the local energy planner since they may in time be reflected in regulatory requirements, taxes, and subsidies.

These selection considerations, goals, objectives, local constraints, and non-economic benefits are discussed in detail in Chaps. 1 and 3, and Appendix B, which also include examples of best practices described in Case Studies Book (IEA 2021).

7.2 Overview of Methodology for the Selection of Energy System Architecture and Technologies

To help analyze the performance of the baseline (or existing) system and energy system alternatives to be used for further consideration, energy planners can model the energy and resilience performance of these systems using typical and inspirational system architectures discussed in Sect. 7.7 and presented in Appendix E as a starting point, along with the catalogue of options and a database of technologies discussed in Sect. 7.8 and Appendix D.

There is a variety of system options used for heating and cooling of campuses, varying by their architectures and technologies used, including options for individual buildings and building clusters, as well as campus-wide and community-level options. The historic transition of district heating (DH) systems from the first system generation with a coal-fired steam production to the modern forth system generation having low-temperature hot water distribution integrated with a thermal storage, district cooling and ambient temperature sources for heat pumps (Fig. 7.1).

The final "generation" represents the maximal integration of the four energy carriers combined with the buildings and all ambient energy sources for heating and cooling, including network for transferring ambient heat to heat pumps for generation of heating and cooling (e.g., see case for Taarnby District, Denmark, cooling).

While the diagram above sketches example district system configurations by generation, the design and architecture of a specific system may include components from several generations to accommodate the end user needs, whether in greenfield, expansion of an existing system, or modernization and renewal of an aged system. For example, some critical hospital buildings and pharmaceutical

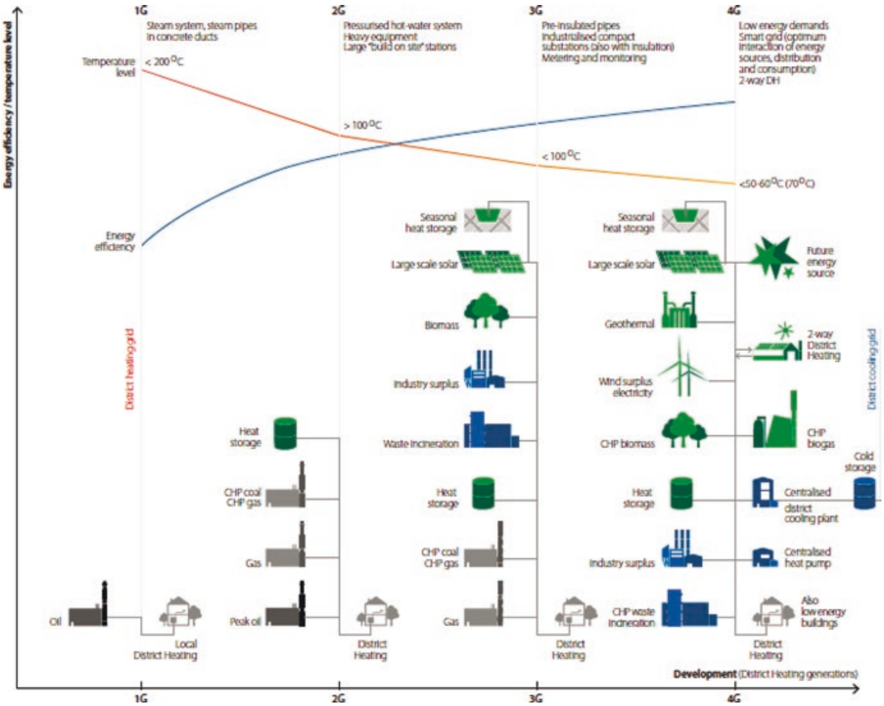

Fig. 7.1 Four generations of thermal district systems. (Reproduced with permission from www.4dh.dk)

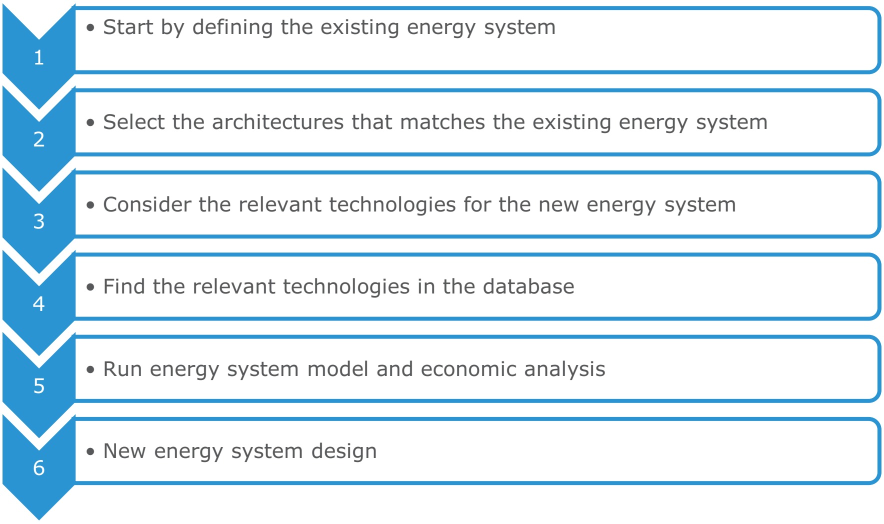

Fig. 7.2 Use of the architectures, database, and energy system model

facilities may need to provide steam to accommodate certain end users, while most other end users may be sufficiently served by hot-water service. Therefore, it is important to split steam demand into process steam and low-temperature demand to be able to identify smarter alternatives for supplying a low temperature. It is similarly important to split the electricity demand into ordinary electricity demand (which only can be supplied with electricity) and demand for heating and cooling, which, in the base case, is supplied with electricity.

System architectures from the catalogue provided in Appendix E can be modified to match an existing system configuration or a desired one, and the list of technologies can be narrowed using constraints discussed in Chap. 4. The database in Appendix D lists the major technical and economic characteristics for technologies that can be used in energy and economic modeling of system alternatives. It is important to understand the assumptions that are contained within the technology characteristics and to adjust them accordingly to the local project conditions. The process flow of how to use system architectures and the database are shown in Fig. 7.2.

7.3 How to Approach Energy System Selection

7.3.1 System Analysis

Chapter 3 discusses the scope of energy master planning and its boundaries. Chapter 6 lists the major categories of data required for the process of energy master planning and resilience analysis, which includes:

- General information
- Campus- and building-level information
- Information on building archetypes and topology
- HVAC systems
- Energy generation systems
- Existing distribution systems
- Basic fuel availability and potentials
- Analysis of constraints
- Possible synergies
- Information required for unique building modeling
- Information required for resilience analysis

This information will be sufficient to identify energy system architectures and their technologies for the baseline and base case and to select several alternatives.

Based on the information of the current energy supply strategies and energy generation at the building level and existing networks, an architecture of the baseline system solution can be developed that includes technologies it is comprised of. Building-by-building energy analysis during blue sky and black sky scenarios will provide the annual load duration curves for the baseline.

This information, complemented by the information on future planned changes in the building stock (demolition, new construction, major renovation), can be used to establish future alternatives with the respective load profiles. At this point of planning, potential changes in centralization or decentralization of energy generation equipment, distribution networks, and their configurations can be proposed and documented. These changes may include conversion from steam to hot-water DH systems, conversion from individual gas-fired boilers to hot-water district systems, or selection between individual chillers, district cooling systems, and ground-coupled heat pumps, which can be further analyzed. These alternatives can be considered for the city, the whole campus, building cluster, or individual building basis.

Most campuses are connected to local or national power grids. Some campuses are, or could be, connected to district energy at the municipality level, e.g., interconnecting campuses and large buildings next to the campuses. Some power supply systems serving military and university campuses in the United States (e.g., Princeton University, Arizona State University) are designed with the capability of generating their own electricity so that, ultimately, they can operate in islanded mode while the national power grid is disrupted during natural disasters and "blackouts/brownouts." While power supply disruption from the national grid in Denmark and some other European countries is not an issue due to robust national grids, energy systems in these countries are design based on the goal of dramatic greenhouse gas reduction in the most cost-effective way. To stimulate greenhouse gas emission reductions, European nations introduced a trading system on greenhouse gas emissions.[1] The policy on fossil fuel reduction in European countries started as a political reaction to the Organization of the Petroleum Exporting Countries (OPEC) oil embargo in the 1970s, and it is still a priority to minimize dependency on imported energy from certain regimes.

7.3.2 *Bidirectional Planning*

A best practice during the selection of energy supply options includes bidirectional planning process: (1) from the higher level to the lower level and (2) from the lower level to the higher level to prevent suboptimization.

- Bottom-up approach:
  - When planning energy improvements of the building stock (building envelope improvements, HVAC system replacement and upgrades, power and thermal energy generation, and storage at the building level), consider plans for building clusters or the campus.
  - When planning energy investments in a campus, especially in the campus heating and cooling networks and local power generation, consider local community resources: existing heating and cooling grids, waste heat availability from local industry, and availability of renewable energy from large-scale generation sources.
  - When formulating local community planning, it is often a good idea to also look at the regional and national planning. Several local communities may join forces and benefit from economies of scale, for example, by investing in a waste-to-energy plant or a heat transmission network. If a large power plant or any other heat source is available, it could be cost-effective to transmit heat to the city instead of duplicating the investment in power capacity.
- Top-down approach:
  - Efficient campus-wide DH systems can use surplus heat from power generation located in the nearby community or use waste generated by this community as a fuel.
  - Campus-level smart energy systems comprised of DH and cooling with thermal storage, electric boilers, CHP, and heat pumps can export power to the local community, based on demand and spot electricity prices, and thereby reduce investments in the local power grid and help to integrate fluctuating renewable energy from, e.g., wind and solar.

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[1] Some European countries like Sweden, Finland, and Denmark have introduced a CO_2 tax. In 2005, an emission trading system has been installed in Europe (Guideline 2003/87/EG), where each country/unit is assigned an amount of CO_2. Any emission less or more than the target value have to be traded. The price of greenhouse gas emission is set by the market. Up to now, experience shows that the actual price of emissions is too low to trigger action.

– In the planning and design of the campus-level district energy system, it may be assumed that the buildings will gradually be renovated such that the heat load and necessary temperatures for heating will be reduced in time.

This dynamic top-down and bottom-up planning is demonstrated in several of the case studies.

7.3.3 Thermal Networks

Using waste heat from power generation for heating/cooling via thermal grids can add to the efficiency and resiliency of the energy system. Thus, a decision needs to be made whether the future energy system should include thermal grids (heating grid only, cooling only, heating and cooling, depending on the climate zone and energy density).

If buildings within a campus or community are spaced too far apart and/or building energy demand is low (e.g., buildings need only DHW and no heating), thermal grid options for these specific buildings can often be excluded from the selection process. Table 7.1 lists the advantages and disadvantages of thermal energy networks.

7.3.4 Thermal Network Temperatures

Selection of network temperatures is dependent on temperature levels required by the buildings and the output temperatures that can be produced from the energy sources. Modern buildings designed to high energy efficiency standards can often operate with low temperatures for their heating systems (and higher temperatures for the cooling systems). With networks intended to supply older buildings, the costs and benefits for retrofitting these buildings to a more modern standard can be compared to the option of operating grids on higher temperature levels for heating and lower temperatures for cooling with corresponding higher heat losses.

While fossil fuels have no restrictions and can provide steam as well as high-temperature hot water, many renewable energy sources and efficient sources, like solar thermal or excess industrial heat, CHP, and large heat pumps, can be integrated more efficiently into DH networks that are operated at lower temperatures. Table 7.2 lists the applications, advantages, and disadvantages of high DH network temperatures.

As described in the case studies, one must consider that a DH hot-water system can be developed at a high-temperature level to meet the demand of consumers and gradually be transferred to lower temperatures to take advantage of the consumers' energy saving measures, in particular lower return temperature and lower demand for supply temperature; see, for example, the case of Vestforbrænding, Denmark,

Table 7.1 Advantages and disadvantages of centralized thermal energy systems

Description	Application, advantages, disadvantages
Centralized systems with hot-water heating and/or cooling grids	**Application**: Communities with high energy density (at least in some parts of the community) Requires space in the streets for the distribution lines Requires space for central energy plants The heating system shall be low-temperature hot water (e.g., below 90 °C [194 °F]) to harvest all benefits, but it can be combined with a separate supply of superheated water or steam to process industries High temperature or steam can be used for processes like sterilization Requires efficient community energy planning and an operator **Advantages**: Distribution of waste heat to a whole community is possible (e.g., from waste incineration, industrial processes, and CHP) Higher reliability and security of supply than decentralized options Larger equipment offers economies of scale for production and storage Only one (or a few) generation site needs to be operated and maintained Switching sources fast, e.g., to larger share of renewables, is much easier than in decentralized options Fuel flexibility as several sources can be connected to the grid, and therefore it is possible to respond on fuel prices and fuel shortage Save space for energy generation plants in buildings and save investment and O&M costs in buildings Reduces or eliminates local pollution from emissions and noise More cost-effective and efficient to reduce emissions Opportunities for sector-coupling Onsite CHP and power improve resiliency against outages on the electrical network Surplus heating from CHP in summer can be used to provide cooling via absorption chillers Electric boilers can convert surplus renewable electricity into heat; heat pumps can convert it to heating and cooling Lower operating costs compared to standalone (because of efficiency and decarbonization possibilities) **Disadvantages**: Additional capital cost of constructing a network Additional effort and cost of maintaining the network However, the main objective of the energy planning in communities and campuses is to identify the optimal zoning of this heavy investment natural monopoly network infrastructure. In particular the planning shall ensure that all extensions of the network to new areas are cost-effective compared to the base line

which is in a transition from superheated water at 165 °C (329 °F) to a lower temperature and the case of Greater Copenhagen in which a steam system in central Copenhagen will have been replaced with hot-water DH over a period of 15 years.

The decision on the network temperature impacts the selection of the type of piping system that can be used to build the grid (steam pipes, pre-insulated pipes, etc.) and thus on the grid investment costs.

Table 7.2 Advantages and disadvantages of high grid temperatures

Description	Application, advantages, disadvantages
DH hot water with high supply temperatures (>90 °C [194 °F] <130 °C [266 °F] or <160 °C [320 °F])	**Application:** High-temperature fuel input, e.g., fossil fuel, biomass, waste incineration, high-temperature geothermal energy, and high-temperature industrial waste heat Existing DH network with pipe diameters dimensioned to serve peak load at a defined temperature difference Existing building substations are dimensioned to serve peak load at a defined temperature difference Building stock with heating and DHW installations requiring high temperatures (e.g., 70 °C [158 °F] supply for DHW) and returning high temperatures to the grid (e.g., 65 °C [149 °F] from DHW circulation in summer) **Advantages compared with low temperature:** High-temperature difference between supply and return allows lower pipe diameters for the same energy transport capacity. (Lower diameters usually mean lower cost to build the network.) Can supply consumers with poor heating installations that require high temperature Can supply absorption chillers more efficiently than low-temperature grids **Advantages compared with steam:** Can use cheaper pipe construction, i.e., pre-insulated pipes Can be stored in thermal heat storage tanks Operates CHP turbines much more cheaply Much lower heat losses More resilient supply **Disadvantages compared with low temperature:** Higher heat losses. However, heat losses in hot-water networks serving consumers in densely areas are typically below 7% Integration of low-temperature renewables is problematic; for example, harvesting heat from CHP plants, excess industrial heat, and heat from heat pumps is more difficult and more expensive Thermal storage is more expensive Piping systems have higher absolute specific costs (per meter pipe of the same diameter; however, this may be outweighed by other factors [see above]) Shorter lifetime of pre-insulated pipes **Disadvantages compared with steam:** Cannot supply high-temperature process demand

7.3.5 Combined Heat and Power (CHP)

Many simple DH systems only use boilers to generate heat. Boilers are inexpensive, reliable, and easy to maintain. In small cooling grids, the electric chiller is usually the first choice.

Most DH system designs do, however, include some type of CHP equipment. Historically, DH systems often came into existence because operators of large condensation power plants wanted to achieve a more efficient fuel use and to gain additional income from selling the waste heat. Many of the smaller, more recent DH systems serving specialized communities like airports, hospitals, universities, or military installations operate their own CHP equipment to reduce the share of electrical power purchased from the grid. Table 7.3 gives an overview of applications, advantages, and disadvantages of CHP systems.

CHP equipment is available in a large variety of technical options, from large-scale plants based on steam turbines (>3.4 MMBtu/hr [>1 MW]) and from combined cycle gas turbines to smaller gas engines (10 MW to <10 kW). Even small fuel cells can be CHP plants. Fuels for CHP plants range from coal, natural gas and waste-to-biogas, biomethane, woody biomass, and straw. Use of CHP can be justified economically in the regions where fuel for power generation is less expensive than the electricity rate. Figure 7.3 highlights areas in the CONUS where CHP are cost-effective.

Obviously, it is important that the new power generation plants be located near cities to use the DH to condense the steam instead of cooling towers. The EU has

Table 7.3 Advantages and disadvantages of CHP generation

Description	Application, advantages, disadvantages
CHP generation	**Application**: Communities with high electricity demand and sufficient heat demand—When onsite power generation is an option with regard to economic and/or resiliency considerations The cost-effectiveness of the CHP plant can be evaluated based on the local conditions and actual prices for fuels and electricity. However, its overall energy efficiency and the actual costs and emissions of the heat production from CHP plants depend very much on the situation in the energy system. See the explanation in Sect. 7.4 "Selecting System Architecture" **Advantages**: More efficient fuel use compared to condensation power generation in combination with decentralized heating/cooling Can be more cost-efficient than separate generation of heat and power Higher degree of independence from electrical mains network Can offer services to the power grid and generate to the grid, in particular for generating hot water to the DH in combination with heat storage tanks (whereas steam-based CHP is expensive and cannot respond to fluctuating power prices as the steam is expensive to store) Using CHP in combination with electric and absorption chillers can be more cost-efficient/reliable than relying on outside electricity supply for (decentralized) electric chillers **Disadvantages**: Additional system complexity (load curves of power, heating/cooling need to be considered), which is a disadvantage in case there is no thermal storage attached to the plant Higher capital cost compared to a "boiler-only" generation Higher maintenance cost compared to fossil boilers

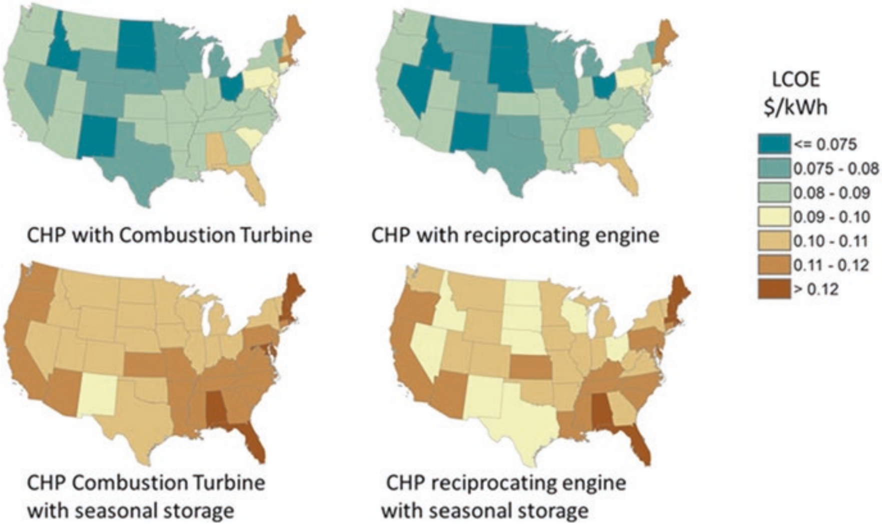


Fig. 7.3 Levelized cost of energy (LCOE) across the CONUS based on 2018 natural gas prices for CHP systems based on combustion turbine and reciprocating engine and with/without seasonal thermal storage

addressed this issue already in 1977 and in its Energy Efficiency directives. The Danish Electricity Supply Act 1976, for example, gives the Minister the power to approve all new power capacity above 170.6 MMBtu/hr (50 MW); since that time, all new power capacity has been located at the most optimal sites and has been designed as extraction or back-pressure plants that include the ability to replace thermal losses with supply of useful heat for DH.

For the United States, based on the utility rate data and natural gas costs combined with the information technology characteristics (initial cost, operation and maintenance costs), the NREL calculated a levelized cost of energy (LCOE) at each location in a geospatial analysis for CHP with combustion turbine and reciprocal engines with and without a seasonal thermal storage. Costs vary from less than $0.075/kWh in western states where natural gas is less expensive to over $0.11/kWh in northeastern states where gas costs are higher. With seasonal storage, the cost varies from $0.09/kWh to over $0.12/kWh. Figure 7.3 highlights areas in the CONUS where CHPs are cost-effective. To enable a comparison with the calculated LCOE maps, the maps shown in Fig. 7.4 show electric rates (left) that vary from less than $0.05/kWh in the Pacific Northwest to $0.20/kWh in California and natural gas rates (right) that vary from <0.02/kWh (thermal) in the Dakotas to $0.045/kWh thermal in the northeastern United States. Appendix H gives more details on developed maps.

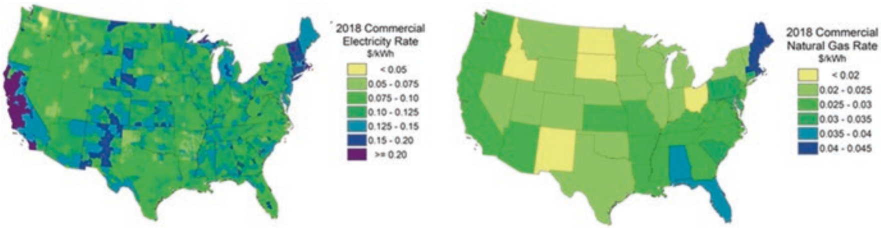


Fig. 7.4 Maps with electric rates (left) and natural gas rates (right)

7.3.6 Renewable Energy

Constraints that must be considered when designing a DH and cooling system architecture that incorporates renewable energy are the limited quantities of renewable energy resources available, the fluctuating nature of renewables, and the constraints of some renewables/excess heat sources regarding output temperature. Table 7.4 gives an indication on how to select a renewable energy source to fit an existing (or new) DH system. Green boxes in the table indicate that the equipment is suitable for the intended purpose, and red boxes show that the option is not suitable. Biomass options can usually replace fossil fuel generation with few complications (although biomass storage can be both a space and potentially a security issue), although careful consideration should be given to the incorporation of low temperature and fluctuating renewables options.

NREL also maintains several geospatial datasets (GIS data) related to renewable energy project feasibility including solar and wind resources. This information, when combined with technology characteristics (initial cost, operation and maintenance costs), enables the calculation of a LCOE at each PV + battery storage; concentrating solar power (CSP) + TES; wind energy conversion system + battery storage; and solar water heating (SWH) with diurnal storage and also with seasonal storage. Figure 7.5 shows resulting maps of geospatial distribution of LCOE, which enable a comparison with maps of prevailing conventional utility rates.

7.3.7 Thermal Storage for Heat or Cold

Thermal hot-water storage can be integrated into energy systems for such different purposes as:

- Maintaining a CHP plants' focus on power generation while providing reliable heat supply:
  - In case of a fixed power-to-heat ratio, the storage will allow the CHP plant to generate heat in an optimal way with respect to the power prices.

Table 7.4 Integration of renewables into DH system

Parameter/Category Characteristic	Woody Biomass			Biogas			Bio Methane		Hydrothermal Deep Geothermal		Solar Thermal		Heat Pump (Ambient Heat Sources, Sewage, etc.)	Electric Boiler
Sufficient Availability of Renewable Energy	Amount of biomass procurable? Problems with fine dust pollution at the location?			Amount of biogas available?			Amount of bio synthetic natural gas available?		Geothermal energy locally available?		Solar thermal installation area 1500 m² or more		Amount of ambient heat available	Amount of renewable electricity available?
Generator Type	Boiler	CHP Steam Power Process	CHP ORC/KC	Boiler	CHP Engine	CHP Micro Gas Turbine	Boiler	CHP All Natural Gas CHP Plants Possible	Heat Only	CHP ORC/KC	Flat Plate Collector	Vacuum Tube Collector	Heating, Cooling, or Both	Boiler
Therm. Capacity														
up to 1 MW [3.4 Mbtu/hr]	✓	✗	✓	(✓) 1)	✓	✓	✓	✓			(✓) fluct.	(✓) fluct.	✓ 7)	✓
1 to 5 MW [3.4 to 17 Mbtu/hr]	✓	✗	✓	(✓) 1)	✓	✓	✓	✓	Capacity site specific (depending on temperature level, geothermal production rate)		(✓) fluct.	(✓) fluct.	✓ 7)	✓
5 to 10 MW [17 to 34 Mbtu/hr]	✓	✗	✓	(✓) 1)	✓	✗ 1)	✓	✓			(✓) fluct.	(✓) fluct.	✓ 7)	✓
10 to 20 MW [34 to 68 Mbtu/hr]	✓	✓	✓	(✓) 1)	✗ 1)	✗ 1)	✓	✓					✓ 7)	✓
> 20 MW (68 Mbtu/hr]	✓	✓	✗	(✓) 1)	✗ 1)	✗ 1)	✓	✓					✓ 7)	✓
Electr. Capacity														
up to 1 MW		✗	✓		✓	✓		✓		✓ 5)				
1 to 5 MW		✗	✓		✓	✓		✓		✓ 5)				
5 to 10 MW		✓	✗		✓	✗		✓		✓ 5)				
10 to 20 MW		✓	✗		✗	✗		✓		✓ 5)				
> 20 MW		✓	✗		✗	✗		✓		✓ 5)				
Load Type														
thermal peak load (in winter)	(✓) 8)	3)	3)	(✓) 1)	3)	3)	✓	3)	4)	3)	✗	✗	4)	✗
thermal base load	✓	✓	✓	(✓) 1)	✓	✓	✓	✓	✓	✓	✗	✗	✓	✗
thermal (daytime) summer load											✓	✓		
renewable electricity surplus (wind, PV)														✓
Temperature Level														
steam grid	✓	✓	✗	(✓) 1)	✗	✓	✓	✓	✗	✗	✗	✗	✗	✓
high temperature grid (T_{VL} > 140 °C [284°F])	✓	✓	✗	(✓) 1)	✗	✓	✓	✓	✗	✗	✗	✗	✗	✓
hot water grid (140 °C [284°F] > T_{VL} > 110 °C [230°F])	✓	✓	✗	(✓) 1)	✓ 2)	✓	✓	✓	site specific		✗	✓ 6)	✗	✓
110 °C [230°F] > T_{VL} > 90 °C [194°F]	✓	✓	✗	(✓) 1)	✓ 2)	✓	✓	✓			✓ 6)	✓ 6)	✗	✓
LowEx grid	✓	✓	✓	(✓) 1)	✓	✓	✓	✓			✓ 6)	✓ 6)	✓ 7)	✓

Key:	
✓	available
✗	not available/does not make sense
(blank)	not applicable

Notes:

1) Using biogas in boilers is technically possible, but not a common practice because the use of biogas in CHP plants is usually economically more attractive due to national subsidy systems. Biogas is usually produced locally by small farms at small quantities. The exact chemical composition tends to vary and so does the calorific value. It is therefore usually used locally in small-sized equipment
2) High-temperature gas engines or micro gas turbines
3) Using CHP plants for peak load is technically possible. In practice, CHP plants are used in base-load generation, because the units are more expensive than boilers and it is usually economically more efficient to use them for a high number of operating hours
4) Geothermal energy and heat pumps can technically be used to produce peak load. Due to the high upfront costs of these types of plants, they are usually used for base load
5) In hydrothermal geothermal projects in Germany, electrical capacities up to 17.1 MMBtu/hr (5 MW) were realized. The Hellisheioi CHP plant in Iceland has an electrical capacity of 1023.6 MMBtu/hr (300 MW)
6) For solar thermal plants, the temperatures in summer operation are decisive (supply temp. (158–176 °F [70–80 °C]) for flat plate collectors, return temp. (122–140 °F [50–60 °C]); the lower the better)
7) The heat load supplied into the DH system is dependent on the temperature level and the flow rate of the sewage, size of the heat exchangers, and the supply and return temperature. Realized projects are often in a small capacity range. In Denmark there are heat pumps from 17.1 to 68.2 MMBtu/hr (5–20 MW) based on wastewater
8) Biomass boilers can cover parts of peak load during heating season, but they are not flexible enough to serve very short-term peaks

   – In case of a heat extraction turbine, the storage will allow the CHP plant to generate maximal power capacity in power peak hours by shifting heat production from the turbine to the storage and to reload the storage in the most optimal way considering power prices and minimum load capacity.

- Storing energy from fluctuating renewables to match supply and demand.
- Improving resiliency by temporarily supplying loads in case of generation shutdown.

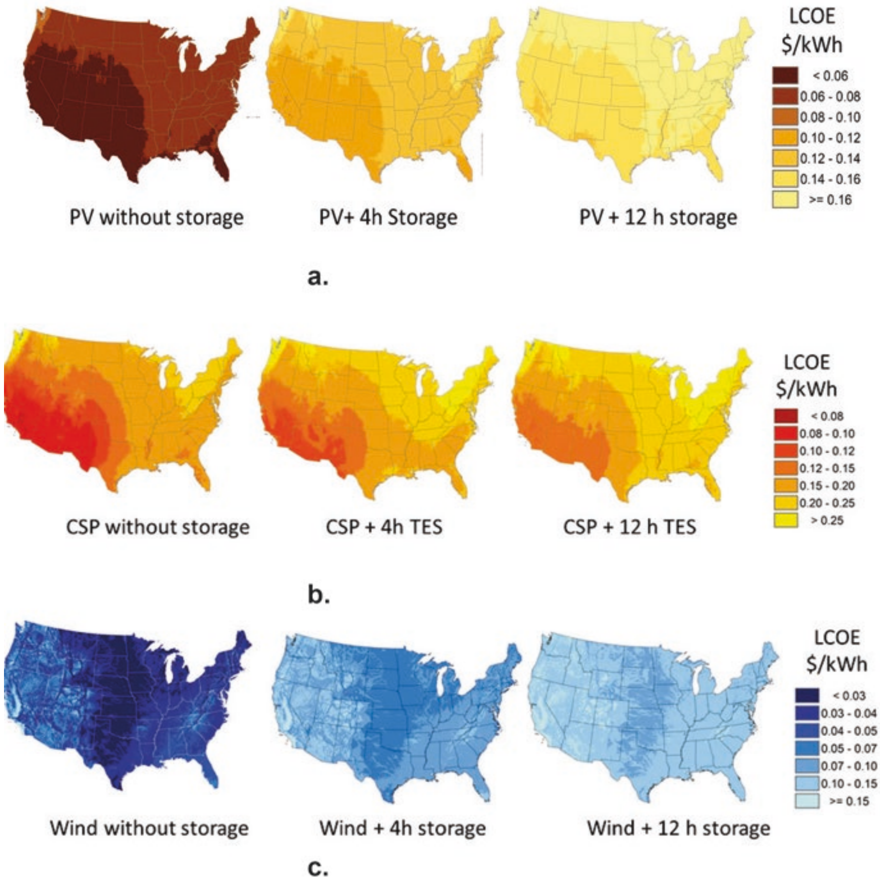


Fig. 7.5 LCOE across the CONUS for (**a**) photovoltaic systems including 4 h and 12 h of battery storage. Costs in sunny areas are on the order of \$0.06/kWh without storage and up to \$0.16/kWh in less sunny areas with 12 h of battery storage; (**b**) concentrating solar power systems including 4 h and 12 h of TES. Costs in sunny areas are on the order of \$0.08/kWh without storage and up to \$0.25/kWh in less sunny areas with 12 h of thermal energy storage; (**c**) wind energy systems, including 4 h and 12 h of battery storage. Costs vary from \$0.03/kWh in windy areas (Great Plains states of ND, SD NE, OK, TX) to as high as \$0.15/kWh in less windy areas with 12 h of battery storage

- Improving operation and optimization of the production plants, in particular by avoiding problems with minimum load and many start/stop operations.
- Offering peak capacity for a certain time in case the maximal load has daily fluctuations.
- Storing makeup water and maintaining the pressure in the network.

Thermal cold-water storage can be integrated into energy systems for such different purposes as:

- Offering peak capacity for a certain time, in particular on warm days in which the cooling demand typically has strong daily fluctuations.

- Storing energy from fluctuating renewables to match supply and demand, typically to respond on electricity prices and, for example, interrupting the production during periods of high energy prices, thereby reducing the “cooling peak” in the power system significantly.
- Improving resiliency by temporarily supplying loads in case of generation shutdown.
- Improving operation and optimization of the production plants, in particular by avoiding problems with minimum load and many start/stop operations.
- Storing makeup water and maintaining the pressure in the network.

For many applications, thermal storage volumes that provide energy supply for several hours up to a few days are sufficient. Chilled water or ice storage tanks are often used to reduce power demands during expensive peak hours, enabling a significant reduction of energy cost. When used in critical facilities, they add an extra layer of redundancy and provide a cushion of time to allow the maintenance crew time to fix the problem or, in the case with a data center**,** allow sufficient time to ramp up another power source or to transfer its functions to another location and close the affected facility.

An example of long-term storage is an energy system in a moderate climate designed to use a large share of solar energy. Solar surplus energy is generated in the summer months and stored for several months, e.g., in thermal pit storages. For a good example, see the case study of Gram, Denmark.

Pit storage can also be designed to accommodate chilled water.

Storage facilities add to the complexity and the upfront costs of the energy system. Energy losses differ from system to system. Storage facilities need to be carefully designed to fit demand curves and generation equipment.

Aquifer thermal energy storage (ATES) is a frequently used option in systems for combined DH and cooling. The groundwater acts like chilled water storage for cold, which can be used directly in the production, whereas the heat storage only stores ambient heat at, for example, 15–20 °C (59–68 °F), to be heated with a heat pump in the winter season.

7.3.8 Miscellaneous Measures to Protect Energy Systems and Improve Their Resilience

In addition to energy system architectures, network configurations and technologies used in these systems, as described in Sects. 7.7 and 7.8, and Appendices E and F, can have their resilience enhanced to different threats by using non-energy-related measures (e.g., building flood walls, burying electrical cables, and other utilities raising equipment, etc.). Spatial distribution of equipment (community level, building cluster level, building level) can also be an option to improve resilience against different threats and hazards.

Utility tunnels or utilidors for mechanical and electrical services are installed by drilling and/or tunneling to carry utility lines such as electricity, steam, DH and

Fig. 7.6 DH systems and other utilities located aboveground in ducts. (**a**) Underground steam lines were replaced by steam lines installed under skyways to research buildings (The University of Texas Medical Branch at Galveston). (**b**) Aboveground supply infrastructure in Qaanaaq, near Thule; see case Qaanaaq (Gudmundsson et al. 2020). (**c**) Rice University underground tunnel. (**d**) Utility tunnel section (University of Washington 2017). (**e**). A flood wall was installed to protect equipment at a power plant (The University of Texas Medical Branch at Galveston). (**f**) Elevated boilers and chillers (The University of Texas Medical Branch at Galveston)

cooling pipes, water supply pipes, sewer pipes, and communication utilities (like fiber optics, cable television, and telephone cables). Tunneling is common for very cold climates where direct burial below the frost line is not feasible. Another option used in Artic climates with permafrost is to locate DH systems and other utilities above the ground in ducts (Fig. 7.6b). The relatively low (15%) heat loss from the

DH distribution system provides frost protection service to other infrastructure such as wastewater and freshwater pipes. The ducts and the heat loss further contribute to serve as walking paths within the community (Gudmundsson et al. 2020).

Direct-buried cable (DBC) is especially designed to be buried under the ground without any kind of extra covering, sheathing, or piping to protect it. Most direct-buried cables are built to specific tolerances to heat, moisture, conductivity, and soil acidity. Unlike standard telecommunications and power cables, which have only a thin layer of insulation and a waterproof outer cover, DBC consists of multiple layers of heavy metallic-banded sheathing, reinforced by heavy rubber covers and shock absorbing gel, wrapped in thread-fortified waterproof tape, and stiffened by a heavy metal core.

7.4 Selecting System Architecture

System architecture selection starts with identification of existing energy supply systems available on the campus and information about other energy supply systems that either are or potentially may be available from the nearby community (e.g., the four energy carriers: electricity, gas, DH, and district cooling). The baseline system architecture represents the architecture that is in use, in its current form. The challenge of the next steps is to select a small number of system alternatives that can be deployed to meet energy framing goals (Chap. 1) in a cost-effective way when compared to the base case (business as usual) alternative. These alternatives may include the following elements, which can be located either at the building level, at the building cluster level, or at the campus level:

- Energy generation to one or more of the energy carriers
- Energy conversion from one energy carrier to one or two other energy carriers
- Energy distribution in one or more of the four energy carriers
- Energy storage in each of the energy carriers
- End users and their ability to use the energy carriers to their actual need for power, gas, or thermal comfort, which can be delivered by the heating and cooling system

Figure 7.7 shows conceivable interconnections between these elements, which are simplified to include only four main energy carriers: electricity, DH, district cooling, and gas. Actually, there are options for several DH grids, e.g., steam, superheated water, high-temperature water, and low-temperature water. Likewise, there can be cooling systems that operate at minus degrees using refrigerants, by using very cold water, or just chilled water.

For each specific situation, energy carriers which can be shared by the community with the campus shall be identified.

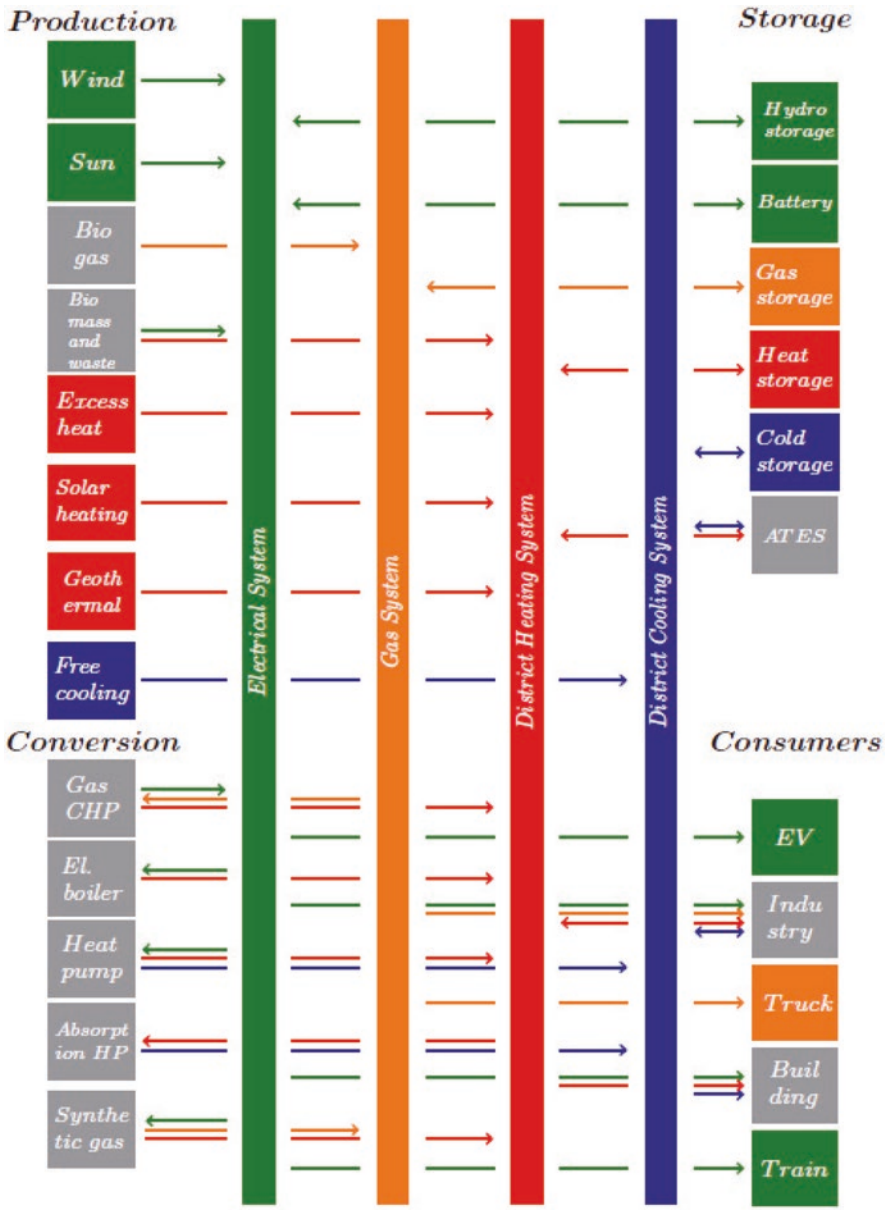


Fig. 7.7 The integrated energy system with four energy carriers

Energy carriers that are available to the campus from the nearby community can be further subdivided to include such subcategories as:

- District steam system
- District high-temperature hot-water system
- District low-temperature hot-water system
- District low-temperature chilled water system
- District high temperature chilled water system
- Biogas
- Natural gas

It is very important that the assessment and modeling of the impact of the energy conversion technologies and their fuel efficiency consider the situation in the power system. The baseline in the power system is characterized by the power production plant, which is operating on the margin. It is therefore not relevant to focus on the total average load dispatch, but rather to consider the unit that regulates the production hour by hour. This is very important in the assessment of the performance of the CHP, heat pumps, and electric boilers; it must be emphasized since the result is of great importance.

Performance of CHP

- **In case of power island operation**, e.g., in remote areas with no connection to the national power grid, the generation of the power plant is determined by the electricity demand.
  - The cost of fuel to generate 1 MWh of electricity is 2.5 MWh fuel when the efficiency is 40%; surplus heat is ejected in a cooling tower or into the sea.
  - The cost of fuel to generate 1 MWh of heat from the plant is 0 MWh.
- **When condensing plants** are operating on the margin and emitting thermal losses in cooling towers or into the sea, the CHP potential can reduce this thermal loss.
  - The cost of fuel to generate 1 MWh of electricity is 2.5 MWh coal when the efficiency is 40%; surplus heat is ejected in a cooling tower or into the sea.
  - The cost of fuel to generate 1 MWh of heat from the coal-fueled plant designed as an extraction plant is a loss of 0.1–0.2 MWh electricity from the plant (for low- or high-temperature extraction respectively), which can be produced using 0.1/0.4–0.2/0.4 = 73.2–146.4 Btu (0.25–0.5 MWh) coal. This is equivalent to a marginal heat efficiency of 400–200%.
  - The cost of fuel to generate 3.4 MMBtu/hr (1 MW) of heat from a local coal-fueled back-pressure plant with a power-to-heat ratio of 0.5 and an efficiency of 85% will be: (1 + 0.5)/0.85–0.5/0.4 = 1.76–1.25 = 0.51 MWh (1.7 MMBtu/hr) coal.
  - The cost of fuel to generate 3.4 MMBtu/hr (1 MW) of heat from a local gas-fueled engine with a power-to-heat ratio of 1.0 and an efficiency of 90% will be: (1 + 1)/0.9 = 2.2 MWh (7.5 MMBtu/hr) gas minus 1/0.4 = 2.5 MWh

(8.5 MMBtu/hr) coal in case coal condensing is on the margin. In other words, the fuel consumption is negative in terms of MWh energy; however, the point is that there is a combination of an energy saving and a fuel shift. It would be more correct in a CHP scenario to compare local gas-fueled CHP plants with the best available gas-fueled power condensing plant technology, as follows:

> The cost of fuel to generate 3.4 MMBtu/hr (1 MW) of heat from a local gas-fueled engine with a power-to-heat ratio of 1.0 and an efficiency of 90% will be: (1 + 1)/0.9 = 2.2 MWh (7.5 MMBtu/hr) gas minus 1/0.55 = 1.8 MWh (6.1 MMBtu/hr) gas in case gas condensing is on the margin. In other words, the gas consumption will be 0.4 MWh (1.4 MMBtu/hr) gas, corresponding to a marginal efficiency of 250%.

- When there is surplus of electricity from hydro, wind, or solar PV, there is no CHP potential, and the electricity market price should be zero. Therefore, all CHP plants should stop or use steam turbine bypass, unless it is a very temporary situation and the plant has large start/stop costs. When the abovementioned very efficient gas engine operates, the cost of fuel for generating 3.4 MMBtu/hr (1 MW) of heat will cost 2.2 MWh (7.5 MMBtu/hr) of gas, in other words, at an efficiency of less than 50%.

Performance of Heat Pumps and Electric Boilers

- **When condensing plants** are operating on the margin and ejecting thermal losses in cooling towers or into the sea, a local heat pump can to some extend compensate for this thermal loss.
  - The cost of fuel to generate 3.4 MMBtu/hr (1 MW) of low-temperature heat with a coefficient of performance (COP) factor of 2.5 will be 1/2.5 MWh = 0.4 MWh (1.4 MMBtu/hr) of electricity, which will cost 0.4/0.4 = 1 MWh (3.4 MMBtu/hr) of coal. In other words, it will cost twice as much as heat from a CHP plant. If we ignore the losses in the power grid, we can say that 0.4 MWh of high-quality electricity uses 0.6 MWh (2.0 MMBtu/hr) of low-quality ambient heat and gains 1 MWh (3.4 MMBtu/hr) of useful heat. In the EU, this ambient heat is classified as “renewable energy” although it is not more renewable than the saved thermal losses from the power plants.
  - The cost of fuel to generate 1 MWh (3.4 MMBtu/hr) of heat from an electric boiler will be 2.5 MWh (8.5 MMBtu/hr) coal in case coal condensing is on the margin.
- When there is a surplus of electricity from renewable sources in the power system, either the surplus electricity must be stored or production must be curtailed so the system generates less, e.g., via wind turbines, which can easily be downregulated.
  - The cost of fuel to generate 1 MWh (3.4 MMBtu/hr) of heat from the heat pump will in that case be 0 MWh, and the heat pump will generate 2.5 MWh (8.5 MMBtu/hr) of heat from 1 MWh (3.4 MMBtu/hr) of surplus electricity.

– The cost of fuel to generate 1 MWh (3.4 MMBtu/hr) of heat from an electric boiler will also be 0 MWh.

Virtual Battery

This interaction between the power and heat sector via CHP, heat pumps, and electric boilers is an important technology for integrating fluctuating renewable energy sources, in that it acts as a "virtual battery." Electric batteries can provide certain capacities in MW from stored MWh energy but only for a short time. The costs of storing MWh energy to respond to the natural fluctuations of hydro, wind, and solar energy are extremely expensive; it will be necessary to curtail, for example, wind and solar and may even be necessary to increase the capacity of the power grid to absorb the large peak capacities from wind and solar.

Therefore, a campus or a community can offer important smart energy services to the power grid, which should be considered in the energy planning and modeling. This can be done by installing DH and cooling (DH&C) combined with CHP, heat pumps, electric boilers, heat storage, and cold storage. This equipment is relatively expensive at the building level, but much cheaper at the campus or city level due to economy of scale.

The campus or community can offer the following services to the power grid and respond on fluctuating market prices and capacity tariffs, which should be considered in the modeling of all costs:

- The community has a large annual electricity consumption.
- When there is surplus of renewable electricity and the market price is close to zero, the community's electricity consumption will be (at least) more than three times the normal consumption (using heat pumps and electric boilers).
- The consumption will be reduced to normal as soon as the prices increase again (the electric boiler stops).
- When there is no wind but large demand (e.g., due the use of many electric heaters and uncontrolled electric chillers) and the electricity prices are above normal, the electricity demand of the community will be reduced to zero, and the local CHP of the community will generate electricity to the grid. (The heat pump also stops, the storage is unloaded, and the gas-fueled CHP plant or emergency generator starts.)
- When there is a capacity constraint in the power grid due to large demand (e.g., due to the use of many electric heaters and uncontrolled electric chillers) or breakdown of a power line, the local community can choose to interrupt the electricity consumption as long as needed and even generate electricity to the grid (using same production and storage as above).
- When the grid is overloaded due to solar PV or wind, and it is deemed necessary to curtail wind capacity to save the grid, the local community can choose to increase the consumption up to its maximal capacity (using electric boiler and heat storage).
- When there are frequent problems related to low inertia in the power grid and large share of wind, the local community can choose to regulate services (e.g., by regulating consumption of the electric boiler).

7.5 Alternatives for Thermal Networks

Energy supply system architecture, technologies used, their types, and sizes are selected based on load duration curves developed for each type of energy used throughout the year-round cycle. These duration curves can be obtained from the measured data (often not readily available) or from building energy simulation (also see Chap. 2). Load duration curves for each energy type for clusters of buildings or the whole campus can be received by overlapping respective energy curves for individual buildings it is comprised of. Note that due to diversity of building use schedules, peak energy use by the building cluster will be smaller than the sum of peak energy used by individual buildings it is comprised of, therefore allowing for reduced energy system capacity.

The simple heat duration curve example shown in Fig. 7.8 illustrates the change of hourly heat demand, MWh (y-axis) over 8670 h of the year (x-axis) with the total

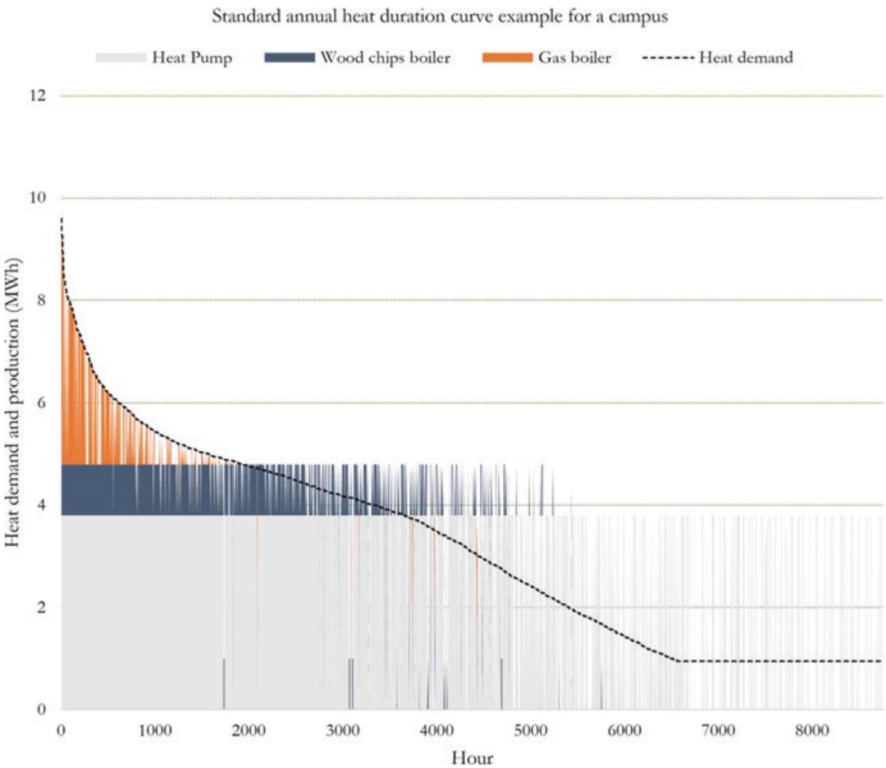


Fig. 7.8 Standard annual heat duration curve example for a campus simulated with EnergyPro. (Provided by Ramboll)

annual demand represented by the area under the curve.[2] The curve has been generated for a notional campus using simulation tool EnergyPro. In this example, heat demand is satisfied using a heat pump, a gas boiler, and a wood chip boiler complemented by a heat storage.

This simple example of duration curve shows how the heating system works and illustrates several ideas about how to improve it:

- The cheapest production using heat pumps is available in summer. Can we use more heat in summer?
- Is the summer demand larger than the minimum capacity of the heat pump?
- Can another generation technology be put into operation at a minimum load, or would a heat storage tank solve this problem?
- Which production plants will increase the production for connecting new consumers and with which share of the total? This can be estimated using this standard heat duration curve, or it can be calculated with a simulation tool like EnergyPro. In the case above, the expensive green gas boiler generates only 10% of the total production, but 40% of the production to a new consumer will come from the gas boiler.

The capacity of the new network can be planned and designed in many ways. It can be very flexible, and it can be adjusted to satisfy end-use demand. However, when pipes are already in the ground, different options to overcome the network limitations, to add additional customers, and to satisfy additional heat demand include, for example:

- Increasing the supply water temperature
- Reducing the return water temperature at the building level
- Increasing the pump head
- Installing booster pumps or pumps at end users at the end of the network
- Installing local peak boiler capacity where it is most needed to cover peak load
- Connecting a new customer/building with consideration that they have their own boiler plant and can therefore be disconnected from the grid when there is a capacity problem
- Considering that some consumers might have their own boiler with the capacity that can be shared with a grid
- Installing a local heat storage tank
- Looking for a cost-efficient solution to remove existing bottleneck in the grid (e.g., additional mesh) using hydraulic analysis

[2] Ramboll established a model for baseload and peak load using EnergyPro from the EMD (https://www.emd-international.com/). The hourly values of time series for typical heat loads from the simulation have been adjusted to a standard heat duration curve model simulated with standard heat duration curve from EnergyPro.

7.6 Energy Supply Alternatives for Mission-Critical Facilities

7.6.1 Electrical Systems and Microgrids

Electricity from large-scale power plants, wind turbines, and solar cells is transported from generation points to the consumer by a utility electric grid. The main electricity transmission network consists of high-voltage transmission lines that are owned and operated by the national **transmission system operator** (TSO). The underlying distribution networks are operated and owned by local distribution companies. Requirements to resilience of energy supply systems as discussed in Chap. 3 depend on mission criticality, system reparability, and facility redundancy. Typical approach to enhance resilience of energy supply to mission-critical facilities is to employ distributed generation (DG) using small-scale technologies to produce reliable electricity or provide backup capacity close to the end users of power. The list of such technologies includes:

- Emergency generators serving individual mission-critical building or its part (Fig. 7.9) with backup capacity.
- Banks of emergency generators serving a cluster of mission-critical facilities with backup.
- Peaking generators serving a cluster of mission-critical facilities, also as backup capacity.
- UPS battery packages that can deliver capacity instantaneously in case of breakdown of the power supply and maintain the supply until the emergency generator is online.
- CHP capacity that can be installed at the building or at the campus to provide critical power to this and adjacent buildings and to replace ordinary or outdated emergency generators, not only as a backup but to provide the opportunity to generate efficient CHP to the local DH grid.
- PV panels connected to a battery package installed at the building that provide fluctuating solar power to the local grid, while the battery package simultaneously provides critical power to this and adjacent buildings (Fig. 7.10).
- Refer to Appendix E for details and additional options.

At a campus level, it can be beneficial to connect onsite generation sources, e.g., CHP, peaking generators, PV panels, and storage batteries, with campus loads into a campus electric network, which can be connected to and synchronized with a national grid or disconnected from the grid to enable it to operate in an island mode and function autonomously as physical or economic conditions dictate. The case of the University of Texas at Austin in the Case Studies Book (IEA 2021) provides a good example of this. A microgrid can distribute locally generated electricity supply power to the campus loads to reduce energy cost during peak hours or can supply emergency power during power blackouts or brownouts or during emergency situations, which improves the resilience of the power supply system. Microgrids are typically an expensive technology to implement, and its applications do require an

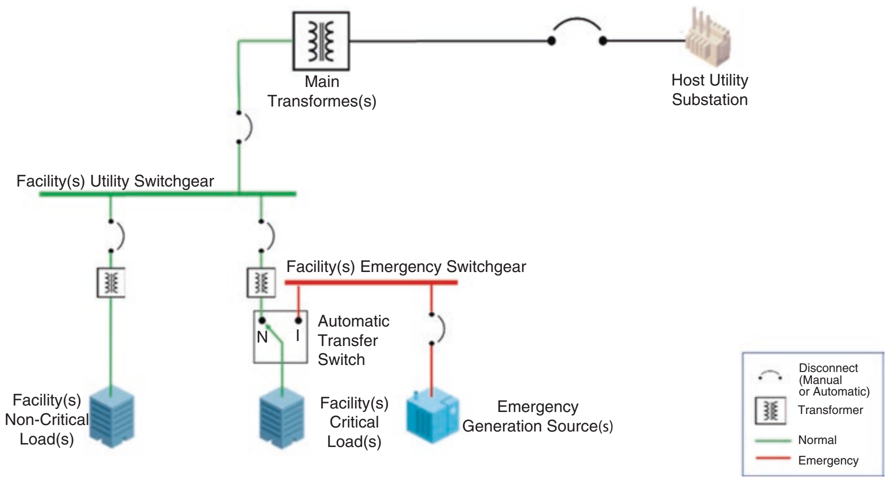


Fig. 7.9 Emergency generator serving mission-critical facility load

Fig. 7.10 Emergency power generation using a PV panel field connected to a battery pack

LCC analysis to understand the cost implications. However, several situations are favorable for its application, for example:

- High electricity costs (>$0.10/kWh) and availability of the national gas grid.
- National power grid is not available, and the campus power system must operate in island mode (island or remote location).
- National power grid is available, but unreliable, and therefore it is important to use onsite generation using power plants or CHP or use emergency generators to bridge gaps.
- Tier 1 mission-critical facilities including hospitals shall have onsite power generation capability, which may include emergency generator, peaking power generator, CHP, etc. that may or may not be connected to the microgrid.

  Figure 7.11 shows several examples of different microgrid architectures.

Appendix E describes further microgrid architectures with their associated pros and cons.

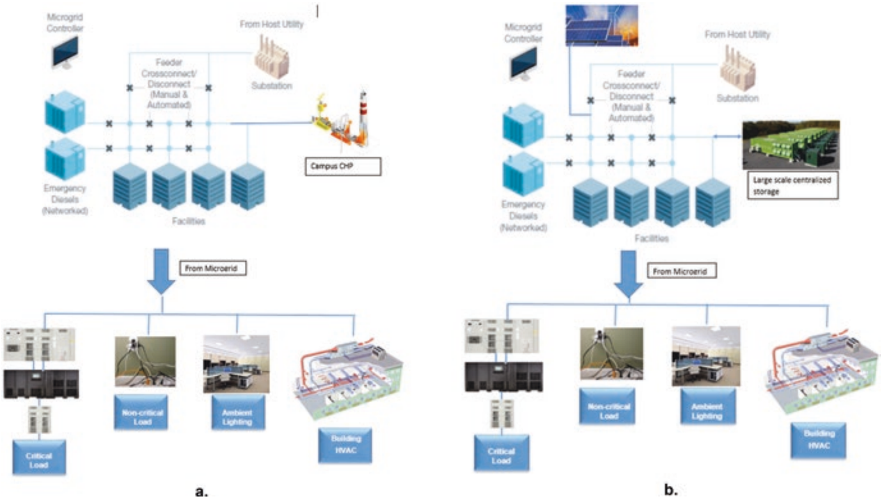


Fig. 7.11 (**a**) Microgrid with centralized emergency generators and CHP plant; (**b**) microgrid with centralized emergency generators, RE sources, and centralized storage

7.6.2 Thermal Supply Systems

While the tolerance to disruption of electric systems providing power to mission-critical facilities is usually rather low and ranges from seconds or few minutes to several hours, disruption of heat supply in mild climates for heating buildings (USDOE c.z. 3–5) can be up to 24 h. In the case of mission-critical facility or a group of facilities, utility operators typically ensure that sufficient backup capacity is connected to the distribution network and that sections of the pipe connected to these facilities can be isolated and operate independently. To prevent heat shortage with the natural load fluctuations on the coldest day, the difference between hourly peak demand and daily average demand on the coldest days can be efficiently supplied from the centralized heat storage, which in the final analysis is significantly cheaper than local thermal storage. When thermal system resilience is analyzed, the following strategies should be considered to satisfy the maximal load on the coldest day using all the production assets in operation. Some examples of some design load scenarios to be met are:

- The maximal demand in the case the largest heat plant is out of operation
- A percentage (e.g., 60%) of the maximal demand in case the largest heat plant is out of operation
- A percentage (e.g., 60%) of the maximal demand in case the two largest plants are out of operation

It should be recognized that the selection of such strategies is not a technical (not a political) issue, but it can be rather expensive to select one strategy over another.

In cold/Arctic climates (USDOE c.z. 6–8) MTTR might be limited to 4–5 h before the building will lose its habitability and 8–10 h before irreparable damage will be done to the building (see Chap. 3).

For the mission-critical facilities with cooling needs, especially those hosting critical IT or communication equipment and hospitals as well as those located in hot and hot and humid climates cooling systems are critical. Tolerance to cooling energy supply disruption can range between minutes and days. Cooling of a server is very critical, whereas comfort cooling is not.

Likewise, some industries, e.g., pharmaceutical, may have critical thermal demands. The storage temperature of certain pharmaceutical products, for example, must remain within very fixed limits, so that both heating and cooling demands can be critical.

The following considerations must be made for emergency equipment serving mission-critical facilities:

Decentralized Heat Supply

- Mission-critical consumers (e.g., hospitals, uninterruptable industrial customers) that need 100% reliable heat supply should have warm backup spare boiler or a heat storage tank combined with a cold backup boiler.

DH Networks

- In case it is not possible to re-establish the heat supply within 24 h upon disruption, at least 60% of the maximal heat demand, roughly the demand on an average winter day, must be available to the district in which the heat is disrupted.
- For districts smaller than 5 GWh (17,061 MMBtu), the grid is prepared to use or integrate a mobile peak boiler plant (around 1 MW [292.8 Btu]) to deliver spare capacity.
- For districts larger than 5 GWh (17,061 MMBtu), there must be an alternative heat supply source to deliver at least 60% of the maximal capacity located in the district in case the largest production plant is out of operation. In Germany, the largest piece of heat generation equipment is usually backed by a redundancy boiler with an identical capacity ($n + 1$).
- Thermal storage tank for heating/cooling can be installed next to mission-critical building with a critical capacity for heating/cooling that can be provided instantaneously in case of breakdown of supply pipes or generation equipment.
- Some of the peak demand boilers/chillers connected to the thermal network can be located at the building to serve a critical heating/cooling demand and to provide a backup capacity.
- In remote location, district heating/cooling system can be complimented by a building-level individual boiler/chiller, or the building can have a receptacle for a mobile boiler/chiller.

DH Production Plants

- Normally there will be several production plants and boilers connected to a DH system. If a new base-load capacity is installed to replace old boilers, the old boilers could be preserved to meet peak capacity and to provide additional backup.
- If the old boiler used heavy oil or coal, one may consider shifting the peak capacity to light oil, which is much better quality for storage.
- Boilers could be configured to use dual-fuel burners, which could enable them to switch, for example, from gas to oil.
- In case of solid fuel boilers, it has to be considered how to operate in case of power disruption. Many DH companies that have solid fuel boilers maintain alternative power generation capacity, e.g., emergency diesel generators, to be able to run the boiler until it is cold. Some of them have connected the whole installation for boiler, crane, and pumps to the emergency generator, enabling them to operate the heat supply to all consumers, even in case of blackout.

Resilience against pipe failure can be improved by including redundant branches creating loops sectioned by stop valves (Fig. 7.12) in the network layout ensuring heating/cooling energy backup.

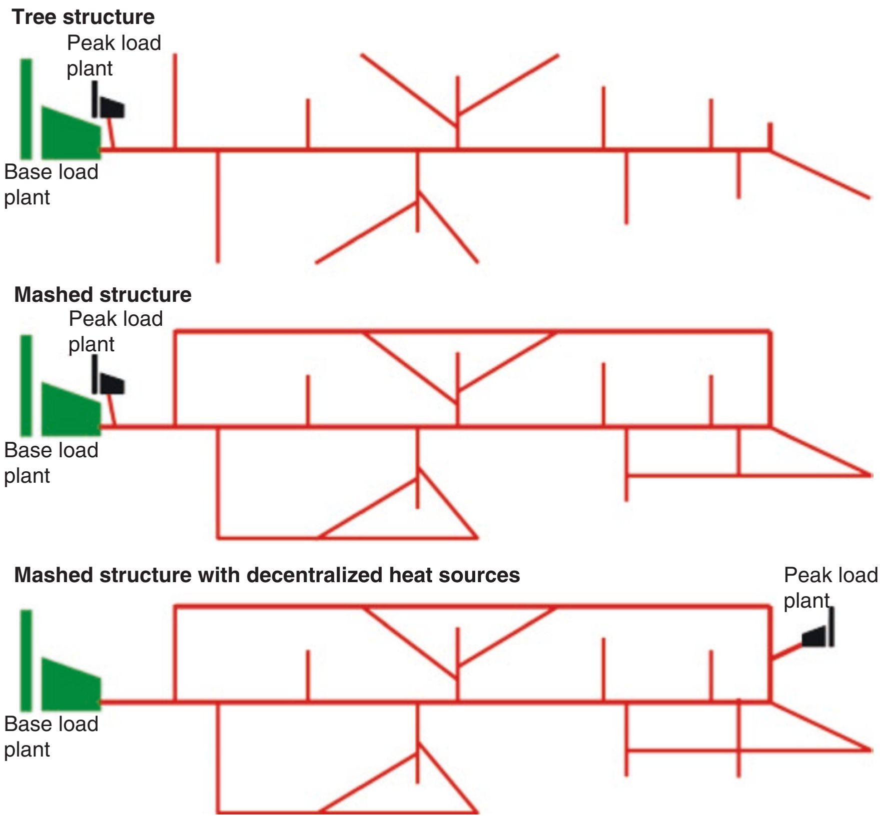


Fig. 7.12 Resilient heat supply strategies using local backup or a meshed network structure

The chosen reserve margin affects the amount of spare peak capacity installed in the system. If the system has one large production unit to meet the base load, the last criterion could be critical for defining the total need for production capacity. The criteria for capacity in case of breakdown of a section of the network will determine the districts where there should be established spare capacity. This part of the spare capacity must be located at distributed locations. The criteria that require supply to critical consumers will determine that certain spare capacity must be established close to these consumers.

District cooling is usually distributed in smaller clusters, which makes the need for distributed backup less relevant. Where power use for cooling is significant compared to the overall power use and where waste heat from power generation or industrial production is available throughout the year, one might consider absorption chillers as an alternative to a district cooling system using, for example, compressor chillers in combination with a large chilled water storage facility.

7.7 Energy System Architectures

7.7.1 Architecture Templates

This section introduces a method to categorize energy system architectures, their technical components, and a database with relevant technical components. System architecture design includes generic preselection of technologies. Important aspects of down-selecting architectures are outlined. Appendix E provides a library of more than 50 architecture templates. An Excel® tool (provided in Appendix D) allows a detailed selection of technologies from a large database and can be used for economic feasibility studies. Section 7.8 explains the database and the calculation tool.

Designing an architecture for a future energy system and selecting technical components of the system are an important part of the energy master planning process. (Chapter 2 provides a more detailed description.) During the phases of the energy master planning process, it is useful to visualize the energy systems with simple schematics when communicating the different options within the team and with both stakeholders and decision-makers. Such schematics can be used to describe baseline and alternative systems and to allow the visualization of simple as well as complex DH&C systems. Section 7.7.2 describes the layout and the symbols used in schematics.

The library in Appendix E provides more than 50 examples for energy system architectures covering central and decentral, fossil, and renewable systems. The library includes general solutions as well as solutions for special situations like remote locations/islands or solutions with electrical enhancements and microgrids to allow islanding power systems from the main electric network. The library of energy system architecture templates in this appendix comprises more than 50 examples for different use cases depicting energy system designs for different

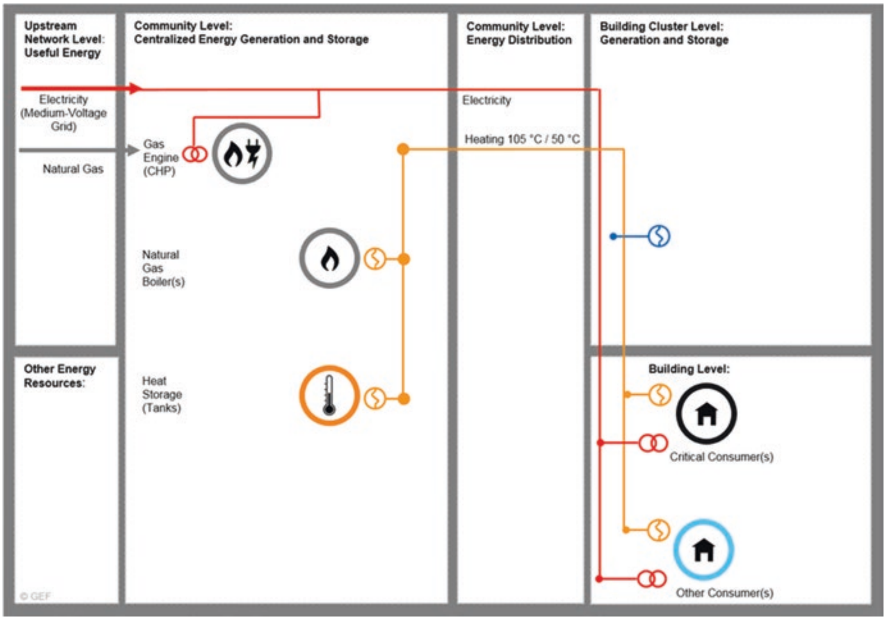


Fig. 7.13 Thermal energy system architecture

climate zones or fuels; for densely populated communities and small, remote communities; and for communities with or without critical buildings. The examples are organized in five main categories and two subcategories referring to spatial location and the energy types that are supplied to the buildings.

7.7.2 Schematics

The main elements that make up the energy system of a community are represented in the schematic by symbols, with different spatial parts of the energy system being displayed by boxes.[3] Figure 7.13 shows an example of a simple DH system with CHP, boilers, and heat storage.

The two boxes on the left show energy inputs from outside the boundaries of the community. While the upper-left box shows different types of grids that supply the community (e.g., electricity, gas, DH, district cooling), the lower box is used to illustrate input of energy resources that are not grid-bound (e.g., fuel oil, diesel, biomass, solar radiation, wind, ambient heat, etc.).

The four remaining boxes contain system components within the community:

[3] Decentral supply options on the building level can also be included, but with a lower level of detail.

- **Centralized energy generation and storage at community level**. In this box, different generation equipment like boilers, CHP generation (CHP), electric chillers, and tanks for storing hot or chilled water are represented by symbols. Colored circles are used to illustrate fuel input into the equipment (gray = gas, red = electricity, green = biomass). Colors also indicate energy output of each element (red = electricity, yellow = heat, blue = cool). Figure 7.14 lists symbols for the most important technology elements that can be included in an energy system design.
- **Energy distribution at community level**. This box shows which grids exist within the community to supply the buildings. Grid types include electricity, steam, heating (hot-water supply), or cooling. Supply and return temperatures can be specified. Gas grids—which may exist within the community to supply buildings—are not represented to keep the schematic simple.
- **Building cluster level**. Many—especially larger—energy systems have distributed the generation equipment to several locations. A classic reason for distributing equipment is system growth. To be able to supply additional customers using the existing pipe system without replacing part of the pipes at larger dimensions, peak-load boilers can be placed close to the new buildings at suitable locations. Distributing generation equipment can also improve system resilience.

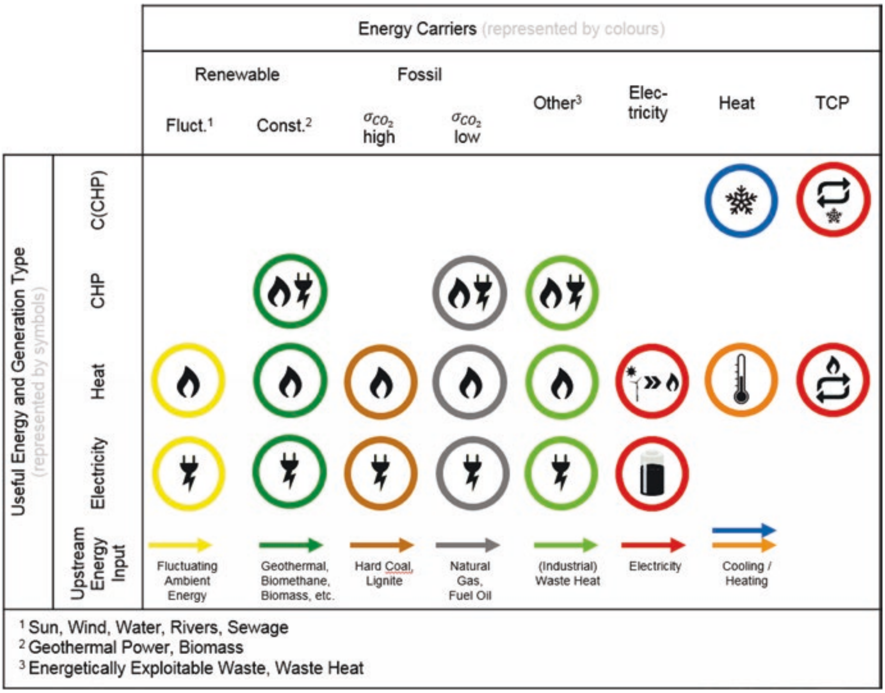


Fig. 7.14 Symbols for energy system description

- **Building level**. Most buildings rely on grids to supply the useful energy:
  - Power for lighting, plug loads, processes, controls, and sometimes cooling
  - Heating for DHW, heating, and sometimes cooling and humidity control
  - Cooling for comfort and processes
  - Process energy—often provided by using gas—for cooking and other processes

In the energy system schematic, buildings are included, but with a lower level of detail, showing the network connections and—in case of decentralized supply options—components like decentralized boilers, chillers, or emergency generators. Details of the equipment with the buildings (e.g., HVAC details) are not illustrated. Mission-critical buildings are represented by a black symbol (higher resilience to "black sky" conditions is required); other consumers are represented by a blue symbol (building functions need only to be maintained in "blue sky" conditions). The number of such buildings and their co-location can be adjusted based on each specific situation.

7.7.3 Symbols

Power and thermal energy systems can use different types of fuels from fossil and renewable energy sources. Figure 7.14 shows an overview over relevant fuel options. In the rows, components are grouped according to the useful energy they can provide and the generation type (power, heating, CHP, combined cool, heat, and power [CCHP]). In the columns, the equipment is grouped according to energy carriers. The different fuels are represented by colored circles. Renewable energy sources are grouped into fluctuating and constantly available sources and fossil fuels into high and low CO_2 fuels.

7.7.4 Categorization

To assist the energy master planning process, Appendix E contains a library of system architecture templates, including a description of the application, and a list of advantages and disadvantages for each template. This library contains more than 50 templates for different supply and demand situations as well as best-practice examples from various countries. The templates are categorized according to different criteria (see Table 7.5) with a four-digit number specifying the individual combination of categories for each template.

Example: the energy system displayed in Fig. 7.12 is numbered 1.3.1.1. Table 7.6 lists baseline templates and gives a number of examples.

Table 7.5 Categorization of energy system architecture templates

No.	Category 1	Category 2 Spatial location of generation/storage	Category 3 Building supplied from the outside with …	Category 4 No. of example
1	Solutions for generation within the community	At the individual building level	Power + heating	1 to × examples for this system type
2	Best-practice examples	At the building cluster level	Power + cooling	
3	Generation outside the community	At the community level	Power	
4	Solutions for remote locations (islands)	Combined	Power + heating + cooling	
5	Systems with electrical enhancement			

Table 7.6 List of baseline templates and number of examples

	Spatial location of generation	Building supplied from the outside with …	Number of examples for this system type
1	**Solutions for generation with the community**		
1.1.3	Generation at building level	Power	4 examples
1.2.1	Generation at building cluster level	Power + heating	1 example
1.2.4	Generation at building cluster level	Power + heating + cooling	4 examples
1.3.1	Generation at community level	Power + heating	3 examples
1.3.2	Generation at community level	Power + cooling	1 example
1.3.4	Generation at community level	Power + heating + cooling	8 examples
1.4.1	Generation at combination of spatial levels	Power + heating	2 examples
1.4.2	Generation at combination of spatial levels	Power + cooling	2 examples
1.4.4	Generation at combination of spatial levels	Power + heating + cooling	2 examples

(continued)

Table 7.6 (continued)

	Spatial location of generation	Building supplied from the outside with …	Number of examples for this system type
2	**Best-practice examples**		
2.3.1	Generation at community level	Power + heating	3 examples
			Gram (Denmark)
			University of British Columbia (CAN)
			Qaanaaq (Greenland)
2.3.4	Generation at community level	Power + heating + cooling	5 examples
			Taarnby District Copenhagen (Denmark)
			Favrholm (Denmark)
			Campus Denmark Technical University (Denmark)
			University of California Davis California National Primate Research Center (CNPRC)
			University of Texas Austin Medical Community
2.4.1	Generation at combination of spatial levels	Power + heating	Smart Thermal Loop University of Melbourne (AUS)
2.4.4	Generation at combination of spatial levels	Power + heating + cooling	Greater Copenhagen (Denmark)
3	**Generation outside the community**		
3.0.4.1	Generation outside the community (= 0)	Power + heating + cooling	1 example
4	**Solutions for remote locations**		
4.3.1	Generation at community level	Power + heating	3 examples
4.3.4	Generation at community level	Power + heating + cooling	2 examples
4.4.1	Generation at combination of spatial levels	Power + heating	3 examples
5	**Solutions with electrical enhancement**		
5.1.4.	Generation at building level	Power + heating + cooling	1 example
5.2.1	Generation at building cluster level	Power + heating	1 example
5.2.4	Generation at building cluster level	Power + heating + cooling	1 example

(continued)

Table 7.6 (continued)

	Spatial location of generation	Building supplied from the outside with …	Number of examples for this system type
5.3.1	Generation at community level	Power + heating	1 example
5.3.4	Generation at community level	Power + heating + cooling	3 examples
5.4.3	Generation at combination of spatial levels	Power	2 examples

- 1.x.x.x Solution for generation within the community
- x.3.x.x Generation at the community level
- x.x.1.x Buildings are supplied from the outside with heating and cooling
- x.x.x.1 Example No. 1 for this category

Table 7.6 gives an overview of the templates included in Appendix E.

7.7.5 Identification of Resources and Constraints

Selection of system architecture is bound by resources and constraints. An example of matrix for system resources and constraints (Table 7.7) can help the energy planner to navigate the selection process.

7.7.6 Identification of Technology Options

Table 7.8 summarizes the technology selection for each system architecture that can be narrowed down by applying constraints related to the availability of different fuels and space available for the installation of specific technologies and plants (see Chap. 1). The data in Table 7.8 provide a matrix that may be used to define technology selections.

7.7.7 Examples of System Architectures

This section illustrates the concept of energy system architectures using three real-life examples described in more details in IEA (2021). The four selected examples below show how different technical components can be combined into energy system architectures to serve a very wide spectrum of energy requirements and to deal

Table 7.7 Identification matrix for system resources and constraints

	Identify resources and constraints for your system architecture	Resource or constraint exists (yes/no)	Resource or constraint spatial level	Constraint limit (capacity, quantity, or maximum)	Constraint limit (units)
1	**External services and networks available**				
	Power available from external electricity grid				MW
	Steam available from external thermal network				klbs/hr (kg/hr)
	Hot water available from external thermal network				MW
	Chilled water available form external thermal network				tons (kW)
	Waste heat from sewage, etc.				MW
	Waste heat from industrial source				MW
	Sea, lake, river, or reservoir				liter/day (gal/day)
	Gas supply available				Dth/day (MMBtu)
	Renewable-energy-based electrical energy available				kW
	Renewable-energy-based heating energy available				MW
	Renewable-energy-based cooling energy available				MW
2	**Fuels available**				
	Natural gas				Therm (MMBtu/hr)
	Fuel oil				kl/day (gal/day)
	Liquid propane gas				kl/day (gal/day)
	Coal				tons/day (kW/day)
	Biomass				tons/day (kW/day)
	Biogas				MW (MMBtu/hr)

(continued)

Table 7.7 (continued)

	Identify resources and constraints for your system architecture	Resource or constraint exists (yes/no)	Resource or constraint spatial level	Constraint limit (capacity, quantity, or maximum)	Constraint limit (units)
	Geothermal energy				MW (MMBtu/hr)
3	**Existing energy systems onsite**				
	Central electric generating plant				MW
	Central steam heating plant				MW
	Central hot-water heating plant				MW
	Central chilled water plant				tons/day (kW/day)
	CHP plant (power generated)				MW
	CHP plant (heat generated)				MW
	Combined cooling, heating, and power plant (power generated)				MW
	Combined cooling, heating, and power plant (heat generated)				MW
	Combined cooling, heating, and power plant (cooling generated)				tons/day (kW/day)
	Decentralized heating (in buildings only)				MW
	Decentralized cooling (in buildings only)				tons/day (kW/day)
	Distribution lines for electricity				MW
	Distribution lines for natural gas				Dth/day (MMBtu)
	Distribution lines for central heating plant				MW
	Distribution lines for central cooling plant				tons/day (kW/day)
	Solar PV (annual average generation)				kWh
	Solar thermal (annual average generation)				MW

(continued)

Table 7.7 (continued)

	Identify resources and constraints for your system architecture	Resource or constraint exists (yes/no)	Resource or constraint spatial level	Constraint limit (capacity, quantity, or maximum)	Constraint limit (units)
	Geothermal electricity generation (annual average generation)				MW (MMBtu/h)
	Geothermal heat generation (annual average generation)				MW
	Wind (annual average generation)				kWh
	Biomass-based electric generating plant				MW
	Biomass-based heating plant				MW
	Biomass-based cooling plant				tons/day (kW/day)
	Biogas-based electric generating plant				MW
	Biogas-based heating plant				MW
	Biogas-based cooling plant				tons/day (kW/day)
	Sea, lake, river, or reservoir-based heating				MW
	Sea, lake, river, or reservoir-based cooling				tons/day (kW/day)
	Electrical energy storage				kWh
	Heating energy storage (water, phase-change material, other)				MW
	Cooling energy storage (water, phase-change material, other)				MW
	Emergency generators				kWh
4	**Energy & water storage systems**				
	Liquid natural gas storage				Liter (gal)
	Liquid propane gas storage				Liter (gal)
	Electricity storage				kWh

(continued)

Table 7.7 (continued)

	Identify resources and constraints for your system architecture	Resource or constraint exists (yes/no)	Resource or constraint spatial level	Constraint limit (capacity, quantity, or maximum)	Constraint limit (units)
	Fuel oil storage				Liter (gal)
	Chilled water storage				Liter (gal)
	Hot-water storage				Liter (gal)
	Potable water storage				Liter (gal)
5	**Personnel & staffing**				
	Type of trained operators available				

Table 7.8 Identification matrix for technology options

Constraint	Resource, system, or constraint exists (Y/N)	Constraint limit (capacity/quantity)	Constraint limit (units)
1. Locational resources			
1a. External energy and water resources			
Power available from external electricity grid			MW
Natural gas			Dth/day (MMBtu)
Fuel oil			kl/day (kGal/day)
Liquid propane gas			kl/day (kGal/day)
Coal			tons/day (kW/day)
Hot water available from external thermal network			MW (MMBtu/h)
Steam available from external thermal network			t/hr (Btu/hr)
Chilled water available form external thermal network			tons (kW)
Water (potable)			kl/day (kGal/day)
1b. External renewable & non-fuel-based energy resources			
Direct normal solar radiation available (annual average)			$kWh/m^2/day$ ($Btu/ft^2/day$)
Wind speed (annual average at 80 meters)			m/sec (ft/s)

(continued)

Table 7.8 (continued)

Constraint	Resource, system, or constraint exists (Y/N)	Constraint limit (capacity/quantity)	Constraint limit (units)
Biomass			ktons/yr (kW/day)
Biogas			MW (MMBtu/h)
Waste heat from sewage, etc.			MW (MMBtu/h)
Waste heat from industrial source			MW (MMBtu/h)
Sea/river/reservoir/lake			MW (MMBtu/h)
1c. Space availabilities for installing technologies			
Space for central electric generating plant			m^2 (ft^2)
Space for central heating plant			m^2 (ft^2)
Space for central cooling plant			m^2 (ft^2)
Space for CHP plant			m^2 (ft^2)
Space for combined cooling, heating, and power plant			m^2 (ft^2)
Space for decentralized heating (in buildings only)			m^2 (ft^2)
Space for decentralized cooling (in buildings only)			m^2 (ft^2)
Space for centralized heat with distribution lines			m^2 (ft^2)
Space for solar PV			m^2 (ft^2)
Space for solar thermal			m^2 (ft^2)
Space for geothermal wells			m^2 (ft^2)
Space for wind energy systems (area)			m^2 (ft^2)
Space for wind energy systems (height)			m (ft)
Space for biomass-based central plant (electric, heating, or cooling)			m^2 (ft^2)
Sea, lake, river, or reservoir available			m^3 (gal)
Space for electrical energy storage			m^2 (ft^2)
Space for TES tanks (area)			m^2 (ft^2)
Space for TES tanks (height)			m (ft)
Space for seasonal TES			m^3 (gal)
Space for emergency generators			m^2 (ft^2)
Building and roof space available for decentralized heating systems			m^2 (ft^2)
Building and roof space available for decentralized cooling systems			m^2 (ft^2)

(continued)

Table 7.8 (continued)

Constraint	Resource, system, or constraint exists (Y/N)	Constraint limit (capacity/quantity)	Constraint limit (units)
Space for electric distribution lines			km^2 (sq mi)
Space for gas distribution lines			m^2 (ft^2)
Space for heating energy distribution lines (steam, hot water)			m^2 (ft^2)
Space for cooling energy distribution lines (chilled water)			m^2 (ft^2)
2. Building-level facility constraints			
Building energy use (site-based)			kWh/m^2 (kBtu/ft^2-yr)
Building energy use limit (primary or source-based)			kWh/m^2 (kBtu/ft^2-yr)
Renewables required			kWh/m^2 (kBtu/ft^2-yr)

with different constraints. When system architecture for the base case and alternatives are selected, technical components for these architectures can be selected from the technologies database described in Sect. 7.8.

7.7.7.1 The University of British Columbia

Figure 7.15 shows a schematic of the energy system at the University of British Columbia (CAN). The system includes older components (steam pipe system) along with more current elements (hot-water pipes, natural gas CHP, and boilers). The share of renewables has been added with biomass boilers and using biomethane as a fuel for the CHP plant. Some buildings are still served by the old steam systems, while other (newer) buildings with more advanced building systems are connected to the hot-water system. The example is numbered 2.3.1.2 in the library database—according to the categorization system outlined in Table 7.5. This campus-level system has the following advantages and disadvantages:

- Pros: Onsite CHP production of electricity and heat, biomass boiler for medium load production, peak, and backup capacity from gas boilers
- Cons: No building-level backup for electricity and heat production

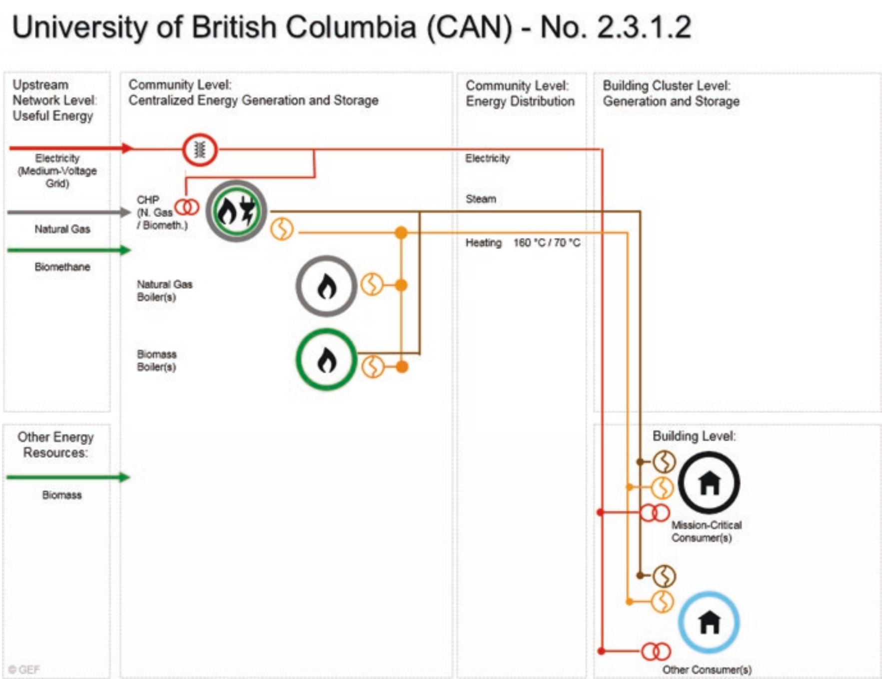


Fig. 7.15 Schematic of the energy system at the University of British Columbia (CAN)

7.7.7.2 The Technical University of Denmark (DTU)

A combination of gas-based and power-based generation elements can be found at the campus of the Technical University of Denmark (DTU) in Lyngby near Copenhagen (see Fig. 7.16, No. 2.3.4.3 in the database). In addition to a 100% campus DH system, which is connected to the DH at the city level and operated at lower temperatures (supply 75 °C [167 °F]/return 50 °C [122 °F]), there is a 100% central cooling system at the campus (supply 10 °C [50.0 °F], return 15 °C [59.0 °F]) that provides all cooling demand, including local refrigeration. Building systems are equipped for operation with these temperatures. Generation equipment at the campus includes:

- A 40 MW electric boiler
- A 30 MW gas-fueled CHP plant
- A 33 MW gas-fueled boiler plant with flue gas condensation
- An 8000 m^3 (282,517 ft^3) pressureless heat storage tank with DH water ready to use (Fig. 7.17)
- A chiller plant

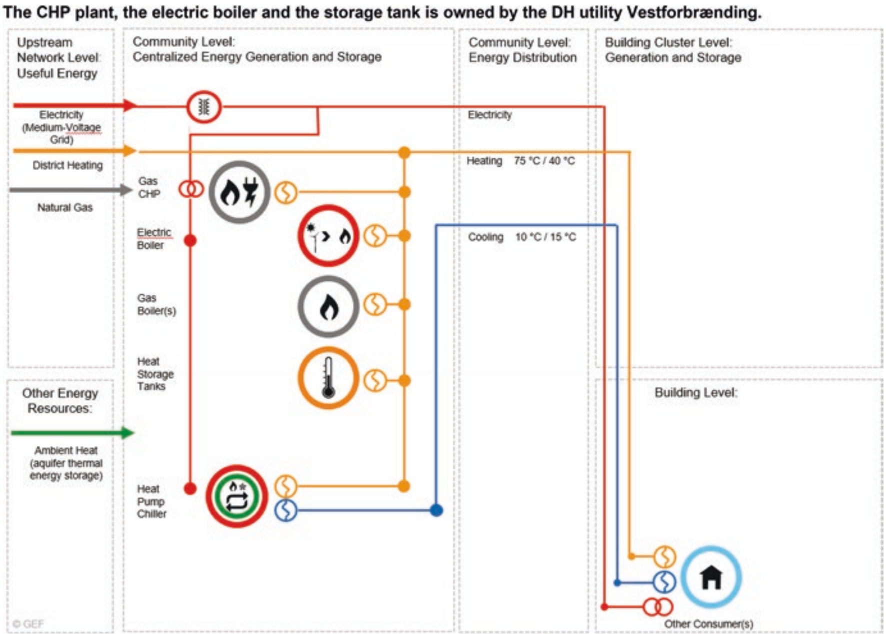


Fig. 7.16 Smart energy system at the campus of the Technical University of Denmark in Lyngby

A heat pump to combine heating and cooling and a heat pump for cooling fresh water are in the planning stage.

The CHP plant, the electric boiler, and the storage tank are owned by the DH utility Vestforbrænding.

The system is characterized by a high degree of sector-coupling involving all three energy carriers: power, heating, and cooling. This campus-level system has the following advantages and disadvantages:

- Pros:
  - Onsite CHP production of electricity and heat, peak, and backup capacity from gas boilers, thermal storage enables production flexibility. It can shift from 40 MW of consumption to 30 MW of production of electricity on short notice, and the plant can offer regulation services to the power grid.
  - The heat pump and chillers integrate cooling and heating.
  - Except emergency generators for the data center.
- Cons:
  - As yet there is no chilled water storage and ground source cooling system; while this is in the planning stages, it must overcome difficulties related to groundwater protection and architecture.

Fig. 7.17 Hot-water storage tank with a capacity of 8000 m^3 (2823 ft^3), ready to use

The stack behind the unit is tall because it was designed in 1965 for heavy oil boilers. Today there are three stainless steel tubes in the stack, one to each gas boiler, designed for flue gas condensation with economizer (55 °C [131 °F] flue wet gas). A project for further condensation with a heat pump for combined heating and cooling is planned (25 °C [77 °F] wet flue gas).

7.7.7.3 Taarnby Sustainable Urban Development

In an urban development district at a new metro station in Greater Copenhagen, the Public Utility of Taarnby Forsyning has developed a system for smart district energy and ambient heat (SDE). It is a high-profile case for the fourth-generation DH as it includes combined heating and cooling with interconnection of ambient heat, in this case treated wastewater, groundwater, and drain water. The concept included the following smart integration of the sectors:

- New urban development next to a new metro station, Kastrup, north of Copenhagen Airport.
- Wastewater treatment basins next to the area have been covered to prevent bad environment, which was a precondition for this symbiosis between the urban development and the wastewater treatment plant.
- DH will be supplied by Taarnby Forsyning to all new buildings and to replace gas boilers in existing buildings (see the case study for DH in Taarnby).
- DH based on biomass CHP and waste from the Greater Copenhagen system is the main source to the DH in Taarnby (see the case study for Greater Copenhagen).
- District cooling will be supplied to all new buildings, offices, and hotels in the district.
- A heat pump 4.3 MW cold/6.3 MW heat is installed to combined production of heating and cooling in three steps and will be the main source for cooling, and all heat will be supplied to the DH.
- A 2000 m^3 (70,629 ft^3) chilled water storage that holds 6–8 °C (43–46 °F) cold water ready for use by all consumers will provide additional capacity and allow smart use of electricity for the combined production.
- The treated wastewater will be delivered to the heat pump (Fig. 7.18) for heat-only production via 150 m (492 ft) "ambient heat network" double plastic pipe from the outlet to the heat pump and back.

Fig. 7.18 Heat pump and chilled water plant in Taarnby

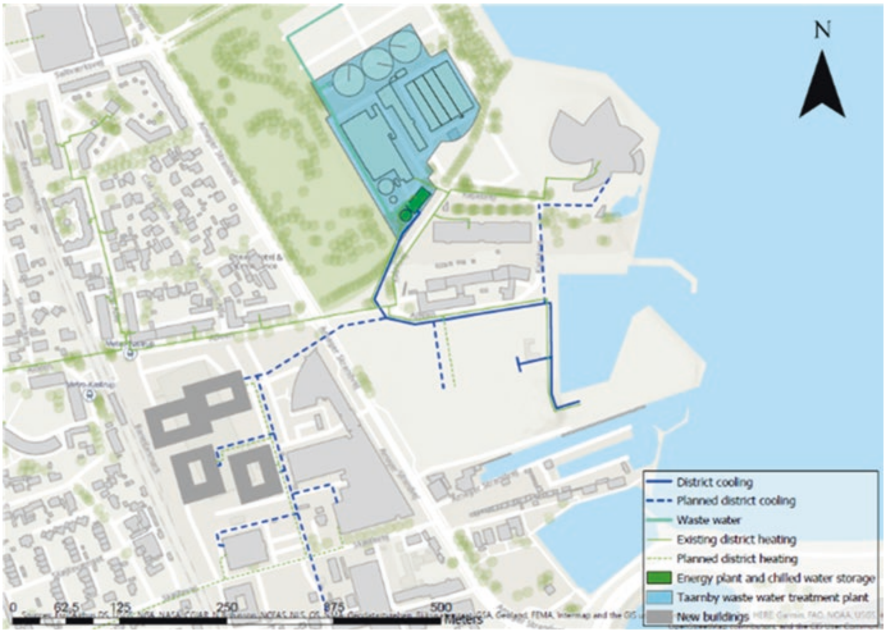


Fig. 7.19 Urban development area and wastewater treatment plant

- Ground source cooling or drain water will according to the plan move heat production from summer to winter by connecting the plant to an existing drain water pipe and by drilling wells to ground source cooling. (This is not established in the first stage, but the plant is prepared for this additional source.)
- Space for the heat pump and the chilled water storage has been made available at the wastewater treatment plant (Fig. 7.19), which saves cost and space in the urban development area.

Pros:

- The sector integration supplies a cost-effective and resilient and environmentally friendly supply of heating and cooling (Fig. 7.20).
- There is no need for building-level installations for generation of heat and cold.
- There is no need for space to the energy plant, as this space has been made available at the wastewater treatment plant.

Cons:

- In the first stage before the drain water and ground source cooling is put into operation, it can be necessary to reduce the heat from the combined heating and cooling by using the wastewater to cool the first stage of the heat pump, as there can be surplus of heat from waste incineration in certain periods during the summer.

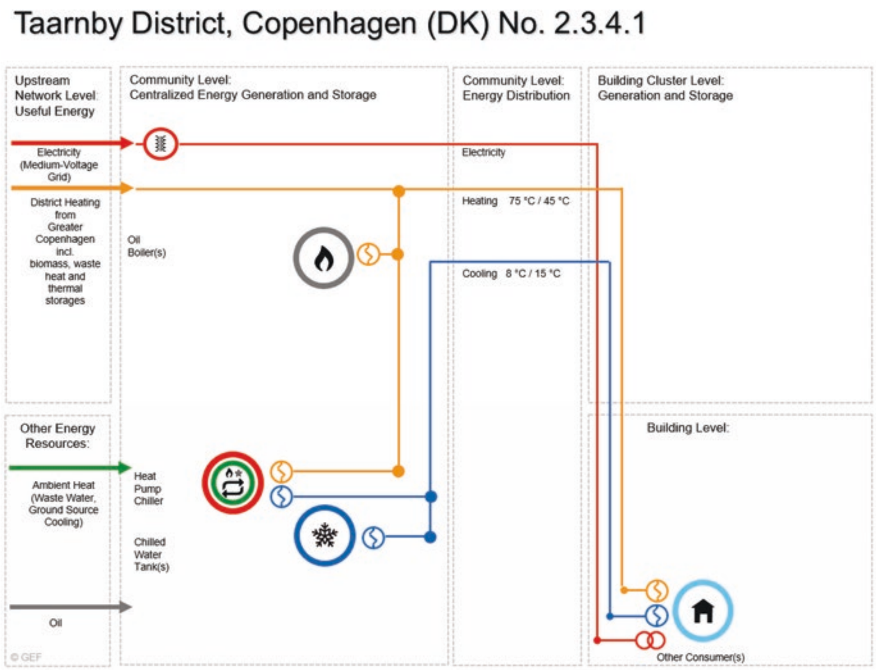


Fig. 7.20 Smart district energy (DK)

7.7.7.4 Smart Thermal Loop (STL)

A modern generation system was designed for a campus of the University of Melbourne in Australia. A single piping system operated at 15/25 °C (59/77 °F) has been proposed to supply buildings with both heating and cooling. The buildings connected to the grid are equipped with reversible heat pumps, which can act as prosumers and can feed energy back into the grid (see Fig. 7.21). A wide variety of generation equipment from waste incineration and biomass boilers to heat pumps and electric chillers feed energy into the system. Storage tanks for hot and chilled water complement the generation. Renewable electricity is generated from biomass and fluctuating sources to provide some level of independence from the upstream power grid.

This system serving a cluster of buildings at the campus has the following advantages and disadvantages:

- Pros: Multiple waste heat producers, renewable energy sources, building-level backup
- Cons: Expensive, breakdown on waste heat sources, reliability, expensive building-level heat pumps, miss the opportunity of economies of scale

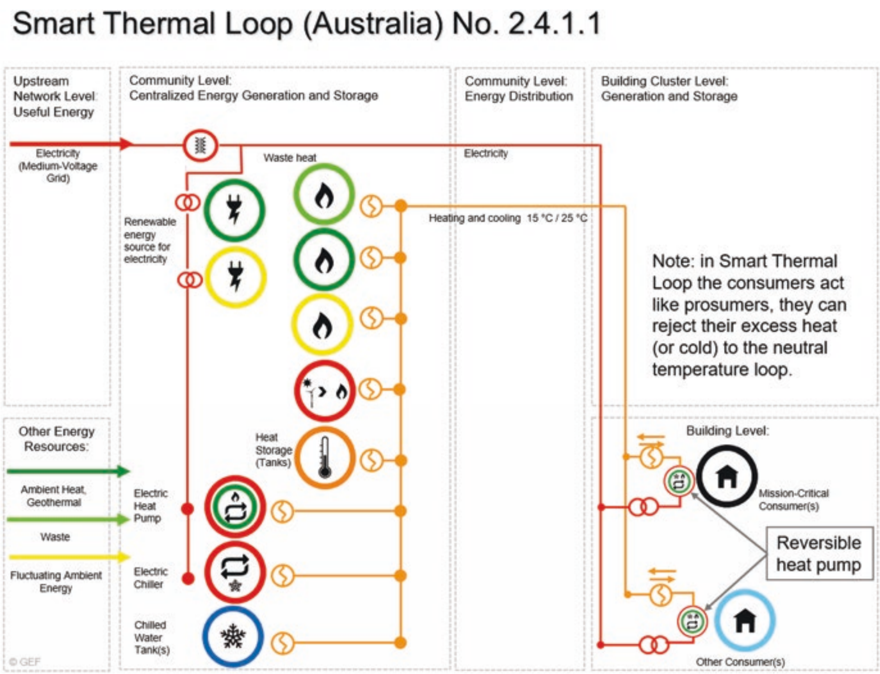


Fig. 7.21 Smart thermal loop, Melbourne (AUS)

7.8 Technologies Database

The technologies database presented in Appendix D was developed based on the information available from various sources. These included the NZP/SMPL tool, MIT LL Energy Resilience Analysis (ERA) tool, REopt tool, US Department of Energy CHP factsheets, Danish Energy Agency Technology Catalogue, and information provided by the International District Energy Association, EATON, Schneider Electric, TKDA, and GEF. The technology reliability data was provided by the US Army Corps of Engineers Power Reliability Enhancement Program (PREP). The database is comprised of multiple energy conversion, distribution, and storage technologies that can be integrated by energy planners into energy system architectures (described in Sect. 7.8) to create different alternatives of community energy systems.

The database features information on mature (first generation) and state-of-the-art technologies available on the market for supplying electricity, heating, cooling, and natural gas. It includes technical characteristics and costs and shows the economies of scale for different technologies and the way different technologies can interact with each other.

The database technology information contains general data that is accurate enough to support comparison of different concepts on the planning level, but that is not designed for making specific investment decisions, system design, or equipment

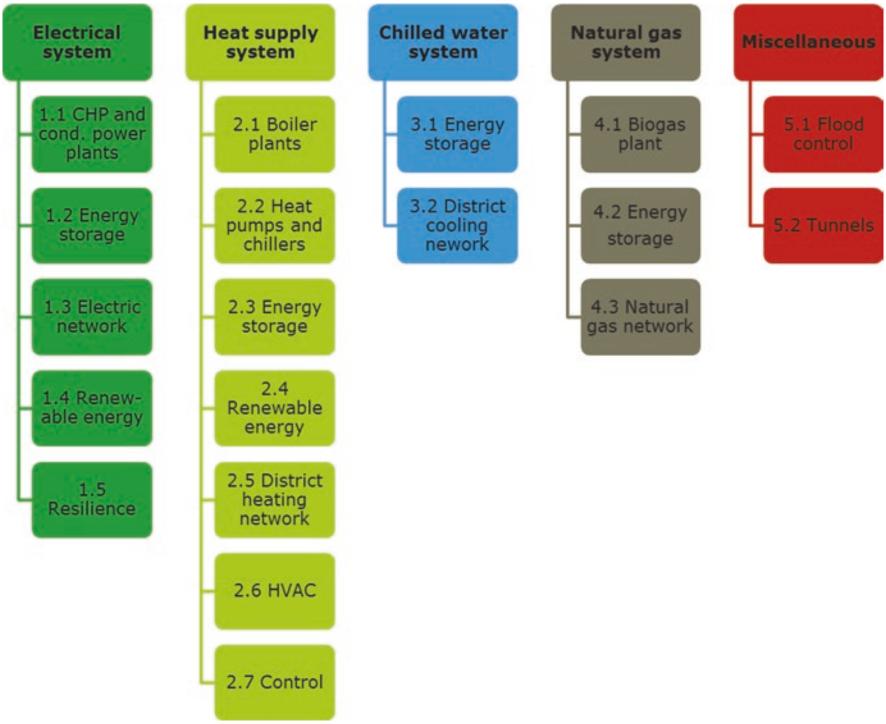


Fig. 7.22 Database structure

specification. Information is supported by references and links to examples of technology implementation, including case studies (Annex 73 Book of Case Studies).

The MS Word® version of the database (Appendix D) with fixed values of technology characteristics is complemented by an MS Excel® version that is integrated into the energy master planning tool that is described in Chap. 1. The Excel® database can be updated and adjusted based on specific fuel prices, currency, and national characteristics and includes text boxes and attachments for guidance. The MS Word version is limited to fixed 2020 values regarding economic assumptions and does not include automatic calculations, for example, the LCOE calculation.

The structure of the database (Appendix D; also see Fig. 7.22) includes the following categories:

- Electric systems
- Heat supply systems
- Chilled water systems
- Natural gas systems
- Miscellaneous

Table 7.9 lists the types of technologies included in the database. Each technology in the database is described using the following categories:

Table 7.9 Database technologies

Technology	Technologies included
Electrical system	**CHP and condensing power plants** Gas engine. For many campus areas with a heating and electricity demand, a small gas engine can be an efficient solution supplying both electricity and heating Gas turbine combined cycle. This type of power plant is typically a large facility (>100 MW). The excess heat can, however, be used as DH Gas turbine simple cycle. This type of power plant is typically a medium facility (25–100 MW). For large campus areas, the technology can be an option Biomass (wood chips, wood pellets, straw) CHP. The power plant configurations cover a range from small organic Rankine cycle (ORC) facilities (5 MW) to large power plants (> 200 MW), which are designed to use biomass instead of fossil fuels. The smaller configurations are likely most relevant for campus areas, although depending on campus size Waste CHP. If a waste resource is available and electricity production of value, a waste CHP can be the preferred solution over a waste boiler (typically in large-scale configurations) **Energy storage** Pumped hydro storage. Requires available land to be filled with water. This type of storage is typically installed in large systems Electric batteries. These can be used to provide peak-load capacity and smoothen the production profile from wind turbines and solar PV **Electric network** Electric transmission. These are large transmission lines connecting cities and countries Electric distribution. These are smaller distribution lines for local supply on campus-level and on city-level distribution of electricity Microgrid. These are small electricity grids located at campus level **Renewable energy** Solar PV. The energy from the sun can be used to produce electricity. Solar PV plants can be installed on rooftops and fields Wind turbine. Onshore wind turbines can be installed as single turbines or clusters or in larger wind farms Solar PVT (photovoltaic thermal hybrid solar collector). A PVT is a solar energy device that uses PV as a thermal absorber and produces both electrical and thermal energy. A wide variety of PVT module configurations exist **Resilience** Emergency generators. An emergency generator is a backup electrical system that operates automatically UPS. A UPS is an electrical apparatus that provides emergency power to a load when the input power source or main power fails Emergency power system. An emergency power system is an independent source of electrical power that supports important electrical systems on loss of normal power supply Reliability technology data: Data on reliability of selected boilers, generators, cables, transformers, etc. are available. The data are for unplanned outages and down times of the respective equipment

Heat supply system	**Boiler plants** Natural gas boiler. Many campuses have natural gas boilers installed. Depending on where in the world the campus is located, the boiler may be a condensing or a non-condensing one Biomass (wood chips, wood pellets, straw) boiler. Depending on the available local biomass, one type of biomass may be preferred over the other. The use of biomass will give an immediate greenhouse gas reduction compared to the use of fossil fuels Electric boiler. For peak DH production, when the electricity prices are low and renewable energy production high, the electric boiler can be a cost-efficient solution that also helps integrate renewable energy into the DH system Waste boiler. If a waste resource is available and any electricity production of little value, a waste boiler can be a good solution Coal boiler. In some areas of the world, coal boilers are still in use. It is not recommended to invest in coal boilers for low-carbon energy systems, but it can be a baseline technology Oil boiler. For peak-load and backup DH production, the oil boiler can be a cheap although not a low-carbon solution. It can also be a baseline technology **Heat pumps and chillers** Electric heat pump. To better integrate renewable energy, an electric heat pump can be used to produce DH and DC via electricity from renewable energy. The possibility for producing heating and cooling in combined mode improves the profitability of installing an electric heat pump Absorption heat pump. An absorption heat pump is powered by both a high-temperature and a low-temperature heat source. The high-temperature drive energy can be flue gases, hot water, steam, or DH water, while the low-temperature energy can come from a low-temperature heat exchanger. The net efficiency of a power plant can be improved Electric chiller. This technology is used to produce cooling in most buildings as of today. For campus areas, district cooling with combined heating and cooling production will be more efficient, but electric chillers can provide the backup cooling capacity needed **Energy storage** Hot-water tanks (pressureless). This type of heat accumulator is the most common technology and is used in both households (hot tap water) up to DH systems (large tanks) Hot-water tanks (pressurized). This type of tank is used in DH systems to control pressure and temperatures, especially at transmission level Pit TES. The development of pit storages has mainly been driven by large solar thermal plants. The economies of scale are obvious and are thus only for use on an industrial and DH scale **Renewable energy** Solar heating. Solar water heating is a natural and simple way to use the energy from the sun to provide hot water for heating and hot tap water, and the technology is simple. Solar heating typically must be installed together with a heat storage

(continued)

Table 7.9 (continued)

Technology	Technologies included
	Deep geothermal. If a geothermal heat reservoir is located beneath a campus area (800–3000 m depth), it is possible to use this heat for DH supply. Temperature boost with a heat pump may be required **DH network** The most important aspect of energy planning on a campus is the thermal infrastructure (heating and cooling). In this section of the database is a description of DH planning provided together with that of a hydraulic analysis, pre-insulated pipes, development of DH, and two-pipe active beam systems. The capacities and losses and pipe prices are also available **HVAC** Heat exchangers (building level). These are substations towards the DH or cooling network, where heat is exchanged into the building Central heating. Central heating is a heating system where the heat is produced at a central place in the building and from there distributed to the rooms to be heated Ventilation system. In many instances, ventilation for indoor air quality is simultaneously beneficial for the control of thermal comfort Ventilation with heat recovery. Ventilation in buildings with flats is typically build as mechanical extraction or as natural ventilation without heat recovery Hot tap water system. Typical domestic uses of hot water include cooking, cleaning, bathing, and space heating. In industry, hot water and water heated to steam have many uses Hydronic balancing. In general terms balancing is about ensuring that the operating conditions of each component in the installation are operating within its design operating conditions, which enables an efficient heating system operation Backup boiler and storage. Used for DH backup production capacity **Control** Heat exchangers. Large heat exchangers on a DH level Pressure sectioning. With direct supply one can avoid the loss in the heat exchangers. Instead, the system can be regulated with pressure section and a safety valves system Pressure regulator. A pressure regulator is a control valve that reduces the input pressure of a fluid to a desired value at its output SCADA systems. SCADA are a control system architecture that uses computers, networked data communications, and graphical user interfaces for high-level process management
Chilled water system	**Energy storage** Cold storage. The pressureless hot-water tank can also be used for cold water, with the same cost structure. Hence, ATES is the only cold storage solution described **District cooling network** A general discussion on district cooling planning is provided. The same pipes used for DH can also be used for district cooling. There is however also a possibility for using cross-linked polyethylene (PEX) pipes at lower pipe dimensions

Natural gas system	**Biogas plant** Biogas plant. Biogas plants produce a methane rich gas based on biodegradable organic material. The feedstock is transported to the plant by road or pumped in pipelines. At the plant, it undergoes an anaerobic process, which generates biogas **Energy storage** Subsurface gas storage. This type of storage requires large amounts of natural gas that needs to be stored and available aquifers. The typical use is for large gas systems **Natural gas network** Natural gas transmission. These are large pipelines that connect countries Natural gas distribution. These are smaller pipelines for distribution of gas on a local campus level and at a distribution level in a large natural gas system Biogas networks. Biogas can be upgraded for natural gas quality level and sent into the natural gas system Hydrogen networks. Small portions of hydrogen can be added in the natural gas system, but a separate system is needed at large quantities of hydrogen distribution
Miscellaneous	**Flood control** Flood control methods are used to reduce or prevent the detrimental effects of floodwaters **Tunnels** A tunnel is an underground passageway, where energy pipelines and cables can be placed inside

- **Technology**: A broad technology description is provided for each technology.
- **Primarily fuels**: Type of fuel(s) that each technology can use for its operation.
- **Energy production**: The output of electricity, heating, cooling, and any relevant byproducts for each technology.
- **Capacities**: The stated capacities are for a single unit capable of producing energy (e.g., a single wind turbine or a single gas turbine), not a power plant consisting of a multitude of units such as a wind farm. In the case of a modular technology such as PV or solar heating, a typical size of a solar power plant based on the market standard is chosen as a unit.
- **Space requirement**: The space requirement for renewable energy installations (solar PV, wind, etc.) is available. The value presented refers only to the area occupied by energy production equipment. The space requirements may, for example, be used to calculate the rent of land, which is not included in the financial cost since this cost item depends on the specific location of the plant.
- **Control ability**: Control abilities are particularly relevant for electricity-generating technologies. This includes the part-load characteristics, startup time, and how quickly it can change its production when already online.
- **Environment**: Environmental characteristics are available including emissions and local pollutants.
- **Financial**: For each technology, the following financial information is provided: investment costs, fixed O&M costs, and variable O&M costs. The costs are provided in Euros and US dollars. The Excel® database allows the selection from a broader range of currencies, which can be adjusted according to current exchange rates.

The use of the database is related to the architectures and the subsequent energy system model; the economic and technical assumptions relating to these are also available in the database. The assumptions can be applied in the subsequent energy system model and economic evaluation.

Furthermore, the assumptions underlying the energy system model must be adjusted to match local conditions and must be double checked by the energy planner before running the optimization. The local costs in terms of manpower and equipment will vary across the world depending on the local conditions. The MS Excel® database (available on the Annex 73 website https://annex73.iea-ebc.org/publications) includes an option for automatically updating to local conditions (and currency), but the MS Word® version (see Appendix F) uses fixed values that must be updated manually. Example of the table of contents for the part of the database related to "Energy Storage" is shown in Fig. 7.23.

Matrix

The matrix (Fig. 7.24) contains an overview of generic energy systems for different climate zones but also actual energy system examples. The user can use filters to narrow the number of relevant cases down to fit the specific location. It is then possible to view the relevant technologies and energy system examples. Besides technical and economic characteristics for different technologies, the database includes information on their reliability that can be used for resiliency analysis (Table 7.10).

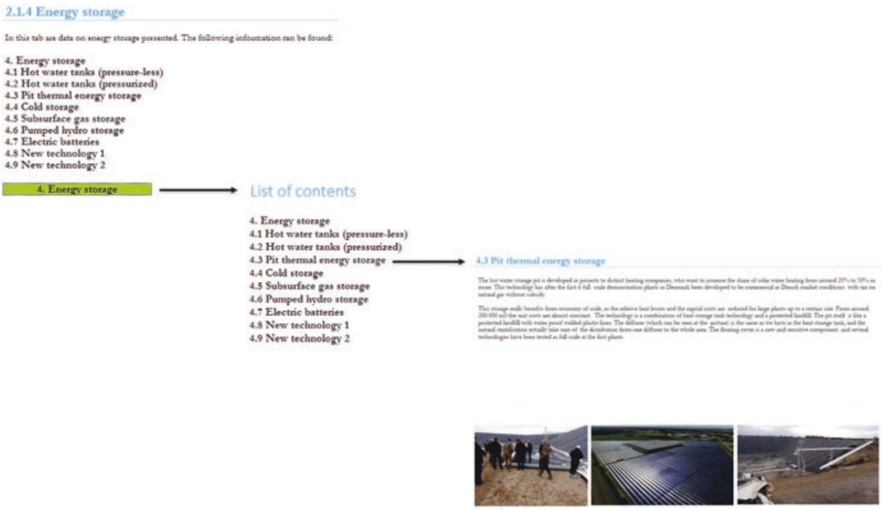


Fig. 7.23 User guide table of contents functionality

	Classification System					Case		District heating				District cooling		Renewable energy				CHP				E2H & E2C				Boiler				Storage			Resiliency		
System design and case number	Type of example	Spatial location	Buildings to be supplied from the outside with...	No. of example	Indexation	Case No. (Task B)	Energy system example (Task C)	Steam system	DH system (160/70)	DH system (110/80/50)	DH system (70/60/40)	High-temperature cooling 10/15	District cooling system (5/10)	Solar Heating	Deep geothermal	Solar PV	Wind turbine	Oil CHP	Gas CHP	Biomass CHP	Waste CHP	Electric chiller	Electric heat pump	Absorption heat pump	Electric boiler	Oil boiler	Gas boiler	Biomass boiler	Waste boiler	Thermal tank storage	Cold storage	Thermal pit storage	Security 0 to 10	Fuel 0 to 10	Description, draft to be considered, and explained in detail in section on system design
1	Best-practice examples	At community level	Power + heating	Example 1	2.3.1.1	---	Arctic Climate	X	---	---	---	---	---	---		---	---	X	---	---	---	---	---	---	---	X	---	---	---	---	---	---	0	1	Risk of breakdown and fuel shortage
1	Best-practice examples	At community level	Power + heating	Example 1	2.3.1.1	Quanaaq, Greenland	---	---	---	X	---	---	---	---	---	---	---	X	---	---	---	---	---	---	---	X	---	---	X	---	---	---			
2	Best-practice examples	At community level	Power + heating + cooling	Example 1	2.3.4.1	Taarn-by district heating	---	---	---	X	---	---	---	---	---	---	---	---	---	X	X	---	---	---	---	---	X	X	---	X	---	---			

Fig. 7.24 Matrix structure

Table 7.10 Reliability technology data table sample

Category/class	Item number	Reliability	Inherent availability	Operational availability	Unit years	Failures	Failure rate (failures/year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/yr
Battery	E2-000	0.993006248	0.999990299	0.999969547	10543.8	74	0.00702	1248161.	12.11	0.1490	0.217	7140	0.2668
Boiler	H8-000	0.878642210	0.999360697	0.995132436	1113.0	144	0.12938	67708.83	43.29	3.2844	3.738	768	42.639
Hot water	H8-100	0.959008598	0.999985268	0.999501894	358.4	15	0.04186	209292.8	3.08	1.0000	1.005	2018	4.3634
Steam	H8-200	0.842870823	0.999064090	0.993057393	754.6	129	0.17094	51245.58	47.96	3.6062	4.120	593	60.817
High pressure	H8-210	0.928026957	0.999619462	0.991492148	468.6	35	0.07469	117277.7	44.63	3.0000	3.162	372	74.528
Low pressure	H8-220	0.719936234	0.998154400	0.995621239	286.1	94	0.32859	26659.1	49.20	0.0000	116.734	26659	38.357
Cable, alternating current (AC) per 1000 ft.	E6-000	0.998679301	0.999998900	0.999987359	698411	923	0.00132	6628468	7.29	4.2810	4.440	351270	0.1107
Cable, AC, 0–600 V	E6-100	0.998924937	0.999998890	0.999995587	130155	140	0.00108	8143981	9.04	6.3706	6.882	1559723	0.0387
Cable, AC, 601–15 kV	E6-200	0.998623048	0.999998903	0.999985474	568256	783	0.00138	6357495	6.98	4.2034	4.333	298329.1	0.1273
Cable, aerial per 1 mile	E7-000	0.988381339	0.999997295	0.999997259	37478.5	438	0.01169	749570.9	2.03	0.3529	1.907	695576	0.0240
Cable, aerial, 0–15 kV	E7-100	0.953928762	0.999990218	0.999990218	6593.7	311	0.04717	185725.9	1.82	0.0000	1.817	185726	0.0857
Cable, aerial >15 kV	E7-200	0.995896395	0.999998806	0.999998762	30884.9	127	0.00411	2130325.	2.54	0.0000	2.081	1680443	0.0108
Cable, DC per 100 ft.	E8-000	0.992748496	0.999998338	0.999998338	412.2	3	0.00728	1203640	2.00	0.0000	0.109	65653	0.0146
Chiller	H10-000	0.888515818	0.999829779	0.997620632	2021.9	239	0.11820	74109.90	12.62	1.0881	1.164	489	20.843
Absorption	H10-100	0.841986658	0.999769437	0.995132437	430.3	74	0.17199	50932.86	11.74	1.0000	0.653	134	42.639
Centrifugal	H10-200	0.955142622	0.999923928	0.997604888	544.7	25	0.04589	190872.1	14.52	5.2247	5.333	2227	20.981
Reciprocating	H10-300	0.864557699	0.999799791	0.998898189	948.2	138	0.14554	60190.78	12.05	1.5457	1.837	1667	9.6519
Rotary	H10-400	0.986993503	0.999964132	0.996197991	76.4	1	0.01309	669120	24.00	6.0723	6.115	1608	33.305

Screw	H10-500	0.956286690	0.999510164	0.996566046	22.4	1	0.04470	195984	96.00	1.0000	1.164	339	30.081
Transformer, dry	E38-100	0.999953743	0.999995817	0.999971899	11025.1	19	0.00005	18937280	xxx	3.2263	3.693	131402	0.2462
Transformer, liquid	E38-200	0.994797669	0.999950735	0.998990580	8819.2	46	0.00522	1679476.	82.74	16.9047	17.588	17424	8.8425
UPS: Uninterruptible power supply	E39-000	0.999078297	0.999998349	0.999951289	553.1	4	0.00092	9499764.	xxx	3.8000	3.688	75701	0.4267

Note:
* Time truncated, chi-squared, 60% single-side confidence interval
Xxx Data not available at time of analysis
The data originates from the report: TM 5-698-5 “Survey of reliability and availability information for power distribution, power generation, and HVAC components for commercial, industrial, and utility installations,” published 22 July 2006; available at: https://www.wbdg.org/ffc/army-coe/technical-manuals-tm/tm-5-698-5

References

Gudmundsson, Oddgeir, Jan Eric Thorsen and Anders Dyrelund. 2020. Thermal Energy Systems Resilience in Cold/Arctic Climates. *District Energy – The Resilient Energy Infrastructure*. Materials of the Consultation Forum. Fairbanks, AK: Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL).

IEA (International Energy Agency). 2021. *Annex 73. Energy master planning for resilient public communities – Case studies*, ed. Anna Maria Fulterer and Ingo Leusbrock. Paris: International Energy Agency, Energy in Buildings and Communities (IEA-ECB), Annex 73. https://annex73.iea-ebc.org/.

University of Washington. 2017. Utility tunnels and tranches. In *University of Washington facilities services design guide*. Seattle: University of Washington. https://facilities.uw.edu/files/media/fsdg-02-u-utility-tunnels-trenches.pdf.

Chapter 8
Energy Performance Calculation Method of Complex Energy Systems

Abstract This chapter describes a computer simulation module (Energy Resilience of Interacting Networks or ERIN) and the process that allows for the assessment of resilience to various design basis threats. The tool operates over networks that supply both individual buildings and districts. These networks are comprised of components (loads, generation, distribution/routing, storage, and transmission assets) and connections. These connections form the topology of the network—what is connected to what. Multiple flows of energy can be modeled, notably, both thermal (heating/cooling) and electrical flows, and their interactions. This chapter further discusses how reliability can be considered with a resilience assessment and how the calculation tool and process can be used with a library of "architectures"—design templates for potential solutions and a comprehensive database of component information. We further present the relationship and interaction with other tools. The chapter describes the relationship between the ERIN tool with other tools, provides an example analysis using this tool, and shows an example of ERIN integration with the Simple Master Planner (SMPL) Tool.

8.1 Introduction

District energy systems play a major role in enabling resilient communities. However, resilience is contextual. That is, one must specify what one is resilient to; this can be planned for using the concept of a design basis threat. Design basis threats are low-probability, high-impact events such as hurricanes, flooding, earthquakes, terrorist attacks, tornados, ice storms, viral pandemics, etc. One must consider relevant design basis threats to enable resilient public communities.

In this chapter, we describe a computer simulation module (Energy Resilience of Interacting Networks or ERIN) and process that allow for the assessment of resilience to various design basis threats. The tool operates over networks that supply both individual buildings and districts. These networks are comprised of components (loads, generation, distribution/routing, storage, and transmission assets) and connections. These connections form the topology of the network—what is

A. Zhivov, *Energy Master Planning toward Net Zero Energy Resilient Public Communities Guide*, https://doi.org/10.1007/978-3-030-95833-6_8

connected to what. Multiple flows of energy can be modeled, notably both thermal (heating/cooling) and electrical flows and their interactions.

This network of components is subject to various scenarios that represent one or more ideal cases (i.e., "blue sky") as well as design basis threats (also known as "black sky" events). Each scenario has a probability of occurrence and zero or more intensities associated with it such as wind speed, vibration, water inundation level, etc. Fragility curves are used to relate the scenario's design basis threat intensities with the percentage chance that a given component will fail to work under the duress of the scenario.

Examining the performance of the network while considering the possibility of failure due to various threats allows resilience metrics discussed in Chap. 5 such as energy robustness (ER), energy system recovery time (maximum single event downtime—MaxSEDT), or energy availability (EA) to be calculated. This can, in turn, help planners to see whether a proposed system or change to an existing system will meet their threat-based resilience goals.

We further discuss how reliability can be considered with a resilience assessment. We discuss how the calculation tool and process can be used with a library of "architectures"—design templates for potential solutions. We also discuss use with a comprehensive database of component information. We further present the relationship and interaction with other tools. Finally, we present an example problem using the calculation tool and discuss future directions, as follows.

A calculation tool and process are required to aid community master planners with:

- Assessing various component technologies and infrastructure options for:
  - Energy usage
  - Overall cost (life cycle, initial investment, operating, and maintenance)
  - Resilience versus various threat scenarios (*design basis threat*)
- Choosing alternatives (different technologies, different topologies) to evaluate based on priority and technical know-how for a given size, climate zone, and operating scenario

Our solution involves a calculation tool and a process. The objective is to assess the cost, energy usage, and resilience of one district system network design versus another to determine the best design for planning purposes.

8.2 Process Overview

8.2.1 General

Figure 8.1 shows the information flow and process for using the calculation tool. The goal of the process is to assist a planner in selecting appropriate architectures, configuring them for their local situation, and assessing them for their costs, energy

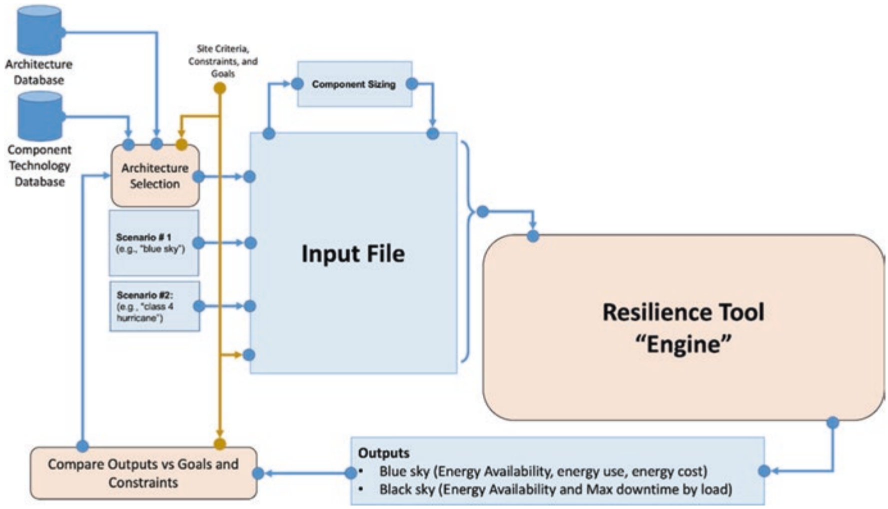


Fig. 8.1 Overall energy and resilience assessment process

usage, and resilience benefits versus relevant design basis threats. This allows them to compare multiple architectures or different configurations of the same architecture (e.g., using different types or grades of equipment).

8.2.2 Conceptual Core of the Resilience Tool Engine

In this section, we express the *conceptual core* or the fundamental design of the resilience tool engine. We would succinctly define the resilience tool engine as:

> A tool that simulates, as a series of discrete events, the negotiated, conservative flows of energy and matter across and between components in a network under some dispatch strategy subject to unreliability over various scenarios.

Let's unpack this dense, compact, statement with a focus on the key *concepts* mentioned:

- *Simulates, as a series of discrete events*: Simulation is seen as a series of discrete events. Specifically, model state (here, the state of flow) *only* changes during events. Discrete events allow us to accommodate the large gaps in time between infrequent events such as component failures and threat scenario activations. During hour-by-hour simulation of load profiles, the simulation will typically jump from hour to hour.
- *Negotiated, conservative flows of energy and matter across and between components in a network*: Although the tool has been created with the idea of modeling district systems, actually, any flow could potentially be modeled. A flow itself is of a given type (e.g., hot water, high-voltage electricity, chilled water, potable

water, etc.) and flows of different types do not directly interact except through explicit conversion components. A flow also has a rate that is expressed as energy, volume, or mass flow per unit of time. As a fundamental rule, the network never provides more flow than is requested but may provide less. Furthermore, any component in the network assumes it will get the flow it asks for unless it hears otherwise. Flows never change direction. Therefore, the minimum flow into any inflow port is 0. Physical flows that may be bidirectional can be accommodated by modeling a flow in each direction. Components are built from elemental machines such as sources, sinks, converters, connectors, storage units, routers (splitters and mixers), and on/off switches (providing on/off behavior). A collection of multiple elemental machines together with their controls can be used to represent the behavior of a real-world component. A network includes the ideas of topology or what is connected to what. It also implies the notion of reachability and what is "on" (or "in") the network and what is not.
- *Dispatch strategy*: Dispatch is the notion of controlling how much, when, and from where in the network energy and/or matter will flow. This initial version of the tool uses a simple priority list strategy for dispatch, but more sophisticated algorithms will be added later as needed.
- *Subject to unreliability*: Unreliability is modeled as being either time-based or scenario-intensity-based. Both forms of reliability involve toggling a component between operational and failed states. Under time-based reliability, when operational, an unreliable component will schedule itself to fail after a given amount of calendar time. When failed, the time-based reliability component will schedule itself for repair, which will take some amount of time determined by the underlying data model. In the case of scenario-intensity-based unreliability, at the start of a scenario, fragility curves are used to map scenario intensity to a chance of failure. If an intensity-based unreliable component fails, it is assumed to be unavailable for the duration of the scenario. If it survives, it is assumed to be available for the duration of the scenario. A future version is planned to include repair for scenario-intensity-based unreliability.
- *Over various scenarios*: A scenario is either active or inactive. Multiple scenarios can exist and are independent of each other; scenarios can even overlap in time since statistics are only aggregated per scenario (i.e., scenarios that overlap do not "see" each other; only one scenario is simulated at a time). A scenario changes the intensity of various damage attributes (things like wind speed, inundation flood level, etc.). As such, unreliable equipment susceptible to the given scenario's intensity metric (e.g., aboveground power lines subject to high winds) may experience failure.

The process begins with the user's description of goals, site constraints, and available resources as shown under "Site Criteria, Constraints, and Goals" label in Fig. 8.1. These criteria can be used to assist the user in the selection (filtering out irrelevant choices and/or recommending especially relevant choices) and evaluation (tracking status of a design versus goals and/or constraints). Chapter 3 of this planning guide discusses constraints, requirements, and goals for energy master planning.

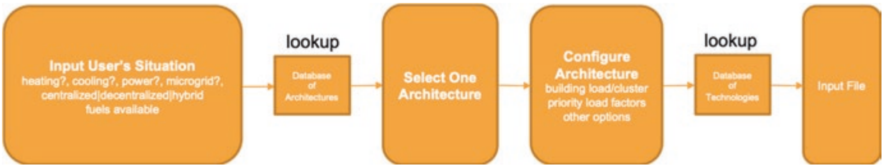


Fig. 8.2 Architecture selection process

Next, the planner can proceed to architecture selection from a database of architectures (see Appendix E). This selection can be guided based on site criteria. For example, if the user specifies that they have electrical and heating loads only (i.e., no cooling load), only those architectures with heating and electrical supply will be made available to browse from. An *architecture* is a pre-constructed template for how certain types of technologies are typically connected together. The architecture, once selected, must also be configured to match the user's unique situation. Figure 8.2 outlines the process of assisting the user in selecting and configuring an architecture and creating an input file. Configuration involves adjusting the selected architecture to better represent the desired situation by choosing specific equipment, specifying multiples, etc. Potential component technologies that fit with the architecture are looked up in a database of technologies. This results in the creation of an input file to be used by the resilience tool "engine."

Additional data needs include building load profiles for *blue sky* scenarios as well as *black sky* scenarios, along with the scenario descriptions themselves. Both *blue sky* and *black sky* are categories of scenarios. A *blue sky* scenario represents normal operating assumptions. In contrast, a *black sky* scenario involves consideration of design basis threats. Load profiles represent the loads on the network over time for electrical, heating, and/or cooling needs. Load profiles correspond to a given building load or cluster of buildings under a given scenario.

Scenarios were introduced in Sect. 5.3.2.2, "Blue sky and emergency energy demands." Scenarios have an occurrence distribution, a duration, an optional maximum number of occurrences during the simulation, and optionally, various design basis threat intensities. Design basis threat intensities specify things like the wind speed during a hurricane, the inundation depth during a flood, and the Richter scale during an earthquake. A scenario can also specify whether normal reliability (failure and repair under typical conditions) should or should not be considered. Probability of occurrence can be based on actual data for an event. For example, Fig. 8.3 shows the likelihood for a hurricane to manifest in the Atlantic over certain times of the year.

A component technology database exists that stores information about actual components that can be used by the tool (see Sect. 7.8, "Technologies Database," and Appendix F, "Technologies Database"). Components represent equipment on the network: chillers, boilers, backup generators, UPS systems, TES tanks, fuel drums, etc. If the user has specific information about a given component, they can specify it. Otherwise, the information can be queried from the component technology database.

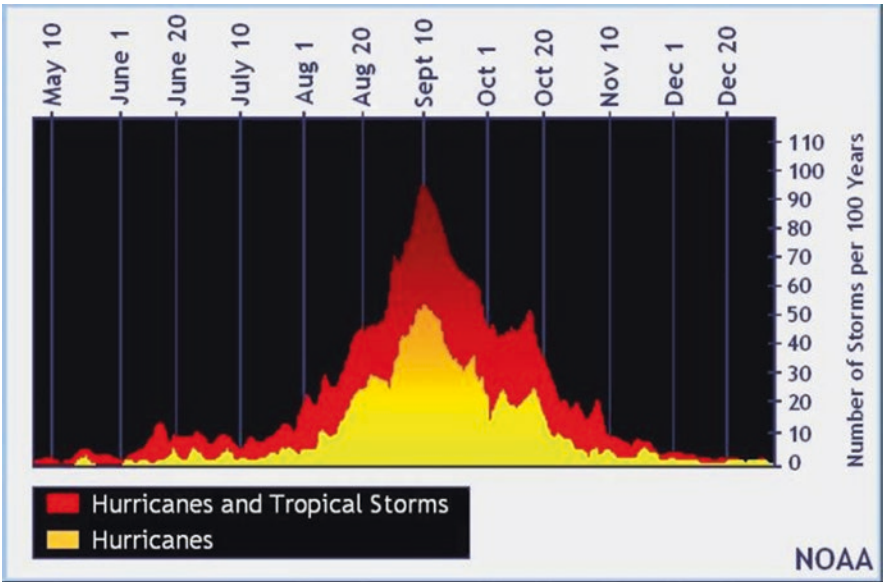


Fig. 8.3 Number of storms in the past 100 years during Atlantic hurricane season

The information required for each component falls into the following categories: energy performance, economics, resiliency, and reliability. Energy performance parameters include things like efficiency of a generator, COP of a chiller, capacity of a battery, leakage rate of a TES system, etc. Economics include items such as purchase and installation cost, operational costs, maintenance/repair costs, and fuel costs. Fragility information is captured in terms of *fragility curves*, which specify the probability of failure as a function of a design basis threat intensity metric that may be present during a scenario. Figure 8.4 shows an example fragility curve. A component can specify zero or more fragility curves. Fragility curves were presented in Sect. 5.2.2.4, "Threat severity." (See Fig. 5.11). The fragility curve shown in Fig. 8.4 is piecewise linear, but actual curves need not be so. As shown, for values below a given intensity of a damage metric, the component is "indestructible." For values above a given intensity of a damage metric, the component will face certain destruction. Between those two values, a percentage chance of failure is specified. The piecewise linear form of the fragility curve is useful when only the (approximate) values of the "impervious" and "certain" destruction points are known.

Finally, reliability information is contained in cumulative distribution curves representing time to failure and time to repair.

Optionally, a user may desire to do a sizing study to evaluate the trade-offs between several combinations of potential component sizes as shown in the top right of Fig. 8.1. External tools such as the *NZI-Opt* module of SMPL (Swanson et al. 2014) or *REopt* (Anderson et al. 2017) can be used to determine the most economical size of a component mix. It is also possible to conduct several runs with the

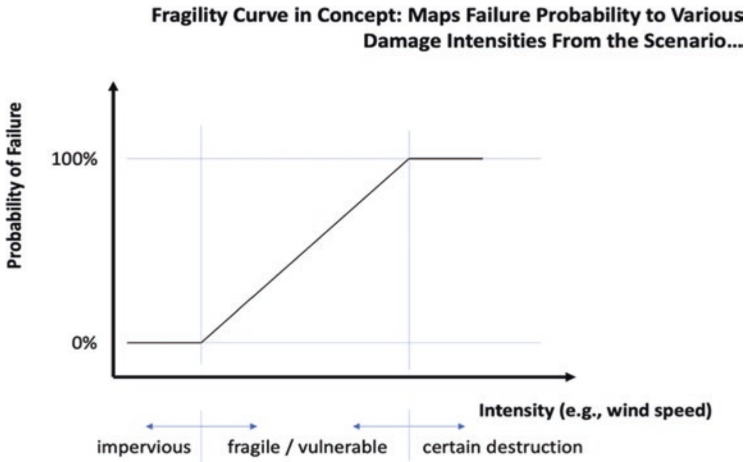


Fig. 8.4 Example fragility curve using impervious and certain destruction information

resilience tool "engine" to evaluate various combinations of component sizes and selections.[1]

Once the architecture selection, configuration, and any sizing have been conducted, an input file can be written for the resilience tool "engine." The input file is parsed by the resilience tool "engine," and a simulation is initiated.

During network simulation, operational components process load requests as best they can. Power is routed according to the dispatch algorithm of the network. At the end of each scenario's simulation, statistics are calculated related to requested load, achieved load, energy availability, and maximum downtime.

When the entire simulation of all scenarios is completed, energy robustness, energy recovery, energy availability, energy use, and energy cost for different loads during different design basis threats can be calculated. Energy system recovery time is represented by *maximum downtime* in the tool. These metrics can be compared to goals to identify gaps or progress towards a target (see bottom and bottom-left of Fig. 8.1). If sufficient progress has not been made, information from the last run can be used to enhance a subsequent architecture selection and configuration, and the process can continue.

A key concept used in the resilience tool engine is that it simulates a scenario zero, one, or possibly many times depending on the scenario's probability of occurrence and occurrence limit.[2] The calculation tool typically simulates over large time horizons to allow scenarios to occur multiple times. When a time horizon of, say,

[1] If this route is pursued, "sizing" scenarios akin to design days can be used for equipment size selection. Multiple combinations of sizes may result, but each would have different cost and performance implications.

[2] We found it convenient to add a limit to the maximum number of times a scenario can occur. By default, there is no limit on the number of times a scenario can occur.

1000 years is chosen, we are *not* forecasting 1000 years into the future. Instead, we are simulating the case year 1000 times to get a statistical feel of how likely rare events are to disrupt operations.

8.3 Inputs and Outputs of the Resilience Tool Engine

In this section, we will discuss the resilience tool engine's inputs and outputs.

8.3.1 Calculation Tool Input File Format

The resilience tool engine uses an input file format written in the TOML (Tom's Obvious, Minimal Language) language (Preston-Werner 2018). The file is a plain-text format. TOML was chosen for its readability and data structures and for the presence of high-quality open-source libraries for parsing. For details in understanding the TOML format, the interested reader is referred to the official website (Preston-Werner 2018).

The file consists of the following sections:

- Simulation information
- Loads (load profiles)
- Components
- Distributions
- Fragility curves
- Networks
- Scenarios

Details of the input file format can be found in the User Guide within Appendix G.

8.3.2 Tool Outputs

The outputs from the tool and process are (by scenario):

- Resilience metrics (see Sect. 5.2 "Quantifying energy system resilience" and 5.2.2 "Energy availability")
  - Energy availability (%) = $\frac{U}{U+D} \times 100\%$ where U is uptime and D downtime
  - Max downtime (hours) = maximum downtime experienced over a scenario
- Costs
  - Upfront (installation)
  - Annual O&M

- Energy/fuel usage
  - Energy usage by stream

See Appendix G for further detail on outputs from the resilience tool engine specifically. Note that energy robustness (ER) can be calculated from energy usage statistics *load not served* and *energy used*, which the tool produces. Recall from Chap. 5:

$$ER_{baseline} = \frac{E_{event}}{E_{baseline}}$$

where:

- E_{event} = energy used
- $E_{baseline}$ = energy used + load not served

8.4 Relation with Other Tools

The resilience tool engine and greater process are designed to allow for the assessment of a given network configuration with explicitly defined components and an explicit dispatch methodology. The ultimate audience for the tool and process will be master planners and energy managers. As such, we are trying to achieve a level of detail (fidelity) that the target audience finds approachable and that also incorporates more depth and nuance than higher-level (i.e., less detailed) campus-level tools.

This section mentions other tools in passing, makes some qualitative statements about how this current effort differs from these tools, and also mentions where those tools could be used in the current process when applicable.

8.4.1 Microgrid Design Tool (MDT) and Performance and Reliability Module (PRM)

The MDT is a tool developed by Sandia National Laboratory as a decision-support tool for microgrid designers in the early stages of the design process (Eddy et al. 2017; Stamp et al. 2015). The MDT incorporates a microgrid PRM, which is used to "statistically quantify the performance and reliability of a microgrid operating in islanded mode." The MDT and PRM have been an inspiration to our solution. However, the MDT is thought to be too detailed for energy planners and master planners to use directly. It requires inputs and knowledge of components that master planners and energy managers do not typically know or possess. Also, as the name implies, MDT is focused mainly on microgrids; in contrast, this process also focuses on the cost, resilience, and energy use of other networks. MDT is capable of doing more sophisticated analysis than that of the resilience tool engine. For example, MDT contains control algorithms to simulate microgrid startup. This extra functionality, however, comes at the cost of added data requirements and complexity; we believe this is out of scope for what most planners and energy managers have available to them.

8.4.2 Energy Resilience Analysis (ERA) Tool

The ERA tool is used to "analyze energy resilience against the cost of possible energy architectures for military installations" (Millar 2019). The program uses a Monte Carlo simulation to run tests of each energy architecture, building a performance and cost model of the most common outcomes. These models reflect the likelihood of the architecture operating as it should, as well as the most common causes of power outages and service interruptions.

The ERA tool is thus similar in objective and scope to what we are building. The resilience tool engine builds upon the thinking of the ERA tool by adding spatial and topological information to the network used in the analysis and brings the analysis to a building-by-building level, rather than just at the installation level. Our understanding is that the ERA tool includes reliability statistics but has only a limited concept of design basis threat events.

8.4.3 REopt and REopt Lite

REopt is summarized as follows (Anderson et al. 2017):

> REopt is a techno-economic decision-support model used to optimize energy systems for buildings, campuses, communities, and microgrids. The primary application of the model is for optimizing the integration and operation of behind-the-meter energy assets. Formulated as a mixed-integer linear program, REOpt solves a deterministic optimization problem to determine the optimal selection, sizing, and dispatch strategy of technologies chosen from a candidate pool such that electrical and thermal loads are met at every time step at the minimum LCC. The candidate pool of technologies typically includes photovoltaics, wind power, solar water heating, solar ventilation air preheating, ground source heat pumps, biomass, waste-to-energy, landfill gas, diesel and natural gas generators and combustion turbines, energy storage, dispatchable loads, and the utility grid.

REopt is an excellent tool for first-pass cost, dispatch, and sizing of various component assets. With regard to resilience, however, REopt does not include detailed topology, spatial orientation, reliability statistics, or design basis threat. From the REopt Lite user manual, "REOpt … estimates the amount of time a PV and/or wind and battery system can sustain the site's critical load during a grid outage and allows the user the choice of optimizing for energy resilience" (NREL 2019).

That having been said, tools like REopt and NZI-Opt (discussed next) can be used for economically optimal sizing of components during *blue sky* scenarios.

8.4.4 System Master Planner and NZI-Opt

The SMPL tool provides planners with a modeling, optimization, and decision-support tool that is designed to find the lowest life-cycle cost solution for an installation while meeting energy, water, waste, and low impact development environmental and legislative goals. These goals can range from “business as usual” to net zero and may include critical mission loads, energy savings, water conservation, waste diversion, carbon emission reductions, renewable energy usage, and others. This is accomplished by reducing overall demands in buildings and then assessing possible combinations of supply and distribution infrastructure to meet mission requirements. SMPL includes three relevant modules: building energy loads and efficiency measure simulation using EnergyPlus, supply and distribution modeling using NZI-Opt (described below), and multicriteria decision analysis (see Chap. 9). The energy load module in SMPL can provide load profiles for input into the resilience tool engine (see Table 8.1).

The NZI-Opt module is described as follows (Swanson et al. 2014):

> [NZI-Opt is] a community-scale, mixed- integer linear programming (MILP) based model to assist in the selection of energy supply and distribution equipment and to determine optimal schedules of operation. NZI-Opt is a module of the System Master Planning (SMPL) tool. The model was developed to minimize the total annual equivalent cost of providing thermal and electric power to clusters of buildings by selecting from existing or potential equipment using a fully centralized, fully decentralized, or hybrid approach, while meeting all other required constraints.

Table 8.1 Building energy simulation models by building category and vintage, etc.

Organization (country) and modeling tool	Building categories	Building vintages	References
USDOE Commercial Reference Buildings (USA), EnergyPlus	Large office, medium office, small office, warehouse, standalone, retail, strip mall, primary school, secondary school, supermarket, quick-service restaurant, full-service restaurant, hospital, outpatient health care, small hotel, large hotel, midrise apartment	New construction (comply with ANSI/ ASHRAE/IESNA Standard 90.1-2004), existing buildings constructed after 1980, existing buildings constructed before 1980	Deru et al. (2011) and USDOE (undated)
USDOE/NREL Reference Load Profiles in REopt Lite (USA), EnergyPlus	Representative electrical loads for a subset of the commercial reference buildings are available online via this tool. They are scaled based on actual annual energy consumption	Post-1980	NREL (2019) and Anderson et al. (2021)

(continued)

Table 8.1 (continued)

Organization (country) and modeling tool	Building categories	Building vintages	References
US Army Corps of Engineers, SMPL (EnergyPlus)	Large office, medium office, small office, warehouse, standalone, retail, strip mall, primary school, secondary school, supermarket, quick-service restaurant, full-service restaurant, hospital, outpatient health care, small hotel, large hotel, midrise apartment plus various military building templates	New construction (comply with ANSI/ ASHRAE/IESNA Standard 90.1-2004), existing buildings constructed after 1980, existing buildings constructed before 1980	Case et al. (2014a, b)
University of Applied Sciences, Stuttgart (Germany), SimStadt	Residential (single-family house, terraced house, multi-family house, apartment block), office and administration, education, health care, hotel, retail, restaurant, industry, sports location, non-heated	Before 1859, 1860–1918, 1919–1948, 1949–1957, 1958–1968, 1969–1978, 1979–1983, 1984–1994, 1995–2001, 2002–2013, after 2014	Nouvel et al. (2015) and Weiler et al. (2019)
EMD International A/S, EnergyPro	Single-family houses, multi-family houses, industry		https://www.emd.dk/energypro/ Primarily based on www.tib.eu, Schlussbericht-zum-Vorhaben-Erstellung-neuer--Referenzlastprofile
CSIRO (Australia), house energy rating tool—AccuRate	Model a house to a fine level of detail, calculate temperatures and heating and cooling energy requirements on an hourly basis, and assess a house's energy efficiency in any 1 of 69 different climatic zones in Australia		www.csiro.au/en/Research/EF/Areas/Grids-and-storage/Intelligent-systems/AccuRate www.energyinspection.com.au/products/accurate/

NZI-Opt performs many functions and calculations to address our needs but does not have a resilience capability. In its capability to select and size equipment, it is similar in nature to REopt.

8.4.5 Unique Contributions

This resilience tool engine has the following key attributes, which in the aggregate we claim to be unique:

- It incorporates topology.
- It incorporates multiple networks—i.e., it is not *just* electricity.
- It works at both the building-by-building level and loads in aggregate.
- It is part of a larger energy and resiliency master planning process.
- Since resilience is more detailed than just "survival time when electrical grid is down," it:
  - Incorporates the concept of a *design basis threat* and mission-critical loads and profiles
  - Is able to analyze losses across multiple energy and material supply streams (natural gas, electrical, trucked-in diesel fuel, potable water and sewage if desired, etc.).
- It calculates energy use and resilience of a given topology.

8.5 Interactions with Other Tools

The process and tools outlined here require coordination with other tools to provide input data.

In particular, load profiles are required for each load on the network. Load profiles are time-series data of load versus time for electrical, thermal, or cooling. They can correspond to either a single building or a "cluster" of multiple buildings. The question of load profile granularity (i.e., single building versus aggregate cluster of buildings) depends entirely on how the analyst wishes to draw their system boundaries. Additionally, load profiles can also represent any asset that presents a load on the network. For example, if you have something like a pumping station, you can specify its load profile, which does not have to be comprised of buildings or clusters of buildings since load profiles are "by scenario."

Figure 8.5 shows the electrical load of a "typical" medium office building ("REopt Lite" [NREL 2019]).

Load profiles represent an area of decoupling between the calculation tool and other tools. For example, an hourly (or sub-hourly) building energy simulation can provide these typical load profiles for buildings. The accuracy of these simulations is not for building design and system optimization, but rather for planning. As such, it is perfectly valid to use models for building archetypes of an appropriate vintage (era of the energy code) and to apply the per area results to the building area of the building of interest.

Table 8.1 gives a partial listing of models available for common building types. These models can be used to generate the load profiles required by the energy and resilience assessment tool. Figure 8.6 shows an example load profile input format in

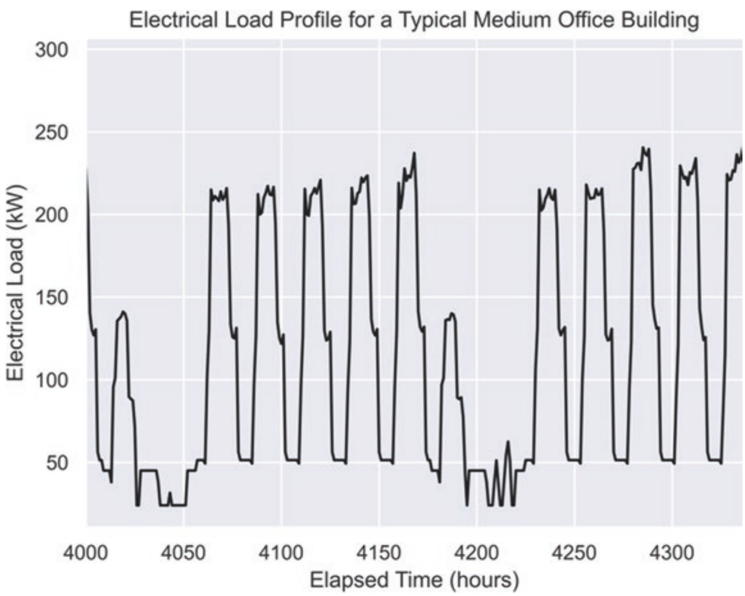
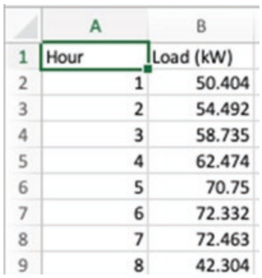


Fig. 8.5 Load profile for a typical medium office building in Palmdale, CA

Fig. 8.6 Snippet of a load profile comma-separated value file



	A	B
1	Hour	Load (kW)
2	1	50.404
3	2	54.492
4	3	58.735
5	4	62.474
6	5	70.75
7	6	72.332
8	7	72.463
9	8	42.304

which a column of time (elapsed time) and a column of load (units of power) are specified. The load can be electrical, thermal, cooling, etc.

Load profiles have the following constraints:

- They must be in comma-separated value (*.csv) format (see Shafranovich 2005). This typically is available directly from the modeling software or via Microsoft Excel® "save as."
- Format must include an elapsed time column and a load (power) column.

8.6 Example Analysis Using Resilience Tool Engine

In this section, we show a basic example using the architecture given in Sect. 7.7.7.1 "University of British Columbia." Architecture templates were introduced in Sect. 7.7 "Energy system architectures" and specifically Sect. 7.7.1 "Architecture templates." Also, see Appendix E. Figure 7.14 shows this architecture, which we will work with. It depicts a building cluster being supplied with electricity, steam, and heating. The system has both a biomass and natural gas boiler, as well as a CHP system. Let's simulate this using the resilience tool engine under a blue sky scenario and under a class 4 hurricane design basis threat (i.e., black sky) scenario. In the depiction, we have two building clusters: mission-critical buildings and other buildings. We desire to see how resilient our building energy supply will be to a class 4 hurricane scenario—with special focus on our mission-critical building cluster.

The blue sky scenario will be 1 year in duration, occur only once, have no damage intensities, and have normal loads. The class 4 hurricane scenario will be simulated with a fixed occurrence of 30 years and will have wind speed intensities of 156 mph (251 km/h) and inundation depth of 8 ft (2.44 m). The duration of the class 4 hurricane scenario is 2 weeks.

Figure 8.7 shows the input file used to describe this architecture

The energy resilience simulation tool is capable of generating a topology graph to check the network connections specified. Figure 8.8 shows the topology map. With this, we can compare the topology of the architecture with Fig. 7.14 to find any discrepancies.

Fig. 8.7 Input file that describes the basic architecture

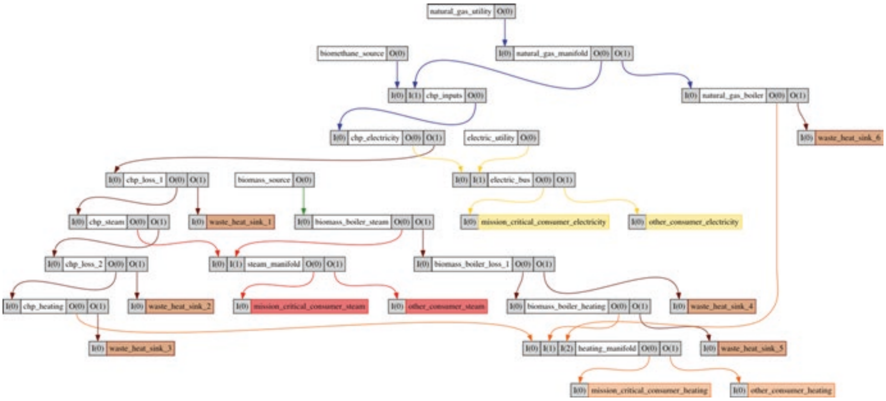


Fig. 8.8 Topology of the network

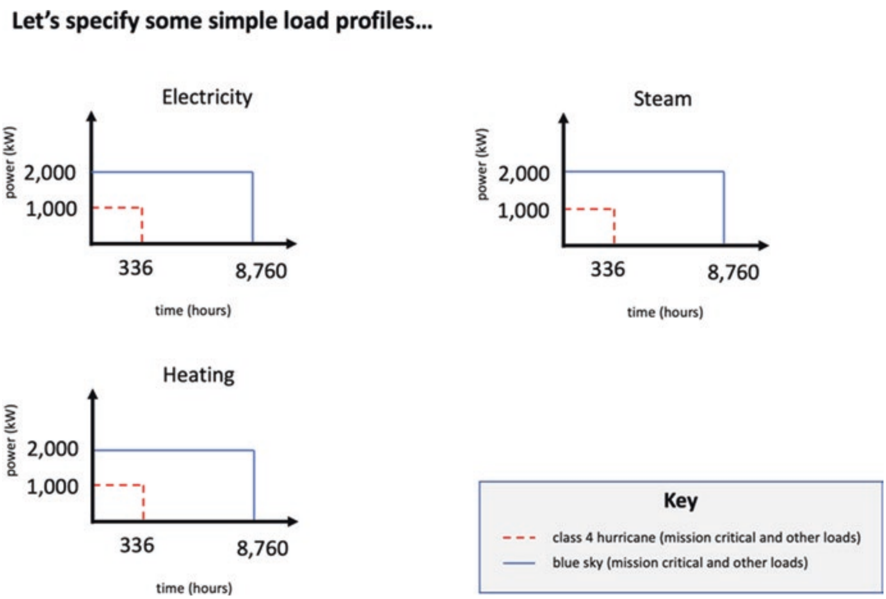


Fig. 8.9 Example load profiles

The load profiles used for the example are given in Fig. 8.9. These simplistic geometrical patterns are great for debugging and understanding what the tool is doing. These profiles, which could be obtained from a building energy simulation engine, could be much more complex. Here, it is important to see that each load has a load profile for each scenario.

The energy resilience simulation tool generates two main outputs:

- A listing of all significant events and the state of flow through the network
- A statistical summary of the energy through the network

Figure 8.10 shows these output files for this example.

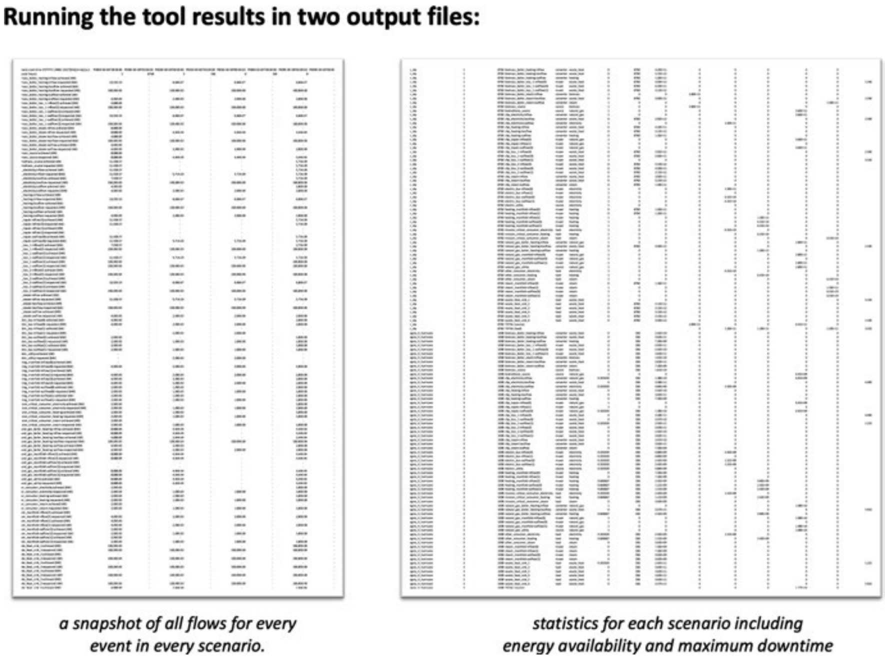
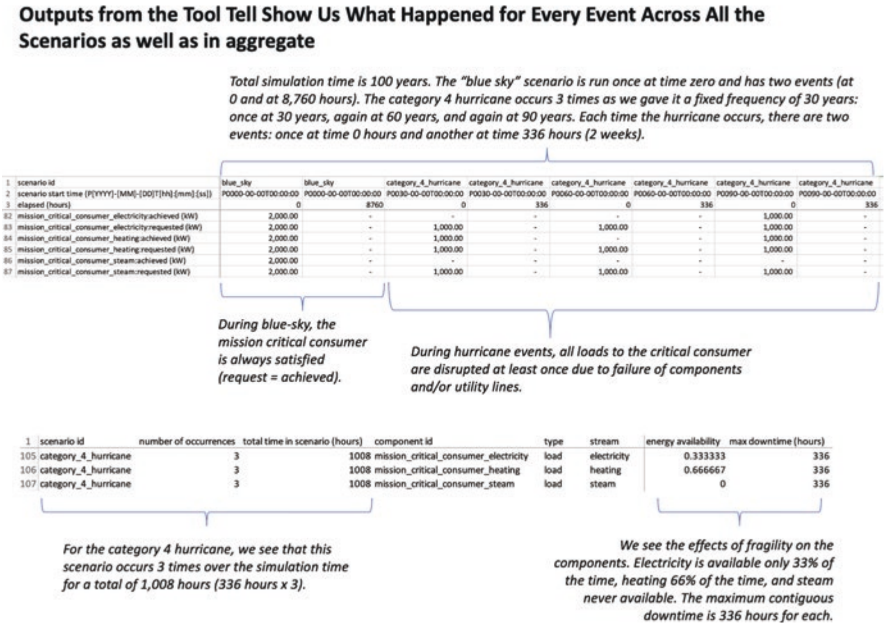


Fig. 8.10 Outputs from the simulation

Figure 8.11 gives a detailed look at the output files. The top part of the figure shows the relevant part of the event-based view. The lower part of the figure shows the statistical summary.

Starting with the top part of Fig. 8.11, we recall that the total simulation time is 100 years. The second row lists the scenario start time using International Organization for Standardization (ISO) 8601 duration format. For example, 30 years from now is expressed as "P0030-00-00T00:00:00." The "blue sky" scenario is run once at time zero and only has two events (at 0 and at 8760 h) due to the simplicity of the network and load profiles. The category 4 hurricane occurs three times as we gave it a fixed frequency of 30 years: once at 30 years, again at 60 years, and again at 90 years. Each time the hurricane occurs, there are two events: once at time 0 h from scenario start and another at time 336 h from scenario start (2 weeks into the scenario). During blue sky conditions, the mission-critical consumer is always satisfied (requested power equals achieved power). However, during hurricane events, all loads to the critical consumer are disrupted at least once due to failure of components and/or utility lines. The lower part of Fig. 8.11, which shows the class 4 hurricane part of the statistical summary, indicates that the class 4 hurricane scenario occurs three times over the simulation time for a total of 1008 h (336 h × 3). We can also see the effects of fragility on the components. During a class 4 hurricane



1	scenario id	blue_sky	blue_sky	category_4_hurricane	category_4_hurricane	category_4_hurricane	category_4_hurricane	category_4_hurricane	category_4_hurricane
2	scenario start time (P[YYYY]-[MM]-[DD]T[hh]:[mm]:[ss])	P0000-00-00T00:00:00	P0000-00-00T00:00:00	P0030-00-00T00:00:00	P0030-00-00T00:00:00	P0060-00-00T00:00:00	P0060-00-00T00:00:00	P0090-00-00T00:00:00	P0090-00-00T00:00:00
3	elapsed (hours)	0	8760	0	336	0	336	0	336
82	mission_critical_consumer_electricity:achieved (kW)	2,000.00	-	-	-	-	-	1,000.00	-
83	mission_critical_consumer_electricity:requested (kW)	2,000.00	-	1,000.00	-	1,000.00	-	1,000.00	-
84	mission_critical_consumer_heating:achieved (kW)	2,000.00	-	1,000.00	-	-	-	1,000.00	-
85	mission_critical_consumer_heating:requested (kW)	2,000.00	-	1,000.00	-	1,000.00	-	1,000.00	-
86	mission_critical_consumer_steam:achieved (kW)	2,000.00	-	-	-	-	-	-	-
87	mission_critical_consumer_steam:requested (kW)	2,000.00	-	1,000.00	-	1,000.00	-	1,000.00	-

1	scenario id	number of occurrences	total time in scenario (hours)	component id	type	stream	energy availability	max downtime (hours)
105	category_4_hurricane	3	1008	mission_critical_consumer_electricity	load	electricity	0.333333	336
106	category_4_hurricane	3	1008	mission_critical_consumer_heating	load	heating	0.666667	336
107	category_4_hurricane	3	1008	mission_critical_consumer_steam	load	steam	0	336

Fig. 8.11 Example outputs from the resilience tool engine

scenario, electricity is available only 33% of the time, heating is available only 66% of the time, and steam is never available. The maximum contiguous downtime is 336 h for each—that is, when disruption occurs, it happens for the entire duration of the scenario. These metrics could be used to compare this design to other competing designs.

8.7 Integration of ERIN with the Simple Master Planner (SMPL) Tool

Although the energy resilience simulation tool, ERIN, is valuable in and of itself for assessment of arbitrary energy networks for their energy resilience, it is meant to be used in conjunction with other tools and processes. As briefly discussed before in this chapter, the US Army Engineer Research and Development Center-Construction Engineering Research Laboratory (ERDC-CERL) has developed a web-based application called the SMPL tool. Created for energy managers, master planners, and policy makers, SMPL provides a graphical interface that allows users to evaluate energy, water, waste, and stormwater scenarios for military installations, districts, and campuses. A collaborative effort between ERDC-CERL and Big Ladder Software LLC is currently redesigning and enhancing the tool to support analysis of resiliency scenarios. As part of that project, the new resilience capabilities developed as part of the IEA Annex 73 effort have been integrated into SMPL. The updated SMPL tool (version 2) will be made available inside the US Department of Defense to government users and outside of DoD to the private sector as a commercial product offered by Big Ladder under another name. This integration of ERIN with SMPL serves as an example of how ERIN can be integrated with other energy planning tools.

The previous chapter of the Guide present results of the Annex 73, which include energy goals and constraints; requirements related to energy system resilience; a database of generation, distribution, and energy storage technologies and a comprehensive listing of various system architectures; and finally, a simulation capability for assessing district system energy resilience. This last capability, which is explained in greater detail in Appendix H, is the focus of this current chapter. These products have been integrated behind a new user interface and data presentation as part of the SMPL tool. The redesign of the SMPL user interface includes graphical user interface (GUI) elements for the new resiliency and network capabilities developed herein.

The component "database" developed herein is a dataset that is meant to be used directly by people and perused using MS Excel®. These data have been used as the starting point to populate ERIN components used in this example. For example, probability distributions for MTBF and MTTR, as well as the first cost and operating and maintenance costs, have been extracted from tables in the appendices of this guide to populate the SMPL database. When ERIN components are created in SMPL, these data are used to create the components. Figure 8.12 shows how the current effort's work maps into the integration work to add resiliency to SMPL. When

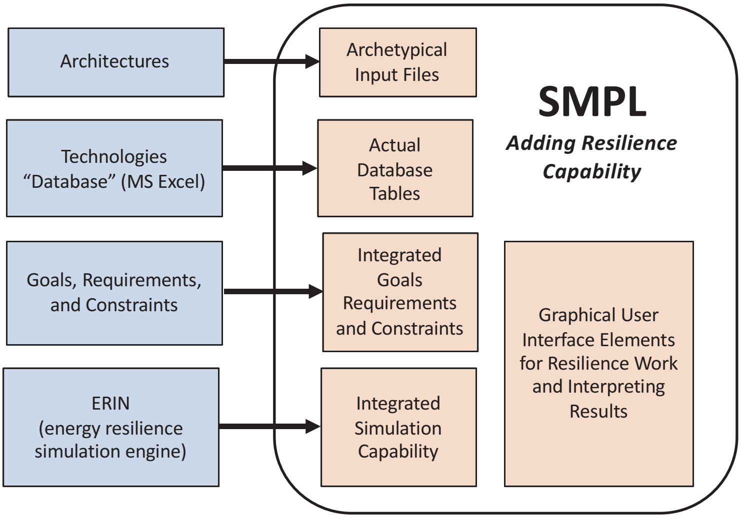


Fig. 8.12 Integration of IEA Annex 73/EW18-5281 technology into the SMPL tool. Currently, the ERIN engine and parts of the technologies database have been integrated into SMPL. Architectures, goals, requirements, and constraints require future work

ERIN is integrated fully into SMPL version 2, energy resilience planners will have access to a fully featured planning suite that can develop and present baselines, base cases, and resilience alternatives to support decision-makers. SMPL's multicriteria decision analysis, planning level cost estimates, energy efficiency measure evaluation, and installation-scale equipment optimization will be enhanced by ERIN's ability to calculate resilience metrics discussed in this chapter. To date, the technologies database and ERIN engine have been integrated with SMPL version 2.

The following is a brief tour of the use of SMPL's user interface to develop, run, and analyze ERIN resilience models. For this example, we present a fictitious community called Fort Illinois, which has a coal-fired CHP plant as well as a connection to the electrical power grid. It is worth noting that Fort Illinois is loosely based on the University of Illinois campus at Urbana-Champaign, with energy also supplied by photovoltaics, wind power, and natural gas. However, this example is simplified to illustrate model development and interpretation.

Figure 8.13 illustrates a schematic of the system that will be modeled. Figure 8.14 shows an overview of this system as modeled in SMPL. Highlights include the CHP plant; commercial grid; color-coded connections for electricity, steam, and diesel fuel; electrical and steam loads; and a diesel-fired backup generator on one of the loads. On the right, the CHP model tree is expanded, showing components that the observant reader will note correspond to ERIN components discussed earlier in this chapter. Using this model, SMPL is able to create TOML and load input files, run ERIN, and import results back into the interface for display.

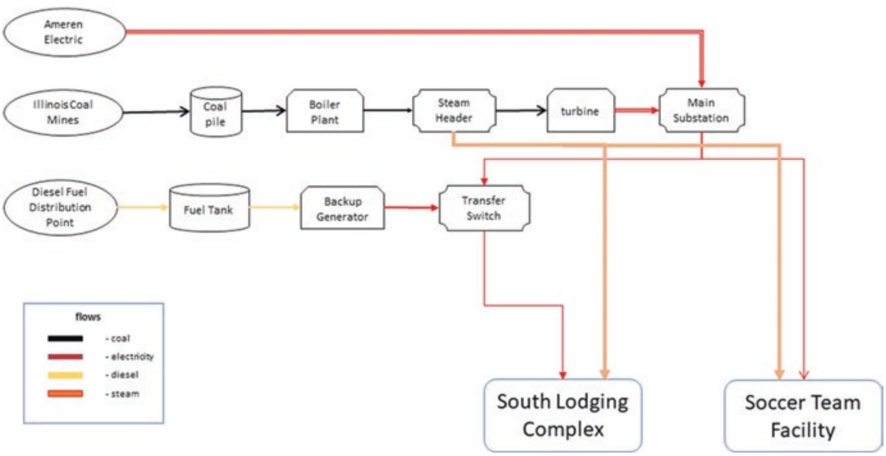


Fig. 8.13 Schematic of a system to be modeled in the ERIN/SMPL integrated tool. Notice that the CHP plant generates both electricity and steam, with additional electricity coming from the commercial grid. The Soccer Team Facility represents a typical energy load with no backup, while the South Lodging Complex represents a "critical" load and thus has a backup generator. Note that there is no backup for the steam beyond redundancy within the boiler plant

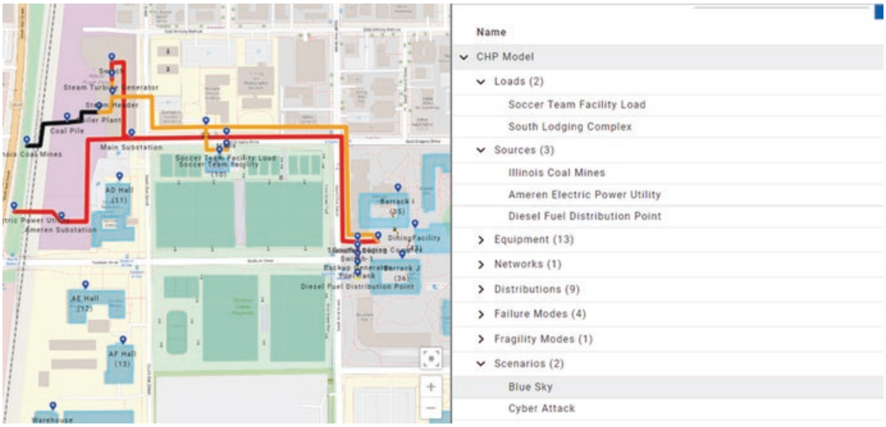


Fig. 8.14 The above figure shows the system as modeled in the integrated SMPL/ERIN system. ERIN components and buildings are represented by blue icons. Utilities such as the CHP plant and commercial grid are on the left of the map, the Soccer Team Facility is at the center, and the South Lodging complex is to the right. The right-hand pane shows a tree of the components of the ERIN model

8.7.1 Development of Load Profiles

Currently, users of SMPL determine the buildings in a community of interest that should be included in a portfolio. After going through a process to calibrate EnergyPlus building models with available data, the user applies packages of energy conservation measures (ECMs) from a database and assesses the results for impact and cost-effectiveness. To integrate ERIN into SMPL, a capability was added to choose buildings from a map to be included for resilience analysis and hence to include their load profiles (i.e., as a *.csv file and reference in the TOML file). Users may also create clusters of buildings graphically and generate aggregated load profiles for use in ERIN. Typically, mission-critical buildings are included individually, while lower-priority buildings are aggregated to simplify the analysis and improve execution speed. Figure 8.15 illustrates two ERIN load components that have been created using the SMPL graphical user interface (GUI). The Soccer Team Facility Load has been associated with the SMPL energy simulation for Building 10. Note that electricity (red) and steam (orange) flows are being provided to the load.

When ERIN requests a load profile, the corresponding EnergyPlus run is retrieved from the database and formatted as an ERIN load profile input file. In contrast, the South Lodging Complex Load has been associated with three buildings, Barracks I (35), J (36), and a Dining Facility (43). The load profile for this complex, in turn, consists of the electric and steam loads, aggregated by type of flow. For example, the electric loads for hour 5 of the Load consist of the sum of buildings 35, 36, and

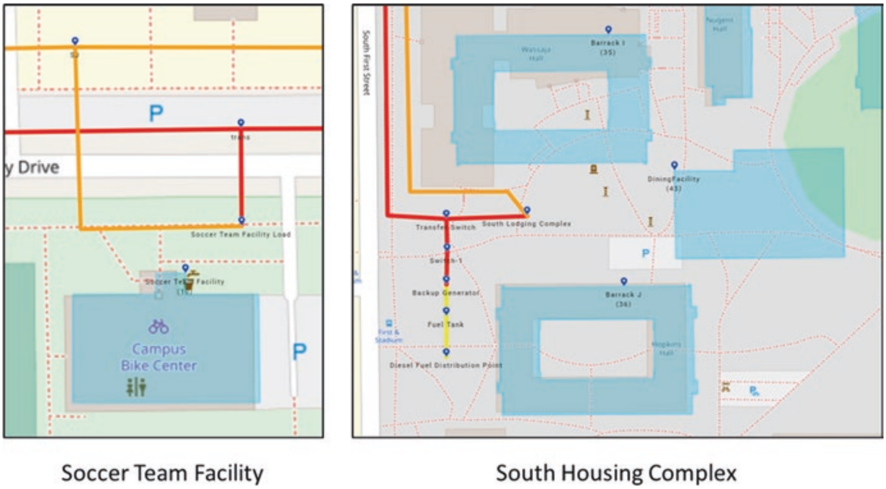


Fig. 8.15 Energy loads in ERIN are modeled by load components. SMPL enables creation of load components and association of SMPL building energy models with those components. When an ERIN simulation is run, SMPL creates energy load profiles for ERIN. If multiple buildings are associated with a load, then SMPL will aggregate the loads prior to creating the load files

43 electric loads for hour 5. The ability to aggregate loads allows the modeler to control the complexity of the model, focusing on important loads while still modeling large campus loads.

The GUI also allows the user to upload custom load files, such as industrial loads not captured by EnergyPlus. In addition, the user can specify alternative loads by scenario. For example, some buildings might be able to operate at reduced loads in an emergency situation. The user could upload a custom file or specify that the building would operate at some specified percentage of the full load, either less or more than 100%. SMPL also includes background logic to reduce complexity for the user. For instance, the user can lead both a steam and electrical flow to a load. SMPL will then create both electrical and steam load components for the TOML file. Notice also that the South Housing Complex has a backup generator attached.

8.7.2 Creation of Sources and Equipment

The NZI-Opt module of SMPL can configure and size equipment in electrical and thermal generation and distribution networks. It does not, however, geospatially locate them or specify the electrical, thermal, or other flows required by ERIN. Once load profiles have been created as described above, the SMPL user can graphically create and place connections to utilities (e.g., electrical, natural gas), major distribution components (e.g., substations, storage tanks), and energy conversion equipment (e.g., central plant cogeneration engines or turbines, boilers, etc.). Figure 8.16

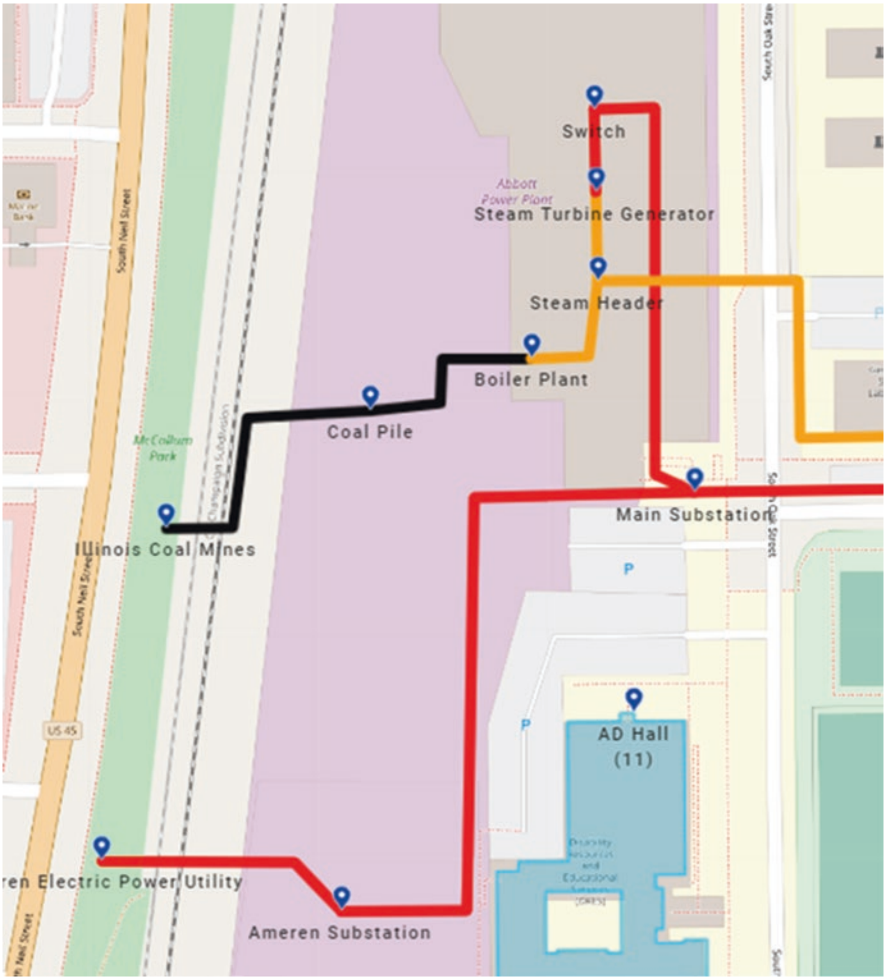


Fig. 8.16 Modeling of ERIN energy supply systems in SMPL

shows a sample model for a combined heat and power plant composed of ERIN components. This diagram illustrates a flow of coal (black line) from local coal mines (an ERIN source) to a coal pile (an ERIN storage component). From the pile, coal flows to a set of boilers (ERIN converter), producing steam (orange lines) at a specified efficiency. Steam then flows to a steam header, with some steam then flowing to a steam turbine electrical generator and the rest available for heating. Following the electrical branch (red lines), electricity flows through a switch. From the switch, electricity flows to the main substation, where electrical flow also comes from the utility substation and commercial grid. The main substation is set up to first pull power from the steam turbine and to make up the difference to meet the required electrical power from the commercial grid through the utility substation.

8.7.3 Creation of Networks

Notice in Fig. C.6 that the energy flows can also be laid out graphically in the SMPL GUI, with color coding indicating the type of flow. The graphical layout capability is much easier to create and understand in the GUI compared to manually typing into the TOML or to the Excel® spreadsheet interface. Within the model different scenarios can use either the same network of connections or alternative connections can be created to simulate situations such as emergency network configurations. SMPL can also be used to set up backup generator configurations as shown in Fig. 8.17. In this example, the fuel distribution point (ERIN source) represents diesel fuel delivered by truck to a local fuel tank (ERIN storage) collocated with the backup generator (ERIN converter). Electrical power is delivered through a switch (ERIN pass-through) to a transfer switch (ERIN muxer). The transfer switch will request power from the main substation during normal operation. When not available, it will request power from the backup generator

8.7.4 Scenarios and Design Basis Threats

SMPL provides editors to develop *blue sky* and design basis threat-based scenarios. The user sets parameters such as duration, probability of occurrence, and intensities (e.g., inundation depth, maximum wind speed, fire intensity). For reliability, the user can specify failure and repair distributions (e.g., MTBF and MTTR). SMPL has editors that the user can use to specify all of the probability distributions and fragility curves that ERIN supports. MTBF is represented as a cumulative Weibull distribution, while MTTR can be represented as a fixed, Weibull, or normal distribution. In our example, Fig. 8.15 showed blue sky and Cyber Attack scenarios. Both of these scenarios model reliability using MTBF and MTTR on selected equipment. The Cyber Attack simulation adds a fragility mode to the boiler plant, indicating a vulnerability to the degree of cyber sophistication (external cyber expertise would be required to interpret and arrive at this scale) as well as a Cyber Repair cumulative probability distribution. The scenario's Cyber Attack sophistication is included in the scenario definition, as shown in Fig. 8.18.

Figure 8.19 illustrates how a fragility curve is set up in SMPL.

8.7.5 ERIN Simulation

Once the user is satisfied with the configuration of the resilience model in SMPL, the ERIN simulation can be launched from the control panel shown in Fig. 8.20. This control panel displays the status of the simulation, including the creation of input files and completion. It can also be used to cancel a running simulation.

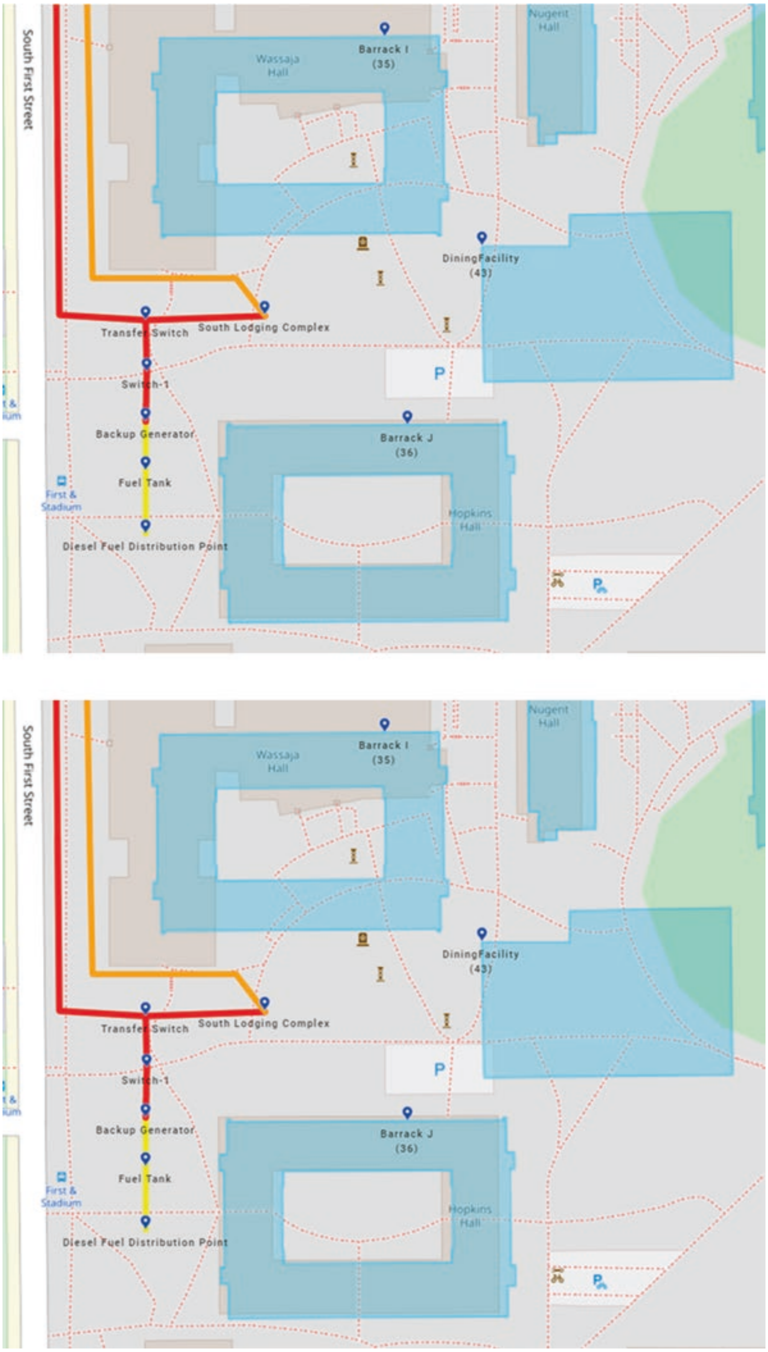


Fig. 8.17 Example representation of system configuration of a backup generator for the South Lodging Complex

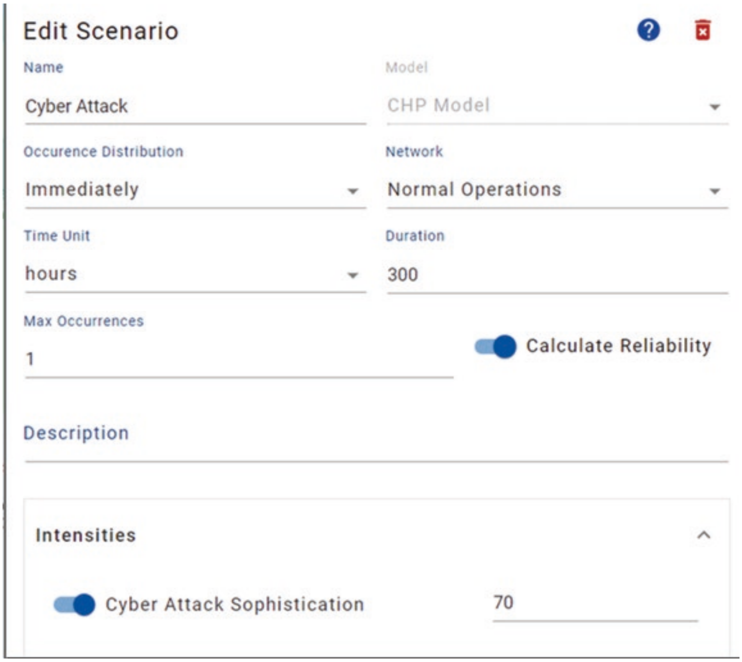


Fig. 8.18 Setting up a Cyber Attack scenario indicating vulnerability to an intensity of cyber sophistication

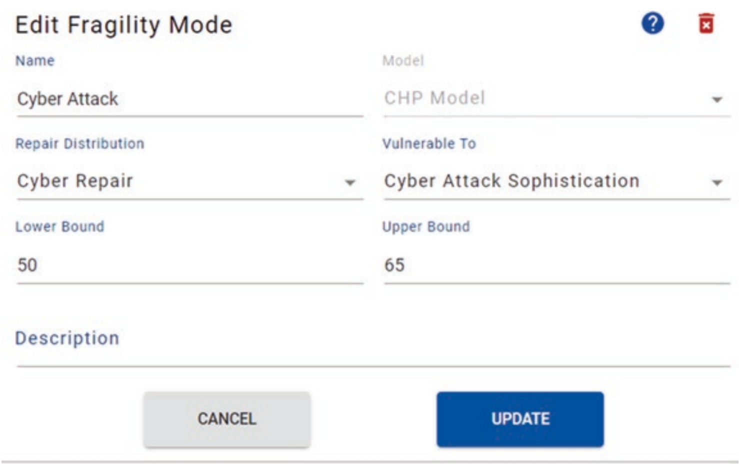


Fig. 8.19 Specifying a fragility curve for a design basis threat. An intensity below 50 will result in no degradation, while an intensity above 65 will result in total failure. This screen also allows the user to include a repair distribution. In this case, the cyber repair uses a normal distribution with a mean value of 76 h with a standard deviation of 10 h (not shown)

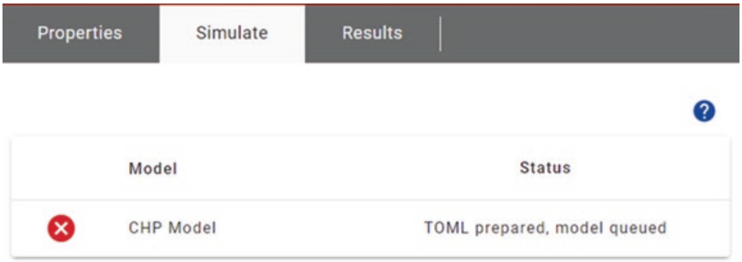
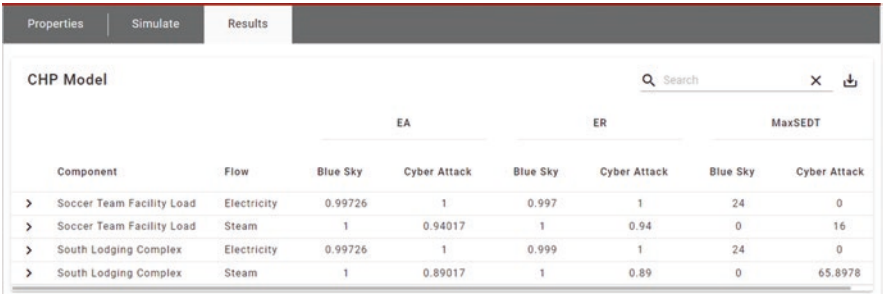


Fig. 8.20 The ERIN simulation control panel in SMPL. This panel allows the user to start and stop the ERIN simulation(s), as well as provide status updates



		EA		ER		MaxSEDT	
Component	Flow	Blue Sky	Cyber Attack	Blue Sky	Cyber Attack	Blue Sky	Cyber Attack
Soccer Team Facility Load	Electricity	0.99726	1	0.997	1	24	0
Soccer Team Facility Load	Steam	1	0.94017	1	0.94	0	16
South Lodging Complex	Electricity	0.99726	1	0.999	1	24	0
South Lodging Complex	Steam	1	0.89017	1	0.89	0	65.8978

Fig. 8.21 Resilience metrics generated by ERIN are displayed in SMPL, organized by model component and scenario. This table displays energy availability (EA), energy robustness (ER), and maximum single event downtime (MaxSEDT)

Behind the scenes, SMPL uses its job server technology to run multiple simulations in parallel, limited only by available computing resources on the ERDC cloud server.

8.7.6 Organization and Presentation of Results

One of the major benefits of the SMPL tool is the organization and display of simulation results. To provide support for decision-making, results are presented as a decision table showing scenarios and metrics. Figure 8.21 shows the two major loads of the example model, with the metrics of EA, ER, and MaxSEDT given for both the Blue Sky and Cyber Attack scenarios. Of note is that the Cyber Attack scenario MaxSEDT for steam of almost 66 h illustrates the vulnerability of the Southern Lodging Complex to a steam outage caused by the attack, even though it has backup generators. This is more than enough time to freeze the building in some locales in the middle of winter. The Soccer facility is also vulnerable but shows a smaller MaxSEDT. This is because downtime is counted as the number of

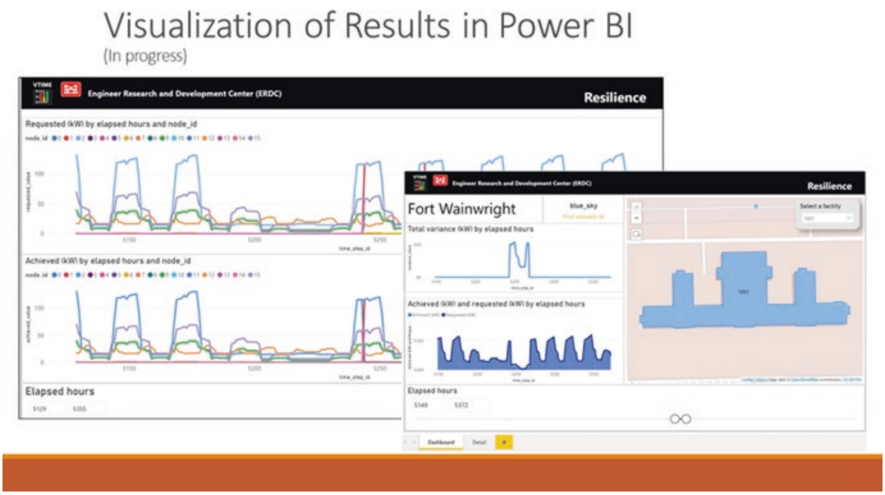


Fig. 8.22 ERIN data saved in the SMPL database can be displayed by third-party business intelligence and analytics applications

continuous hours that the building requested an energy flow and did not receive it. Looking at the energy demand behind the scenes, the building did not request steam after 16 h, so the MaxSEDT counter started over. This metric would still be a red flag for this building and would require further investigation.

Display by Business Intelligence and Analytic Applications SMPL stores results from ERIN in its database, where they are accessible to third-party applications such as Microsoft Power BI or Tableau. Figure 8.22 shows an experimental display of data from a SMPL/ERIN model. With this capability, users are not limited to functionality from SMPL, but can access the underlying data to conduct analysis and create new ways to view and explain data.

8.7.7 Summary and Future Work

Integration of ERIN into SMPL has shown that the basic ERIN functionality is much easier to use and interpret when incorporated into a map-based GUI with a database of components behind it. Qualitatively, building and modifying models are much less time intensive and error prone than when working with the text-based TOML file. The Excel® spreadsheet tool provided with ERIN is quite workable but is still harder to understand the network of connections between components. There are several areas of work to be done to fully realize the potential of the integration, however. Many of the products of Annex 73, such as system architectures, goals, and constraints, remain to be incorporated into SMPL. ERIN also produces a tremendous amount of data, so there is significant potential in using "big data" approaches to post-process the output data and develop visualization methods to more fully understand the impact of threat events. With respect to future work, SMPL and ERIN will be incorporated into ERDC's Virtual Testbed for Installation Management Effectiveness or VTIME effort, and research will continue on methods of energy master planning and resilience analysis. For further information regarding the progress of SMPL and ERIN, contact the guide authors associated with ERDC-CERL.

References

Anderson, Katherine H., Dylan S. Cutler, Daniel R. Olis, Emma M. Elgqvist, Xiangkun Li, Nicholas D. Laws, Nicholas A. DiOrio, and H.A. Walker. 2017. *REopt: A platform for energy system integration and optimization*, Technical report NREL/TP-7A40-70022. Golden: National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy17osti/70022.pdf.

Anderson, Kate, Dan Olis, Bill Becker, et al. 2021. *REopt lite web tool user manual*. Golden: National Renewable Energy Laboratory (NREL). https://reopt.nrel.gov/tool/REopt%20Lite%20Web%20Tool%20User%20Manual.pdf.

Case, M., R. Liesen, A. Zhivov, M. Swanson, B. Barnes, and J. Stinson. 2014a. A computational framework for low-energy community analysis and optimization. *ASHRAE Transactions* 120: 130–144.

Case, Michael, Richard J. Liesen, Alexander Zhivov, Matthew Swanson, Benjamin Barnes, and James Stinson. 2014b. *A computational framework for low energy community analysis and optimization*, NY-14-011, 283. New York: ASHRAE Winter Conference.

Deru, Michael, Kristin Field, Daniel Studer, Kyle Benne, Brent Griffith, Paul Torcellini, Bing Liu, Mark Halverson, Dave Winiarski, Michael Rosenberg, Mehry Yazdanian, and Drury Crawle. 2011. *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock*, Technical Report NREL/TP-5500-46861. National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy11osti/46861.pdf.

Eddy, John, Nadine E. Miner, and Jason Stamp. 2017. Sandia's microgrid design toolkit. *The Electricity Journal* 30 (4): 62–67. https://doi.org/10.1016/j.tej.2017.04.002.

Millar, Madelaine. 2019. *New software helps users build resilient, cost-effective energy architectures*. Lexington: Massachusetts Institute of Technology (MIT) Lincoln Laboratory. https://www.ll.mit.edu/news/new-software-helps-users-build-resilient-cost-effective-energy-architectures.

Nouvel, Romain, K-H. Brassel, M. Bruse, Eric Duminil, Volker Coors, Ursula Eicker, and D. Robinson. 2015. *SIMSTADT, a new workflow-driven urban energy simulation platform for Citygml City Models*. Lausanne: CISBAT 2015 International Scientific Conference.

NREL (National Renewable Energy Laboratory). 2019. *REopt Lite*. Golden: NREL. https://reopt.nrel.gov/tool.

Preston-Werner, Tom. 2018. *Tom's Obvious, Minimal Language V0.5.0*. https://github.com/toml-lang/toml.

Shafranovich, Yakov. 2005. *Common format and MIME type for comma-separated values (CSV) files. RFC 4180. Internet Requests for Comments*. Reston: The Internet Society. http://www.rfc-editor.org/rfc/rfc4180.txt.

Stamp, Jason E., John P. Eddy, Richard P. Jensen, and Karina Munoz-Ramos. 2015. *Microgrid design analysis using technology management optimization and the performance reliability model*, SAND2016-0429. Albuquerque: Sandia National Laboratories. https://doi.org/10.2172/1235988.

Swanson, Matthew, Benjamin Barnes, Richard J. Liesen, Michael Case, and Alexander Zhivov. 2014. Community-scale energy supply and distribution optimization using mixed-integer linear programming. *ASHRAE Transactions* 120 (January): 145–162.

USDOE (U.S. Department of Energy). Undated. *Commercial reference buildings*. Washington, DC: U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/buildings/commercial-reference-buildings.

Weiler, Verena, Jonas Stave, and Ursula Eicker. 2019. Renewable energy generation scenarios using 3D urban modeling tools-methodology for heat pump and co-generation systems with case study application. *Energies* 12 (January). https://doi.org/10.3390/en12030403.

Chapter 9
Multicriteria Analysis of Alternatives and Scenario Selection: Integrating Economic, Energy, and Resiliency Targets

Abstract Analysis of the base case and alternatives produces quantitative results that allow a determination of how close the users were able to come to achieving their goals and objectives, and a comparison of the baseline, base case, and alternatives using defined criteria. There may be additional conflicting qualitative and quantitative criteria (e.g., risk, safety, comfort, fuel availability, etc.) that can support decisions in defining the roadmap to achieving ultimate framing goals. The decision criteria are not usually equally important. To support the installation's decision process, users must elicit relative weights for the different criteria from decision-makers. This is not always an easy process, but it does encourage decision-makers to reflect on how they make their decisions.

Multicriteria Decision Analysis (MCDA) described in this chapter can be used to create weighted decision models and support traceable decision processes that integrate quantitative and qualitative factors. MCDA allows for the selection of a reduced set of good, non-dominating alternatives to be presented to decision-makers for final selection.

Analysis of the base case and alternatives produces quantitative results that allow users to determine how close they were able to come to achieving their goals and objectives and to compare the baseline, base case, and alternatives using defined criteria. There might be additional conflicting qualitative and quantitative criteria (e.g., risk, safety, comfort, fuel availability, etc.) that can support decisions in defining the roadmap to achieving ultimate framing goals. MCDA can be used to create weighted decision models and support traceable decision processes that integrate quantitative and qualitative factors. MCDA allows users to select a reduced set of good non-dominating alternatives that they can then present to decision-makers for the final choice.

Typical alternatives may simply examine the investment and/or the total equivalent annual cost (see Fig. 9.1). Then an alternative is selected based on the lowest investment or the lowest total annualized cost. In the cases discussed below, the better case could be selected, or alternatively, the best case with 50% renewables may be selected if the initial investment is acceptable.

A. Zhivov, *Energy Master Planning toward Net Zero Energy Resilient Public Communities Guide*, https://doi.org/10.1007/978-3-030-95833-6_9

Alternative	Investment	Total Equivalent Annual Cost (Dollars/Year)
Baseline	0	12,249,182
Basecase	0	17,096,926
Better Case	29,111,488	15,736,697
Best Case	47,955,068	14,066,687
Best Case w 50% Renewables	71,635,072	11,779,615
Best Case Net Zero	185,848,672	13,318,683

Fig. 9.1 Typical data used to determine alternatives based on investment and/or the total equivalent annual cost

Table 9.1 Typical criteria used at the beginning of the MCDA process

Money ($)	Energy efficiency	Energy security/resilience
Total investment	Site energy	Electric energy
Annualized cost $/Yr	Source energy	

However, there may be additional criteria that are important to the stakeholder. This is where a MCDA tool allows other criteria in the selection process.

Step 1 At the beginning of the MCDA process, users select the list of criteria C1, C2 … Cn that are relevant to their project. Examples are site energy, source energy, energy security, first cost, etc. Table 9.1 lists several typical such criteria.

Step 2 For each criterion, a value function is assigned between 0 and 1 in such a way that the value of 1 is assigned to the highest/best value for the criterion V(Cn) (e.g., percentage of energy and greenhouse gas reduction, 100% uptime for energy resilience, lowest first cost (0 for the baselines), lowest total annualized cost, etc.), and the value 0 is assigned to the lowest/worst value (e.g., percentage of energy and greenhouse gas reduction with the baseline, max (V^{max} [Cn] of criteria such as total first costs, total annualized costs, 0 uptime time for resiliency, etc.) with a linear function between them. Figure 9.2 shows an example of a value function for energy use reduction.

Usually, the decision criteria are not equally important to each other. To support the installation's decision process, the users need to elicit relative weights for the different criteria from decision-makers. This is not always an easy process, but it does encourage decision-makers to reflect on how they make their decisions. The relative weights (W_j) are selected by each decision-maker for each criterion (see Fig. 9.3 for an example) in such a way that their sum equals to 1. Note that the criteria can be grouped as well (e.g., site and source energy are grouped under Energy,

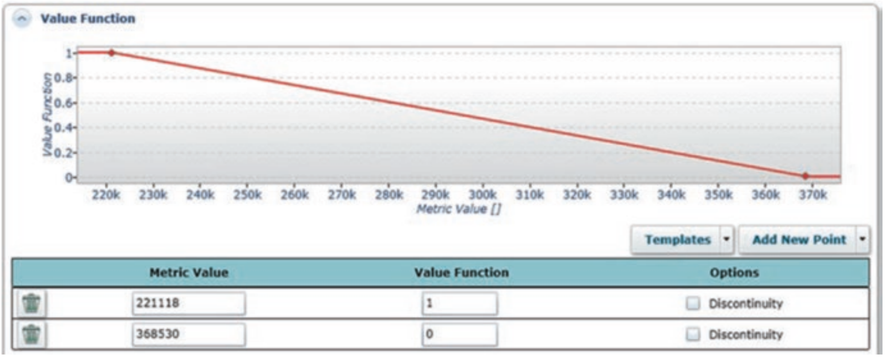


Fig. 9.2 Example value function for source energy

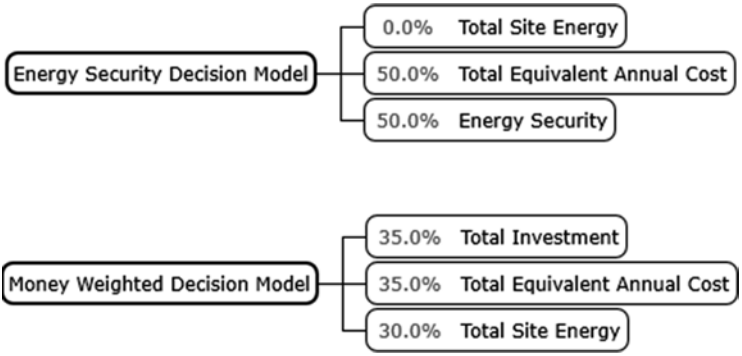


Fig. 9.3 Two examples of MCDA weight distribution among criteria and their groups

although they are not weighted equally.) Weights (W_j) to be used in the analysis are calculated as an average from those proposed by individual decision-maker.

Step 3 The weighted score of the alternative A_i is defined as follows:

$$\text{Ai} = \sum_{n}^{J=1} Cj \times Wj, \text{for } j = 1,2,,\ldots n; i = 1,2,\ldots k \tag{9.1}$$

Figure 9.3 shows two different example weighted models; one is energy security weighted and the other cost or dollar weighted. The energy security model is split between energy security and annualized cost. The dollar weighted model is 70% weighted towards dollars with an equal split between investment and annualized cost.

The weightings can be achieved in several ways. One way is to survey your stakeholders and then input the average from all participants. Another way is to take senior decision-makers' options and produce models for each. The two models shown above can be representative of two different perspectives or leaders. The energy security model is representative of the person who is in charge of the mission but still sees responsibility for the total budget. The second model may be representative of a financial leader, and the cost is dominant in that decision.

Step 4 The weighted scores of the alternatives A_i are compared and ranked for each model.

The example shown below for the MCDA process allows the user to construct and compare weighted decision models that relate back to the study goals. In this example, the list of criteria includes energy use reduction, total investment, total equivalent annual costs, and energy security of system resilience, which are used in the two models illustrated in Figs. 9.4 and 9.5.

As can be seen in the two different models and the rankings of the alternatives, each shows a distinctly different decision process. In the energy security model, the capability of producing your own energy makes the net zero model rank first, while the first cost weighting puts the best envelope case with 50% renewables in first. Remember that the baseline is included for reference only; the actual comparisons are against the base case, which for both models is the worst decision.

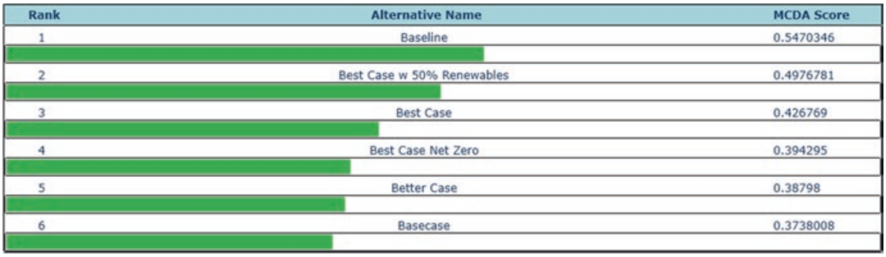
Step 5 Sensitivity analysis can be performed on the weighting of different criteria.

A tool described in Chap. 1 supports sensitivity analysis on the weighting of the criteria. Figure 9.6 shows an example in which the weight attributed to the energy group criteria is 30%, resulting in the best case with 50% renewable alternative achieving the highest score. Remember that the baseline is only there for reference with the base case as the comparison since the base case has the future plans specified. In this scenario, there is future construction that increases the total building square footage in the base case.

The top part of Fig. 9.6 shows the original ranking as a reference with best-case net zero ranked fourth given a 30% energy weight—but how sensitive is the 30% weight? The middle in Fig. 9.6 shows the sensitivity analysis with the slider at the bottom. The slider has been moved to ~43% with the grayed out original sensitivity shown at 30%. The criteria list right below the slider shows that the total site energy is selected for this comparison. On the right of that is the new ranking given the slider position and now the best-case net zero is ranked second. The color legend in the ranking is shown in the sensitivity graph for each model, and you can see that

Rank	Alternative Name	MCDA Score
1	Best Case Net Zero	0.5222414
2	Best Case w 50% Renewables	0.3574308
3	Baseline	0.2403489
4	Best Case	0.1763139
5	Better Case	0.1173747
6	Basecase	0.0593616

Fig. 9.4 Example of MCDA ranking and score for each alternative in the *energy security model*



Rank	Alternative Name	MCDA Score
1	Baseline	0.5470346
2	Best Case w 50% Renewables	0.4976781
3	Best Case	0.426769
4	Best Case Net Zero	0.394295
5	Better Case	0.38798
6	Basecase	0.3738008

Fig. 9.5 Example of MCDA ranking and score for each alternative in the 70% cost weighted model

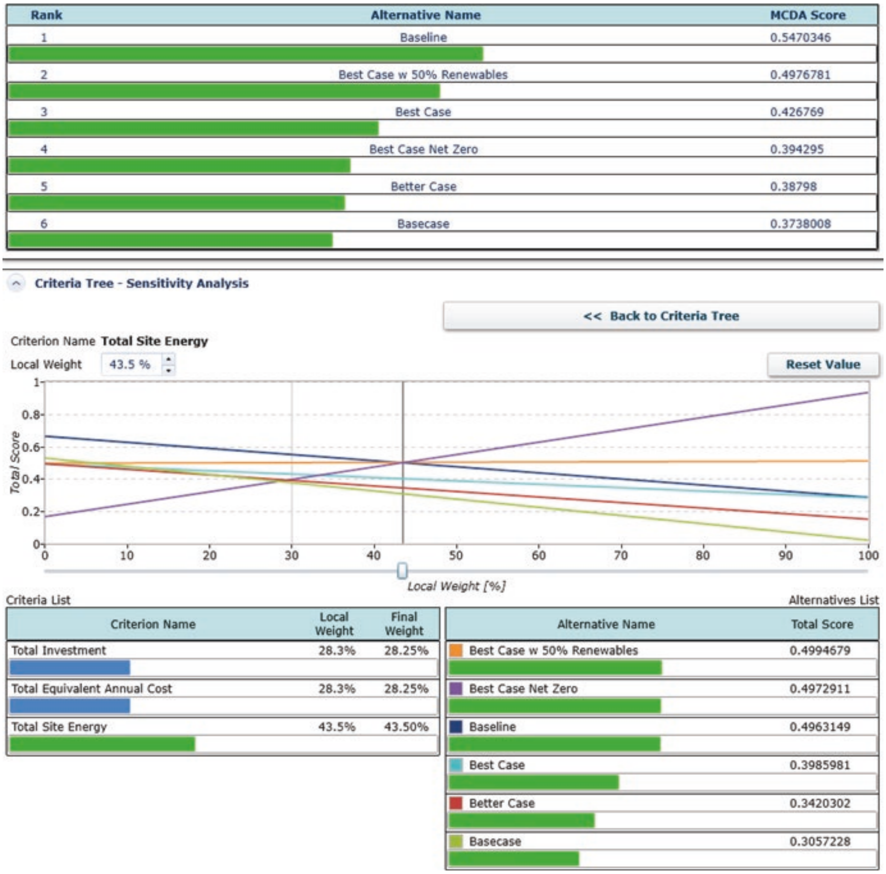
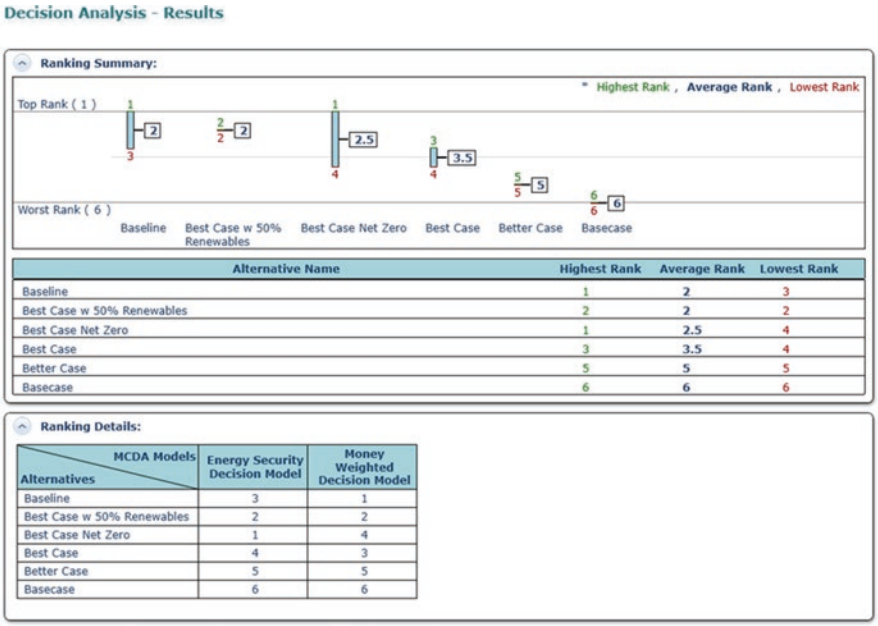


Fig. 9.6 Sensitivity analysis can be conducted on the criteria weights by moving the slider bar

the slider is at the crossover point of several models. Also, just to the left of the original 30% setting are several more model crossing points. Using this information, the user can determine if just changing the weightings slightly will change the



Alternative Name	Highest Rank	Average Rank	Lowest Rank
Baseline	1	2	3
Best Case w 50% Renewables	2	2	2
Best Case Net Zero	1	2.5	4
Best Case	3	3.5	4
Better Case	5	5	5
Basecase	6	6	6

Alternatives \ MCDA Models	Energy Security Decision Model	Money Weighted Decision Model
Baseline	3	1
Best Case w 50% Renewables	2	2
Best Case Net Zero	1	4
Best Case	4	3
Better Case	5	5
Basecase	6	6

Fig. 9.7 Decision analysis final rankings

decision or not, with the new rankings shown dynamically. With this aid and the ability to investigate any criterion, a final weighting can be determined.

Now that that the weightings have been determined, how can the two or more MCDA models be reconciled to a single decision?

To determine a final decision, the models can be compared with rankings and statistical analysis. In the example shown in Fig. 9.7, the baseline is used only for reference so the best case with 50% renewables seems to be the highest ranking between the two models. The other apparent decision is that the base case (future case projected with business as usual [BAU]) is the worst decision. After that, the other cases change rankings and are there for comparison. The final decision is best built through consensus, and if a case like the best case with 50% renewables trends in both models, then this may be the best final decision.

Chapter 10
Economics of Energy Master Plan Implementation

Abstract An Energy Master Planning (EMP) is not limited to energy-related projects; it may include a spectrum of non-energy-related projects, including new building construction and demolition, utility modernization projects, and non-energy-related measures to enhance the resilience of energy systems, such as the elevation of energy equipment, construction of floodwalls, burying of cables. In most cases, an EMP covers multiple interrelated projects where the outcome of one project or a group of projects influences one or more other projects (e.g., building efficiency improvements impact the size of required energy generation capacity; thermal energy supply to a new building requires installation of a pipe connection to existing district system; connection of additional buildings to a hot water district system allows for an increase of CHP baseload). Therefore, the selection of alternatives for an EMP shall be based on the cost-effectiveness of the entire EMP instead of individual projects that comprise the EMP. It is possible that some individual projects will not be cost-effective when considered separately. This chapter discusses the development of the business case, different costs throughout the project life cycle that the Energy Master Plan must consider, and business and financial models that can be used for implementation.

10.1 Introduction

Chapter 3 discussed methodologies for selecting alternatives that will meet minimum energy requirements and that will, to the greatest extent possible, reach the desired goals and cost-effectiveness. Chapter 2 discussed a multicriteria analysis of alternatives and scenario selection that allow the integration of economic, energy, and resilience targets to address decision-makers' priorities that go beyond economics. When an alternative is selected, it must be implemented. Chapter 10 discusses the development of the business case, different costs throughout the project life cycle that the energy master plan (EMP) must consider, and business and financial models that can be used for implementation.

A. Zhivov, *Energy Master Planning toward Net Zero Energy Resilient Public Communities Guide*, https://doi.org/10.1007/978-3-030-95833-6_10

10.2 EMP Scope and Life-Cycle Cost

The cost and implementation strategies of the energy master plan depend on its scope, timeline, and complexity.

10.2.1 Scope

The scope of the EMP can be broad and may include new construction, demolition, and consolidation projects; energy supply; and energy distribution and energy storage components, including creative methods to build innovative site-to-grid arrangements that may provide grid stability or site resilience. An EMP is not limited to energy-related projects; it may include a spectrum of non-energy-related projects, including new building construction and demolition, and utility modernization projects and non-energy-related measures to enhance the resilience of energy systems to design-based threats, such as the elevation of energy equipment, construction of flood walls, and burying of cables (Fig. 10.1).

In most of cases, an EMP covers multiple interrelated projects (see Fig. 10.2) where the outcome of one project or a group of projects influences one or more other projects (e.g., where building efficiency improvements impact the size of required energy generation capacity, thermal energy supply to a new building requires installation of a pipe connection to existing district system, or connection of additional buildings to a hot-water district system allows for an increase of CHP base load). Therefore, *selection of alternatives for an EMP shall be based on cost-effectiveness of the entire EMP instead of individual projects* that comprise the EMP. It is possible that some individual projects will not be cost-effective when considered separately.

Fig. 10.1 Scope of work under EMP

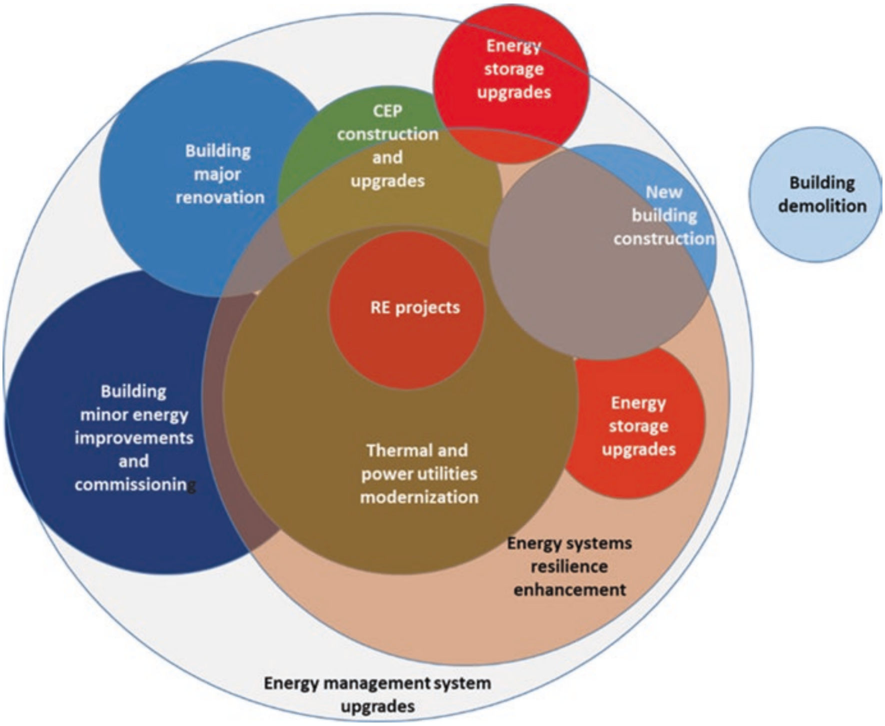


Fig. 10.2 Interrelation of projects under EMP

10.2.2 Life-Cycle Cost Analysis

LCCs typically include the following two cost categories: investment-related costs and capital expenditures (CAPEX), and operating expenditures (OPEX).

Investment-related costs include costs related to planning, design, purchase, construction, and replacement. The selection of the data sources for investments greatly impacts the reliability of an LCCA. For an LCCA to be plausible, three main data sources must be considered and merged:

- Manufacturer, supplier, and/or contractor data
- Empirical data (e.g., case studies)
- Data from building modeling databases

Investment costs describe the total expenses of the investment into (1) buildings and (2) energy supply and distribution systems. These costs include the planning, modeling, design, and implementation of new materials and the replacement and disposal costs of replaced materials, including both material and labor costs. The number and timing of **capital replacements or future investments** depend on the estimated life of a system and length of the service period. Sources for cost estimates for initial investments can be used to obtain estimates of replacement costs and expected service lives. A good starting point for estimating future replacement costs is to use initial investment costs along with price escalation factors related to comparable building construction and energy supply investment cost indices.

Synergetic Impacts The determination of the investment costs must consider synergetic impacts that can be obtained from a holistic EMP approach. For example, one approach could be to combine demand reduction on building and energy supply level measures, which would in turn allow supply to be reduced as a result of the reduction in demand on the building level. Another approach could be to organize piping and cable configurations for thermal and electrical grids located in infrastructure trenches to reduce trenching costs, which, depending on underground conditions, can comprise over 50% of the total grid costs.

Grants Grants, rebates, and other one-time payment financial subsidies for energy-efficient and sustainable design reduce the initial investment costs and are used to create a political climate that creates sufficient incentives to promote energy demand, supply, and distribution structures on the regional and local level. In European countries, major grant programs provide grants for partial or holistic renovations based on a percentage of the incremental investment costs compared to the national minimum requirements. Rates vary from country to country ranging from 20% to 50% of the incremental initial investments. The political framework in the EU has created incentives for centralized systems because these systems accommodate fuel and technology transitions more easily than do detached systems, which can involve more complex, multiple-party decision-making processes. Also, the setup of local, smaller district heating grids is a necessary prerequisite to the creation of a high-efficiency energy system that can use waste heat, such as that produced by medium-sized heating plant (HP) systems, to generate electricity. As power grids prioritize renewable power production, the setup of a new parallel grid structure on the local and regional level has become necessary to provide sufficient grid capacities. Many EU countries promote thermal and electrical microgrids by providing subsidies to set up or refurbish existing grids. These subsidies aim to reduce the incremental costs of connecting grids and detached individual supply solutions in areas with middle or low energy demand density, with a prioritization of centralized systems.

The **residual value** of a system (or component) is its remaining value at the end of the study period. The study period for an LCCA is the time over which the costs and benefits related to a capital investment decision are of interest to the investor. Residual values can be based on value in place, resale value, salvage value, or scrap value or on the net value of any selling, conversion, or disposal costs. The "economic life" of a system refers to the time its components are kept active in the balance sheet, which is defined in national tax and accountancy regulations. A system's economic life often differs from its technical life; technical life is typically longer than economic life. Second investments are made at the end of the longer technical service life; such investments are more cost-effective at this point than if they were made at the end of the (shorter) economic life. As a general rule of thumb, the residual value of a system with remaining technical useful life can be calculated by linearly prorating its initial cost. For example, a system with an expected technical life of 15 years that was installed 5 years before the end of the study period would have a residual value approximately 2/3 (= [15−5]/15) of its initial cost. This is comparable to the ISO 15686-5 (ISO 2017), USDOE Federal Energy Management Program (FEMP) LCC methodology, which requires that **residual values** (resale, salvage, or disposal costs) and capital replacement costs be included as investment-related costs. Capital replacement costs are usually incurred when replacing major systems or components, which are paid for using capital funds (Table 10.1).

A more detailed analysis should consider the lifetime of each major component. In the most cases, the selected study period will be less than the expected technical life of some major components. For these components, the residual value should be included in the LCCA. For components with a technical life that does not span the selected study period, reinvestments should be considered in the investment schemes.

Operating Costs An economic evaluation usually considers energy costs for the complete energy system (supply, distribution, and buildings) and the following operational costs:

1. Maintenance, operation, and management (including regulatory maintenance costs, e.g., repairs, replacement, refurbishment) are necessary to ensure that a building cluster and its energy supply and distribution structure function and can be operated properly throughout its life cycle. Maintenance activities usually include inspection, monitoring, testing, condition inspections, maintenance planning, repairs, refurbishment, and partial replacements. The evaluation may also consider indirect impacts of maintenance work such as costs due to downtime (loss of function for a period of time), which would include lost income in offices or hospitals and costs for onsite backup systems.
2. Insurance costs for building and component hazard, fire protection, pipe work, and electric installation.
3. Energy, water, and sewage costs.

Each scenario should consider the non-energy benefits from the following cost reductions, relative to the baseline scenario:

1. Energy cost reduction due to shifting energy peak loads, switching to different fuels (e.g., using cogeneration or tri-generation), or replacing fossil-fuel-based thermal or electrical systems with renewable energy systems

Table 10.1 Typical technical and economic life-cycle periods (LCP) for component groups

Component group	Technical LCP	Economic LCP
Thermal grids	40–60 years	20–30 years
Electrical grids (underground)	30–40 years	20 years
Heating supply station boilers	30 years	20 years
Heating supply station CHP	10–15 years	10 years

2. Maintenance cost reduction due to replacement of worn-out equipment before the end of its life cycle
3. Maintenance cost reduction due to downsizing of mechanical systems with reduced heating and cooling loads
4. Operation cost reduction using advanced building automation systems (BASs)

In some scenarios, energy use may increase compared to the base case due to new requirements for indoor air quality or thermal comfort. For example, adding cooling or humidity control requirements will result in additional energy use for cooling systems, which impacts the investment costs and LCCA. Maintenance costs for some systems may increase due to the complexity of controls system although such additional costs may be offset by reduced energy use resulting from more efficient HVAC system operation.

10.2.3 Improving the Cost-Effectiveness of Community Projects: Multiple Benefits

While a standard building LCCA broadly considers many operational costs, most cost-effectiveness calculations either on the building or the community level consider only energy cost benefits. However, ambitious energy investments often produce benefits beyond reduced energy consumption and peak demand shaving. Many of these additional benefits contribute to the objectives of organizations that implemented the projects and can have significant added value for those making investment decisions. Prior research has investigated such benefits as the impact of increased thermal comfort on the productivity of the building occupants or the willingness to pay increased sales prices or rental rates for higher-performing buildings (Jungclaus et al. 2017; Zhivov 2020); nevertheless, the monetization of non-energy benefits ("co-benefits") is still not broadly used on the building or building cluster level.

The first step to providing a systematic assessment of co-benefits is to list and classify potential benefits by their potential impact, the primary beneficiaries, first approaches for monetization, and the way that the measurement and verification (M&V) process can be conducted. It will be easier to monetize co-benefits using costs and benefits that have already been explored and quantified in the context of building LCCA and that provide M&V schemes.

Methods of quantification vary widely across benefits and depend on the desired accuracy of financial estimates. As yet, there are no standards for quantification, but to be included, the benefits must be measurable. A benefit's quantified value often depends on a combination of avoided costs relative to the base case and appropriate, conservative estimates. Of particular interest are high-value benefits that go beyond energy costs (e.g., labor costs, sick day costs) that can be reduced by providing better indoor environmental quality (thermal comfort, indoor air quality, natural lighting). The concept of non-energy benefits is still evolving; such benefits are being studied in different applications, and methods are being developed for their inclusion in building-level analyses. Although current methodologies do not yet consider building clusters, campuses, and communities, the methodologies in use for buildings could in some instances be transferrable to these larger aggregates.

An important requirement for co-benefits is their relevance to project financing. In other words, a benefit should be considered part of the equity rate that is necessary to gain access to a bank loan or other third-party financing. In a financial assessment of a project, this means that co-benefits are considered to be a revenue source, which can then be considered on the equity side of project.

Most of the benefits resulting from a refurbishment of the energy supply and distribution system relate directly to energy costs (e.g., improving the insulation of the grid, reducing the temperature level of the grid, reducing the volume per time).

The evaluation of grid refurbishment projects in Europe also indicates such additional non-energy-related benefits as:

- **Reduced maintenance costs for grids**: Repair costs of grids with more than 40 years of technical life often occur as the result of unscheduled emergencies with high repair costs. These costs can accumulate to comprise 1% of the first investment cost per year. Setting up a plan to refurbish grid sections with high flow volume or other mechanical burdens can reduce the number and severity of unscheduled emergencies while lowering annual costs of scheduled non-emergency repairs (0.25%–0.6% of first investment costs per year).
- **Leakage rates** can be reduced by implementing a repair schedule. Besides energy cost savings, the schedule should also consider the costs for water treatment and the risk of hazards from oxidative freshwater injections or limescale. The savings can be quantified in costs per unit of fresh water and the value of water chemistry components required to reduce limescale, oxidation, and other harmful water components.
- **Insurance cost reduction** resulting from improved backup systems has not been evaluated. There are not yet sufficient available data drawn from case studies to demonstrate a positive correlation between increased investments in resiliency and reduced insurance premiums. However, a simple assumption can be made for the resilience case: insurance only compensates the losses related to the insured hazard. If investments are made into resilient technologies and also into outdated or insufficiently reliable equipment, then when both scenarios are compared, the resiliency investment will show itself to be the more sufficient solution if: (1) it provides the necessary investments to increase resilience, (2) it reduces the probability of failure significantly, and (3) it meets most insurance companies' requirements for certain standards of maintenance and replacement (which will require investments anyway). From the perspective of a community energy supply company, the economically best strategy will be to invest in resilience to increase the availability of the energy system up to an affordable level and then, if necessary, to insure the remaining risks.
- **Feed-in values**: This is the value of the electricity quantity multiplied by the achievable electricity price in NPV. Grid usage includes the sale of electricity

from the community grid to the surrounding grid or to third-party customer. The latter is possible in countries with liberalized grid access where the usage of the grid can only be limited by the grid operator (DSO) if the feed-in is not fulfilling minimal technical standards (frequency, etc.) and the stability of the up-taking grid is in danger or the grid capacity is exhausted. In this case, the electricity production in the community grid must either to be stopped or stored. However, the grid operator can charge a grid usage fee, which must be evaluated in the LCCA. In some EU countries, the grid operators have time schedules with different usage costs in different specified time periods of a day.

- **Utility or independent system operator programs**: Independent system operator programs may provide additional benefits through demand response programs, which provide incentives to campuses to reduce campus power demands at the request of the regional utility or grid company. If the power demand reduction is provided for a longer time period, the "demand curtailment" provides additional benefits to the campus or community. The increasing numbers of detached power generators allow the grid company to provide incentives for the frequency regulation, in which the community or campus is required to use its systems (e.g., a CHP, chillers, batteries, etc.) to inject or absorb power over very short durations—on the order of seconds or at most a few minutes. The remuneration increases as the reaction time (time between call for action and reaction of the campus) decreases. Table 10.2 lists the major relevant cost benefits for building clusters and their supply and distribution schemes.

10.2.4 Decision-Making by Comparing EMP Alternatives

As it was stated in Sect. 3.4, one of the EMP alternatives, the **base case**, serves as a benchmark for LCCA of other alternatives. These alternatives might have different initial investment costs as well as different overall future cost savings, which could result in achieving better performance (e.g., greater energy use reduction, better environmental quality, and/or higher resilience of energy systems).

Net savings (NS) of an alternative relative to a base case is shown in the following formula:

$$\begin{gathered} NS = NPV\left[\Delta\, Initial\, investment\, cost\right] + NPV\left[\Delta\, Energy\, cost\right] + \\ NPV\left[\Delta Maintenance\, cost\right] + NPV\left[\Delta Replacement\, Cost\right] + \\ NPV\left[Incentives, rebates, tax\right] + \\ NPV\left[Benefits\ from\, resilience\, improvement\right] \end{gathered} \tag{10.1}$$

where NPV (Δ Initial investment [cost] ($)) is the present value of initial investment cost savings (or excess costs if negative) for the project relative to the base case. Initial investment costs are already in NPV if they occur in Year 0 of the study period.

Table 10.2 Multiple benefits in building clusters and their values

	Multiple benefit	Calculation method	Variations and values
1	Energy savings: effects from improving the energy performance	kWh savings x energy price	Fixed or flexible energy price; reductions resulting from demand-side measures and improvement of supply/ distribution schemes Energy demand reduction x energy price
2	Energy savings II	kWh RE replacing fossil x energy price (RE-fossil)	Fossils replaced by RE; calculation based on fixed or flexible energy prices energy demand x energy price reduction
3	Reduced maintenance I	Maintenance costs for replaced worn-out equipment at the end of its life cycle as a percentage of the new investment value	Average percentage value or end of life-cycle value maintenance cost reduction= maintenance cost of new equipment vs. maintenance cost of replaced equipment
4	Reduced maintenance II	Downsizing of investment in supply and distribution when demand-side measures are carried out, which leads to reduction of investment cost-related maintenance	A component downsized by 30% reduces maintenance costs of this component; in a first estimate a linear reduction can be assumed
5	Reduced operation costs	Building automation reduces operation workloads	Consider work plans and operation schedules individually. Cost savings from reduced daily staff costs
6	Insurance costs I	Replaced building components achieve lower premiums and improved protection against loss	EU: compared to pre-refurbished status, -2 up to -4€/m^2 on building surface area; distribution systems, n.a.; supply installations, 3–5% of total LCC
7	Independent system operator	Demand management and frequency management	Incentives for stabilizing the power demand by switching off and by frequency stabilization

NPV (Δ Energy [$]) is a present value of future energy cost savings for the project with the project life of N years, due to reduced use of electricity (E), gas (G), and other fuels (OF).

$$NPV\left[\Delta\, Energy\right] = NPV\left[\Delta E \times CE\right] + NPV\left[\Delta G \times CG\right] + NPV\left[\Delta OF \times COF\right] \quad (10.2)$$

where:

$C_{E,}$ $C_{G,}$ C_{OF} = unit fuel prices
ΔE, ΔG, ΔOF = annual electricity, gas, and other fuel saving

For each fuel type, NPV of energy cost-saving NPV can be calculated using the following formula (using gas as an example):

$$NPV\left[\Delta G \times C_G\right] = \left[\Delta G\right]_{t=1} \times C_{G(t=1)} \times \sum_{t=1}^{t=N} It \times \left[\left(1+d\right)^N - 1\right] / \left[d \times \left(1+d\right)^N\right] \quad (10.3)$$

where:

It = projected average fuel price index
$\mathbf{C_{G(t=1)}}$ **=** gas unit price in the first year

To simplify calculations, the energy unit price change from year to year can be assumed to be at a constant rate (or escalation rate) over the study period. The escalation rate can be positive or negative. The formula for finding the present value (**NPV [ΔG x** $\mathbf{C_G}$**]**) of an annually recurring cost savings at base-date prices ($\mathbf{C_{G(t=1)}}$) changing at escalation rate **e** is:

$$NPV\left[\Delta G \times C_G\right] = \left[\Delta G\right]_{t=1} \times C_{G(t=1)} \times \left(1+e\right) / \left(d-e\right) \times \left[1 - \left(1+e\right) / 1 + d\right)^N\right] \quad (10.4)$$

In Eq. 10.1:

NPV [ΔMaintenance ($)] is the present value of future maintenance cost savings.
NPV [ΔReplacement Cost ($)] is the present value of future replacement cost reduction.
NPV [Incentives, rebates, tax ($)] is the reduction in cost related to national or local incentives, rebates, and taxes.
NPV [Benefits from resilience improvement ($)] is the reduction in losses caused by interrupted power or thermal energy supply or reduction in insurance premium due to improvement system resilience. When the monetary benefits related to improved energy system resilience cannot be assigned, methodology described in Sect. 10.4 can be applied.

The formulas for calculating NPV [ΔMaintenance ($)] and NPV [ΔLease Revenues ($)] are based on the discount or inflation rate, d:

$$NPV\left[\Delta Maintenance\left(\$\right)\right] = \left[\Delta Maintenance\right] t = 1 \times \left[\left(1+d\right) N - 1\right] / \left[d \times \left(1+d\right) N\right] \quad (10.5)$$

where $[\Delta \text{Maintenance}]_{t=1}$ represents the maintenance costs savings in the first year.

$$NPV\left[\Delta Lease\ Revenues\left(\$\right)\right] = \left[\Delta Lease\ Revenues\left(\$\right)\right] t = 1 \times \left[\left(1+d\right) N - 1\right] / \left[d \times \left(1+d\right) N\right] \quad (10.6)$$

where [ΔLease Revenues ($)]t=1 represents the lease revenues increase in the first year.

$$NPV\left[\Delta Replacement\, Cost\left(\$\right)\right]T = \left[\Delta Replacement\, Cost\left(\$\right)\right]T \times \left(1 + d\right)T \tag{10.7}$$

where [ΔReplacement Cost ($)]$_T$ is the equipment replacement cost saving in the year (T).

Equation 10.1 does not include an option of financing projects included into EMP. Therefore, there is no financing cost involved, and no need to account for the interest rate of financing.

When some part of the EMP is financed, the net savings for the project will include the capital cost financing. Different scenarios with private funds can be used to extend the capacity of limited public funds. However, these models come at a cost of capital cost financing. The cost of financing depends on the study period and the interest for borrowing money. Also, there might be a cost of project delay due to the time required for budgetary appropriations. Sometimes, this cost will exceed the cost of capital cost financing.

Each term in Eq. 10.1 can be calculated in terms of net present dollars ($) or constant dollars ($). Instead of calculating the NPV of each term, this can be simplified by using economic scalar ratios (SRs) for energy and scalars (S) for maintenance and replacement. This simplification avoids the difficulty of selecting all of the individual economic parameters in determining the cost-effectiveness of projects, thus establishing a comparative economic feasibility threshold for analysis.

Also, Eq. 10.1 does not include revenues that can be harvested when electrical and power energy is sold outside the campus to external customers or to the grid, which adds the value of the electricity quantity multiplied by the achievable electricity price to the NPV.

10.3 How to Calculate Risk and Resilience Costs and Benefits

A long-duration power interruption and loss of thermal energy, especially in extreme climates, may significantly degrade regional and even national security (e.g., due to the loss of critical infrastructures or degrade critical missions at military bases). It can also affect the health and safety of a community and even result in a loss of human life (Viscusi and Aldy 2003).

While the cost of a given resilience measure is well understood (e.g., the costs of labor and materials to "underground" power lines), the resulting benefits are more difficult to assess, particularly because of a lack of supporting data (LaCommare et al. 2017). Although resilience has currently been acknowledged as a distinct benefit, its value has typically not yet been quantified.

Murphy et al. (2020) argue that the types of data that would support the benefits associated with resilience measures are difficult to collect because of the time and types of events needed to demonstrate the value of resilience investments. For example, 100-year flood events happen so infrequently that the benefits of mitigation measures associated with those events are difficult to quantify in a realistic timeframe. Moreover, even if the health, safety, and economic impacts of a threat could be quantified, it is very challenging to translate those impacts into financial consequences that will ultimately indicate to a given stakeholder whether a change in investment or operations is warranted.

10.3.1 Practical Approaches for Resilience Value

Resilience remains difficult to value because the desired future resilience needs do not mirror past needs. In the example of energy savings, the savings profile from an examination of past energy costs, future energy expenditures, and expected use variations is included in a baseline adjustment. In the following discussion, a standard case of the energy baseline adjustment is shown and pasted into the calculation of resilience values.

A standard case of energy baseline adjustment includes:

- Energy consumption baseline for a building operation 9 am–5 pm: 100 units of energy
- Ex-post-retrofit energy demand of the building (9–5): 50 units of energy
- Energy savings from retrofit: 50 units of energy

If we assume that the building operation hours are extended, this can be reflected in the energy baseline for the extended operation hours from 9 am to 11 pm as 120 units of energy.

Then, if the post-retrofit building uses 55 units in the 9 am–11pm operational scenario, ex-post energy savings of the building is (120 – 55) or 65 units of energy. The example shows that adjustments to the building usage must be stated in adjustments to the baseline.

Resiliency must be examined using the same methodology as the baseline adjustment shown above: assumed operational cost baseline for a building in the ex ante status of any resiliency measure is 100 units. To protect the building and its systems against additional threats (weather, terrorism, increased reliability expectation, etc.), the building operational cost baseline must be adjusted in the same way as shown above for additional usage hours.

10.3.2 Practical Approaches for the Resilience Value (2)

One very common way of quantifying energy resilience is measuring the amount of time that a critical load can be met at a certain probability. It is quantified as a probability because the load and solar resource varies throughout the year, so the length of time the load can be sustained will change depending on the time of the outage.

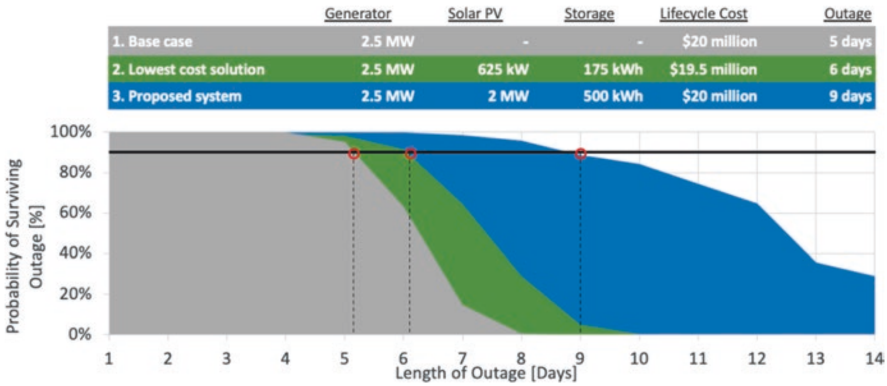


Fig. 10.3 The probability of surviving varying outage durations with different energy systems and costs (Anderson et al. 2017)

Cost-Neutral Approaches In some cases, an energy system that is cost neutral (i.e., utility bill reduction benefits over the system lifetime equal the capital and operating costs) can provide significant resilience benefits. Anderson et al. (2017) present such an example for a military base with a baseline energy life-cycle cost of $20M and an existing 2.5 MW backup diesel generator system. By installing 625 kW PV and 175 kWh li-ion energy storage system, the base could save roughly $500k over 20 years (in present value terms) and increase the outage survivability from 5 days to 6 days, with 90% probability, by extending fixed onsite diesel fuel supplies. If the $500k in savings is used to increase the PV and storage system capacities to 2 MW and 500 kWh, respectively, then the outage survivability increases further to 9 days (Fig. 10.3). This is known as "resilience for free" because the additional survivability is achieved with no increase in life-cycle cost of energy.

Non-Cost-Neutral Approaches (1)
In other cases, resilience cannot be achieved for free. In these cases, sustaining the critical load during an outage requires investment in assets that will not provide enough utility bill reductions over their lifetime to offset the upfront capital and operating costs. In these cases, it is important to consider the resilience value that the system provides. Without backup power, the site would incur costs from the outage such as spoiled goods, damaged equipment, or lost productivity. When a backup power system helps a site avoid these outage costs, the avoided costs can be incorporated into the economic cost-benefit analysis.

Non-Cost-Neutral Approaches (2)
The case study described in Yamanaka (2020) shows how a win-win approach can be successfully implemented to improve electric system resilience through collaboration between the Army Garrison and the regional utility. Through the Utility Enhanced Lease, the utility was allowed to set up a 50 MW CHP power plant on the land of the Garrison. By avoiding long land grid connections (with higher failure

probability) and providing onsite power supply 24/7, the resiliency issue of the Garrison has been successfully resolved. The value has been estimated to be comparable to the value of the ground on which the utility installed the 171 MMBtu/hr (50 MW) unit and, due to local land scarcity and other factors, equates to $360k/yr. These values might differ in other regions, but the idea of putting a value on the resilience in this case has been resolved to the benefit of both sides.

The Value of Lost Load (VoLL)

The cost of an unmet unit of energy is commonly used in bulk power system analyses as a proxy for consumers' willingness to pay for avoiding an outage (see, e.g., Schröder and Kuckshinrichs [2015]). VoLL is also used in bulk power system markets as an upper limit on the wholesale price of energy. Analysts at NREL have recently incorporated VoLL into a behind-the-meter (BTM) distributed energy resource (DER) model for cost-optimal sizing and dispatch of DER called REopt (www.reopt.nrel.gov, Laws et al. 2018). In this context, VoLL acts as the site-owner's proxy for the value of resilience and is balanced against the microgrid upgrade costs (the cost to make a DER islandable from the grid). Accounting for VoLL can make a project cost-effective in some cases.

Figure 10.4 shows an example where accounting for VoLL can make an otherwise negative NPV positive. This scenario models a hospital located in Pacific Gas and Electric's service territory. Using the REopt Lite Webtool (www.reopt.nrel.gov/tool), we optimize a system to meet a 14-day design outage and 75% critical load at a minimum life-cycle cost. The best bill savings can be achieved with a combination of a 2297 kW PV array, 1,433 kWh capacity battery, and a CHP system with a 534 kW reciprocating engine. The NPV of the energy system is $2.6M before accounting for the microgrid upgrade cost. The estimated additional cost of microgrid components required to island the system is $3.04M. This reduces the NPV of the project to approximately -$440k. However, if we include a $750/kWh VoLL, the avoided outage costs are $700k, resulting in a final, positive NPV of $250k. This shows that it is important to include the full costs and benefits of the system when assessing project economics.

While VoLL is a useful concept for valuing resilience in theory, monetizing this value can be approached in at least two ways:

1. ***Value determination by insurance costs***: For public and private energy users and producers, insurance premiums they have to pay to cover loss of utility revenue, grid damage, and cost of recovery as well as loss of assets, perishables, or business can be considered as monetizable indicators of the value of resilience. In this context, the full scope of the insurance cost must be considered; insurance companies often claim minimum requirements for the components that they are asked to insure, especially when the components in focus are variable. Any costs incurred to make components "insurance-ready" must be considered.
2. ***Value determination by standards***: In regard to military applications, since DoD requires the installation of a standalone diesel generator at every building that houses a critical load, Marqusee et al. (2017) argue that the cost of a standalone

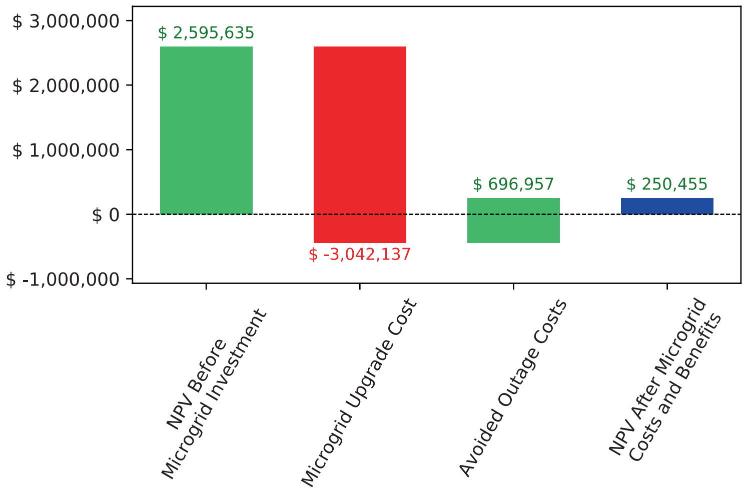


Fig. 10.4 Costs and benefits of a hybrid PV, battery energy storage systems (BESS), CHP system with a 40% microgrid upgrade cost, and $280/kWh VoLL for a 14-day outage

diesel generator (including upfront capital, O&M, and incremental fuel costs) should "represent the value (price) that DoD places on energy security."

Practical approaches for the resilience value (3): Lost-income method. To illustrate the practical use of an EMP design, one example power supply system on a ***health care campus*** shows the different steps of the risk analysis and the potential conclusions. This first stage does not examine the quality criteria of the power supply system in detail. The calculation measures the OPEX losses of the power supply system in "lost income per day and bed" (LIPDB). The risk evaluation is done for several different scenarios:

1. **Base case**: A hospital with a peak load of 10 MWe is connected *to one line* of the mid-tension grid providing factor 1.2 of the peak-load capacities of the campus. Each line has a demonstrated availability of 99.1% in terms of frequency, load, and stability. The calculated probability that considers construction issues results in a total availability of 98.8%. A total LIPDB is assigned a value of 390 (i.e., all 390 beds are unoccupied for 1 day). Costs are calculated by the load costs (€/kW) 10 MW x 1.2 x 20 €/kW =240,000 €/yr. The utility contract provides the right for the costumer to reclaim costs occurring on natural hazard events.
2. **Availability plus**: The hospital is connected *to two different* lines of the mid-tension grid providing factor 1.8 of the peak-load capacities of the campus. Each line has a demonstrated availability of 99.8% in terms of frequency, load, and stability. The calculated probability that considers construction issues results in a total availability of 99.1%. A total LIPDB is assigned a value of 290 (i.e., all 290 beds are unoccupied for 1 day). The incremental availability costs are calculated using the additional load costs (€/kW) in comparison with the base case and the additional transmitter station capitalized over 20 years: 10 MW x (1.8 –

1.2) x 20 €/kW = 120,000 €/yr + NZV (90,000 €, 4%, 20yrs) 7,200 €/yr.= 127,200 €/year. The improved LIPDB is 100, which equates to 80,000 €/yr. Availability plus is not paid back by the reduced losses.

3. **Availability 1 plus CHP**: Basic scenario + CHP with quick start functionality. NZV of the CHP is 42,000 €/year; since the potential use of the CHP occurs for only a short time, fuel costs need not be considered. With the same availability as in the previous two scenarios, the LIPBD of this scenario is cost-effective and even generates a positive income in the event of a hazard.

10.4 Methodology of LCCA Analysis of Energy Systems with Enhanced Resilience

Based on the discussion of different resilience value approaches in Sect. 10.4, this chapter provides one example of a potential approach to comparing different resiliency approaches from the LCCA perspective. LCCA of energy systems supporting mission-critical operations for new construction and energy system upgrade projects and additional non-energy-related measures protecting these systems (e.g., burying power cables, building flood walls around equipment, raising mounting level, or installing equipment inside buildings) must be performed against the base case described below. If the “baseline model” in 10.3 is used, the base case can be the system that is operated under comparable resiliency assumptions.

For new construction projects, the base case scenario for comparing different energy systems’ alternatives should include systems for power and thermal energy supply in non-emergency operation modes and individual building energy supply systems for emergency operation modes, i.e., distributed backup diesel generators, UPSs (as needed for the mission), and fuel storage.

The configuration of the base case emergency generation and storage systems and the level of redundancy of major equipment should be adequate to meet the energy requirements for mission-critical and safety and health operations for the specified common threats (identified through risk assessment for the specific location), where capacities to meet minimum requirements (maximum downtime, power, and thermal energy quality, etc.) are specified by Federal agencies. Calculations should include recurring purchase of equipment and the cost of adequate systems testing and maintenance as well as cost of fuel used for testing and replacement. Figure 10.5 illustrates the concept of the base case used for LCCA.

The base case scenario shown in Fig. 10.5 for the new construction group of graphs (on the left side of Fig. 10.5) is a combination of the single-building heating and cooling systems with the power supply from the grid. Because the building hosts a critical mission, to increase resilience of energy supply, energy systems used during non-emergency operation mode are supplemented by backup diesel generators, UPSs, redundant boilers and chillers (to achieve, e.g., N+1 redundancy), and fuel storage for 14 days operation (or other period of time as specified by Federal

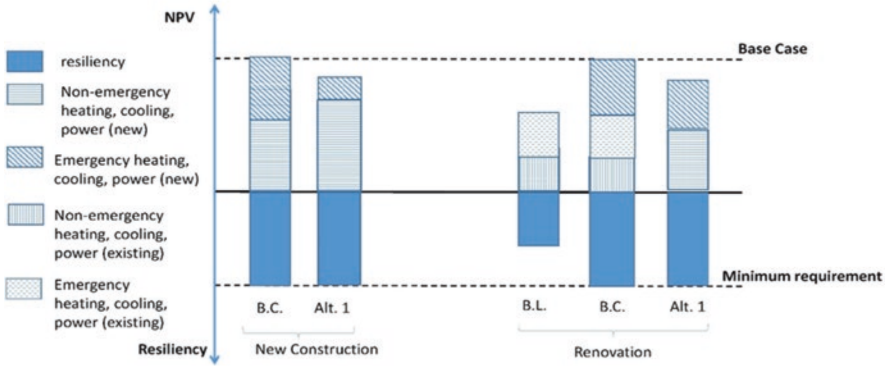


Fig. 10.5 Concept of LCCA for new construction and renovation projects

agencies) in the emergency mode. All equipment serving the building are provided with adequate maintenance and testing of emergency generators and with fuel supply for equipment testing and fuel replacement.

Alternative 1 used as an example in Fig. 10.5 is designed to increase the building's energy efficiency by reducing the need for heating, cooling, and lighting. A CHP plant provides the building's baseline heating and electricity needs. Excessive waste heat is stored in a mid-term storage, which permits peak shaving and allows for a reduction in the size of the heating equipment. The remaining heating and cooling needs are provided using heat pumps powered by electricity. Additional power during the normal operation mode is provided by the grid. To shave peak loads during the daytime and thereby reduce electricity costs, large-scale power batteries are charged during nighttime and over the weekend. Emergency operation mode energy needs are served by CHP plant and HPs complemented by a smaller emergency generator. The Alternative 1 architecture is designed to meet resilience requirement similar to the base case but has smaller life-cycle costs due to reduced size of emergency generator, smaller fuel and fuel storage costs, the elimination of peak electricity costs during regular operation, and the reduction in fuel use resulting from the use of waste heat from the CHP.

For renovation projects with energy systems upgrades (right three graphs in Fig. 10.5), it is first necessary to establish the baseline of the existing energy systems and to analyze their resiliency to the most relevant local threats. The resilience of these systems depends on their architecture, type and age of equipment used, and the historical level of their maintenance and level of protection against the most relevant local threats. Typically, the resilience of energy supply systems serving a building built to previous requirements will not be sufficient based on current regulations but will have relatively smaller operation and maintenance costs. The scope and cost of upgrade to the **base case** architecture of the system should be based on the identified gap in the systems' capacity and resilience and should be based on the minimum requirements specified by Federal agencies. Additional distributed backup diesel generators, UPSs, and fuel storage will be added if necessary. In the LCCA of renovation projects, a comparison of systems' alternatives should include the residual value of existing equipment and distribution systems, their remaining useful life, and the cost of maintenance corresponding to the age of equipment. In the base case alternative, the resilience of the energy supply system will be brought up to minimum requirements specified by Federal agencies with the corresponding life-cycle cost increase compared to the pre-renovation baseline.

Alternative 1 will be developed similarly to the way described for the new construction case, with limitations on energy efficiency improvements and with the use of some of the existing equipment when cost-effective. The architecture of Alternative 1 is designed to meet resilience requirement similar to the base case.

Recommendations:

1. Configuration of the base case of emergency generation and storage systems and the level of redundancy of major equipment shall provide adequate resiliency for the specified common threats (identified through risk assessment for specific location) with capacities that meet the minimum requirements specified by the national framework.
2. Alternative cases shall provide a level of resiliency that is the same or better as that of the base case.
3. In both new construction and renovation, life-cycle cost analysis of alternatives shall be made against the base case scenario. System architectures to be compared may include those servicing individual mission-critical operations (distributed system solutions), and clusters of mission-critical and safety and health-related operations/facilities or areas, which include both mission-critical and non-critical operations. Life-cycle cost analysis shall include all systems providing power and thermal energy to facilities served throughout the year-round cycle including non-emergency, emergency, and testing operation modes.

10.5 LCCA Variation Calculation: Economic Key Risk Factors (KRFs) and Key Risk Indicators (KRIs) for Community Energy Systems

The decision-making process underlying the implementation of an EMP is comparable to the processes supporting any other investment decisions needed to provide variation analyses, i.e., they are based on assumptions regarding the relative prices, taxes, and benefits of community energy systems under consideration. To overcome the challenges of providing energy supply and distribution systems for building clusters, it is first helpful to identify a simple set of KRFs identified using the risk evaluation processes described above. In practical terms, identifying KRFs is essential to achieving an EMP project's economic targets. Interviews with 18 project facilitators, ESCOs, financiers, and insurance companies identified the following KRF:

1. **Investment costs**. Investment costs, usually the “first investment costs,” are single payments made at the beginning of the project to pay for design, equipment components, and labor. To integrate these costs into the annual cost-based cash-flow scheme, the investment costs are transferred by annuity factors into equal annual *capital costs* of the calculation period, which contain both interest costs and payback. In EMP projects, the capital costs usually capture a large portion of the total costs. For NZE projects, investment and capital costs usually comprise the largest costs in the overall cash-flow scheme. This means that relatively small increases in investment costs may significantly impact cash flow.
2. **Energy cost**. Energy costs can be accounted for as direct cost or as cash-flow income (based on cost savings). If considered as income, the performance of the energy savings plays a pivotal role in the cash flow such that any large compromise to energy savings may significantly impact the cost-effectiveness of the project’s cash flow.
3. **Maintenance cost and other life-cycle costs**. In the evaluated case studies, the “other” life-cycle costs do not comprise more than 20%–25% of the total costs. However, insurers (especially) and ESCOs that are responsible for long-term functionality of the energy systems indicate a strong relationship between availability of energy systems and its maintenance and operations schedule.

Finally, a series of indicators are necessary to monitor the operational risk management model. KRIs are statistics or parameters used to anticipate changes in the exposure of projects to risks. Typically, these indicators are regularly checked since they provide alerts to changes that may reveal negative patterns of risk exposure. The main goals of the KRI methodology are:

- To provide information on level of operational risk to multiple projects and to identify the main causes of any changes
- To set warning levels and limits for decision-making
- To identify and measure the effectiveness of controls and any improvements made
- To identify correlations between KRIs and operating losses

Recent risk analyses one for national and international EMP research projects for building clusters, communities, and hospital and university campuses have identified the KRIs listed in Table 10.3. The KRIs vary widely from country to country depending on each country’s energy and investment costs. To date, relatively few projects with consistent and comparable parameters have been evaluated. For example, data from only six projects in Germany are publicly available. It is recommendable to evaluate as many national case studies as possible to gather reliable KRIs over time.

De-Risking Methods and Tools in EMP for Building Clusters

From the economic point of view, the design and execution of de-risking measures in different stages of EMP development are crucial for the EMP’s success. The following paragraphs focus on de-risking measures for the KRFs of investment and energy costs.

Table 10.3 Key risk factors, indicators, and values

Key risk factor	KRI	KRI values
Capital costs for energy supply and distribution	Specific costs overall for the building cluster[a] Specific investment costs per m^2 total gross floor space of the building cluster Investment costs per kW thermal or kW electrical maximum load	Evaluates and compares the total investment costs for the energy system (building and supply). Sources: ST B results
Energy savings	Specific capital costs per kWhth or kWh el saved per year Energy cost savings/m^2 yr. (per total gross floor space)	Evaluates the cost of investments per kWh saved to compare between different scenarios and investments
Energy costs	Energy costs per m^2 (per total gross floor space of the building cluster)	Value in use in facility and energy management processes for single buildings, building clusters, industrial parks, etc.

[a]Reference investment costs including demand side measures (buildings), grids, and supply buildings

Evaluation of De-Risking Measures: Total Cost of Risks

Risks can be quantified, as can de-risking measures. Different risk factors are characterized by different levels of risk; similarly, the level of de-risking depends on the identified risk costs (cost of losses) that may occur in the most probable risk case and the cost to mitigate this risk to a certain level. A cost-benefit analysis is necessary to be able to decide if (and to what level) a risk can be mitigated. For effective risk management, the total cost of risk is made up of two elements:

- Cost of insured risk (CostIR), which corresponds with the insurance policy premium or any other measure put in place to compensate the identified risk
- Cost of uninsured risk (CostUR), which corresponds with the loss borne by the project

The total cost of risk (TCOR) is then:

$$TCOR = CostIR + CostUR \tag{10.8}$$

Both components will be defined by both the retention levels ("R," loss levels below which losses are borne by the project) and the insured limit ("L," maximum loss covered) of the insurance scenario:

$$TCOR = CostIR\left(R,L\right) + CostUR\left(R,L\right) \tag{10.9}$$

This equation may be used to set up and compare risk management strategies in terms of the cost-effectiveness of de-risking measures.

10.6 Business Models

10.6.1 Introduction

Backcasting and forecasting techniques (shown in Fig. 10.6 and described in Sect. 3.11) are two major concepts applicable to the development of EMP implementation strategies (Zhivov et al. 2014; Annex 51 2011; Kimman et al. 2010).

Backcasting denotes the process of defining milestones (mid-term goals) and determining the necessary steps to reach the final goal. Backcasting allows concrete actions in the short term to be formulated from the long-term goals. Forecasting, by contrast, refers to the planning of projects to meet milestones defined through the backcasting process, i.e., setting project requirements, and optimizing and designing projects and sets of projects in a holistic way that is geared to meeting each milestone.

In practice, the implementation of EMP project requires forecasting approaches to ensure that the design of the EMP matches the project's final goals. Planning and execution of the EMP projects can spread over multiple years based on the mission requirements, funding limitations, and sources of funding available. To meet the overall targets in the given limitations (time, budget, qualitative targets such as resilience level, etc.), a strict monitoring process is required on (at least) an annual basis. This monitoring includes a comparison of the target and performance levels and the development of corrective measures for recognizable target deviations.

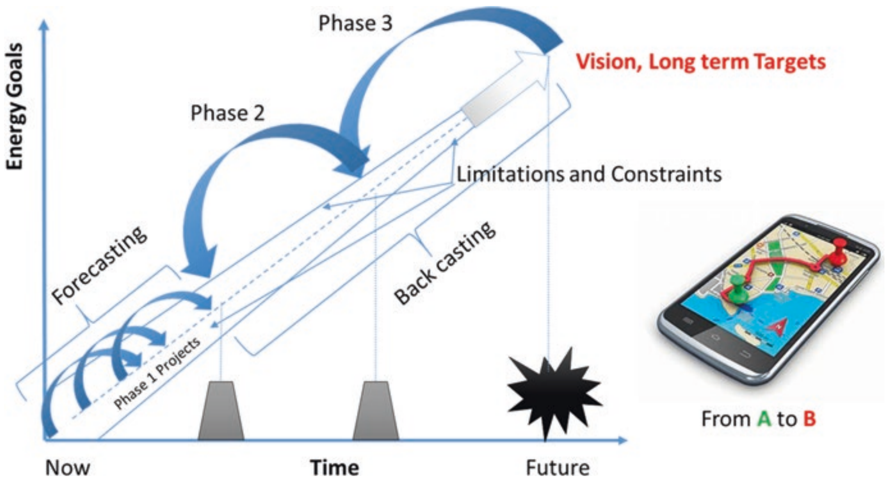


Fig. 10.6 Energy master planning: backcasting and forecasting

10.6.2 Context and Technical Scope of the EMP in Communities

The technical scope of the EMP may be limited to some degree of improvement of the energy efficiency of the communities' building stock; or it may broadly include demolition and new construction, along with refurbishment or reconstruction of the energy supply system including its energy generation, energy distribution, and energy storage components.

EMP is not usually carried out as a standalone activity but as a part of the partial or complete constructive redesign project that opens the technical scope to a spectrum of non-energy-related projects, e.g., demolition, new building construction, and measures to improve utilities and to enhance the resilience of buildings and their infrastructure (including energy systems) to withstand design-based threats. The best-practice approach to integrating an EMP into the larger design context occurs after the spatial and architectural concept has been fully developed. This means that the community's usage concept has been developed to the level of individual buildings and their infrastructure so that the future floor space of single buildings is, at least conceptually, determined and described.

The EMP will be set up based on the status-quo baseline of energy consumption, the use and construction of the redesigned buildings, and a first draft of the infrastructure plan, which includes the energy delivery infrastructure and other pathways, intersections with the power, gas, or district heating grids outside the community.

As described in Chap. 3, the EMP will preselect potential technical scenarios for the energy supply and the energy demand side, and then start the modeling phase. The EMP models will be recalibrated according to the baseline consumption of the status-quo community. The model will consider the investment and life-cycle cost assumptions provided in Chap. 1 based on the different energy system components and on demand-side measures determined by the level of building and distribution grid insulation.

Although the decision-making process primarily considers cost-effectiveness, the life-cycle cost evaluation focuses on a cost-effective solution that provides the most benefits at the lowest cost. The planning and execution of such complex projects can spread over multiple years based on mission requirements, funding limitations, and sources of funding available.

The technical scope of an EMP project aiming at NZE will at least replace or refurbish old systems, using four relevant measures typically in use:

1. Demand-side measures:
   (a) Buildings: minor renovation and commissioning that aim to yield <50% savings of heating and cooling energy compared to the baseline of the reviewed buildings
   (b) Building: major renovation with a deep energy retrofit that aims to yield >50% of heating and cooling energy compared to the baseline of the reviewed buildings

   (c) Process heating/cooling: reduction of heating/cooling demand for processes (mostly independent from heating degree days such as DHW, physical and chemical hot water-/steam-supported processes)

2. Energy supply (centralized/detached/partly centralized) measures:

   (a) High-temperature-systems: steam boilers, medium to large CHP plants with steam extraction on various pressure and temperature levels (>120 °C [>248 °F])
   (b) Mid- to high-temperature systems: boiler/ CHP/CHCP on natural gas, oil, coal or lignite, or solar basis (70–120 °C [158–248 °F])
   (c) Low-temperature systems: condensing boilers, electric, gas, or solar-driven heat pumps with different ambient heat sources (<70 °C [<158 °F])
   (d) Energy distribution for heating, cooling, and power, including exchange and housing stations for the handover of the distributed energy
   (e) High-temperature system grids for steam and hot water >120 °C (>248 °F) with/without condensate return
   (f) Mid- to high-temperature system grids for hot water with temperatures between 70 °C and 120 °C (158 °F and 248 °F)
   (g) Low-temperature systems for hot water with temperatures below 70 °C (158 °F) in the average of time (partial exceedingly, e.g., for hygienical requirements for DHW supply systems, etc.)
   (h) Cold-temperature systems for the distribution of water or refrigerants for the use of low- or cold-temperature geothermal heating sources for centralized or detached heat pumps with temperatures below 40 °C (104 °F) in the average of the year.
   (i) Cooling distribution systems with average temperatures <20 °C (<68 °F) containing cold water or refrigerants
   (j) Power grids for low-middle tension systems in or above ground level including transformer stations to the next tension level
   (k) Gas with low to middle pressure and transformer station to the next pressure level

3. Storage systems:

   (a) Thermal high-medium or low-temperature storage with insulation for the optimization of the performance of load peaks and time of operation for CHP/CHCP/biomass and heat pumps. (Usually 1–4 hrs of load output capacity of the relevant component can be stored and kept with small losses.)
   (b) Thermal seasonal storage for high- to medium- or low-temperature storage with low level insulation and high capacity of, e.g., the overproduction of solar thermal fields to be available in the heating season
   (c) Power storage systems based on onsite solutions that use batteries with 1–3 hrs storage capacity or that use power production from PV panels to be made available in periods of high-demand time in the same or next day; also often used as a storage/charging system for e-mobility

   (d) PtG-storage systems with >5 MW power capacity that can convert overproduction from medium to large PV fields to synthetic gas fuel

4. Resilience measures:

   (a) Cross functional surpluses that help to meet the increased resilience requirements of energy supply and energy distribution systems. Energy demand measures are considered to reduce demand and contribute to the overall availability of energy systems and buildings (e.g., insulation increases that slow the loss of heat in cold climates in the case of a heating supply outage).

10.6.3 Selection of Business Models in Community Projects

The selection of the business models must be considered from the standpoint of the users, who are the public community owner(s)/manager(s), etc. The business model that is most relevant is one that best serves the users' needs, i.e., that provides the most suitable services and technical scope, a remuneration model that matches the users' financial situation, a monitoring and verification system simple enough so the user can understand and handle it. Users need not have a deep understanding of business model theory; an appropriate business model can be selected for a community by simply using a profile of services and requirements that match the users' expectations.

The following sections summarize different services that correspond with typical EMP projects and the major risks to be considered in the selection of a business model. The resulting profile can be used to create statement of work (SOW) documents during the tendering processes and to cross-check with standard business model contracts.

10.6.3.1 Scope 1: EMP Design Phase

In the very beginning, after defining a concept, it is necessary to consider where to allocate the design phase. In many performance-based business models (ESPC, utility models, etc.), the service provider (e.g., energy service company [ESCO]) will take only the performance risk—if the service provider is responsible for the design phase. (This is not as relevant in other business models that do not involve performance-based remuneration.) The following design services should be considered:

1. Acceptance and finalization of the EMP modeling
2. Finalization of the design that is ready to execute
3. Definition of the scope of work and the specifications
4. Avoidable risks, e.g., lack of quality assurance in the design phase may lead to significant investment cost increases and reduced cost-effectiveness

10.6.3.2 Scope 2: Implementation Preparation Phase

The complexity of the legal framework, requirements from public authorities, environmental issues, and other processes often motivate communities to decide to delegate larger parts of the implementation preparation to third parties such as planners, utilities, ESCOs, etc. Such preparation may include:

1. Listing all allowances pertaining to spatial, environmental, and other legal restrictions
2. Procuring the specification until hiring and signing of executive contractors, ESCOs, etc.
3. Risks: Additional investment required to receive the allowances may increase the total investment costs and reduce cost-effectiveness; the procurement process itself may lead to higher investment costs and reduced cost-effectiveness

10.6.3.3 Scope 3: Financing Phase

The financing phase may involve:

1. Preparation of financing decision-making pertaining to cash flow, investment planning, and calculation of risk variation
2. Setup of the financing scheme as a combination of equity, third-party money, and potentially available subsidies and loan guarantees
3. Signature of financing contracts, loan securities, and loan guarantees
4. Risks: Fluctuations in interest rates in the period between decision-making and execution of the financing introduce the potential risk of additional financing costs

10.6.3.4 Scope 4: Construction Phase

In most cases, construction will be delegated to third parties such as contractors or ESCOs; the community will often also hire architects, planners, third-party engineering firms, or project managers to monitor such aspects of the project as:

1. Setup of construction site
2. Implementation of the installation design, usually done through contractors and subcontractors during design and specification
3. Overseeing project cost and time management over specified time periods
4. Ensuring quality assurance in the implementation process
5. Performing interim and final functionality tests, obtaining project owner and customer approval
6. Performing cash management
7. Risks: Increases in investment costs and/or delay in construction phase, e.g., by unforeseen technical issues, incomplete design, unavailability of subcontractors,

delays in the time schedule, and bankruptcy of contractor; all these circumstances can generate additional financing needs and costs and can reduce the cost-effectiveness of the EMP

10.6.3.5 Scope 5: Operation Services

To some extent, military or other restricted areas cannot hand over the operation of installations' systems to third parties. If operation services are of interest, the following subtasks help to define what is needed and what the installation or facility staff can provide. In many cases, services can be combined. For example, utility services often provide 24/7 operation, which can help to reduce staff costs in the community. Operation services include:

1. Setup of operation, first adjustments, and optimization
2. Setup of operation schedule and building to accommodate internal and third-party operating staff
3. M&V plan and execution and system adjustments in accordance with modeling results and practical experience
4. Planning and execution of maintenance and refurbishment activities and monitoring of maintenance and refurbishment costs
5. Cash-flow management
6. Reporting to involved key stakeholders: financiers, community owner/admin, and others
7. Major risks: Disturbance of energy supply endangers mission and function of the community and/or single buildings with consequent negative impacts on cash flow; performance indicators will not be achieved, which increases the operational costs and reduces the cost-effectiveness and financial performance of the project

10.6.3.6 Scope 6: End of Term Phase (In Project with Fixed End of Term Definition)

In a project with a fixed end of term, this phase involves:

1. Determination of the residual value
2. Deconstruction of relevant components
3. Finalization protocols to approve the handover of the site, components, and documentation according to project specifications
4. Major risks: If the residual value is less than assumed (e.g., due to poor maintenance), the cash flow and the financial performance indicators will be compromised

Table 10.4 lists the advantages and disadvantages of different business models. For many public agencies and communities, it is important to reduce the number of

Table 10.4 Community business models

Business model	Description	Pros	Cons
Appropriated funds	Funds appropriated by the governing agency as part of the yearly budgetary process, execution supervised by agency and subcontracting parties	Straightforward; follows the normal processes for capital improvement program Can be done incrementally for several years Manage resource to highest priority areas	Subject to normal budget priorities Must be managed internally Follows normal design-build processes, makes no extended guarantees No energy performance guarantees No budget limitation guarantee
Fixed payment	Funded by a utility. Paid back via fixed payments on the utility bill or on the property tax bill	Easily implemented Usually low interest rates Payment stays with the property in case property is sold	No energy guarantee Usually limited to small projects EMP implemented in pieces
ESPC	Energy savings performance contract	Budget neutral Energy/operations savings pay for the upgraded systems. Third party manages the contract Energy savings are guaranteed, resulting in lowered financing rates Multiple technical updates can be built in	Not readily understood by many municipal officials Typically need a 3rd-party expert to advocate for the customer Long approval cycles on final project/financing by customer Concerns by some decision-makers on long-term debt
UESC	Utility energy savings contract	Budget neutral Energy/operations savings pay for the upgraded systems. Third party manages the contract Customer contracts with their utility (people they know) Customer decides level of energy guarantee	Not readily understood by many municipal officials Typically need a 3rd-party expert to advocate for the customer Long approval cycles on final project/financing Concerns by some decision-makes on long-term debt Not all utilities offer this service

(continued)

Table 10.4 (continued)

Business model	Description	Pros	Cons
Blended funding	Combing appropriated funding with ESPC/UESC	Same as ESPC/UESC Shorten financing term by injecting one time or multiple cash payments Can get more ECMs in the project	Same as ESPC/UESC Ensuring that the cash payments are available in the budget
PPA	Power purchase agreement (buys power from a non-utility partner or developer)	Developer pays all costs Customer buys power at a price At the end of the contract period, customer can buy the equipment for fair market value or have it removed Developer may pay a lease payment to use customer land Consistency of long-term budget planning	Long-term procurement contract (typically 20 years) for customer Energy prices may be fixed or escalated Locked in prices result in not being able to take advantage of potential future lower pricing
EUL	Enhanced use lease (customer leases underutilized land to a 3rd party in exchange for resiliency)	Developer pays all costs Lease payment is often "in kind consideration," which is often required or needs customer infrastructure updates If utility power is lost, the power being produced on the leased land is sent to the customer	Lease is 30–40 years Power from the leased land is sold to the utility grid or may be bought by the customer Land is unavailable for future customer expansion

parties involved to minimize the effort required to manage these parties and to avoid the complex interactions between the different activities that each party is committed to perform. Table 10.4 also lists the number of different parties involved in the process to fully describe all six stages. The following section further describes the different business models.

10.7 Description of Most Common Business Models for Communities

10.7.1 Appropriated Funding and Execution Model

Funding Mechanisms This model assumes that government agencies or public administrations (e.g., universities, public housing companies) are responsible for budget planning and execution of the investments in their building stock and campus-level utilities. The budget may include public equity (tax payments, etc.) and dedicated bank loans. In most European countries, however, bank loans are limited by a public debt ceiling that is related to the available equity of the public body.

In the budget planning stage, building refurbishment and utility modernization projects compete with other tasks that a public entity must fulfill. These projects are not usually first priorities on the national, regional, and municipal levels. Thus, the selected model often has limited appropriated funds to renovate existing buildings, repair aging infrastructure, plan for disaster preparedness and resilience, or perform energy upgrades. Agencies typically have some funding available for specific building improvements under programs like (in the United States) the DoD's SRM program. Resilience ECMs that remain unfunded for years leave the facilities at risk and unable to operate in the event of a major weather event, a cyberattack, or some other critical, crippling event.

Main Responsibilities and Risk Distribution In this model, campus owners take responsibility for projects' design, implementation, operation, management, and financing. However, these activities are often subcontracted although the general management responsibility remains with the campus owners, who take full responsibility and assume liability for both the quality of the project and the economic return on their investments. The campus owner controls contracting, component and systems selection (and hence the project price), and project management. The campus owner is fully liable for the project's subsequent economic performance (i.e., volume of energy required to deliver post-retrofit living conditions), and for the financing (which is possibly secured), but not directly for the overall energy performance. By assuming the risk for all the project components, the campus owner is well placed to benefit from any economic outperformance (i.e., when energy prices go up faster than planned) and can clearly benefit directly from a higher-grade energy performance certificate and from improved livability of the campus facilities.

Remuneration The current contract and remuneration models do not provide incentives to the planners, architects, and craftsmen to provide high-energy and cost-efficient project structures, technologies, or methods of implementation. In some countries, as in Germany and the United States, architects earn greater financial compensation for designs that increase the building's complexity and total of investment costs; this relation between payment and investment costs is detrimental to the project's cost-effectiveness.

Strengths and Shortcomings Beyond that, this model has several serious shortcomings that lead to cost increases, cash-flow underperformance, and other serious problems:[1]

[1] Public investment projects have in average 35% of investment cost increasement during the design and implementation phase according to the Institute of Building Economics, University of Stuttgart, 2012.

- The feedback model is "open," i.e., there is no feedback based on operational experience. This influences the quality of planning, construction, and operation.
- Decision-making is fixed to one key criterion, initial investment, which does not account for LCCs.
- Neither planners nor architects are required to provide follow-up or respond to questions related to energy performance or the investment costs.
- Although this model is commonly used, few reports on current research projects are available. An Annex 73 case study evaluation plainly shows that the typical division of the scope of work is between a design company, a contracting company, and, in a number of cases, a professional operator with the community owner in the role of supervisor. Financing often seems to occur as a combination of a smaller amount of equity and third-party financing (via bank loans). So far, the experience from implemented EMPs has not been collected, evaluated, or distilled into lessons learned. In other commercial or industrial settings, the business process would follow well-defined steps that would include a "feedback loop." The building sector would benefit from adopting these steps. In the public sector, these steps are seldom followed.

Recommendation Although most community projects are obviously executed with this model, the selection of this business model seems to incorporate numerous performance risks that can lead to massive investment cost increases or disturbed cash flow. If a community decides to use this business model, it should either ensure that a flexible refinancing structure that can accommodate cost increases is available or, alternatively, consider a combination of strict project management and a stipulation that subcontracts penalize cost increases.

10.7.2 Fixed Payment Model and Utility Fixed Repayment Model

Funding The fixed payment model and utility repayment model, which are primarily used by commercial building owners, are **fixed repayment models** in which the upfront capital cost of an energy efficiency retrofit is organized, subsidized, and at times fully provided by either a utility or by a Property Assessment Clean Energy (PACE) program financing mechanism established by a city, county, or Port Authority in the United States and in a handful of European countries.

Remuneration These investments are repaid through monthly, fixed, non-performance-related surcharges. The "utility fixed repayment" version of this model requires a supportive policy framework to function; the types of legislative changes that regulators have may include: requirements for electric and gas utilities to improve their customers' energy efficiency by a certain amount each year; the application of white certificate programs or the decoupling utility profits from the quantity of electricity sold; and requirements that utilities invest first in the lowest-cost sources of energy. Although the remuneration of the utility is not related to the actual performance of an implemented project, the **utility fixed repayment model** has several immediate advantages over the **appropriated funding model**:

1. Utility cost of finance, access to funds, and available leverage should be considerably better than that achieved by owners under **appropriated funding model**.
2. Friction costs (total direct and indirect costs associated with a financial transaction) are reduced from the economies of scale created by a utility executing many hundreds or thousands of its individual client retrofits.
3. Customer "ease of execution" is enhanced as execution is streamlined, and there is less work for the building's owner than in owner-financed model.
4. Government can use its relationship with the utility sector to align interests and push national energy efficiency targets down to the corporate level through the imposition of standards and market-based programs like "CERT" in the United Kingdom or the white certificate scheme in Italy.

Currently, countries in EU are encouraged by the European Commission to enter into this business scheme by using energy mortgage repayment models that have been developed recently.

Responsibilities PACE models often involve utilities that act as a general contractor in scope 1–4 for the building or community owner. As design, implementation, and, oftentimes, operation are in the hands of the utility, this model provides opportunities for "self-learning" systems in which design approaches that did not work out well in the operation or implementation phase can be adjusted and optimized.

Strengths and Shortcomings The "fixed" payment models provide up-scaling advantages (reduced specific investment costs), standardized design, implementation, and operation processes provided by the utility and some incentives for the service providers to stay on track with the predicted investment costs, energy savings performance, and cash-flow performance. The incentive for the service provider is to keep the costs (at least) at the same level as the fixed payments. The service provider has the same incentive to manage subcontracting parties in a much more professional and target-driven manner than could a public community manager. However, the performance component of the remuneration is not very strong, as it does not rely on the energy savings performance that is monitored at the energy meter, which in some cases may lead to differences between prediction and performance.

Recommendation The fixed or utility fixed models provide the full scope of services for communities; besides taking care of renewables and efficiency, setting up microgrids and energy systems is "normal business" for the service providers. The service provider often takes responsibility for the most critical aspects of a community project and has sufficient incentives to keep the costs and cash-flow performance under control.

10.7.3 Energy (Saving) Performance Contracting (ESPC) Model

Funding Third-party funding to implement EMPs can be obtained far more quickly than can government funds such as energy savings performance contracts (ESPC) or utility energy service contracts (UESC, 10.7.4). The ESPC standard contracts transfer energy and other LCC savings into investments over a contract phase of several years. With the ESCO providing the first investment, ESPC allows communities to implement their EMP project in one step by replacing or complementing public funding sources by ESCO funding. The appeal of ESPC is that the net present value (NPV) of the total project is greater than or equal to zero over the life of the contract. Legislatively allowed ceilings for ESPC durations (financing term) vary by state but are typically in the 15–25-year range. The US Federal Government caps the duration of an ESPC term at 25 years; in Germany's federal buildings, the ESPC terms are limited to 15 years, but upfront payments are allowed if the payback period is longer.

Responsibilities ESCOs began in the early 1990s–2000s as control system providers into the ESPC business. In recent years, ESCOs have been adapted to better meet user needs by allowing building renovation, microgrid, and energy storage to become part of the technical scope. ESCOs claim to provide a full-service approach in which the ESCO takes responsibility for all six scopes.

Remuneration The ESCO facilitates funding for the first investment, and the ESCO is repaid via energy and/or operational savings as described in Sect. 10.3. The savings are usually measured and verified using standardized processes, e.g., the USDOE standard,[2] the EWO-Schemes,[3] or other national schemes.

Strengths and Shortcomings Essentially, the utility and O&M budget is held constant (except for escalation) for the duration of the contract, and the energy savings derived from new infrastructure repay the loan. However, there are inherent obstacles in using these financing mechanisms:

- Primary stakeholders often distrust the ESPC or UESC financing vehicle, primarily because they do not fully understand it.
- Public sector processes for ESPC projects and M&V results often involve long approval cycles.

The M&V is a standardized but work-intensive process that requires expertise and capacities. Some specific elements to help make an ESPC or UESC economical are:

[2] https://www.energy.gov/eere/femp/measurement-and-verification-federal-energy-savings-performance-contracts

[3] https://evo-world.org/en/products-services-mainmenu-en/protocols/ipmvp

- CHP, which allows the substitution of power purchase with less costly CHP power
- O&M savings (see 10.2)
- Utility savings, e.g., optimize grid and off-grid, demand charge avoidance and peak shaving and curtailment programs
- Offsite sales
- Bundling with fast-payback ECMs (e.g., fixing steam or water leaks is usually very low cost but delivers a lot of savings that can then be used to subsidize a boiler with a 30-year payback or windows with a 50-year payback)
- Equipment-need avoidance, e.g., use of a CHP may obviate the need for planned individual building boilers

Recommendations The ESPC model has been used in a large number of community projects in Germany and the United States. The ESPC model is useful for communities with limited funding resources since the ESCO funds the first investment and is repaid through energy and other LCC savings. The limitation of ESPC is the balance between investment and LCC savings over the project's lifespan; this limitation can only be bridged by upfront payments by the user.

10.7.4 UESC

Funding Mechanism UESC and ESPC contracts are very similar, except that in a UESC the government agency contracts with the utility and the ESCO is a subcontractor to the utility. In a UESC, similar to an ESPC, all facility or campus improvements may be paid for with energy or other LCC savings.

Strengths and Shortcomings UESCs are specifically used on the US Federal Government level as a means to rapidly update facility or campus infrastructure. The government customer can contract with a local utility directly, which then retains an ESCO to perform the work. This saves the customer time and money associated with competing the contract to multiple ESCOs and pushes this responsibility to the utility. One recent trend in UESCs is that some US Government agencies require the ESCO to guarantee savings for the duration of the contract. This is not typical for UESC projects but is being explored by some US Federal agencies. In Europe, Federal agencies are not able to contract a utility directly without a procurement process so the UESC does not exist in EU countries. However, this way of initiating ESPC projects would help to accelerate the EU energy service market more quickly.

Recommendations Effectively implementing community projects in an UESC can be a straightforward process—award an ESPC or UESC and allow the ESCO to implement most or all of the EMP. The implementation may be done in phases, but better continuity can be achieved if a single entity does the work. This inherent synergy allows new technology and new visions to be readily integrated into the designs over time.

10.7.5 Blended Funding (Public and Private Combined Funding)

Funding Mechanism This financing model, which applies appropriated funding to ESPC projects as a one-time payment (attributed to cost avoidance), can improve the economics by reducing the total cost to be financed (Lohse and Zhivov 2019; Jungclaus et al. 2017). This model allows the project to include longer payback measures, thereby increasing the amount of energy savings, energy system resilience improvements, and infrastructure renewal that an ESPC would not be able to achieve without this one-time payment. In the United States for some government agencies like the DoD, this appropriated funding must be designated solely for energy-related projects before being used as supplementary ESPC funding. There is often a strong argument for applying funds designated for non-energy projects as a one-time payment for an ESPC project to drive greater value, but the legal limitations of combined funding models must be considered.

There are a number of ways to fund a resilience project in whole or in part with private financing. First, for both ESPC and UESC, the law allows agencies to combine appropriations with private financing and for UESCs to be fully funded by appropriations. This can be especially beneficial for a resilience project that may rely on the coordination of construction and interoperability in operation. Also, including all appropriations in a project will leverage the savings that the additional funding generates for the project. For example, new transformers save energy, just not enough to pay for themselves. If appropriations are needed to augment private financing to include transformers in a project, the savings they do generate can be leveraged to support the project rather than delivering the savings back to public funds or to the treasury.

To maximize the value of this business model, agencies need to both understand the opportunity of pursuing combined funding and be prepared to act when the timing is right. A solid energy master plan developed by an unbiased third party is the critical first step to understanding the opportunities that a site may offer and can inform the need for appropriated funding and potential ESPC projects over time. This energy master plan should be closely coordinated with an energy capital investment plan so the agency can be prepared to execute and fund energy-related projects appropriately as funding becomes available. Additionally, the energy master plan should remain flexible to pursue combined funding projects as energy-related funds become available. The alignment of the work being performed by the ESCO with the arrival of appropriated funding that could be applied to the ESPC is critical when evaluating the availability of those funds to the ESPC.

10.7.6 *Combined Energy and Non-energy Projects with Participation of ESCOs*

While a combined funding approach can deliver deeper savings on limited budgets, several barriers prevent broad implementation of this model for US Federal Government agencies. These limitations do not apply to other cases including state and city government projects. In Federal contracts, ESPCs can only be paid from the savings that are generated from work that is executed as part of the ESPC. When an installation receives appropriated funding for an SRM project, that project is supposed to be solicited based on the rules in the Federal Acquisition Regulation (FAR). This process can but does not currently consider the potential to combine an ESPC effort with the SRM "funding" that could be used for "related" (energy-related) projects. If there is no relationship between the ESPC projects and the "funded" project, the FAR would prevail, and the non-energy-related scope would need to be solicited separately from the ESPC efforts. In the combined funding model #1 illustrated by Fig. 10.7, the general contractor (GC) constructs the entire project, but the energy-related portion is implemented under a subcontract with ESCO. The GC has two managers (the government customer and the ESCO), but the government customer is ultimately in charge of the entire project.

Soliciting non-energy-related scope separately from the ESPC efforts would significantly complicate the project's efforts. From a logistical standpoint, having two or more contractors onsite, implementing closely intertwined scopes, adds significant complexity to project implementation. Client teams would need to coordinate

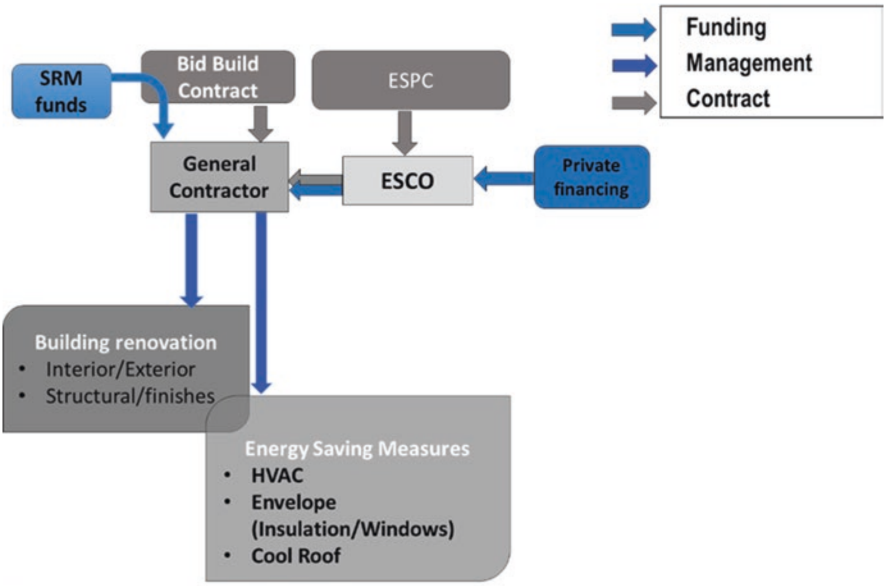


Fig. 10.7 Schematic of the combined funding model #1. (Source: Lohse and Zhivov 2019)

two contractors with different contracts, schedules, subcontractors, and scopes to work together in the same space, at the same time, without adversely impacting the project as a whole.

Potential contractor arrangements. There are many challenges associated with having separate contractors working on the respective energy and non-energy project scopes. This collaboration could take many forms. In one instance, an ESCO could serve as a subcontractor to a prime contractor delivering non-energy services as part of the SRM project. In this scenario, privacy of contract would prevent the agency from having any direct communication with the subcontractor; they would have to work through the prime contractor. Also, the agency's relationship with the prime contractor would likely be awarded as a construction contract or an operations and maintenance (O&M) contract, or as a service contract, which could include some construction effort. Those types of contracts would be subject to the FAR and can generally be in place for only 5 years. This would prevent the agency and the ESCO from benefitting from the partnership for a contract term of up to 25 years, which is necessary to deliver substantial energy savings as part of a DER. There are no regulations in place that can bridge this gap by enabling the agency to work with the subcontractor.

There are also challenges if the ESCO is the prime contractor and the agency is trying to incorporate the SRM project or project funding in with the ESCO work. In the combined funding model #2 illustrated by Fig. 10.8, the ESCO is awarded a design/build contract for non-energy-related building renovation and ESPC for energy-related measures. ESCO hires a GC but provides single point of contact for the government customer.

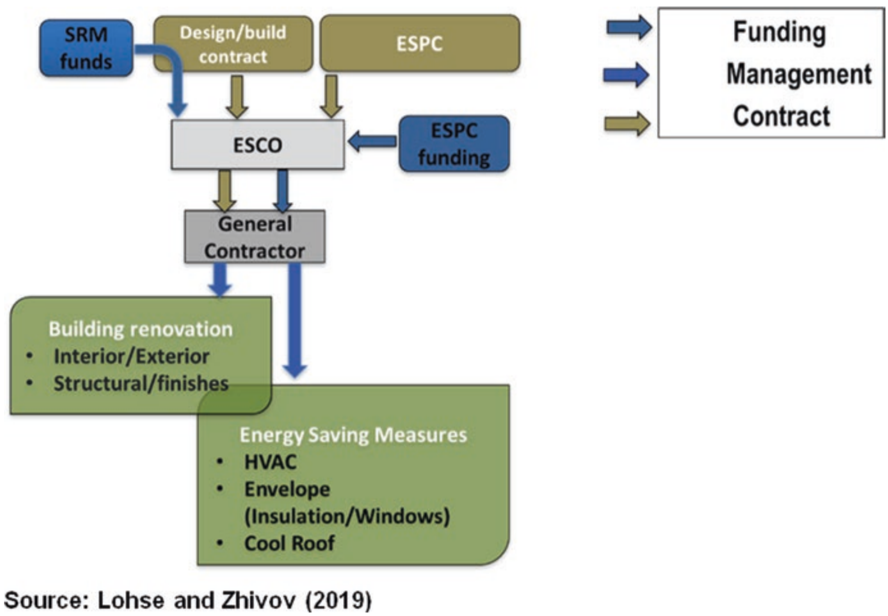


Fig. 10.8 Schematic of the combined funding model #2. (Source: Lohse and Zhivov 2019)

There has been ongoing discussion to evaluate methods that could be used where an ESCO is in place and has the potential to add value to SRM work. One potential option could be for the ESCO to provide equipment to a prime contractor as government furnished equipment. There are several challenges with how this could transpire, since the SRM contract assumes that the funding covers the entire project (including energy and non-energy scope). The ESCO and an SRM contractor would have to work out the specific arrangements that would allow for this to happen, thereby ensuring that neither contractor performs work outside of the scope of their respective contracts. There could also be challenges during the operation phase of the ESPC if the ESCO alleges that the provided equipment was damaged or not properly installed by the SRM contractor, and this is the reason that savings are not being realized. So, there are many challenges when separate contractors are hired to perform related energy and non-energy work on an SRM or similar project.

In summary, there are legal issues with how a contract can be structured to comply with 42 USC 8287 and not violate the FAR if appropriated funds are anticipated to be available at the time of contract award. There are privacy contract issues if the ESCO is a subcontractor to a prime contractor on an SRM project, which would inhibit the agency's ability to accept a comprehensive ESPC project from the prime. There are also issues with an ESCO performing work that is not energy work. Some limited non-energy work could be allowed, but substantial non-energy-related work performed by the ESCO or a subcontractor to the ESCO would not be allowed. So if there is a potential project that could achieve greater savings using the DER concept, it is critical that the team evaluating that project knows and understands the procurement rules and clearly delineates the energy and non-energy scopes to bring the greatest value to the ESPC project.

10.7.7 ESPC Energy Sales Agreements

ESPC energy sales agreements (ESAs) use the ESPC authority to implement distributed energy projects on federal buildings or land. ESAs are implemented as an ECM within an ESPC. The ESA ECM is initially privately owned to potentially qualify for tax incentives. The federal agency purchases the electricity it produces with guaranteed cost savings in the form of a lower electric rate than currently paid to the electric utility. The ESCO owns, operates, and maintains the ECM, and any tax incentives (e.g., investment tax credits, accelerated depreciation, state/local incentives), RECs, or other incentives can be applied by the ESCO to reduce the ESA ECM price to benefit the agency. The major advantage that ESPC ESAs have over PPAs is that an ESA ECM could be one or more components of a microgrid that is implemented in a comprehensive ESPC project to contribute to resilience needs.

10.7.8 Power Purchase Agreements

DoD's 30-year authority (10 U.S.C. § 2922a) can be used for power purchase agreements (PPAs) at DoD sites to implement onsite distributed energy projects with no or minimal upfront capital costs. As explained in the FEMP whitepaper *Financing Microgrids in the Federal Sector*,[4] in a PPA the developer finances and installs the equipment, and the agency buys the power at a cents/kWh rate, based on a competitive procurement. The PPA may or may not include a minimum power purchase provision in the contract. The developer owns the equipment, assumes performance risk, and provides O&M, repair, and equipment replacement for the term of the contract. A PPA most likely will not be able to fund a comprehensive microgrid, but it could be used to finance a component such as a large PV system, which could be incorporated into a microgrid system.

If a PPA were previously used to implement distributed energy project prior to a resilience planning effort, that contractual arrangement may not allow those DERs to be included in the microgrid. The agency will have to obtain permission from the PPA provider/DER owner to include the asset in the microgrid, likely requiring renegotiation of contract terms and pricing if the owner agrees.

10.7.9 Enhanced Use Lease (EUL)

An EUL is used in many ESPC- and other ESCO-based contracts in the EU and the United States. In EU countries, CHP power production is considered to be the residual power reserve in case the renewable power production is not sufficient. The feed-in power in the high-voltage grid is subsidized to provide incentives for ESCOs to set up detached CHP stations between 1 and 50 MWel (3 and 171 MMBtu/hr).

In the United States, EUL are used by DoD installations that have underutilized land that is offered to a third-party developer (e.g., a utility, ESCO, or other power plant developer/operator) for lease to build a power plant. This power plant will be built on the land and the power sold to the grid. The developer is responsible for all development (engineering, operation, financing, etc.) of the power plant. In exchange for a long-term lease (30–40 years), the customer receives (1) the power from the power plant built on their land should the grid fail and (2) "in kind consideration" (IKC) for the land. IKC can take the form of cash payment but more often involves needed infrastructure upgrades at the installation or facility (substation work to accept the power during a utility outage, advanced power controls, etc.). All financial concerns fall on the developer—selling the power, paying back loans, etc. The customer receives needed resiliency with no cash outlay. The main drawback to the customer is that the leased land is not available for use (expansion) for 30–40

[4] https://www.energy.gov/sites/prod/files/2020/08/f77/financing-microgrids.pdf

years. Use of EUL for energy system resilience enhancement can be illustrated by the following example described in Yamanaka (2020).

The Army Office of Energy Initiatives (OEI), US Army Garrison-Hawaii (USAG-HI), and Hawaiian Electric Company (HECO) developed the 50 MW Schofield Generating Station (SGS) to provide grid stability and to increase resilience for the Army and island of Oahu. The Army provided HECO a 35-year lease for 3 ha (8 acres) for SGS. In lieu of lease rent payment, HECO modified their existing 46 kV infrastructure to create a Schofield microgrid that enables SGS to provide dedicated power within 2 hours of an Army request for Schofield Barracks, Wheeler Army Airfield, Field Station Kunia, and South Range. SGS consists of six 8.3 MW, quick-start reciprocating internal combustion engines that operate on diesel or biodiesel (Fig. 10.9). This configuration provides the flexibility needed to mitigate Oahu's renewable variability and increase the amount of solar and wind on the HECO system. It also meets the Army's power and resilience requirements. Since the Schofield microgrid requires only four of the units to meet all power needs, two units are redundant, which further increases resilience. Over 5 days of fuel is always stored on site with enough storage capacity to store 13 days of fuel.

The lease requires 3 million gallons of biodiesel be used annually to contribute to Federal renewable goals. To provide additional flexibility, the Army will perform annual reviews to ensure that the biofuel requirement remains mutually beneficial and cost-effective throughout the term of the lease.

Because SGS provides power to all HECO customers during normal conditions, it is a rate-based asset and paid for by all HECO customers. HECO finances, constructs, owns, operates, and maintains the SGS and the microgrid infrastructure. The Army continues to purchase power through existing contracts with no premium charge when microgrid services are used.

As the only power generation facility on Oahu located above the tsunami strike zone, this plant will dramatically improve the resiliency of the entire island grid network. It can also black-start other plants in the event of island wide blackout to improve restoration to benefit the entire community beyond the military.

According to HECO, this project represents about $167 million in capital investment and approximately 315 jobs during construction and 10 during operations.

Fig. 10.9 50 MW HECO Schofield Generating Station located on Schofield Barracks, HI

References

Anderson, Katherine H., Dylan S. Cutler, Daniel R. Olis, Emma M. Elgqvist, Xiangkun Li, Nicholas D. Laws, Nicholas A. DiOrio, and H.A. Walker. 2017. *REopt: A platform for energy system integration and optimization*, Technical report NREL/TP-7A40-70022. Golden: National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy17osti/70022.pdf.

ISO (International Organization for Standardization). 2017. *Buildings and constructed assets – Service life planning – Part 5: Life-cycle costing*, ISO 15686-5:2017(en). Geneva: ISO.

Jungclaus, Matt, Cara Carmichael, Chris McClurg, Margaret Simmons, Randall Smidt, Kinga Porst Hydras, Sharon Conger, Alexander Zhivov, Fred Winter, John Shonder, and Cyrus Nasseri. 2017. Deep energy retrofits in federal buildings: the value, funding models, and best practices. *ASHRAE Transactions* 123 (1): 55–70.

Kimman, J., R. Rovers, and R. Ravesloot. 2010. *Toward 0-impact buildings and built environments*. Amsterdam: Techne Press. ISBN:978-90-8594-028-9.

LaCommare, Kristina, Peter Larsen, and Joseph Eto. 2017. *Evaluating proposed investments in power system reliability and resilience: Preliminary results from interviews with public utility commission staff*, LBNL-1006971. Berkeley: Lawrence Berkeley National Laboratory. https://doi.org/10.2172/1342947.

Laws, N.D., K. Anderson, N.A. DiOrio, X. Li, and J. McLaren. 2018. Impacts of valuing resilience on cost-optimal PV and storage systems for commercial buildings. *Renewable Energy* 127: 896–909.

Lohse, R., and A. Zhivov. 2019. *Deep energy retrofit guide for public buildings – Business and financial models*. Basel: Springer.

Marqusee, Jeffrey, Craig Schultz, and Dorothy Robyn Noblis. 2017. *Power begins at home: Assured energy for U.S. military bases*, 24. Reston: Noblis, Inc. https://www.pewtrusts.org/~/media/assets/2017/01/ce_power_begins_at_home_assured_energy_for_us_military_bases.pdf.

Murphy, Caitlin, Eliza Hotchkiss, Kate Anderson, Clayton Barrows, Stuart Cohen, Sourabh Dalvi, Nick Laws, Jeff Maguire, Gord Stephen, and Eric Wilson. 2020. *Adapting existing energy planning, simulation, and operational models for resilience analysis*, NREL/TP-6A20-74241. Golden: NREL. https://www.nrel.gov/docs/fy20osti/74241.pdf.

Schröder, T., and W. Kuckshinrichs. 2015. Value of lost load: An efficient economic indicator for power supply security? A literature review. *Frontiers in Energy Research* 3: 55. https://www.frontiersin.org/articles/10.3389/fenrg.2015.00055/full.

Viscusi, W. Kip, and Joseph E. Aldy. 2003. The value of a statistical life: A critical review of market estimates throughout the world. *Journal of Risk and Uncertainity* 27 (1): 5–76.

Yamanaka, Keith. 2020. Hawaiian Electric Company Schofield Generating Station. Information Paper IMHW-PW.

Zhivov, Michael. 2020. Enhanced life-cycle cost analysis of sustainable office buildings. *ASHRAE Transactions* 126 (1): 691–712.

Zhivov, Alexander M., Michael Case, Richard Liesen, Jacques Kimman, and Wendy Broers. 2014. Energy master planning towards net zero energy communities/campuses. *ASHRAE Transactions* 119 (1): 325. NY-14-010. New York: ASHRAE winter conference.

Appendices

Appendix A. Building Metrics and EMP Framing Constraints for Different Countries

A.1 Building Energy Use Maximums (Limits), Targets, and Related Metrics for Different Countries

Table A1: United States
Table A2: United States
Table A3: Australia
Table A4: Austria
Table A5: Denmark
Table A6: Finland
Table A7: Norway
Table A8: United States
Table A9: United States

A.2 Summary of EMP Framing Constraints and Limits That Affect Technology Selection by Country

Table A10: Multiple countries (Tables A.1, A.2, A.3, A.4, A.5, A.6, A.7, A.8, A.9, and A.10).

A. Zhivov, *Energy Master Planning toward Net Zero Energy Resilient Public Communities Guide*, https://doi.org/10.1007/978-3-030-95833-6

Table A.1 United States: Building primary energy use targets for existing buildings in the United States (targets also available in ANSI/ASHRAE/IES Standard 100)

Energy use targets by building activity (EUI) (I-P Units)[a]																		
No.	**Commercial building type**	**EUIs by building type by climate zone (source kBtu/ft²-year)**																
		ASHRAE Climate Zone																
		1A	**2A**	**2B**	**3A**	**3B Coast**	**3B Other**	**3C**	**4A**	**4B**	**4C**	**5A**	**5B**	**5C**[2]	**6A**	**6B**	**7**	**8**
1	Administrative/professional office	130	134	120	138	100	118	98	114	94	124	93	93	95	103	97	111	156
2	Bank/other financial	185	190	170	196	142	168	140	161	134	177	132	133	137	146	138	158	222
3	Government office	162	167	149	172	125	148	123	142	118	155	116	117	120	129	121	139	195
4	Medical office(non-diagnostic)	111	114	102	118	85	101	84	97	80	106	79	80	81	88	83	95	133
5	Mixed-use office	151	155	139	160	116	137	114	131	109	144	108	108	110	119	112	129	181
6	Other office	126	130	116	133	97	114	95	110	91	120	90	90	93	100	94	108	151
7	Laboratory	595	588	521	581	448	503	470	483	413	551	404	419	442	446	433	480	637
8	Distribution/shipping center	41	52	50	66	33	54	42	67	54	67	69	67	59	95	83	116	217
9	Nonrefrigerated warehouse	20	25	24	32	16	26	21	32	26	33	33	32	29	46	40	56	105
10	Convenience store	449	487	413	505	387	423	418	413	357	484	345	362	407	373	367	401	507
11	Convenience store with gasoline	362	393	333	407	312	341	336	333	288	390	278	292	329	300	296	323	408
12	Grocery store/food market	374	406	344	421	323	353	348	344	298	403	288	302	339	310	306	334	422
13	Other food sales	113	123	104	127	98	107	105	104	90	122	87	91	102	94	93	101	128
14	Fire station/police station	219	217	192	214	165	185	173	178	152	203	149	154	163	164	160	177	235
15	Other public order and safety	200	197	175	195	150	169	158	162	139	185	136	140	149	150	145	161	214
16	Medical office (diagnostic)	112	108	99	106	92	98	79	79	73	87	59	66	68	60	62	59	67
17	Clinic/other outpatient health	167	162	149	159	137	147	119	119	109	130	88	100	102	90	93	89	101
18	Refrigerated warehouse	231	228	202	225	174	195	182	187	160	213	157	162	171	173	168	186	247
19	Religious worship	78	77	68	76	59	66	62	63	54	72	53	55	59	59	57	63	84
20	Entertainment/culture	78	77	68	76	58	66	61	63	54	72	53	55	59	58	56	62	83

21	Library	205	202	179	200	154	173	161	166	142	189	139	144	151	154	149	165	219
22	Recreation	88	87	77	86	66	75	70	72	61	82	60	62	66	66	64	71	95
23	Social/meeting	92	91	81	90	69	78	73	75	64	85	62	65	68	69	67	74	99
24	Other public assembly	94	93	82	92	71	80	74	76	65	87	64	66	71	71	69	76	101
25	College/university	206	205	185	207	138	179	150	184	148	201	159	151	163	184	167	201	298
26	Elementary/middle school	126	124	110	124	93	106	94	102	85	111	82	82	85	89	84	94	139
27	High school	150	149	134	151	100	130	109	131	105	145	110	106	115	127	116	139	206
28	Preschool/day care	163	160	141	160	120	137	122	131	110	144	105	106	112	115	108	122	179
29	Other classroom education	84	84	75	85	56	72	61	73	58	81	62	60	66	71	65	78	115
30	Fast food	873	895	801	920	723	811	746	762	668	875	641	674	720	700	684	757	957
31	Restaurant/cafeteria	472	485	429	499	384	435	405	413	361	480	347	364	405	376	371	410	516
32	Other food service	258	265	235	273	210	238	221	226	197	262	190	199	222	206	203	224	282
33	Hospital/inpatient health	473	477	427	468	408	422	385	358	307	416	269	283	329	274	268	276	319
34	Nursing home/assisted living	281	278	246	274	211	237	222	228	195	260	191	198	207	211	205	226	301
35	Dormitory/fraternity/sorority	134	142	129	157	96	132	119	144	115	166	127	123	127	144	136	164	229
36	Hotel	165	169	147	171	142	149	142	136	124	161	111	123	129	118	121	125	144
37	Motel or inn	185	176	160	169	145	154	137	129	119	147	102	113	120	107	107	110	132
38	Other lodging	177	168	153	162	139	147	131	123	113	141	98	108	115	103	103	105	126
39	Vehicle dealership/showroom	164	167	149	175	115	146	125	149	123	160	131	131	142	150	142	167	240
40	Retail store	94	96	85	100	66	83	71	85	71	92	75	75	81	86	81	96	137
41	Other retail	163	167	149	174	114	145	124	148	123	159	130	130	139	150	141	166	239
42	Post office/postal center	143	141	125	139	107	121	112	116	99	132	97	100	105	107	104	115	153
43	Repair shop	95	94	83	93	71	80	75	77	66	88	64	67	71	71	69	77	102
44	Vehicle service/repair shop	110	109	96	108	83	93	87	89	76	102	75	77	81	83	80	89	118
45	Vehicle storage/maintenance	48	47	42	47	36	40	38	39	33	44	32	34	37	36	35	39	51

(continued)

Table A.1 (continued)

Energy use targets by building activity (EUI) (I-P Units)[a]																		
No.	**Commercial building type**	**EUIs by building type by climate zone (source kBtu/ft²-year)**																
		ASHRAE Climate Zone																
		1A	**2A**	**2B**	**3A**	**3B Coast**	**3B Other**	**3C**	**4A**	**4B**	**4C**	**5A**	**5B**	**5C[2]**	**6A**	**6B**	**7**	**8**
46	Other service	201	199	176	196	152	170	159	163	140	186	137	142	149	151	147	162	216
47	Strip shopping mall	197	196	176	206	140	174	151	178	147	196	158	157	173	182	172	203	291
48	Enclosed mall	187	187	167	196	133	165	143	170	140	186	151	149	166	173	164	194	277
No.	**Residential building type**	**EUIs by building type by climate zone (source kBtu/ft²-year)**																
		ASHRAE climate zone																
		1A	**2A**	**2B**	**3A**	**3B Coast**	**3B Other**	**3C**	**4A**	**4B**	**4C**	**5A**	**5B**	**5C[2]**	**6A**	**6B**	**7**	**8**
49	Mobile home	126	134	121	148	90	125	111	135	108	156	119	116	120	136	128	154	216
50	Single family-detached	94	99	90	110	67	92	83	101	80	116	88	86	88	101	95	115	160
51	Single family-attached	108	114	104	126	77	106	95	116	93	134	102	99	102	116	109	132	184
52	Apartment in 2–4 unit	159	168	152	186	113	156	140	170	136	196	149	146	149	170	160	194	270
53	Apartment in 5+ unit	108	114	104	126	77	106	95	116	92	134	102	99	102	116	109	132	184

Source: Oak Ridge National Laboratory, T. R. Sharp, calculated from U.S. DOE/EIA Commercial Buildings and Residential Energy Consumption Surveys (CBECS and RECS) microdata

[a]Based on U.S. DOE/EIA CBECS 2003 and RECS 2005 microdata

Note: Site to source multipliers used to create Table 3: electricity- 3.34 kBtu source/kWh site; fossil fuel- 1.047 kBtu source/kBtu site, except for College/University buildings where fossil fuel- 1.22 kBtu source/kBtu site was used (since college/university buildings are often on district heating systems)

Table A.2 United States: Building site energy use targets for existing buildings in the United States (targets also available in ANSI/ASHRAE/IES Standard 100)

Energy use targets by building activity (EUI) (I-P Units)[a]																		
No.	**Commercial building type**	**EUIs by building type by climate zone (kBtu/ft^2-year)**																
		ASHRAE climate zone																
		1A	**2A**	**2B**	**3A**	**3B Coast**	**3B Other**	**3C**	**4A**	**4B**	**4C**	**5A**	**5B**	**5C[2]**	**6A**	**6B**	**7**	**8**
1	Administrative/professional office	39	40	39	42	33	39	33	46	40	40	48	42	39	54	47	58	81
2	Bank/other financial	55	57	56	59	46	55	47	65	56	57	68	59	56	76	67	82	115
3	Government office	49	50	49	52	41	48	42	57	49	50	60	52	49	67	59	72	101
4	Medical office (non-diagnostic)	33	34	33	35	28	33	28	39	34	34	41	36	33	46	40	49	69
5	Mixed-use office	45	46	45	48	38	45	39	53	46	47	56	48	45	62	55	67	94
6	Other office	38	39	38	40	32	37	32	44	38	39	47	40	38	52	46	56	78
7	Laboratory	178	176	171	175	147	165	159	194	173	179	209	187	181	232	211	249	331
8	Distribution/shipping center	12	16	16	20	11	18	14	27	23	22	36	30	24	49	40	60	113
9	Nonrefrigerated warehouse	6	8	8	10	5	9	7	13	11	11	17	14	12	24	19	29	54
10	Convenience store	135	146	135	152	127	139	141	166	150	157	178	162	167	193	179	208	263
11	Convenience store with gas	108	118	109	122	102	112	114	133	121	126	144	130	135	156	144	168	212
12	Grocery store/food market	112	122	113	127	106	116	118	138	125	131	149	135	139	161	149	174	219
13	Other food sales	34	37	34	38	32	35	36	42	38	40	45	41	42	49	45	53	66
14	Fire station/police station	66	65	63	64	54	61	59	71	64	66	77	69	67	85	78	92	122
15	Other public order and safety	60	59	57	59	49	55	53	65	58	60	70	63	61	78	71	84	111
16	Medical office (diagnostic)	33	32	32	32	30	32	27	32	30	28	30	30	28	31	30	31	35
17	Clinic/other outpatient health	50	48	49	48	45	48	40	48	46	42	46	45	42	47	45	46	52
18	Refrigerated warehouse	69	68	66	68	57	64	62	75	67	69	81	72	70	90	82	96	128
19	Religious worship	23	23	22	23	19	22	21	25	23	23	27	25	24	30	28	33	43
20	Entertainment/culture	23	23	22	23	19	21	21	25	23	23	27	24	24	30	28	32	43
21	Library	61	61	59	60	50	57	55	67	60	61	72	64	62	80	73	86	114

(continued)

Table A.2 (continued)

22	Recreation	26	26	25	26	22	24	24	29	26	26	31	28	27	34	31	37	49
23	Social/meeting	28	27	26	27	23	26	25	30	27	28	32	29	28	36	33	39	51
24	Other public assembly	28	28	27	28	23	26	25	31	27	28	33	30	29	37	33	39	52
25	College/university	62	61	60	62	45	58	50	72	60	65	78	65	65	90	78	99	147
26	Elementary/middle school	38	37	36	37	30	35	32	41	36	36	42	37	35	46	41	49	72
27	High school	45	45	44	46	33	42	37	52	44	47	57	48	47	66	57	72	107
28	Preschool/day care	49	48	46	48	39	45	41	52	46	47	54	47	46	60	53	63	93
29	Other classroom education	25	25	25	25	18	24	21	29	25	26	32	27	27	37	32	40	60
30	Fast food	261	268	263	277	237	266	253	305	280	284	332	301	295	364	333	393	497
31	Restaurant/cafeteria	141	145	141	150	126	143	137	166	151	156	179	163	166	195	181	213	268
32	Other food service	77	79	77	82	69	78	75	91	83	85	98	89	91	107	99	116	146
33	Hospital/inpatient health	142	143	140	141	134	138	130	143	129	135	139	126	135	142	130	144	166
34	Nursing home/assisted living	84	83	81	83	69	78	75	91	82	84	99	88	85	109	100	118	156
35	Dormitory/fraternity/sorority	40	43	42	47	31	43	40	58	48	54	65	55	52	75	66	85	119
36	Hotel	50	51	48	52	47	49	48	55	52	52	57	55	53	61	59	65	75
37	Motel or inn	55	53	52	51	48	50	46	52	50	48	53	50	49	56	52	57	69
38	Other lodging	53	50	50	49	46	48	44	49	48	46	50	48	47	53	50	55	66
39	Vehicle dealership/showroom	49	50	49	53	38	48	42	60	52	52	68	58	58	78	69	87	124
40	Retail store	28	29	28	30	21	27	24	34	30	30	39	33	33	45	40	50	71
41	Other retail	49	50	49	52	37	48	42	59	52	52	67	58	57	78	69	86	124
42	Post office/postal center	43	42	41	42	35	39	38	46	41	43	50	45	43	56	51	60	79
43	Repair shop	28	28	27	28	23	26	25	31	28	28	33	30	29	37	34	40	53
44	Vehicle service/repair shop	33	33	32	32	27	31	29	36	32	33	39	35	33	43	39	46	61
45	Vehicle storage/maintenance	14	14	14	14	12	13	13	16	14	14	17	15	15	19	17	20	27

46	Other service	60	60	58	59	50	56	54	65	59	60	71	63	61	78	71	84	112
47	Strip shopping mall	59	59	58	62	46	57	51	71	62	63	82	70	71	94	84	106	151
48	Enclosed mall	56	56	55	59	44	54	49	68	59	60	78	67	68	90	80	101	144
No.	Residential building type	EUIs by building type by climate zone (kBtu/ft^2-year)																
		ASHRAE climate zone																
		1A	2A	2B	3A	3B Coast	3B Other	3C	4A	4B	4C	5A	5B	5C[2]	6A	6B	7	8
49	Mobile home	38	40	40	45	30	41	38	54	45	51	62	52	49	71	62	80	112
50	Single family-detached	28	30	30	33	22	30	28	40	34	38	46	38	36	52	46	60	83
51	Single family-attached	32	34	34	38	25	35	32	46	39	43	53	44	42	60	53	69	96
52	Apartment in 2–4 unit	47	50	50	56	37	51	47	68	57	64	77	65	61	89	78	101	140
53	Apartment in 5+ unit	32	34	34	38	25	35	32	46	39	43	53	44	42	60	53	68	96

Source: Oak Ridge National Laboratory, T. R. Sharp, calculated from U.S. DOE/EIA Commercial Buildings and Residential Energy Consumption Surveys (CBECS and RECS) microdata

[a]Based on U.S. DOE/EIA CBECS 2003 and RECS 2005 microdata

Table A.3 Australia: Building energy use limits for residential buildings in Australia (buildings must achieve the 6-star values shown)

NatHERS star band criteria (Energy loads [thermal] in MJ/m^2.annum)

Climate zone	Location	Energy rating (stars)											
		0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6
1	Darwin	853	773	706	648	598	555	516	480	446	413	381	349
2	Port Hedland	643	569	507	455	411	373	340	310	284	260	237	215
3	Longreach	654	550	465	396	340	294	257	226	200	178	159	141
4	Camarvon	209	181	157	137	120	105	93	82	73	66	59	53
5	Townsville	337	309	283	259	238	218	200	183	168	153	140	127
6	Alice Springs	681	562	464	385	321	269	228	196	170	148	130	113
7	Rockhampton	344	295	255	222	194	171	152	136	122	110	99	90
8	Moree	597	481	388	315	258	214	180	155	135	119	106	94
9	Amberley	407	334	275	226	187	157	132	113	97	85	75	67
10	Brisbane	245	203	167	139	116	97	83	71	62	55	48	43
11	Coffs Harbour	286	232	188	153	125	103	86	73	63	55	49	44
12	Geraldton	349	285	233	191	158	132	112	96	83	73	64	57
13	Perth	483	387	311	251	204	167	139	118	102	89	79	70
14	Armidale	801	661	545	451	375	314	266	227	195	169	147	128
15	Williamtown	429	349	284	232	191	159	133	114	98	86	76	67
16	Adelaide	584	480	394	325	270	227	192	165	143	125	109	96
17	Sydney East	286	230	184	148	120	98	81	68	58	50	44	39
18	Nowra	517	423	346	284	235	195	164	140	121	105	92	81
19	Charleville	525	434	359	298	249	209	177	151	131	114	100	87
20	Wagga	804	663	548	455	380	321	273	235	204	178	156	137
21	Melbourne	676	559	462	384	321	271	230	198	171	149	131	114
22	East Sale	791	653	541	449	376	317	269	231	201	175	153	133
23	Launceston	895	740	615	513	431	366	314	272	237	208	183	160

24	Canberra	957	792	657	547	458	387	330	284	247	216	189	165
25	Cabramurra	1666	1404	1188	1012	870	753	658	580	513	454	401	352
26	Hobart	876	723	598	498	417	354	303	262	229	202	177	155
27	Mildura	660	541	444	367	305	256	218	187	163	143	126	110
28	Richmond (NSW)	555	450	365	298	245	2D3	171	146	127	112	99	87
29	Weipa	830	743	671	611	560	517	479	445	414	384	355	326
30	Wyndham	1229	1071	943	839	754	685	626	576	530	488	447	406
31	Willis Island	427	391	359	330	305	282	261	242	224	207	191	176
32	Caims	330	302	276	253	232	214	197	181	167	153	140	128
33	Broome	732	652	585	531	486	448	416	387	360	335	310	285
34	Learmouth	511	439	379	330	290	256	228	204	184	166	149	134
35	Mackay	275	248	224	202	183	165	150	136	123	112	102	92
36	Gladstone	220	191	167	146	129	114	101	90	81	73	66	59
37	Halls Creek	755	649	563	492	434	387	348	315	286	259	235	211
38	Tennant Creek	631	545	473	414	366	325	291	262	236	213	191	170
39	Mt Isa	656	560	481	417	363	320	284	253	227	205	184	164
40	Newman	631	527	442	373	318	273	237	207	183	162	144	127
41	Giles	517	429	357	298	252	215	185	161	142	126	111	98
42	Meekatharra	437	358	293	241	200	167	141	120	104	91	79	70
43	Oodnadatta	596	495	412	344	289	244	208	179	155	135	118	103
44	Kalgoorlie	490	396	320	259	211	173	144	122	105	91	80	70
45	Woomera	552	446	362	295	243	203	172	148	130	115	102	90
46	Cobar	580	469	379	308	253	210	176	151	131	115	101	89
47	Bickley	595	485	397	325	269	224	189	161	140	122	107	94

Source: Australian building code (2019)

Table A.4 Austria: Building energy use limits for Austria (heating energy use limits for non-residential buildings)

		Neubau	Größere Renovierung
$HWB_{Ref,RK}{}^{a}$ in [kWh/m²a]	ab Inkrafttreten bis 31.12.2016	$16 \times (1 + 3{,}0/l_c)$	$23 \times (1 + 2{,}5/l_c)$
	ab 01.01.2017	$14 \times (1 + 3{,}0/l_c)$	$21 \times (1 + 2{,}5/l_c)$
$HWB_{max,Ref,RK}{}^{a}$ in [kWh/m²a]	ab Inkrafttreten bis 31.12.2016	54,4	–
	ab 01.01.2017	47,6	–
$KB^{*}_{max,RK}$ in [KWh/m³a]	ab Inkrafttreten bis 31.12.2016	1,0	2,0
	ab 01.01.2017		
$HEB_{RK}{}^{a}$ in [kWh/m²a]	ab Inkrafttreten bis 31.12.2016	$HEB_{max,WG,RK}$	$HEB_{max,WGsan,RK}$
	ab 01.01.2017		
$EEB_{RK}{}^{a}$ in [kWh/m²a]	ab Inkrafttreten bis 31.12.2016	$EEB_{max,WG,RK}$	$EEB_{max,WGsan,RK}$
	ab 01.01.2017		

Source: Guidelines of the Austrian Institute of Building Technology, March 2015

[a]… bezogen auf eine Geschoßhöhe von 3,00 m mit Nutzungsprofil Wahngebäude

Table A.5 Danish Methodology for calculating building energy demand maximums in Denmark

Energy framework of BR18 for new buildings	
Dwellings, student accommodations, hotels, etc.	**Offices, schools, institutions, etc.**
Total energy demand per year must not exceed:	Total energy demand per year must not exceed:
$30{,}0 + \frac{1{,}000}{\text{heated floor area}}\ \text{kWh/m}^2\ \textit{per year}$	$41{,}0 + \frac{1{,}000}{\text{heated floor area}}\ \text{kWh/m}^2\ \textit{per year}$

Source: Energy Requirements of BR18. A quick guide for the construction industry on the Danish Building Regulations 2018

Table A.6 Finland: Building energy use limits for Finland

Intended use category	Limit for E-value $kWh_E/(m^2\ a)$
Category 1) Small residential building:	
a) Detached houses and link-detached houses with a net heated area (A_{net}) of 50–150 m²	200–0.6 A_{net}
b) Detached houses and link-detached houses with a net heated area (A_{net}) exceeding 150 m² but not exceeding 600 m²	
c) Detached houses and link-detached houses with a net heated area (A_{net}) exceeding 600 m²	116–0.04 A_{net}

Intended use category	Limit for E-value $kWh_E/(m^2\ a)$
d) Terraced houses and blocks of flats with residential storeys on a maximum of two storeys	92 105
Category 2) Blocks of flats with residential storeys on at least three storeys	90
Category 3) Office buildings, health centres	100
Category 4) Commercial buildings, department stores, shopping centres; wholesale and retail trade buildings, excluding grocery trade units under 2000 m^2; shopping halls, theatres, open, concert and congress halls, cinemas, libraries, archives, museums, art galleries, exhibition halls	135
Category 5) Accommodation establishment buildings, hotels, boarding houses, assisted living accommodation, retirement homes, residential care institutions	160
Category 6) Education and training buildings and daycare centres	100
Category 7) Buildings for sports and physical exercise, excluding indoor swimming pools and indoor ice rinks	100
Category 8) Hospitals	320
Category 9) Other buildings, warehouses, transport and communications buildings, indoor swimming pools, indoor ice rinks, grocery trade units under 2000 m^2, portable buildings	no limit

Source: Decree of the Ministry of the Environment on the Energy Performance of New Buildings

Table A.7 Norway: Building energy use limits (total net energy use requirement) for Norway

Table: Energy budgets

Building category	Total net energy requirement [kWh/m^2 heated gross internal area per year]
Small houses and leisure homes with more than 150 m^2 of heated gross internal area	100 + 1600/m^2 heated gross internal area
Block of flats	95
Kindergarten	135
Office building	115
School building	110
University/university college	125
Hospital	225 (265)
Nursing home	195 (230)
Hotel building	170
Sports building	145
Commercial building	180
Cultural building	130
Light industry/workshop	140 (160)

Source: Regulations on technical requirements for construction works, July 2017

Table A.8 United States: Building energy use metrics for existing buildings in the United States (metrics also available in ASHRAE Handbook: 2019 HVAC Applications)

				Calculated, Weighted Energy Use Index (EUI) values					
				Source energy, MJ/year per gross square metre					
	Calculated, weighted			Percentiles					
Building use	Number of buildings, thousand	Floor Area 10^9 m^2	Actual number of buildings, N	10th	25th	50th	75th	90th	Mean
Administrative/professional office	558	0.84	766	547	880	1379	2059	3452	1776
Bank/other financial	91	0.08	79	1285	1663	2653	3409	4193	2707
Bar/pub/lounge	71	0.03	60	1228	1914	3427	6073	7504	4226
Clinic/other health	87	0.12	135	728	1207	1768	2622	4703	2216
College/university	27	0.17	104	886	1195	1803	2674	4329	2467
Convenience store	79	0.03	47	2120	3924	7456	12,750	15,798	8125
Convenience store with gas station	52	0.02	32	3692	7396	8692	12,091	15,835	9348
Courthouse/probation office	6	0.04	26	1483	1799	2396	2757	3156	2354
Distribution/shipping center	151	0.53	307	207	431	773	1259	1822	920
Dormitory/fraternity/sorority	25	0.07	48	365	723	1341	2165	2364	1404
Elementary/middle school	189	0.57	397	612	904	1258	1751	2665	1506
Enclosed mall	1	0.08	34	404	1479	2121	2438	3030	1872
Entertainment/culture	51	0.12	89	132	550	893	1961	3379	1604
Fast food	92	0.03	94	2732	6277	11,451	17,338	21,630	12,080
Fire station/police station	69	0.05	53	480	731	1263	2236	2832	1596
Government office	113	0.25	205	653	1132	1755	2631	3337	1954
Grocery store/food market	45	0.07	48	3092	4749	5627	7478	8789	5985
High school	43	0.28	142	756	1075	1606	2190	3258	1861

Hospital/inpatient health	10	0.22	409	2354	3430	5427	6420	7495	5111
Hotel	30	0.24	159	1207	1472	2060	2623	4362	2437
Laboratory	16	0.04	41	1488	2040	4066	5857	13045	5815
Library	24	0.07	37	1012	1602	1804	2385	2562	1885
Medical office (diagnostic)	60	0.05	62	431	912	1541	2295	2871	1791
Medical office (non-diagnostic)	50	0.03	42	632	913	1524	1832	2259	1523
Mixed-use office	125	0.25	212	391	715	1305	1886	2858	1529
Motel or inn	61	0.06	61	1007	1531	1834	2890	4311	2282
Non-refrigerated warehouse	427	0.50	350	71	215	538	1037	1737	739
Nursing home/assisted living	30	0.12	94	1068	1901	2667	4321	5488	3095
Other	109	0.14	87	44	516	1017	2684	6977	2456
Other classroom education	62	0.07	62	447	637	1011	1858	2332	1300
Other food sales	1	0.00	2	5123	5976	5976	5976	5976	5784
Other food service	37	0.01	27	177	1246	3114	7032	11496	4426
Other lodging	13	0.04	27	925	990	1750	3051	3947	1996
Other office	74	0.04	52	433	705	1101	2138	2891	1506
Other public assembly	41	0.06	63	541	851	1201	1807	3805	1774
Other public safety	9	0.04	22	1631	2199	3464	4183	4786	3409
Other retail	59	0.03	41	427	1047	1984	3433	5314	2425
Other service	114	0.06	83	359	707	1236	2387	8343	2719
Post office/postal	30	0.04	26	724	1279	1644	1835	2231	1586
Preschool/daycare	68	0.04	50	691	1112	1606	2351	3269	2057
Recreation	100	0.18	127	435	562	1225	2383	4117	1827
Refrigerated warehouse	8	0.04	21	541	1264	3009	5596	10856	4389
Religious worship	412	0.42	352	195	368	642	1067	1849	915
Repair shop	84	0.05	53	298	447	932	1794	2627	1153

(continued)

Table A.8 (continued)

	Calculated, weighted			Calculated, Weighted Energy Use Index (EUI) values; Source energy, MJ/year per gross square metre; Percentiles					
Building use	Number of buildings, thousand	Floor Area 10^9 m^2	Actual number of buildings, N	10th	25th	50th	75th	90th	Mean
Restaurant/cafeteria	179	0.10	180	1569	3174	6653	11,094	14,522	7649
Retail store	336	0.42	294	385	639	1478	2447	3750	1750
Self-storage	209	0.15	81	71	137	449	1035	2486	981
Social/meeting	135	0.09	98	282	505	1127	1933	3541	1466
Strip shopping mall	163	0.47	296	1171	1934	2947	4726	6053	3678
Vacant	296	0.30	247	26	114	274	711	1251	541
Vehicle dealership/showroom	43	0.05	34	495	1009	1522	2963	3990	2078
Vehicle service/repair	214	0.15	149	346	671	1247	2044	3361	1603
Vehicle storage/maintenance	176	0.12	113	182	461	837	1414	3278	1471
SUM or Mean for sector	5557	8.09	6720	289	658	1328	2494	5207	2315

Source : Oak Ridge National Laboratory, T. R. Sharp, calculated from U.S. DOE/EIA 2012 CBECS microdata

Table A.9 Building energy use metrics for existing buildings in the United States (metrics also available in ASHRAE Handbook: 2019 HVAC Applications)

Table A5 2012 U.S. Commercial Sector Floor Area and EUI Percentiles*

	Calculated, weighted			Calculated, Weighted Energy Use Index (EUI) values Site energy, MJ/year per gross square metre Percentiles					
Building use	Number of buildings, thousand	Floor area, 10^9 m^2	Actual number of buildings, N	10th	25th	50th	75th	90th	Mean
Administrative/professional office	558	0.84	766	218	356	577	820	1388	712
Bank/other financial	91	0.08	79	516	673	1002	1299	1723	1059
Bar/pub/lounge	71	0.03	60	479	740	1240	2618	3522	1873
Clinic/other health	87	0.12	135	241	490	718	1009	1622	885
College/university	27	0.17	104	299	442	620	998	1796	980
Convenience store	79	0.03	47	691	1252	2486	4048	5154	2754
Convenience store with gas station	52	0.02	32	1310	2469	2802	3981	5253	3246
Courthouse/probation office	6	0.04	26	579	776	1056	1190	1190	988
Distribution/shipping center	151	0.53	307	80	181	324	508	811	396
Dormitory/fraternity/sorority	25	0.07	48	116	229	595	727	1318	594
Elementary/middle school	189	0.57	397	231	323	525	800	1214	641
Enclosed mall	1	0.08	34	306	489	707	797	1041	660
Entertainment/culture	51	0.12	89	54	231	432	829	1197	654
Fast food	92	0.03	94	1088	2219	4671	7842	9585	5126
Fire station/police station	69	0.05	53	152	360	642	938	1590	725
Government office	113	0.25	205	243	405	644	925	1468	762
Grocery store/food market	45	0.07	48	1176	1518	2241	2657	3418	2203
High school	43	0.28	142	261	481	670	992	1428	800

(continued)

Table A5 2012 U.S. Commercial Sector Floor Area and EUI Percentiles*

	Calculated, weighted			Calculated, Weighted Energy Use Index (EUI) values — Site energy, MJ/year per gross square metre — Percentiles					
Building use	Number of buildings, thousand	Floor area, 10^9 m^2	Actual number of buildings, N	10th	25th	50th	75th	90th	Mean
Hospital/inpatient health	10	0.22	409	979	1519	2058	2985	3463	2259
Hotel	30	0.24	159	482	645	747	1131	1876	1006
Laboratory	16	0.04	41	507	841	1730	2424	7118	2386
Library	24	0.07	37	321	509	745	972	1122	738
Medical office (diagnostic)	60	0.05	62	203	378	643	835	1164	691
Medical office (non-diagnostic)	50	0.03	42	255	337	555	725	1021	592
Mixed-use office	125	0.25	212	161	287	504	726	1305	621
Motel or inn	61	0.06	61	345	517	624	1221	1552	874
Non-refrigerated warehouse	427	0.50	350	23	72	197	448	849	304
Nursing home/assisted living	30	0.12	94	573	860	1255	1800	2196	1439
Other	109	0.14	87	14	179	445	1366	2617	1118
Other classroom education	62	0.07	62	145	267	421	1002	1311	633
Other food sales	1	0.00	2	2075	2470	2470	2470	2470	2381
Other food service	37	0.01	27	56	395	1045	2286	3649	1542
Other lodging	13	0.04	27	426	637	808	1446	1804	967
Other office	74	0.04	52	137	249	460	893	1415	658
Other public assembly	41	0.06	63	211	366	637	889	2083	801
Other public safety	9	0.04	22	735	837	1345	1431	1625	1236
Other retail	59	0.03	41	242	451	795	1443	1881	905
Other service	114	0.06	83	154	276	540	1223	3598	1487
Post office/postal	30	0.04	26	337	515	717	878	1008	698

Preschool/daycare	68	0.04	50	304	407	736	941	1387	827
Recreation	100	0.18	127	169	280	569	988	1694	748
Refrigerated warehouse	8	0.04	21	285	401	955	2623	3446	1454
Religious worship	412	0.42	352	78	143	280	570	933	473
Repair shop	84	0.05	53	94	162	387	849	1315	566
Restaurant/cafeteria	179	0.10	180	680	1414	3218	5442	7391	3665
Retail store	336	0.42	294	126	259	574	939	1428	689
Self-storage	209	0.15	81	23	44	143	383	789	327
Social/meeting	135	0.09	98	90	201	418	1002	1400	630
Strip shopping mall	163	0.47	296	440	672	1175	2004	3011	1596
Vacant	296	0.30	247	8	45	127	343	573	240
Vehicle dealership/showroom	43	0.05	34	246	393	693	1143	1615	869
Vehicle service/repair	214	0.15	149	128	246	505	1011	1832	810
Vehicle storage/maintenance	176	0.12	113	64	188	368	836	1507	697
SUM or Mean for sector	5557	8.09	6720	101	262	563	1046	2182	982

Source: Oak Ridge National Laboratory, T. R. Sharp, calculated from U.S. DOE/EIA 2012 CBECS microdata

Table A.10 Framing constraints and limits that affect technology selection by country[a]

		Country-Specific Limits		
Constraint Category	Constraint (that could limit technology selection)	U.S.A.	Norway	Australia, Denmark, Finland, Germany, UK
1. Natural Constraints: Locational Threats	**Regional/local air quality**	Assess (US-NAAQS)		
	Low-lying area (flooding)	Constraint typically impacts the way technologies are installed (bermed, raised, etc.), not technology selection.		
	Extreme temperatures			
	Extreme/high humidities			
	High winds, Fire, Lightning			
	Ground threats (volcano, earthquake, etc.)	Constraint typically impacts the way technologies are installed (isolated, hardened, etc.), not technology selection.		
2. Natural Constraints: Locational Resources	**Solar insolation; Wind; Biomass; Land & Roof area;**	Limit is local amount available		
	Electricity; Natural Gas; Liquid fuels (oil, LPG, etc.)			
	District chilled or hot water; District steam; Water			
3. Energy & Water Distribution & Storage Systems	**Electricity; Natural gas; Fuel oil; District chilled or hot water; District steam**	Limits are local distribution and storage capacities	Limits are local distribution and storage capacities. Installation of fossil fuel heating systems not permitted (NO19)	Limits are local distribution and storage capacities
	Water (domestic/potable)			

			Country-Specific Limits						
Constraint Category		Constraint (that could limit technology selection)	U.S.A.	Denmark	Finland	Norway	Germany	United Kingdom	Australia
4. Building and Facility Constraints	**4a. Energy use and efficiency**	**Energy use (site)**	Military (Army): Maximum annual energy use limits by building type (US1). Commercial: Maximum annual energy use limits by building type if standard adopted (Std100). Outperform simulated reference building or perscriptive requirements if standard or code adopted (Std90.1, IECC)			Natl code has max kWh/m2 values by building type (net demand, i.e. without efficiency of technical systems). (NO15, 16, 17, 18). (BREEAM-Nor, NS3700, NS3701)	Outperform simulated reference building. EnEV-Energy Saving Ordinance (DE1)		
		Energy use (primary/source)	Maximum annual energy use limits by building type if adopted by local code (Std100)	Maximum annual kWh/m^2 by building type (DK1).	Maximum annual KWh/m^2 by building type. (F1)	Requirements (BREEAM-Nor, NS3700, NS3701)	EnEV (DE1) regulates primary energy demand for newly built buildings as well of existent buildings. There are no explicit limits.		Maximum annual hourly average kJ/m^2-h by building type. (NCC Sec. JP1). Class 6 building, 80 kJ/m^2.h; Class 5, 7b, 8 or 9a building or Class 9b school, 43 kJ/m^2.h; Other classes (with limits): 15 kJ/m^2.h.

(continued)

Table A.10 (continued)

Constraint Category		Constraint (that could limit technology selection)	Country-Specific Limits U.S.A.	Denmark	Finland	Norway	Germany	United Kingdom	Australia
		Energy efficiency	Commercial and Military: Minimum thermal requirements of building components (walls, roofs, etc.) Minimum air tightness. (Std90.1, IECC)			Requirements on U-values for the envelope, SFP, air thightness, and cold bridges (National Building Code) (NO15-18, BREEAM-Nor, NS3700, NS3701)		1. Building Regulations and Government Buying Standard Minimum (UK4, UK5) 2. Defence Related Environmental Assessment Methodology, DREAM (UK6)	National limits (NCC, Sec. J). State limits. (c) solar radiation being utilised for heating;
	4b. Environmental	**Renewables**		Must use renewables. District heating assumed (DK1)		Heating systems using fossil fuels are not allowed. (NO 17, NO 20)	Fixed quotas for heating and cooling.	No obligation to include renewables.	No obligation to include renewables.
		Emissions	None at building level.			Requirements. (BREEAM-Nor, NS3700, NS3701)		Must achieve Target CO2 Emissions Rate (Building Regulations) (UK4)	None at building level.

	4c. Operational	**Resilience**	Military: 14-day, grid-independent operation for critical facilities. (US2)			Buildings heating over 1000 m^2 shall: a) have energy flexible heating systems, b) be adaptable to low-temperature heating solutions. (NO19)		No set standard, assessed on individual basis to meet resilience requirements.	
		Financial/Cost				Requirements (NO18)		Government: DREAM or equivalent (e.g. CEEQUAL6, BREEAM7 etc.) assessment required. New projects require 'excellent' and major refurbishments require 'very good' rating (Regulations/Govt Buying Std). (CEEQual, BREEAM, UK4, UK5, UK6)	
		Maintenance (simple, low cost)						Different Regulation Documents for home based UK Countries	
		Work force							
		Critical facility							

(continued)

Table A.10 (continued)

		Country-Specific Limits						
Constraint Category	Constraint (that could limit technology selection)	U.S.A.	Denmark	Finland	Norway	Germany	United Kingdom	Australia
5. Indoor Environment Constraints	**Indoor temperature (DB-dry bulb/ WB-wet bulb)**	U.S. Army: Occupied: min DB: 70F, max. DB: 75F Unoccupied (short term) min DB: 55F,max DB: 85F Unoccupied (long term) min DB: 40F,max DB:none Critical equipment min DB: Equip min Critical equipment max DB: Equip max Commercial: Comfort zones limits vary by occupant conditions if	Requirements exist (DK1). Occupied min: 20 C Occupied max: 26 C (cooling penalty). Dwellings: Max 100 h above 27 C and 25 h over 28 C; Offices/buildings with similar usage pattern: Max 100 h above 26 C and 25 h over 27 C. Recommendations for minimum workplace temperatures.	Requirements exist (F1). Heating season: 20–26 °C Other time: 20–32 °C (30 °C old people's house)			As per CIBSE Guide A—Environmental Design (UK2). MOD Estate—Joint Service Publication 315—Building Performance Standards Estate Wide Standards and Guidance (UK3).	Maximum contaminant limits
	Humidity	U.S. Army: Occupied maximun: 50% Unoccupied (short term) max: 50% Unoccupied (long term) max: 50% Critical equipment max: 50% or equipment max Commercial: Limits vary by occupant conditions if standard adopted (Std55)	Recommendations exist (DK1).		Requirements (NO8-NO12)		As per CIBSE Guide A—Environmental Design (UK2). MOD Estate—Joint Service Publication 315—Building Performance Standards Estate Wide Standards and Guidance (UK3).	Refer to NABERS Energy for Offices (NABERS)
	Lighting levels	Level requirements if code adopted (US3).	Lighting levels and daylighting requirements.		Requirements (NO6)		Regulated (UK2, UK3)	
	Radon	Mitigation in states of NJ,WA,MI,MN,MD, OR,IL,MA,CT			Requirements (NO5)			

	Ventilation	Requirements per person and area per space occupancy category when code adopted (Std62)	Requirements per person and area by building type (daycares, shools, etc.) (DK1)	Requirements per person and area by building type	Requirements per unit area.		Regulated (UK2, UK3)	Required per person and area based on occupancy category
6. Equipment in Buildings and District Systems Constraints	**Space heating**	Min efficiencies by equipment type (Std90.1, IECC)	Minimum efficiencies by equipment type.				Equipment energy efficiency requirements (Building Regulations and Government Buying Standard Minimum) (UK4, UK5)	Minimum efficiencies by equipment type (AU1) per Equipment Energy Efficiency Program (E3) Performance rating of water-chilling and heat pump water heating packages using vapor compression (AHRI 551/591). Gas fired water heaters for hot water supply & central heating (AS 4552)
	Space cooling							
	Ventilation equipment	Numerous control requirements (US-Std 90.1/US-IECC)	Minimum efficiency and maximum power use		Energy efficiency requirements (NO1,NO2,NO3)			
	Humidity control equipment	Equipment requirements (Std 90.1)			Requirements. (NO8, NO9, NO12)			
	Water heating equipment	Service water heating requirements (Std90.1, IECC)	Minimum efficiencies by equipment type. (DK1)	Min/max hot water temp. 50 °C, 65 °C	Requirements. (NO19, NO21)			
	Cooking equipment							
	Waste handling equipment				Requirements. (NO45,NO46,NO47, NO48,NO49)			
	Control systems	Specific controls requirements (Std90.1, US-IECC)	Minimum efficiency					
	Combustion-type electric generation systems	Emission and noise limits (NSPS, NESHAP, US4). Local noise/nuisance ordinaces.				Regulated emissions & noise.		
	District steam/hot water, chilled water	Minimum efficiencies by equipment type.(Std 90.1, IECC)						

[a]Note references for this table are identified in brackets "( )" and are provided in the published paper: *Energy Master Planning: Identifying Framing Constraints that Scope Your Technology Options*, Sharp et. al., ASHRAE Transactions 2020, Volume 126, Part 1.

Appendix B. Case Studies Summary

Experience without theory is blind,
but theory without experience is mere intellectual play.
Immanuel Kant

B.1 Introduction

Wherever humans have lived, they had to cope with everyday challenges and rare disruptive events that threatened their lives. Buildings, energy systems, and in fact all infrastructure comprise a built environment designed to protect and comfort us. In a general sense, the challenge has always been to either adapt to local circumstances by using potentials to handle those challenges or to run away and look for a better place to live.

We now enjoy the benefit of a great lot of technological aid that helps us to cope with the environment. The challenges we have to face have also evolved; weather extremes threaten our complex and often vulnerable infrastructure. Moreover, in many countries of the world, infrastructure built since industrialization that was designed for high efficiency or that is deteriorating must be modernized to enable the use of more renewable energy.

So, what are the barriers to applying our knowledge to create a truly integrated, efficient, resilient energy infrastructure? The first significant obstacle is the difficulty in overcoming entrenched habits. People are creatures of habits; we like to continue doing what we have always done. Moreover, we have created structures, both in legislation and infrastructure that allow for certain solutions and prevent others. A second barrier is cost; innovative or special solutions usually incur investment cost that are higher than the costs of traditional technologies. If the primary motivation for our actions is to maximize profit in the short term, then that assumption allows no room for better solutions that might be more cost-effective in the long run, over the life cycle of newer, innovative technologies. A third barrier is complexity; integrated systems require cooperation and communication. At the start, integrated systems take longer to involve all stakeholders, but over the long term, they create better solutions. In general, better integrated solutions often require more cooperation and communication and a larger first investment. Up to now, it seems that this additional effort is not being made in most cases. If we wish to meet the need to continuously adapt to the changing environment, then our ways of planning and building must also evolve.

Let us look at places where people handle their local challenges and demands in an exemplary way. They have used experience and know-how gathered over a long time, learned from unsuccessful tries, and invested time, effort, and resources to build better. They considered possible threats and local potentials and cooperated in large teams to reach truly admirable results. Let us learn from these cases and see what methods were applied and what might be done even better in the future. Let us find out where people struggled to go on and experience the bottlenecks that they encountered to learn from them.

One part of the Annex 73 project "Towards Net Zero Energy Resilient Public Communities" was to investigate case studies of community energy master planning. The goal of this study was to investigate how energy master planning for entire communities is performed and to find out how it can be improved. Thus, in each of the participating countries, cases of community master planning have been chosen, studied, and analyzed. Case studies included military camps, universities, research institutes, hospitals, small communities, towns, and large cities. In most of these cases, the buildings and systems under investigation were publicly owned. Systems included critical infrastructure like data servers or life-sustaining systems, so resilience and reliability play an important role in the master planning process.

The impact of local climate conditions is a crucial factor that influences the choice of energy supply systems. The described case studies are located in different areas of the world, ranging from tropical regions in Australia to icy Greenland.

This appendix briefly summarizes case studies developed under the Annex 73 "Towards Net Zero Energy Resilient Public Communities" that have been documented and published separately in the case studies book (IEA 2021), which includes more detailed information on the drivers, the goals, and the methods used for planning, implementation, and financing and on the obtained results and lessons learned by the project owners.

Here, we include only a brief information about case studies and describe lessons learned that were helpful in development of the guide. While most of the case studies developed under this project and summarized in Sect. B.2 pertain to civilian communities, there are still few case studies on military installations. Other recent studies describe case studies done on military installations (Zhivov et al. 2014, 2015a, b, Liesen et al. 2015; Case et al. 2015). Section B.3 provides a tabular listing of case studies, categorized by relevant attributes like energy use, climate conditions, and business models.

Section B.4 summarizes the main lessons learned derived from the studied best practices, and Sect. B.5 groups the lessons learned according to categories in the master planning process. Here, we describe what can be drawn from the studied cases, specifically to improve the design of the energy master planning process.

Finally, Sect. B.6 concludes with a brief summary of the current trends in energy master planning and gives a projected overview of the future of community energy master planning processes.

B.2 Case Study Overview

To simplify this complex topic, the case studies were broken into three categories (types):

- Type 1 case studies focus on energy supply systems in large cities, towns, and villages. Here, buildings are considered to be consumers that are connected to

the supply systems. For energy planning, building-level energy production facilities are compared with the energy system energy production. Additionally, spare and backup capacities can be installed to serve critical demand in some buildings.
- Type 2 case studies focus on campuses such as univerity campus, millitary installations, and research centers, in which groups of buildings are analyzed along with their energy supply systems.
- Type 3 case studies focus on single components that may have been added to enhance an energy supply system. Most of these cases are from Finland and address heat recovery using heat pump or heat storage systems integrated into traditional energy supply systems.

The case studies can also be differentiated by their state of completion. Some case studies (e.g., some of the Danish cases) investigated existing energy supply systems from a historical viewpoint by analyzing how it was possible to plan and implement these systems and offered conclusions on long-term performance and operation. Other cases focused on planned actions that are currently in process or nearing completion. In such cases, the planning process itself is the focus of the case study.

The case studies are presented in Table B.1, which includes information on the location (country, location) as well as the type of use (type). In addition, a graphical representation of the case study has been inserted, which can be a photo, rendering, map, or scheme. The symbols in the last column represent special points of attention. The legend for these symbols is shown in Fig. B.1.

B.3 Categorization of Case Studies

To allow for a faster and more efficient analysis, case studies were categorized according to different attributes. Categorization includes type of case, climate, energy sources, storage methods, redundancy, and many more. Categorization has been performed by various teams and leads to different results, depending on what was focused on. The results are shown in tables in this appendix. Appendix E discusses energy system architectures. The following sections give a short overview and introduction to the case studies and some information drawn from categorization.

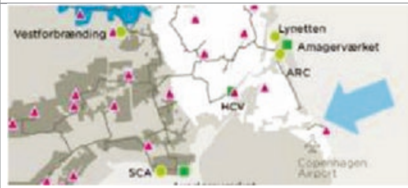
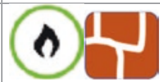
“Campus” and “District” are distinguished as separate “Types of Case Study.” Case studies on universities, military installations, and other cases where buildings and their energy systems have been studied in combination are considered to be “campuses.” Case studies that treat district heat and/or cooling networks, and often more specifically include single measures or components installed to enhance these networks, are considered to be “districts.”

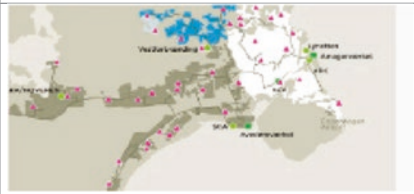
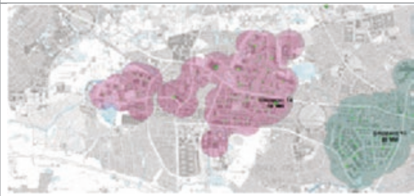
Table B.1 List of case studies conducted in Annex 73

Case No.	Country	Location	Specific type	Photo	Special points of attention
1	Australia	Townsville	University campus		
2	Australia	Cairns	University campus		
3	Austria	Innsbruck	University campus		

(continued)

Table B.1 (continued)

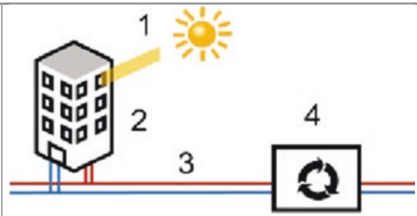
Case No.	Country	Location	Specific type	Photo	Special points of attention
4	Austria	Vienna	University campus		
5	Denmark	Skrydstrup	Military air base		
6	Denmark	Taarnby	Energy supply system District heating in a town including a large airport campus		

7	Denmark	Taarnby	Energy supply system District cooling in an urban development area		
8	Denmark	Greater Copenhagen	Energy supply system District heat in a large city including 20 communities and many campuses		
9	Denmark	Vestforbrænding	Energy supply system District heating in five suburbs		
10	Denmark	DTU close to Copenhagen	University campus District heating and cooling in a university campus		

(continued)

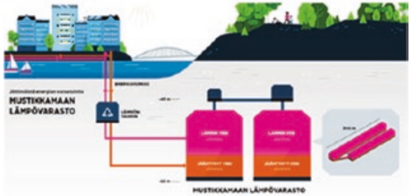
Table B.1 (continued)

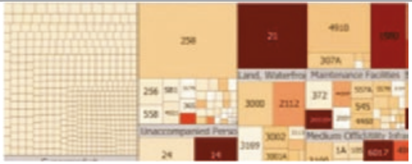
Case No.	Country	Location	Specific type	Photo	Special points of attention
11	Denmark, Greenland	Quaanaap	District District heating in a small town		
12	Denmark	Danfoss Campus	Campus Company campus		
13	Denmark	Favrholm	Energy supply system District heating and cooling in urban development		
14	Denmark	Gram	Energy supply system District heating in a small town		

15	Finland	Helsinki Kalasatama	Single components SunZEB building for district		
16	Finland	Merihaka	Campus District refurbishment		
17	Finland	Helsinki Esplanadi Park	Single component Heat pump for district heat		
18	Finland	Helsinki Katri Vala	Single component Heat pump for district		

(continued)

Table B.1 (continued)

Case No.	Country	Location	Specific type	Photo	Special points of attention
19	Finland	Helsinki Mustikkamaan	Single component Heat storage for district		
20	Finland	Helsinki Kruunuvuori	Single component Seasonal heat storage for district		
21	Germany	Stuttgart	University campus		
22	Germany	Detmold	Campus Education campus		

23	Germany	Karlsruhe-Rintheim	Energy supply system District		
24	United States	Guam	Campus Military town		
25	United States	Texas Fort Bliss	Campus Military town		
26	United States	Denver National Western Center	Campus		

(continued)

Table B.1 (continued)

Case No.	Country	Location	Specific type	Photo	Special points of attention
27	United States	St. Paul	Campus New district		
28	United States	Austin	University campus		
29	United States	Davis	Campus Research center		
30	Canada	Vancouver	University campus		

31	United States	Fort Bragg	Campus Military town		
32	Norway	Trondheim	University campus		

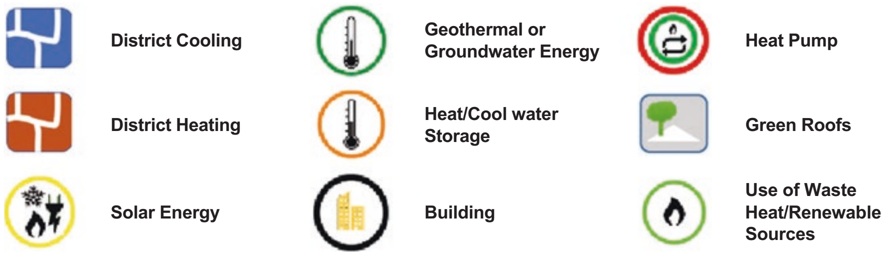


Fig. B.1 Symbols for special points of attention to be used to highlight focus of case studies

Table B.2 Case studies come from different countries and climate zones

Country	Type of case study	Climate zone
Australia	Campus	Tropical monsoon
		Tropical savanna
Austria	Campus	Humid continental
Canada	Campus	Oceanic
Denmark	Campus	Temperate
	District	Arctic
		Temperate
Finland	Campus	Humid continental
	District	Humid continental
Germany	Campus	Humid continental
	District	Humid continental
United States	Campus	Cold desert to hot desert
		Humid
		Humid subtropical
	District	Mediterranean
		Semiarid continental
		Tropical rainforest
Norway	Campus	Oceanic and humid continental

B.3.1 Climate

Case studies include different countries and climate zones, as listed in Table B.2.

B.3.2 Energy System

The use of local resources and energy storage was investigated for each case study. Table B.3 lists the type of energy needed in the area of interest (AOI), i.e., cold, heat, and power; energy sources used; storage type; and climate. As the data in Table B.3 indicate, thermal storage is common. Heat storage has been realized in

Table B.3 Case studies have different energy needs and energy system architectures, depending on climate zone and locally available resources

Study name	Main energy needs	Energy sources	Storage	System architecture	Climate zone (according to IECC/ASHRAE)
James Cook University, Townsville, Queensland	Power, cooling	Power grid	Thermal	Type 1.3.2	Tropical savanna
James Cook University, Cairns Queensland	Power, cooling	Power grid	Thermal	Type 1.3.2	Tropical monsoon
University of Innsbruck, Technology Campus	Power, heating, cooling	Power grid, heat from gas, groundwater		Type 1.3.4	Humid continental
Vienna University of Economics and Business, Campus	Power, heating, cooling	Power grid, groundwater + heat pump	Groundwater	Type 1.3.4	Humid continental
Air Base Skrydstrup, Denmark	Power, heating,	CHP, biogas	Thermal and power	Type 1.2.1	Temperate
Taarnby district heating	Heating	Waste heat, CHP, gas, heat pump	Thermal	Type 3.1.1	Temperate
Taarnby district cooling	Cooling	Ambient, waste, heat pump	Thermal	Type 2.3.4.1	Temperate
Greater Copenhagen District heating	Heating	Waste heat, CHP, gas, heat pump	Thermal	Type 1.3.4	Temperate
Vestforbrænding District Heating	Heating	Waste heat, CHP, gas, heat pump	Thermal	-	Temperate
Danish Technical University	Power, heating	Power grid, waste heat, CHP, gas, heat pump	Thermal	Type 2.3.4.3	Temperate
Quaanaap district heating	Power, heating	CHP		Type 4.3.1	Arctic
Favrholm Urban development district	Heating	Waste heat, CHP, gas, heat pump	Thermal	Type 3.3.4	Temperate
Denmark, Danfoss campus	Power, heating, process heat	Waste heat, CHP, heat pumps, power grid	Thermal	Type 1.3.1	Temperate
Village of Gram	Heating	Waste heat, CHP, gas, heat pump	Large-scale thermal	Type 2.3.1.1	Temperate
SunZEB Kalasatama	Heating, cooling	Heat recovery, heat pump	Large-scale thermal	Type 2.3.4.1	Humid continental
Horizon 2020 Lighthouse project MYSMARTLIFE actions in Merihaka retrofitting area				Type 3.1.2	Humid continental

(continued)

Table B.3 (continued)

Study name	Main energy needs	Energy sources	Storage	System architecture	Climate zone (according to IECC/ASHRAE)
Esplanadi Park	Heating, cooling	Waste heat, heat pump	Large-scale thermal	Type 1.3.4	Humid continental
Katri Vala	Heating, cooling	Waste heat, heat pump	Large-scale thermal	Type 1.3.4	Humid continental
Mustikkamaan	Heating, power			Type 1.3.4	Humid continental
Kruunuvuori				Type 1.3.4	Humid continental
HFT Stuttgart	Power, heating, cooling, solar	Power grid, district heat		Type 1.3.1	Humid continental
Detmold	Power, heating	Power grid, district heat		Type 1.3.1	Humid continental
Karlsruhe-Rintheim	Power, heating	Power grid, district heat		Type 1.3.1	Humid continental
Guam	Power, cooling	Power grid		Type 1.1.3.1	Tropical rainforest
Fort Bliss	Power, heating, cooling	Power grid		Type 1.1.3.1	Cold desert to hot desert
National Western Center in Denver, CO	Power, heating, cooling	Power grid, waste heat from sewage, and heat pumps		Type 1.2.3	Semi-arid continental
St. Paul Ford site in St. Paul, MN	Power, heating, cooling		Thermal	Type 1.3.4	Continental
UT Austin	Power, heating, cooling	Power grid, emergency generators	Thermal	Type 2.3.4	Humid subtropical
University of California, Davis	Power, heating, cooling	Power grid, solar thermal	Thermal	Type 1.2.4	Mediterranean
University of British Columbia	Power, heating, cooling	Power grid, renewables	Thermal	Type 1.3.1	Oceanic
Fort Bragg	Power, heating, cooling			Type 1.1.3.1	Humid
NTNU Gløshaugen campus	Power, heating	Power grid, solar PV, district heating, waste heat, heat pump, biogas CHP		Type 1.3.1	Oceanic and humid continental

almost all cases with district heating and cooling systems. Thermal energy storage becomes a necessity, especially when volatile resources are used. Power storage is often provided in the form of diesel power units. The data in Table B.3 do not consider this kind of backup, which in many cases is locally available, especially to accommodate the needs of critical infrastructure.

To allow for a more efficient energy system design, system architectures have also been categorized. The categories are identified by a combination of numbers, e.g., column 5 ("System Architecture") of Table B.3 (e.g., Type 1.1.3.1,). The method behind this numbering is described in detail in Chap. 8, including a standardized graphical representation of the energy system architecture. In some case studies, the energy system has been mapped following this methodology. Figures B.2, B.3, B.4, and B.5 show the results.

With a special focus on technologies, energy systems of some case studies have been categorized according to a series of characteristics that have been developed together with the classification of energy system architectures. Figure B.6 shows the result of this work. The full table can be found in Annex 73 book of case studies (2021).

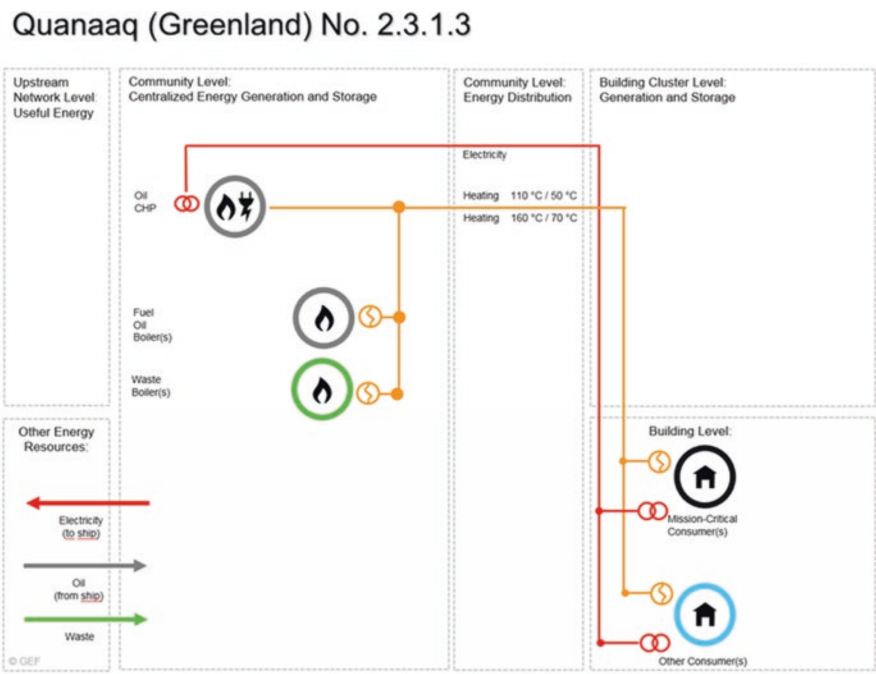


Fig. B.2 Energy system architecture for case study on Qaanaaq, Greenland

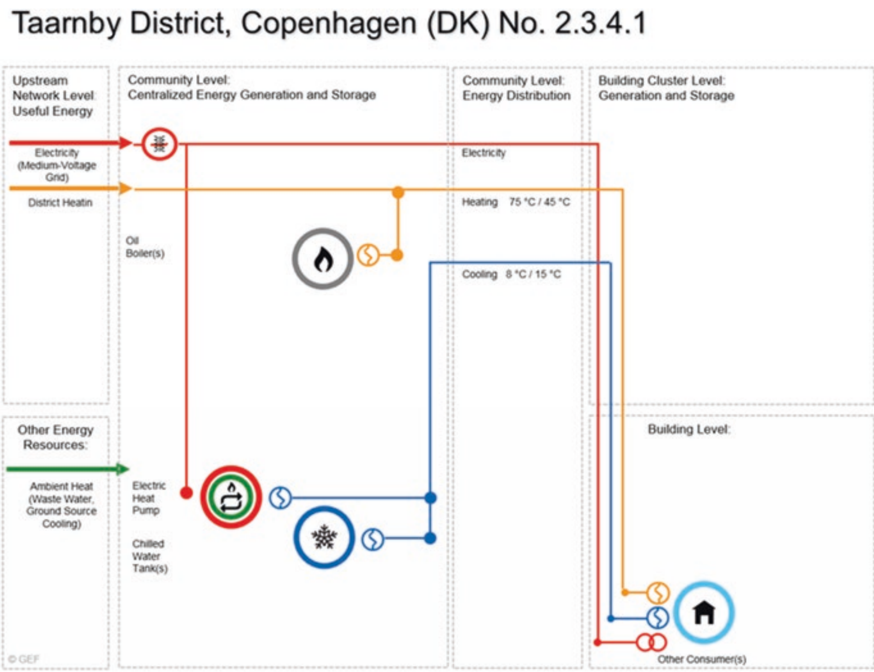


Fig. B.3 Energy system architecture for case study on district cooling in Taarnby, Denmark

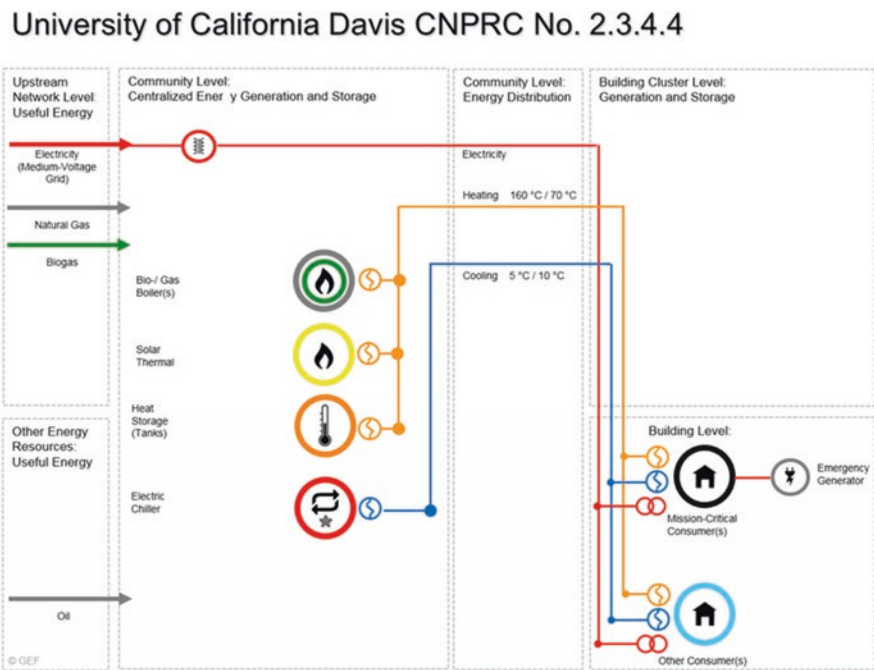


Fig. B.4 Energy system architecture for case study on University of California, Davis, United States

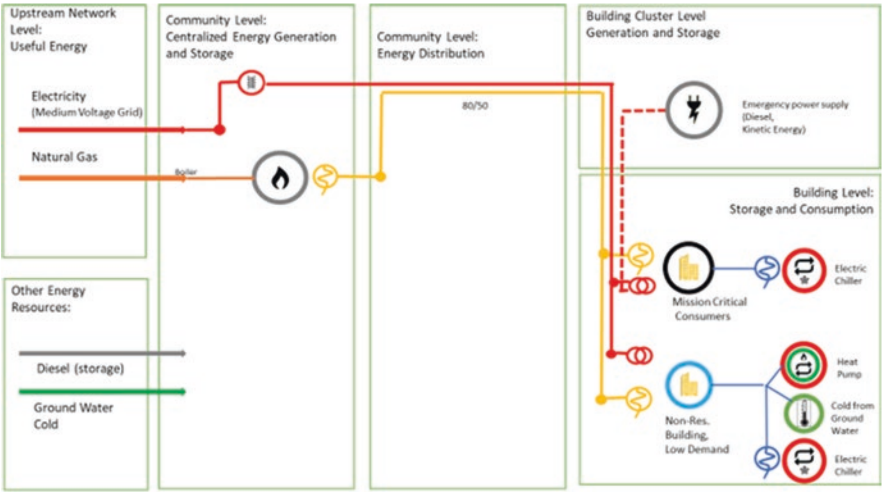


Fig. B.5 Energy system architecture of the University Campus Technik in Innsbruck (AUT). The system is of type 1.3.4

	Classification System					Case		District heating				District cooling		Renewable energy				CHP			
System design and case number	Type of example	Spatial location	Buildings to be supplied from the outside with ...	No. of example	Indexation	Case number (Task B)	Energy system example (Task C)	Steam system	District heating system (160/70)	District heating system (110/80/50)	District heating system (70/60/40)	High temperature cooling 10/15	District cooling system (5/10)	Solar Heating	Deep geothermal	Solar PV	Wind turbine	Oil CHP	Gas CHP	Biomass CHP	Waste CHP
1	Best practice examples	At community level	Power + heating	Example 1	2.3.1.1	Quanaaq, Greenland	---	---	---	X	---	---	---	---	---	---	---	X	---	---	---
2	Best practice examples	At community level	Power + heating + cooling	Example 1	2.3.4.1	Taarnby district heating	---	---	---	X	---	---	---	---	---	---	---	---	---	X	X
3	Best practice examples	At community level	Power + heating + cooling	Example 2	2.3.4.2	Taarnby district cooling	---	---	---	X	X	X	---	---	---	---	---	---	X	X	X
4	Best practice examples	Combination	Power + heating + cooling	Example 2	2.4.4.2	Greater Copenhagen district heating	---	---	---	X	X	X	X	---	---	---	---	---	X	X	X

Fig. B.6 Detail of classification table from technology database

B.3.3 Drivers

We closely reviewed the case studies to identify the driving forces for change. Common drivers include campus growth, growing demand of supply, economic reasons like oil crisis, supply costs, taxes, and targets that have been fixed by governments. Table B.4 lists pertinent details from the case studies.

Table B.4 Drivers for master planning processes, as documented in case studies, sorted by country

Australia
Campus growth, system load
Austria
Building age, indoor conditions Demonstration, operation costs
Canada
Living lab, aging infrastructure, carbon tax
Denmark
Reduce cost for the society including cost of greenhouse gas emissions. City growth, cost efficiency, and lower prices for the consumers. Comfort, lower costs, and flexibility. Costs, resilience, efficiency, living lab, and cooling. Growing cooling demand, symbiosis between district cooling and district heating. More available space in buildings and no environmental problems with cooling. Avoided energy production facilities in buildings and in local neighborhood. Oil crisis, Denmark will for political reasons not rely on certain regimes. Reduce dependence on oil. Reduce use of fossil fuel, resilience, and efficiency.
Finland
Attractive apartment buildings. Climate change. Climate change mitigation. Regulation. Reduce GHG emissions. Find alternative energy sources for district heating and cooling. Initial drivers often vary and may arise from individual needs.
Germany
Aging systems Aging systems and low comfort High consumption and costs New quarter
United States
Aging systems and demonstration Campus growth, costs, and GHG emissions New district Regulation Regulation and installation growth
Norway
Campus growth, different building age cohorts High-energy consumption (both electricity and heating) Goal of achieving a zero energy/emission neighborhood in 2050 Greenhouse gas reduction

The full categorization table is added to this report as attachment. It contains objectives, measures for efficiency, measures for resilience, climate change impacts, and other useful information.

B.3.4 Financing and Business Models

The case studies identified some typical business models (also, see Table B.5):

- Identified solutions are typically lower in life cycle costs than the existing (base line) solution or alternatives. Thus, investment can be paid off by the tenant over the life cycle.
- Projects are often owned by public entities like energy providers or communities. These have access to market credits at low interest rates and often even give a guarantee for the loans. In some cases, money from government bonds has been used instead of capital market loans.

Table B.5 Categories of financing/business models in the best practice cases

Project owner	Financing	Resilience	Cost reduction by	Example cases
Public/ municipality	Financed on capital market, guaranteed by municipality	Asked for by law, reliable grids	Use of renewables, diverse generation plants, switching between energy sources	Most Danish cases
Public/ university	Public funds	By efficiency, demand reduction, and storage	Efficiency, avoided costs of installing higher capacity	Australia
Private	Financed on capital market, proprietary capital, and 25% public funds	Reliable grids, local generation	Efficiency	Denmark, Danfoss
Public	Financed on capital market and by national bonds	UPS in case of necessity, reliable grids, local generation	Use of renewables, efficiency	Austria
Public utility company	Loans from financial institutions (capital market) and proprietary capital	By redundant energy generation	Use of previously waste heat by storage and heat pump, cogeneration of cold, heat	Finland
Public, department of defense	Financed by operation and maintenance budgets	Financed by bundling these measures to energy efficiency cost reducing ones	Energy efficiency	United States
Public/ municipality	Energy system is created, owned, and operated by private company that sells the energy		Use of waste heat, energy efficiency, renewable power production	United States
Private, University	Financed on capital market, partly supported by public funds for renewable energy	Redundant supply, smart grid	Efficiency, cost-effective generation of own power and heat, use of alternative sources like of landfill gas	United States

- In some cases, public funding was used to support part of the project like solar energy production or studies on life cycle costs.
- When setting up new district energy systems for cooling, investments are at least partly covered by connection fees and fixed annual payments of future customers.
- Banks and financing institutes are often involved in the planning phase to offer competitive financing.

Apart from this, some variants and sometimes innovative business models have been found in the context of the case studies:

- In Denmark, most energy systems are owned by communities. This has shown to be most profitable for the local community. To benefit from market forces, some services are outsourced to private companies.

It was a political decision to allow communities to have their own companies for gas, heat transmission, and distribution. These companies operate completely independently from municipal budgets; all costs are covered by tariffs, and the municipality can guarantee for loans.

- Some cases from Denmark deal with distributed ownership, for example, if district heating grids are combined to increase resilience and optimize reaction to energy costs. The District Heat Act specifies that no profit can be made in heat supply, so the approach is to cover costs of each player.
- District cooling is not bound by any such regulation. However, district cooling must compete with consumer individual solutions and is coupled with district heating due to the co-creation of heat and cooling.
- In case of the Danish Danfoss, a private company modernized its infrastructure. The payback period for investments was 3.1 years, which was below expectation. Public funding provided 25% of project's financing.
- In Gram, Denmark, the district heating for storage and heat generation is provided by contractors.
- Sponsorship is another form of financing, as realized at WU Vienna, Austria (Vienna University of Economics and Business), where specific university institutes were sponsored by a private company (which provided funding in exchange for access to research results and publicity) (WU Vienna, Austria).
- WU Vienna (Austria) also provides an example in which the university and a public building company shared responsibility by creating a shared venture that planned, owns, and operates the campus.
- The case study in Merihaka, Finland, focused on an existing district where energy efficiency measures need to be established. Here, a lack of suitable financing methods for the private apartment owners has been identified and is addressed by the local energy supplies.
- Stuttgart University has considered different financing options like intracting, contracting, green bonds, and crown-financing, before settling with public finance.
- The military settlement in Guam had a need to increase resilience. Analysis of measures showed that demand reduction and energy efficiency measures could

be used to finance resilience measures. Thus, measure bundles attractive for third-party investment (public utility investment and private energy performance service contracts) were created.

- The case study at the US Army Installation Fort Bliss shows that, depending on the goal or type of energy measures and the ownership of the energy system (privatized or public), the approach can vary between using existing utility privatization contracts, operation and maintenance budgets, military construction, and third-party financing like utility energy saving contracts. Most US Army projects are projected to be funded using operation and maintenance budgets.
- In the case of the Denver National Western Center, the city as building owner did not have the funds to invest and thus issued the energy systems to a private company that will be repaid for investments through utility bills (private public partnership, contracting).
- US university campus refurbishment projects, including the energy systems, are often privately owned by the university itself. Investments can be justified based on future savings and can be obtained at reasonable cost on the capital markets.

B.4 Lessons Learned in Best Practices

In the case studies, projects owners were asked about major success factors, bottlenecks, and lessons learned. The following sections summarize the answers to these questions.

B.4.1 Success Factors

We have grouped the success factors identified in the case studies into four main topics: goals, cooperation, integration, and analysis.

It is critically important to know the case study's goals. The experience of Danish energy system planning institute Rambøll, which is responsible for most of the Danish case studies, shows that goals often differ according to stakeholder role:

- For a campus owner, the goal will typically be to minimize the total life cycle cost of providing a sufficient indoor climate and resilient energy supply, based on energy prices at the campus gate, including taxes and subsidies.
- For local communities, the goal of the planning authority will typically be to minimize the total life cycle cost of providing a sufficient low-carbon and resilient energy supply to all buildings and campuses in the community, based on energy prices at the city gate, including taxes and subsidies.
- For the national community, the goal of the planning authority will typically be to minimize the total life cycle cost of providing a sufficient low-carbon and resilient energy supply to all buildings and campuses in the country, based on import/export energy prices, excluding taxes and subsidies.

Another factor often mentioned in the case studies is cooperation. To find the best solution for a community, it is important that all major stakeholders cooperate and give access to all necessary information to the planning authority and that, later, they become part of the solution according to their role. Before implementation, it is important that all agree on how to share the benefits of the best solution and on how to implement it.

Integration of local potentials and possible reactions to rare catastrophic events has also been important in the studied cases. In Denmark, planning teams draw on rich experience gathered in at least four decades of planning and implementing integrated energy systems. When systems are to change, experts consider planning one or two levels above the project and improve projects by identifying the smart sector integration:

- To plan installations in a building, it is necessary to consider planning at the campus and city level.
- To plan installations in a campus, it is necessary to consider planning at the city level.
- To plan at the city level, it is necessary to consider planning at the national level.

Calculation and analysis have also been reported as important methods to help achieve good results with the limited resources. Chart B.1 lists the major success factors. Some of them have appeared in many case studies or are general conclusions from the case studies. Others refer to one specific case study, which is then mentioned for cross-reference.

Chart B.1. Major Success Factors Identified in the Case Studies

Goals and Framework

- Define clear goals, targets, and priorities from the start.
- Have a framework for your planning and for analyzing and evaluating proposed alternative options.
- Tying the project to the strategic goals (carbon neutrality and others) of the city, energy company, and real estate developers (e.g., the SunZEB, Finland case study).
- The energy infrastructure in the area, especially the connection to the large central heat pump, was a key enabler (SunZEB, Finland).

Cooperation

- Identify, involve, engage, and manage all stakeholders (as described in case study on Ford Site, United States).
- Gather support and ensure engagement from main stakeholders and drivers right from the start.
- Have a clear mandate; define clear roles and clear responsibilities; and find suitable organizational structure (e.g., the WU Vienna, Austria case study).
- Gather a strong and well-rounded project team that encompasses major stakeholders (UC Davis, United States).
- Establish good, frequent communication and team spirit as these projects last (usually) for several years (e.g., the WU Vienna, Austria and HFT Stuttgart, Germany case studies).
- Trust in people, technology, and concepts.
- If necessary, build up trust in smaller pre-projects and demonstrations.
- Inclusiveness, shared decision-making boosting local participation, knowledge transfer, networks of best practice solutions and their providers, matchmaking, and district level learnings for early planning (Merihaka, Finland).

Integration

- Long-term thinking in planning and investments is vital.
- Bear in mind potential future development (like population growth, additional need for capacity, climate change).
- Think holistically, do not treat matters as standalone, and always try to address them as part of bigger whole (as shown in Danish case studies).
- Look for integration of/in existing energy systems.
- Ability to integrate renovation activities with daily business activities was important and successful at Danfoss Campus.
- Successful implementation of stakeholder involvement is described in the case study on Denver National Western Center.

Analysis

- Adjust your level of detail to the progress of the project.
- Have a clear business case with cost efficiency and cost-effectiveness: based on life cycle costs and on long-term planning
- Weigh in reduced operation and maintenance costs and environmental costs like greenhouse gas costs (Danish Case Studies, Rambøll).
- Also, include and monetize aspects such as resilience, sustainability, comfort, and quality of living/working.
- Show and highlight verified cost estimates including investment, operation and maintenance, and delivered energy and cost savings.

Costs and Financing

- If a sustainable solution has similar life cycle costs as the standard solution, this can be very helpful. In case of SunZEB (Finland), the “affordable solution with a similar lifetime cost compared to the conventional approach” was chosen.

B.4.2 Bottlenecks

Bottlenecks slow a project down and in the worst case could even impede or stop it. Bottlenecks represent serious challenges.

Several case studies reported lack of information or data in the early process phase. Many decisions need to be made early in the process. It is not possible to find good solutions if input is missing or denied in this process phase.

On the other hand, good motivation can help overcome bottlenecks: When encountering challenging situations, it is critically important that there be a strong driver or need for the proposed solution. A clear layout of drivers and need for the chosen concept or idea can help to overcome obstacles. Chart B.2 lists bottlenecks (BN) and ways to overcome (ME) them that were reported in the case studies.

Chart B.2. Bottlenecks (BN) and Means to Overcome (ME) That Were Reported in the Case Studies

Early-Stage Availability

- BN need for relevant data/information: No data and information, no next steps. In the case of Fort Bliss, it was difficult to obtain data on privatized infrastructure.
- BN stakeholder involvement: Preferably, all stakeholders should be motivated to contribute and identify with the project from the early stages. In the case of Fort Bliss, United States, even with motivated stakeholders, it was difficult to gather all data, due to the enormous number of interviews to be held with involved persons.
- BN lack of knowledge on planning renovations and energy efficiency measures (case of Merihaka, Finland).

Organizational Means

- BN need for relevant data/information: No data and information, no next steps. In the case of Fort Bliss, it was difficult to obtain data on privatized infrastructure.
- BN stakeholder involvement: Preferably, all stakeholders should be motivated to contribute and identify with the project from the early stages. In the case of Fort Bliss, United States, even with motivated stakeholders, it was difficult to gather all data, due to the enormous number of interviews to be held with involved persons.
- BN lack of knowledge on planning renovations and energy efficiency measures (case of Merihaka, Finland).

Investment

- BN need for relevant data/information: No data and information, no next steps. In the case of Fort Bliss, it was difficult to obtain data on privatized infrastructure.
- BN stakeholder involvement: Preferably, all stakeholders should be motivated to contribute and identify with the project from the early stages. In the case of Fort Bliss, United States, even with motivated stakeholders, it was difficult to gather all data, due to the enormous number of interviews to be held with involved persons.
- BN lack of knowledge on planning renovations and energy efficiency measures (case of Merihaka, Finland).

B.4.3 Lessons Learned

Chart B.3 lists the major lessons learned from the case studies.

Chart B.3. Major Lessons Learned

Synergies

- Address multiple problems and challenges at once for larger impact and reduced investments.
- Combine different infrastructures and disciplines in your approach.
- Even if certain infrastructure measures are only due in a number of years, think of them as well, to avoid lock-in scenarios and stranded investments.
- 1+1>2.

Innovation

- A novel combination of things (read: concepts, technologies, approaches, methods) may offer huge potential even if appearing questionable at a first glance.
- Look for innovation in concepts, technologies, and people.
- Reflect, not only for checking your progress, but also to reflect on what you have done and why.
- All technologies required for energy improvements are readily available on the market. There are no missing fundamental technologies to realize significant energy savings (Danfoss Campus, Denmark).

Cooperation

- Cooperation and open dialogue with peers are vital.
- Failure is a great way to learn something, yet it does not hurt to talk to others beforehand.
- Knowledge transfer, dissemination, and good documentation are key.
- Include, do not exclude.
- Establish a "communication hub" to create a shared vision.
- In the case of SunZEB (Finland), the buildings act as energy sources. Close collaboration between energy concept developers and architectural and technical planners of the building is necessary for successful results.
- Cooperation of neighboring buildings' and district level collaboration can be considerably improved to reach shared targets more easily, to reduce risks, and to lower the bar for the need of individual investments (Merihaka, Finland).

Financial Resources and Business Models

- Technically and economically, sound concepts still need a framework for implementation and an investor who wants to go through with the concepts.
- Early involvement of investors (if needed)!
- The project owner, e.g., a campus owner, a public utility, or a consumer cooperative, is engaged in the planning and investment. In case the project is profitable, the project owner can finance 100% of the investment at lowest interest rate (Danish Case Studies, Rambøll).
- Most savings are achieved with simple improvements of existing systems and application of proper automatic control equipment (Danfoss Campus, Denmark).

Side Effects and Resilience

- While being an "early adopter" or "frontrunner" means additional complexity and courage, later benefits may outweigh this point.
- Integrate resilience and sustainability into your energy master planning initiatives as soon as possible, instead of waiting for the inevitable crisis, natural disaster, and change to spur you to action.
- Do not wait and react; instead act and plan beforehand. Challenges, future and present, will not disappear if you neglect them. See these challenges as a chance to evolve, not as a threat.

B.5 Lessons Learned Regarding Energy Master Planning

The following sections summarize what can be drawn from the studied cases regarding the design of energy master planning process. Information and statements are drawn from major success factors, bottlenecks, and lessons learned reported in the case studies. The answers to these questions have been grouped to categories and summarized.

B.5.1 Resilience

In the case studies, resilience has been addressed by asking for known risks, critical functions, and strategies adopted to realize a supply system that remains available in challenging situations.

From the answers, we learned that often regulation and standards required by law are the strongest drivers for resilience. In many cases, emergency power units were installed to reduce damage by power outage, usually diesel-fed engines with kinetic storage for immediate load (see, e.g., Fig. B.7). In other cases, resilience was increased by combining the thermal energy supply systems in two neighboring areas, thus creating a n+1 redundancy for generation and distribution, e.g., in the Danish (district heating systems) case studies. Here, resilience is a by-product of cost efficiency; the existence of redundant systems allows the choice of the most cost-effective energy source.

The case study of the US Army installation in Guam highlights the role of district systems for providing resilience. Here, demand reduction is shown to improve resilience cost-effectively. Another measure that has a positive side effect on resilience is to actively help to manage responses from the electric utility to reduce load under an interruptible tariff notice, e.g., the Fort Bliss, US case study. Another outcome of

Fig. B.7 Tractor providing power to a mountain resort during 3-hour blackout. This is a typical mobile backup method used in agricultural and sparsely populated areas (February 2020, Sommeralm in Austria. Source: AEE INTEC) the Fort Bliss case study was that many solutions undertaken to reduce risk are low cost, operation-based solutions. When planning for these US Army sites, the procedure developed in context of Annex 73 was applied, as described in *Energy Master Planning for Resilient Public Communities—Best Practices from US Military Installations* (Urban et al. 2020).

In the Australian case studies, existing energy or water supply cannot cover demand peaks. Here, thermal energy storage was the method of choice. Resilience is increased via demand shifting.

In summary, one can say that innovative solutions that increase resilience are primarily considered if required by local/national legislation, unless resilience is a by-product of cost efficiency or is specifically required by critical functions or sensible function owners, as in the cases of US university campuses:

> *Resiliency is key for the Medical District and the microgrid at the University of Texas Austin has 100 percent onsite generation capacity, including N+1 redundancy for prime movers under 99 percent of all load conditions. This provides flexibility to serve the critical research customers and Medical District. UT Austin also has a redundant electric interconnection to the Austin Energy grid to provide 2N+2 system redundancy for nearly all system load conditions.*
>
> *The campuses have integrated resilience into energy master planning initiatives as soon as possible, instead of waiting for the inevitable crisis or natural disaster to spur the administration to action.*
>
> *Combined with efficient and sustainable energy and water strategies, resilience efforts can reduce operational and maintenance costs in addition to reducing (or avoiding entirely) the costs of responding to a catastrophic event. Insurance premiums may be significantly lowered, too (e.g., the UT Austin, US case study).*

B.5.2 Available Resources

Available resources include opportunities for local energy production and storage and supply from existing energy infrastructure like power lines, gas piping, and district heating. Other resources reported to be as significant in case studies as access to mobility networks include know-how, experience, and sympathetic regulations.

As mentioned in the section on resilience, supply via grid may be limited, especially at demand peaks. In some of our case studies (especially in hot climate regions, e.g., Australia), the reduced electrical consumption and demand benefited both the building owners (university) and the energy operating company.

Another important local resource is mobility. In one case, the importance to find the right lot for the campus is emphasized. The chosen area can be used for local energy generation and even more importantly guarantees a high accessibility by public transport. The lot and its surroundings were essential and strongly determined the outcome (e.g., the WU Vienna, Austria case study).

The existing knowledge and experiences of the research team and the included network in similar projects are important resources (e.g., the HFT Stuttgart, Germany case study).

Another success factor reported is the cooperation with an institution holding experience in similar projects, like offered in an open dialogue with American universities (e.g., the University of British Columbia [UBC], Vancouver case study, on IDEA cooperation in case).

General information on how available resources can be included into energy master planning is found in Chap. 4 of the guidebook where local circumstances and resources define constraints for the master planning process.

B.5.3 Organizational Matters

Organizational matters range from team building to internal communication, to involvement of third parties. Here, we summarize lessons learned on organizational matters.

Good communication and efforts to improve "team spirit" were generally good working solutions to ensure team success.

If more parties are involved or interested, communication is essential; slow communication leads to bottlenecks.

B.5.4 Communication

- In one case, communication with administration of university and other stakeholders outside the campus was reported to be a major bottleneck (e.g., HFT Stuttgart, Germany case study).
- In another case, the operational planning effort was led by staff in the Department of Planning and Economic Development. However, much of the adopted master plan was informed by other departments in the city, and while they were responsive, the potential remained for progress to get held up (e.g., the Ford site, St. Paul, US case study).

B.5.5 Team/Structure

- A well-rounded project team that encompasses major stakeholders has been reported as an important success factor (e.g., the UC Davis, US case study).
- If owner and user are not identical, it is important to find the right organizational structure to allow owner and user/tenant to develop this project together and to define common targets and fulfill all requirements (e.g., the WU Vienna, Austria case study).
- In the Danish cases, it was also shown that it is a good idea for city district heating companies and campus owners to cooperate to find the best common solutions.

- The choice of the best planning for the project ("integral planning, with the responsibility lying with the main planner allowed for good solution") is important (e.g., the Innsbruck, Austria case study).

In Denmark, energy planning has become a natural part of urban planning in the local community, and there is obligation to plan for cost-effective heating and cooling in cooperation with local stakeholders, first of all the energy utilities, e.g., the public utility who owns the infrastructure. This framework conditions have contributed to create the modern and resilient energy supply infrastructure.

The case studies show that it is important that all stakeholders provide all relevant information that allows the planning authority to find the least cost solution and to prepare a stakeholder analysis indicating how the benefit can be shared among the parties.

Commissioning is not an integral part of planning but can be considered in the planning process. The Austrian case studies showed that cost-effectiveness can be improved by splitting construction work into feasible, competitive, yet still economical pieces for commissioning (WU Vienna, Austrian case study).

B.5.6 Financing/Economics

This section summarizes remarks collected in the case studies regarding financing and economics. Generally, the evaluation of case studies shows that most business models take a "business as usual" approach, which assigns the major cost and benefit risks to the building or community owners. Most business models assume that the public community will take all performance and investment risks. The deeper analysis of three cases showed that some business models such as energy supply contract or even energy performance contracts are not known or not considered at all. Also, utilities and ESCOs do not provide specific services for net zero energy communities.

In the Danish cases, ESCO companies were not necessary, as the public utilities and consumer cooperatives can manage projects alone or with help of consultants and they can obtain loans to finance all necessary costs. Experience from the case studies shows the importance of an accurate business case as well as consideration of public funding and of avoided costs.

- It is important to create an accurate financial business case around forecast electrical power prices. Thorough knowledge on future carbon pricing and carbon tax can increase the accuracy of the business case and thus facilitate financial planning (e.g., the JCU Townsville, Australia case study).
- The calculations should consider additional savings achieved at the other side of the meter due to cold mechanical rooms. In one of the case studies, this amounted to unexpected 10% savings (e.g., the UBC, Canada case study).
- Life cycle costs and energy implications should be controlled at decision points (e.g., the Innsbruck, Austria case study). Ideally, one would consider demolition as well.

- The acquisition of appropriate financial subsidies allows for developing and tracking of nonstandard procedures (integral planning, innovative measures, monitoring, LCCA, e.g., the Innsbruck, Austria case study).
- Permanent monitoring and temporal monitoring do lead to similar costs (e.g., the Innsbruck, Austria case study).
- In one case, a foundation grant was used to fund a series of planning studies conducted, including energy studies. This enabled an energy consultant team to evaluate onsite energy system options for the site, including technical and financial feasibility (e.g., the UC Davis, US case study).
- Leverage alternative funding to support project implementation (e.g., the Fort Bliss, US case study).
- Life cycle cost calculations show that low-tech solutions have lower life cycle costs (e.g., the Innsbruck, Austria case study).
- Another important issue is to check and evaluate use of local and sustainable materials and carbon embedded in materials.
- In a big project, it is very important to use more than just one method to check costs (e.g., the WU Vienna, Austria case study).
- Different options for the financing of the proposed measures were considered and discussed with the project partner "Stuttgart Financial" and other experts. Among them were intracting, contracting, green bonds, or crowd investing. In the end, the Department of Treasury Baden-Württemberg agreed to finance the project such that other options were no longer needed. However, the ideas can be applied to future projects (e.g., the HFT Stuttgart, Germany case study).
- In the Merihaka case study in Finland, large buildings with privately owned apartments needed to be upgraded. To resolve financing issues in such cases where there is no supporting government funding, the local energy company Helen Ltd. is actively participating in the business case and will be creating new business model studies as part the project.
- The first analyses of the business cases for the Merihaka study included the PESTEL (political, economic, social, technological, environmental, and legal) and SWOT (strengths, weaknesses, opportunities, and threats) analyses as well as TALC methodology, which identifies customer profiles to see how society is prepared to accept it. Quick summaries of market size and a porter diagram were prepared for the project partners, the energy company, and SMEs, with an emphasis on power consumption and supply, threat of competition, energy substitutes, and new entrants into the energy market.
- In the case study of NTNU Gløshaugen campus, four energy efficiency packages were introduced to help reduce energy to meet the 2050 target of becoming a zero energy/emission neighborhood. Most of the buildings, which were built between 1951 and 1970, were expected to undergo demolition; meanwhile a campus expansion is anticipated to continue until 2025, in which 2050 new buildings will meet the passive house standard. It is likely that this expansion will achieve self-sufficiency for heating use but will remain largely dependent on electricity imported from the grid until 2050.

The following conclusions can be drawn from the best practice examples:

- In most best practice cases, investment payback will occur in the long term by reduced operation and maintenance costs. Projects can thus be financed by loans on the capital markets.
- In case the energy system has been privatized and is not owned by the campus building owner, it is more difficult to renovate it, since the investor does not profit from savings in operation.
- Most public entities (nations, municipalities, etc.) can get financing even for very long-term investments (>20 years). Private companies instead look for a return of investment at a shorter time scale of around 4 years. The case of Danfoss in Denmark shows that it is possible to reduce energy consumption with established technologies and reach a very short payback time (here 3.1 years).
- Many countries offer financial support for renewable generation, innovative technologies, or outstanding procedures. Such subsidies can help to reduce payback time.
- Resilience can be obtained in many ways, ranging from UPS units for each critical function to redundant production and delivery systems. Danish cases show that redundant production and supply systems can also be used to exploit price variations of energy supply and thus reduce operation costs.

Information on financing and business models are described and analyzed in Chap. 8 and Appendix F of the guidebook.

B.5.7 Framework

In this context, the term “framework” denoted external factors that affect community master planning, like nationwide regulation on energy use or planning procedures, and project-specific goals. It is often the framework that defines what measures to apply and which solutions to prioritize. The guidelines for community master planning that you hold in your hands can also be seen as framework, since it informs tools and procedures.

Lessons learned during these case studies about different types of frameworks include:

- Framework for assessment of options:
  - It is important to have a framework with which to assess alternative options.
  - However, it is important to consider the overall framework at least one level above the level of the project, e.g., a project for assessment of investments in buildings has to be assessed at the campus or city level and be compared with alternative options including this level. Likewise, a project for assessment of investments at the campus level has to be assessed at the city level or national and be compared with alternative options including this level (Rambøll, experience from Danish case studies).

  - In one case, high-level criteria for energy efficiency and sustainability led to better than usual results because they were defined early (should be before commissioning to planner team) and checked throughout the process. The same applies to costs (e.g., the Innsbruck, Austria case study).
  - The framework deployed on one project consisted of an economic evaluation of the life cycle cost, an evaluation of whether the option would align with campus initiatives and whether the solution would provide sufficient reliability and redundancy (e.g., the UC Davis, US case study).

- About framework for implementation:

  - In one case, although a new vision had been created for the site, a new developer who will purchase and develop the site may not find it feasible to implement all the ideas and concepts laid out during the city-led visioning for the site within the time frame needed for horizontal and vertical development to proceed. While the city conducted a significant amount of study to ascertain the financial and technical feasibility of a district energy system, more focus could have been placed on implementation frameworks to better prepare for the period between identification of a developer and execution of a development agreement (e.g., the Saint Paul, Minnesota, Ford Site, US case study).
  - The city is also considering how the lessons learned from large district projects can be translated to smaller, parcel-scale projects. One important conclusion from some case studies is on the possibility of drawing from pilot studies to modify framework in legislation/regulation (e.g., the Saint Paul, Minnesota, Ford Site, US case study).
  - City staff can lead a process of active community engagement and act as a hub for all city departments to create a shared vision that optimizes community benefits from the redevelopment of a property. As the city works through the due diligence period with the developer, staff are developing a better understanding of how to define expectations and policy in advance of projects being initiated (e.g., the Saint Paul, Minnesota, Ford Site, US case study).

For information on framework in the form of goals and constraints, consult Chap. 4 and Annex A of the guidebook. Table B.6 lists the framework conditions to be considered regarding later planning and later phases.

Table B.6 Framework conditions to be considered regarding later planning and later phases

Phase	Details	Examples
Operation	Availability of personnel	Denmark/Greenland
Acquisition	Low-tech costs less	
Monitoring	Optimization Evaluation before bringing methods to other districts	Austria/Innsbruck, Finland/Merihaka
Planning	Privatized infrastructure	Fort Bliss (United States)

B.5.8 Technology

This section discusses lessons learned from case studies on the use of technology. Changing climate and disruptive events pose challenges to supply energy supply. Innovations and new technologies can help to create and maintain efficient, resilient, low-carbon energy systems. Lessons learned on technology and outcomes (which range from general remarks to very specific suggestions) follow.

- The challenge was to deliver system capacity that covers high-demand days (e.g., case studies from Australia).
- The use of innovative technologies is sometimes accompanied by difficulties. One needs to define:
  - Technical requirements for feasibility
  - Critical factors like error-proneness of control systems, space requirement
  - Conditions for cost-effectiveness and cost drivers
  - Criteria for the request for proposal (RFP) (e.g., the Innsbruck, Austria case study)
- In the Merihaka, Finland case study, the building envelope already had sufficient insulation. Thus the key intervention in the retrofitting process to lower energy consumption is installation of smart controls for management of apartments' heat and electricity demand: "smart heating control is applied with added focus of testing heat demand response to optimize energy systems and implement the human thermal comfort study with a Quick Response (QR) code feedback system (based on the Human Thermal Model [HTM] developed by VTT). Together with HTM, predictive algorithms are also used to optimize energy use to achieve savings."
- "The company has been first mover as regards new technologies in the pit storage in large-scale. This has caused some problems and reduced the economic benefit the first years of operation. It has however been to the benefit of the next generation of storage capability, e.g., a storage pit in Toftlund not far from Gram; it was learned from this experience how to manage the technology to avoid holes in the liner during the construction" (e.g., Gram, Denmark case study).
- Consider the huge benefits of reduced power consumption, reduced costs, and reduced carbon equivalents that can result from the use of a centralized plant (e.g., case studies on central cooling, Townsville and Cairns, Australia).
- Include plans on future thermal load growth and allow for system expandability to meet these future loads (e.g., the UBC, Vancouver, Canada case study).
- Substitution of technology offers opportunities: "The steam-to-hot-water conversion project eliminated $190 million in deferred maintenance costs, reduced operating costs, improved safety and resiliency, and dramatically reduced energy and water consumption" (e.g., the UBC, Vancouver, Canada case study).
- Consider the transition period. What to do with new buildings that cannot connect to new technology (e.g., hot water) yet should connect to steam (old technology being eliminated) (e.g., the UBC, Vancouver, Canada case study).

- Regarding the operation mode of chillers, "Ensure that the centralized centrifugal chillers are run highly loaded, for continuous periods as long as possible and do not surge" (e.g., the Townsville and Cairns, Australia case studies).
- Consider the structural design parameters for the modular tank for hot/cold water storage (e.g., case studies on Townsville and Cairns, Australia).
- Groundwater can be a powerful source of energy (e.g., case studies on WU Vienna, Austria).
- Process steam scoping. Several labs and/or process requirements were not captured under original scoping; after change from steam to hot water heating, they were out of steam (e.g., the UBC, Vancouver, Canada case study).
- Provide cost-effective alternatives to generators (storage, photovoltaics, demand response, e.g., the Fort Bliss, US case study).
- It depends on the situation whether a specific innovative solution is possible. For example, as reported in SunZEB case study from Finland, "district cooling with access to a heat pump that can reuse the energy is needed."
- Moreover, the campus can have a feedback on its surrounding energy system so that necessary adaptations of the system can be made: "If a large number of SunZEB buildings are developed, adapting the district energy system for the loads is needed" (e.g., the SunZEB case study from Finland).
- There is constant waste heat with capacity of 1MW from the IT center in the campus, which is already used for heating and will contribute to the campus heat supply. A heat pump is expected to supply around half of the total heating use. The contribution to electricity from solar PV is less than 10% in new buildings and less than 5% in existing buildings. Regarding the contribution from a biogas-based CHP, both electricity and heating are negligible (e.g., the NTNU Gløshaugen campus, Norway case study).

The case studies describe various technologies used for storing energy (Table B.7). In fact, energy storage is one of the biggest current research topics, with storage technologies ranging from storage by chemicals (batteries) and fuels (hydrogen, biogas) to latent and sensible heat storage.

Generation on the other hand has been subject of research in the last decades and is increasingly been integrated in solutions, as we have seen in our case studies. Table B.8 lists some examples. Appendix D includes some generic information on technologies.

Table B.7 Storage solutions featured in case studies

Storage Type	Details	Examples
Thermal water storage	Hot water	Denmark/Gram, Finland
	Cold water	Australia, Finland, Denmark
	Groundwater	Austria/WU Vienna, Denmark
Fuel storage	Hydrogen	Denmark/Nymindegab

Table B.8 Generation types featured in case studies. The list is not complete; only some exemplary case studies are listed for each generation type

Generation type	Details	Examples
Fuels	Oil, natural gas, biomass	Denmark, United States
Ambient heat	Groundwater river	Austria/WU Vienna
Ambient heat	Sea	Denmark, Finland
Waste heat	CHP	United States, Denmark Copenhagen
Waste heat	From cooling	Finland, Denmark/Taarnby cooling
Waste heat	From building	SunZEB, Finland
Recovery	Of exhaust air heat/cold	Austria/Innsbruck (only heat) Norway/Gløshaugen
	Of wastewater heat	Denmark/Taarnby cooling
Photovoltaics	St. Paul, United States	
Cogeneration of heat/cold	Heat pump	Finland, Denmark/Taarnby cooling
Waste heat	Heat pump	NTNU Gløshaugen campus (Norwegian University of Science and Technology), Norway
Biogas	CHP	

B.5.8.1 District Energy Systems

District energy systems play an important role in Annex 73 "Towards Net Zero Energy Resilient Public Communities" case studies. This section summarizes lessons learned about district energy systems, going from steam to hot water and going from heating or cooling to combination of both and integration of power. Specific case studies are cited so the reader can find relevant additional information.

B.5.8.2 Advantages of District Heating and Cooling

It is possible to:

- Use efficient waste heat from industry and power generation, in particular at low temperatures.
- Include energy from different sources including renewables.
- Include storage that enhances use from volatile sources.
- Choose generation source according to actual prize level, due to variable flow operation.
- Reduce costs for generation plants due to economy of scale.
- React to power costs by choosing heat source accordingly (e.g., gas turbine or heat pump).

See case studies from Denmark for more details.
Especially for district cooling:

- Storage reduces the dependence on power supply. If the local power system is at its limits, cold water storage can be part of the solution.
- Storage provides capacity due to strong daily fluctuations.
- Storage is an option to optimize operation and use of electricity.

See case studies from Australia.

Advantages of combining heating and cooling systems:

- Waste heat from cold production can be used for heating, and waste cold from heat production can be used for cooling.
- Heat pump for combined heating and cooling can be combined with ground source cooling (aquifer thermal energy storage, short, ATES).
- Cooling with small devices on building level has some disadvantages:
  - In cold regions, this heat is lost, while it is needed elsewhere.
  - In hot regions, this heat further warms up the environment, aggravating the situation, while DHW is usually still provided with fossil fuels.
  - Problems with noise, visual impact, and space.
- In regions where heat and cold are needed concurrently, use one heat pump for combined cooling and heating.
- In regions where heat and cold are needed in different seasons, consider seasonal thermal energy storage, e.g., ATES.

See case studies from Finland, Denmark, and Austria (WU Vienna) for more details.

Advantages of combined heat and power:

- Ability to react to supply costs by choosing appropriate generation plants, e.g., combined heat and power vs. heat only.
- Combined with thermal storage tanks, the extraction CHP plant can generate power only at power peak hours and generate combined heat and power in the most optimal way.
- Combined with thermal storage tanks, the back-pressure CHP plant and gas engines can generate combined heat and power in the most optimal way, e.g., at maximal load in power peak hours.

See the case studies from the United States and Denmark for more detail, especially university campuses, towns, and cities.

Generally, the case studies show that a district infrastructure that includes generation and storage benefits the local community.

Table 7.1 in Chap. 7 of the guidebook contains a full list of disadvantages and advantages of district thermal energy systems.

B.5.8.3 Planning

All lessons learned regarding planning are presented in this section. For easier review, we distinguish between different categories, including method, goals, simulation, costs, monitoring, and involvement of user/operator.

Planning method:

- To enable innovative solutions, use integral planning at the level of society to include all potential sectors (Danish cases, Campus Technik Innsbruck).
- Ensure that the planner has access to the necessary vital data from all stakeholders and facilitate an open cooperation.

- Planning should include major stakeholders and representatives from legislative bodies since their engagement offers many benefits, including less opposition for zoning change and help for the developers in showcasing the project to clients for whom they are building, i.e., to highlight the fact that the project directly responds to the needs of the market and that the business models show positive cash flows and increased rental/sale numbers in less time. These positive side attributes will offset some of the perceived risks of the private developers. Institutional builders, and community and private developers as well, should be part of the equation of sustainable development metrics.
- To reduce barriers and promote the use of digital methods, the public authority can offer information to planners. In case study on Merihaka, the City of Helsinki has collected extensive data on buildings' energy information for open-source use in the Energy and Climate Atlas as an integral part of the 3D city model (see https://kartta.hel.fi/3d/atlas/#/).
- In the same project, VTT Technical Research Centre of Finland performed a comprehensive technical and cost efficiency study on suggested renovation measures for particular type of apartment buildings (see the information table embedded as pop-up clickable feature onto the model Merihaka apartment buildings).
- Use simulation tools, e.g., EnergyPro for simulating the most optimal operation and network analysis systems for design of the energy carriers (e.g., see the Danish case studies, Taarnby district cooling).
- Create different scenarios and compare them, as has been done in Merihaka case, Finland, by using the Multi-Objective Building Energy Optimization (MOBO) study to map best scenarios and combinations of energy conservation measures (ECMs). In the Merihaka case study, energy, emissions, and life cycle costs have been compared for a period of 25 years.
- Use LCCA including actual costs in an NPV analysis based on a reasonable lifetime and discount rate, including residual value for infrastructure for which the lifetime exceeds the project period (e.g., see the Danish case studies).
- Note: life cycle should start at the acquisition of the land if demolishing and soil remediation are required.
- For nonstandard energy supply and building components and rarely used technologies, invite manufacturers to cooperate in planning phase:
  - "No construction company would deliver the innovative prefabricated facade as it was planned, thus the design had to be adapted, including standard elements to achieve the aspired result" (e.g., the Innsbruck, Austria case study).
  - In the US case studies on Army campuses, planning for resilience and sustainability procedure described in "Energy Master Planning for Resilient Public Communities—Best Practices from US Military Installations" (Urban et al. 2020) was applied.

B.5.9 Goals and Framework

- Define energy and cost limits in an early planning phase (preliminary design) (e.g., the Innsbruck, Austria case study).

- Coordination of some tasks needs more adjustment to prevent duplication of efforts (e.g., refurbishment scenarios should be final before simulation, etc.) (e.g., the HFT Stuttgart, Germany case study).
- Optimization variants (e.g., regarding HVAC) should be defined and assessed in the preliminary phase.

B.5.10 Simulation

- Simulation tools can provide resilient results but require reliable input information (e.g., the HFT Stuttgart, Germany case study, see Table B.9).
- Detailed simulations are not necessary in some situations (e.g., the HFT Stuttgart, Germany case study).

Table B.9 Software and tools reported in case studies

Type of software, application	Application used in case studies
Geographic information system	ArcGIS
Simulation of energy systems	SYSTEMRORNET (hydraulic analysis in Danish cases) INSEL and PVsol for PV (e.g., the HFT Stuttgart, Germany case study) SMPL/Net Zero Planner (US Army case studies) Vision Simulation Tool from AECOM (US Army case studies) CEIP Vision Scenario Planning Tool (US Army case studies) IDA-ICE (SunZEB case study, Finland)
Business	Excel® sheets for business models and calculation Rambøll business plan model in Danish cases Life cycle costs (e.g., econ calc, Austria) Excel® tool for economic efficiency, in-house by HFT Stuttgart
Resilience	ERA tool developed by MIT (in US Army case studies)
Optimization	Use of monitoring data, e.g., on flow and temperature of wastewater (Denmark) Mentor planner for optimized operation(Denmark) EnergyPro: simulation of cost-optimal operation (Danish cases)
Building comfort simulation	IDA-ICE for dynamical building simulation of indoor comfort (Austrian case studies, Merihaka, Finland) PHPP passive house planning platform (Austria, Germany) Daylight simulation
Surrounding	Wind simulation for outdoor comfort (e.g., the WU Vienna case study)
Building design	CAD software for design
Building energy use	Energy performance certificate according to ÖNORM (Austria) Certification tool (PHphit) (Germany) SimStadt simulation platform (Germany)
Project organization	Project platform Project leaders and construction supervision used different cost tools to control cost development (WU Vienna, Austria)
Optimization, hybrid solutions	Multi-Objective Building Performance Optimization MOBO (Merihaka, Finland)

B.5.11 Monitoring

- Consider monitoring already in the planning phase (e.g., the Innsbruck, Austria case study).
- Permanent monitoring and temporal monitoring do lead to similar costs (e.g., the Innsbruck, Austria case study).

B.5.12 Involvement of Users/Operators

- Complex control system in one of the buildings requires the tenants' attention and know-how (e.g., the Innsbruck, Austria case study). Training can help remove barriers to behavior modification.
- In the case of complex technical installations, involve the future operator from an early phase (e.g., the Innsbruck, Austria case study).
- It may be difficult to keep and attract qualified staff to ensure efficient operation and a high maintenance standard in remote areas (e.g., the Greenland, Denmark case study).

B.5.13 Motivation/Mobilization

Motivation and engagement are always essential. In some case studies, they were mentioned as driving factor for reaching a high-level solution.

- Where there is demand for additional space, a required reduction of energy use can leverage the process to reach sustainable systems:
  - "Institutions of higher education are requiring that campus growth go hand in hand with objectives of reliability, efficiency, and carbon reduction on campus when evaluating options for expanding or managing existing district energy infrastructure" (IDEA, United States).
  - The motivation of campus users and the owner is a success factor: "Both tenant and owner have know-how on building and were interested in achieving a high-level result" (e.g., the Innsbruck, Austria case study).
  - Engagement of management team (e.g., the HFT Stuttgart, Germany case study).
  - In the case of UBC (United States), the economic impact of a carbon tax played a strong role in reducing natural gas use and moving to fuel diversity by adding bioenergy (e.g., the UBC, Vancouver, Canada case study).
- Certification and prices:
  - "In November 2017, the 14-acre Dell Medical District at The University of Texas Austin became the first project to hold SITES, LEED, and Performance Excellence in Electricity Renewal (PEER) certifications, making it one of the most holistically sustainable and resilient facilities in the world" (e.g., the UT Austin, US case study).

– The engagement of stakeholders increases acceptance and may in this way reduce future costs for adaptations: "The non-technical planning success was the dedication of time and effort the City of Saint Paul planning department put into extensive community stakeholder engagement from 2007 through 2017." This stakeholder engagement effort was visible and reached the community through:

  Over 80 presentations to business, civic, and nonprofit groups.
  Forty-five public meetings with over 1300 people attending those meetings.
  Over 100 articles in print, radio, and television media.
  Thousands of ideas and comments were received through this engagement effort, and the key themes from the community were able to be incorporated into the vision statement and six guiding principles that were ultimately adopted by the city council and mayor as the Ford Site Zoning and Public Realm Master Plan. The new vision for the site, rather than the existing industrial use, was available to developers as they made bids on the site (e.g., the St. Paul, Ford site, US case study).

- In the case of Merihaka, Finland, private apartment owners need to be motivated and included. An energy advisor has been brought on board to assist with engagement of private stakeholders and to continue and trigger further co-creative discussions. Another activity was performing a study on renewable energy and discussion of results with the local building owners to acquire more feedback on their interests.
- The retrofitting work of the privately owned apartment buildings was first introduced through pre-pilot experiences. This helped in creating a level of acceptance for the project actions (e.g., the Merihaka, Finland case study).
- "Discussions with the local housing association chairpersons aim to motivate them and encourage exchange of knowledge to raise more awareness on the energy matters. Some events are open to the public and some are specifically for the building owners in the form of living lab co-creation sessions. As an example, three events consist of cascading workshops with experts, residents, and interested stakeholders, such as solution providers and financiers for energy retrofits. This exchange of ideas aims toward matching the preferences and transforming retrofitting on district level. Joint discussions between the housing associations, the district real estate management company, local energy company, and energy optimization study provider are continuing to have more detailed discussions. The program on the city level is supported by the administration and conducted in conjunction with the City Strategy" (Merihaka, Finland).
- Successful projects serve as role models: "The CNPRC will be used to demonstrate the feasibility, cost, effectiveness, and challenges faced in implementing energy efficiency and environmentally friendly" (e.g., the UC Davis, US case study).

Chapter 3 of the guidebook presents the developed energy master planning procedure that considers resilience.

B.6 Conclusion

In summary, some trends were observed in the case studies. In some cases, power demand has strongly increased, due to the use of electrical equipment and cooling demand, which may again be caused by electrical equipment and higher outdoor temperatures. This results in low summer comfort, rising costs for cooling, and sometimes even capacity overload. Measures applied include:

- Replacement of electrical devices (e.g., lighting) by more efficient ones
- Shading
- Use of renewable cold, e.g., ventilation (day and night), groundwater, etc.
- Centralized cooling systems with thermal energy storage to shave demand peaks and move consumption from day to night

In other cases, thermal supply networks are being expanded or combined with each other to replace fossil fuels with renewable energy and surplus heat and to increase the overall energy efficiency. Moreover, thermal storage capacity has been increased to use more thermal and electrical energy from volatile regenerative sources.

In Denmark, integrated energy systems that act as so-called virtual battery: the district heating is supplied from a CHP plant, a heat pump, an electric boiler, and storage units. The system is operated in response to the electricity market prize.

Experience from case studies shows that there is often large potential using standard/well-tried technologies. These include efficiency measures like insulation of envelope, upgrade of building technology, and use of heat pumps, renewable generation, and heat storage.

In some cases, the heat pump can deliver cooling to district cooling in combination with an ATES. In many cases, both for district cooling and district heating networks, thermal storage is being installed to avoid stress by consumption peaks and to optimize the production and operation, thereby reducing the risk of load shedding and blackout on warm and cold days (e.g., case studies from Finland).

One important advancement is the replacement of steam systems by hot water systems. In Greater Copenhagen, one of many subprojects in the city center is to replace the old steam system with hot water district heating and thereby reduce costs and increase efficiency, the use of renewable energy, and the level of resilience. This experience is valuable for US campuses, as 95% of all campus heating systems are steam based.

In single ownership areas such as university campus, energy efficiency measures can be undertaken to reduce demand peaks, e.g., building shell renovation and replacement of energy-consuming devices by more efficient ones, as the campus owner is able to optimize the whole chain from thermal comfort in buildings to use of resource and fuels. Thereby the campus owner can also find the right timing for modernizing building installations and optimizing the insulation and HVAC system with respect to the real costs of energy supply (e.g., the HFT Stuttgart, Germany case study).

In cases where the energy supply system is owned by the city or consumers (like in Denmark), the utility has the aim to minimize the cost for all consumers in total. In fact, this leads to optimal solutions as in single-owner campus situations. Cost-based tariffs are important to stimulate efficient use of energy.

For backup power supply, the most common solution is still kinetic plus diesel-fed units, which serve only very limited purposes such as emergency ventilation and lighting as well as server systems and life-sustaining measures in hospitals. To date, microgrids are being realized in the United States and supplied from gas-fueled CHP plants at the site to increase resilience where the power systems are degenerating. Microgrids are not common in other European countries, where the power grids are reliable. However, microgrids are used in some cases, e.g., the Danish Technical University, to avoid distribution tariffs as the costs of operating their own low-voltage grid are lower than the distribution tariff from the utility. Even a large gas CC CHP plant at the campus is not connected to the campus grid but is connected to the utility grid and operates on the market for energy and regulation.

For existing large areas, the planning process is complex and includes consideration of future use and energy costs as well as maintenance and operation of existing infrastructure. Implementation plans for energy systems can take many years of effort to increase efficiency, resilience, and reliability. These plans are important to allow for third-party financing that requires a schedule and security.

Energy master planning that considers resilience has been further developed in the framework of this Annex "Towards Net Zero Energy Resilient Public Communities" and is being increasingly applied in planning processes. It helps to build a constructive and informed energy master planning process that considers various aspects and that proposes procedures and solution sets for long-term implementation plans that lead to highly sustainable, cost efficient, and resilient supply systems.

The requirement of energy security is growing due to the increased complexity of the built environment. First of all, it is a challenge to develop a low-carbon energy system and integrate volatile energy sources. This is further caused by use of electrical devices in many aspects of our lives that help to resolve both challenges in responding to outdoor conditions and in meeting high standards for indoor climate. Water and energy supply systems must be adapted to provide for a resilient supply system. Due to the complexity of requirements, many stakeholders need to be involved. The energy master planning process for single ownership areas and for local communities designed in Annex 73 "Towards Net Zero Energy Resilient Public Communities" helps to create such resilient communities.

Appendix C. Mission-Critical Functions, Facilities, and Their Energy Needs

C.1 Introduction

Mission-critical/essential function is defined as a function that is vital to the continuation of operations of the organization or agency (AR 500–3, HQDA 2008a, b, c). These functions include those required by statute or executive order and other functions deemed essential by the head of each organization and must be performed without interruption to execute critical missions including during and after a disaster.

C.2 Critical Function

The concept of "critical function" serves as an intermediary between the community/campus/military installation mission or purpose and the function of individual buildings or their infrastructure systems. Concentrating on providing resilience to the critical functions instead of to critical assets builds flexibility into the resilience investment plan and ultimately reduces cost in most applications. For instance, many functions can be provided by more than one building—human shelter is a prime example. Many buildings provide or can be adapted to provide multiple functions. Alternatively, a function may be supported by a small part of a single building, and thus resilience for critical energy loads would not require full facility backup. Finally, different threats or scenarios can dictate that certain buildings are used to provide a function over others—for instance, when a subset of buildings are flooded or damaged.

In addition to core critical facilities and operations, there are critical facilities that impact the safety of the public and its property during and after a disaster if not maintained. The latter typically include police stations, fire stations, hospitals and clinics, sewer lift stations and water treatment plants, electric generating facilities, and facilities that store hazardous materials. For different categories of communities, this list will be different and may include categories listed in Table C.1.

Even within one building, operations can be classified as critical/essential or support/noncritical. Some critical operations can be dependent on support operations. Critical operation linkages to support operations must be identified for the success of critical function. Support operations may form a system of critical infrastructure that is necessary for success of a single critical operation.

Table C.2 provides examples of hospital "critical care" areas.

Table C.1 Examples of mission-critical functions and life, health, and safety operations

Core mission	Life, health, and safety operations
Global Intelligence	Fire and police stations
Surveillance and Reconnaissance	Hospitals
Special Operations	Ambulatory care centers
Strategic Command Communication	Dining facilities
Network Enterprise Centers	Shelters
Air Superiority	Sewer lift stations
Global Precision Attack	Water pumps
Cyberspace Superiority	Drinking water treatment plants
Nuclear Deterrence Operations	Central energy plants
Power Projection (Mobilizing, Deploying, and Demobilizing)	Chilled water plants
Agile Combat Support	Transportation
Critical Data Center Operations	Firefighting water/pumps
Security and Force Protection Operations	Emergency communications centers
Petroleum, Oil, Lubricants Facility Operations	Wastewater treatment plants
Ammunition storage	
Mobilization and Force Generation	
Critical Manufacturing and Maintenance	
Logistics	
Chem-bio laboratories	
Critical research facilities	
Strategic training	
Rapid Global Mobility	
Transportation and shipping	
Aircraft hangers and maintenance facilities	
Air traffic control tower and runaways	
Range control buildings and radar sites	
Telecommunications facilities	
Banking and finance	

Table C.2 Examples of critical areas—critical care areas within a hospital

Operating rooms	Intensive care and isolation care nursery
Labor and delivery rooms	Cardiac cauterization
Cystoscope rooms	Angiographic exposure room
Oral surgery, maxillofacial surgery, periodontics, and endodontics	Hemodialysis (patient station)
Recovery (surgery and labor recovery beds)	Surgery suite preparation and hold
Coronary care units (patient bedrooms)	Hyperbaric chamber
Intensive care unit (patient bedrooms)	Hypobaric chamber
Emergency care units (treatment/trauma/urgent care rooms and cubicles)	Radiation therapy (including simulator room)
Labor rooms (including stress test and preparation)	Nuclear medicine (camera room)

C.3 Determination of Mission-Critical Functions and Facilities

The determination of whether a particular facility is critical hinges on whether the facility is essential to the mission or the function of the site (FEMP). For different categories of communities/campuses/military installations, this list will be different. For example, one way to determine a priority of assets is to use the DoD Mission-Based Critical Asset Identification Process (DoD Instruction 3020.45, DoD 2018) along with the appropriate data and inputs from other determining sources. The assessment methodology described below is provided as an example. This methodology allows to determine the importance of each asset and prioritize the assets based on consequence of loss and is based on the process that has been developed by US Army North that guides planners through a prioritization of assets with focus on mission execution (USARNORTH 2019). The assets to be considered usually include those listed in existing Mission Essential Vulnerable Area (MEVA) lists, High Risk Targets (HRTs), and assets that are critical to tenants/organizations on the installation at all levels. The criticality methodology uses a modified version of the metrics from DoD O-2000.12-H, where "importance" is the sum of all of the following metrics: effect, recoverability, substitutability, mission functionality, and repairability. Each of these criteria is assigned defined metrics per Table C.3.

To obtain the value of the criticality criteria, add the total score of each of the criticality metrics above and using Table C.4, place a numeric and linguistic value to the impact of loss of the asset.

Criticality in this context refers to the impact that incapacity or destruction of a mission would have on physical or economic security or public health or safety. This criticality level can be assigned based on national priorities or within the scope of a local project. In many cases, specific details related to the level of criticality of a mission may be classified.

C.4 Energy Requirements for Mission-Critical Operations

For each critical facility, the required energy quality and quantity for regular (blue sky) and emergency operations shall be identified. Every effort shall be made to reduce energy use to only what is required to support critical loads, and these loads shall be prioritized and optimized. This will result in smaller primary and alternate energy systems and efficient way of fuel usage and the size of fuel storage. Energy quality provided to mission-critical operations is another important factor. Some operations consuming electric energy (e.g., pumps, freezers, HVAC systems) can accept power quality available from utility or emergency generators. Equipment and critical processes included in other mission-critical operations have more stringent requirements to downtime and power quality, since critical mission can be jeopardized, and equipment can be damaged from power interruption and disturbances, such as voltage spikes, surges, sags, EMI, transients, harmonics, and high-frequency noise.

For thermal energy systems, energy quality required by the building/mission can be described in terms of the type of thermal energy required by the process and

Table C.3 Mission-critical facility metrics

Numerical rating	0–4	5–8	9–12	13–16	17–20
Effect metrics					
Description	Destruction or disruption of this asset would have little or no psychological, economic, sociological, and military impacts	Destruction or disruption of this asset would have local, psychological, economic, sociological, and military impacts	Destruction or disruption of this asset would have regional, psychological, economic, sociological, and military impacts	Destruction or disruption of this asset would have national psychological, economic, sociological, and military impacts	Destruction or disruption of this asset would have worldwide psychological, economic, sociological, and military impacts
Recoverability metrics					
Description	Immediate restoration (less than 24 h)	Short-term restoration (more than 24 h, less than 72 h)	Mid-term restoration (more than 72 h, less than 7 days)	Long-term (more than 7 days, less than 30 days)	More than 30 days or no restoration possible
Substitutability metrics					
Description	Can accomplish mission with substitutes available for personnel, facilities, or materiel	Not difficult to accomplish mission with substitutes available for personnel, facilities, or material	Difficult to accomplish mission with substitutes available for personnel, facilities, or material	Very difficult to accomplish mission with substitutes available for personnel, facilities, or material	No substitutes available for personnel, facilities, or material
Mission functionality metrics					
Description	Destruction or disruption of this asset would have little or no impact on the ability of the unit/installation to accomplish its mission	The unit/installation could continue to carry out its mission if this asset were destroyed or disrupted albeit with some degradation in effectiveness	Half of the mission capability remains if the asset were successfully destroyed or disrupted	Ability to carry out a primary mission of the unit/installation would be significantly impaired if this asset were successfully destroyed or disrupted	Unit/installation cannot continue to carry out its mission until the function of the asset is restored
Repairability metrics					
Description	Immediate repair/low cost (less than 24 h)	Short-term repair/moderate cost (more than 24 h)	Mid-term repair/significant cost (more than 72 h, less than 7 days)	Long-term/high cost (more than 7 days, less than 30 days)	More than 30 days or repair possible

Table C.4 Criticality total score

Linguistic Value	Low	Moderate	Significant	High
Numerical rating	0–25	26–50	51–75	76–100

thermal comfort systems. This may include different energy carrying media, such as steam; high-temperature, medium-temperature, or low-temperature hot water; chilled water; water-antifreeze mixture; electricity for heating or cooling; gas; other fossil fuel; etc. Energy quality concept for thermal energy systems is less important than for electric systems. If the internal system is water-based or uses antifreeze, the energy supply system can be steam or hot water based and can use a steam-to-hot-water heat exchanger. The conversion from steam to hot water energy supply system requires a system of heat exchangers, radiators, or convectors inside the building to support its heating loads. If some processes, e.g., sterilization or industrial processes, require steam, a local steam boiler can be installed to complement the heating system, which would be converted to hot water. In most cases, a closed loop building heating system can be designed to accommodate any type of thermal energy that is provided to the building; supplemental thermal storage can be added to the system to accommodate variations in energy flow.

Most of the mission-specific energy quality requirements (both electric and thermal), including short-term interruptions, can be handled by the building-level energy systems, or nanogrids, which are designed based on class or tier of such requirement and are described in Sect. C.5.

C.5 Power Systems

C.5.1 Uninterruptible, Essential, and Nonessential Electrical Loads

According to UFC 3-540-01, it is important to conduct the standby power load analysis to classify each load as to the type of power that it should have and to determine the loads within the facility that need to continue to function following a loss of normal power. Based on this analysis, evaluate that loads that must be uninterruptible and those to which power must be restored within a set period of time to perform an essential function (essential) or those that are not required for the facility/mission to function if the normal power source is interrupted (nonessential).

- Uninterruptible—loads in this category require continuous power and cannot experience even momentary power disruptions. Loads in this category usually involve those used for command and control, computer and data center, communications systems, and life and safety or include hazardous or industrial process equipment. These loads will usually require the use of battery standby or a UPS to power them until supplied with power from an ATS and engine generator system combination.
- Essential—loads in this category require standby power but can be de-energized until they can be supplied from an engine generator system. Loads in this category usually include HVAC loads to vital facilities or other load types that can be de-energized for short periods without severe consequence.

- Nonessential—loads in this category can be de-energized for extended periods without severe consequence. Although these loads might be classified as nonessential, they might still be capable of being energized from engine generators, depending on the facility design. For most systems, nonessential loads do not require generator standby.
  Figure C.1 shows example of the one-line diagram for a notional facility.

C.5.2 Electric System Classes

The selection of electrical equipment to meet transient response to step loads can result in the oversizing of both motor and generator. Equipment selection is based on performance classes (Table C.5), which in accordance with ISO 8528-1 (ISO 2018), are specified as following:

- ***Class G1:*** Connected loads have basic requirements to voltage, such as general purpose lighting and other simple, mostly resistive, electrical loads.

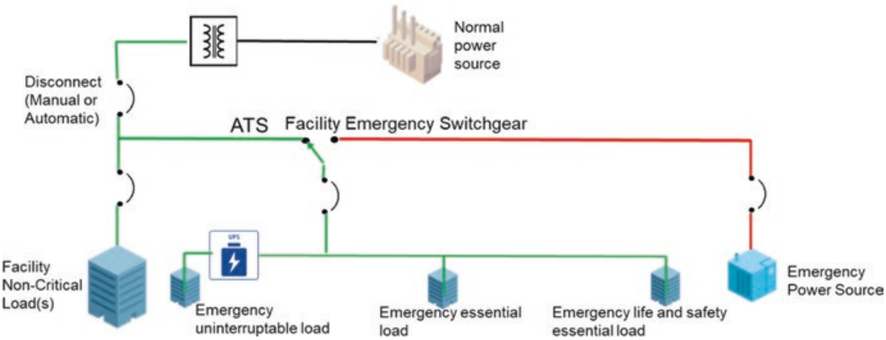


Fig. C.1 Schematic of the one-line diagram for a notional facility

Table C.5 Performance class transient limits (UFC 3-540-01)

Parameter	Performance class			
	G1	G2	G3	G4
Frequency deviation (percent) for 100% load decrease	<+18	<+12	<+10	TBD
Frequency recovery time (seconds) for 100% load change	<10	<5	<3	TBD
Voltage deviation (percent) for 100% load increase	<-25	<-20	<-15	TBD
Voltage deviation (percent) for 100% load decrease	<+35	<+25	<+20	TBD
Voltage recovery time (seconds) for 100% load change	<10	<6	<4	TBD
Frequency droop (percent)	<-8	<-5	<-3	TBD
Steady-state frequency band (percent)	<2.5	<1.5	<0.5	TBD
Steady-state voltage regulation (percent)	<5	<2.5	<1	TBD

Note: The Table C.5 column for performance class G4 states “TBD,” which means that a site-specific analysis is required to determine the voltage and frequency limits

- ***Class G2***: Applies to generating set applications where the required voltage characteristics are very similar to those for the commercial public utility electrical power system with which it operates. When load changes occur, there may be temporary but acceptable deviations of voltage, frequency, and power factor. Examples of this category include lighting systems, pumps, fans, and hoists.
- ***Class G3***: Applies to applications where the connected equipment makes severe demands on the stability and level of the frequency, voltage, and waveform characteristics of the electrical power supplied by the generating set. Examples of this category include telecommunications and thyristor-controlled loads. Note that both rectifier and thyristor-controlled loads may need special consideration with respect to their effect on generator voltage waveform. Class G3 loads require an evaluation by the designer of record to document the system voltage and frequency limitations, including transient response.
- ***Class G4***: Applies to applications where the demands made on the stability and level of the frequency, voltage, and waveform characteristics of the electrical power supplied by the generating set are exceptionally severe. Examples include data processing equipment or computer systems. Class G4 loads require an evaluation by the designer of record to document the system voltage and frequency limitations, including transient response.

In the event that the normal/primary power source fails, emergency and standby power systems provide an alternative source of electrical power to essential loads in buildings and facilities. Standard NFPA 110 (NFPA 2016) contains requirements to capacity, reliability, and quality of power provided to loads by emergency power supply systems (EPSS) for a length of time specified in Table C.6 and within specified time (Table C.7) following loss or failure of the normal power supply.

Table C.6 Classification of emergency power supply systems

Class	Minimum time
Class 0.083	0.083 h (5 min)
Class 0.25	0.25 h (15 min)
Class 2	2 h
Class 6	6 h
Class 48	48 h
Class X	Other time, in hours, as required by the application, code, or user

Table C.7 Types of emergency power supply systems

Designation	Power restoration
Type U	Basically uninterruptible (UPS systems)
Type 10	10 s
Type 60	60 s
Type 120	120 s
Type M	Manual stationary or nonautomatic—no time limit

The NFPA 110 (NFPA 2016) standard recognizes two levels for equipment installation, performance, and maintenance requirements:

- Level 1 systems shall be installed where failure of the equipment to perform could result in loss of human life or serious injuries.
- Level 2 systems shall be installed where failure of the EPSS to perform is less critical to human life and safety.

Level 1 and Level 2 systems shall ensure that all loads served by the EPSS are supplied with alternate power that meets all the following criteria:

1. Of a quality within the operating limits of the load
2. For a duration specified for the class as defined in Table C.6
3. Within the time specified for the type as defined in Table C.7

Allowable downtime or time to repair and power quality requirements for some representative mission-critical facilities can be illustrated using the following examples.

C.5.2.1 Data Centers and Other Buildings with Computing Capability

This category of mission-critical facilities or dedicated spaces within these facilities may include the following: emergency operation centers, sensitive compartmented information facilities (SCIFs), network operations centers (NOCs), network enterprise centers (NECs), command-control-communications-computers-intelligence facilities (C4I), house computer systems, and associated components, such as telecommunications and storage systems. Since IT operations are crucial for business continuity, they generally include redundant or backup components and infrastructure for power supply, standby generators, UPS, ATSs, data communication connections, environmental controls (e.g., air-conditioning, fire suppression), and various security devices. The Telecommunications Industry Association (TIA) Standard for Data Centers, ANSI/TIA-942-A (TIA 2012), specifies the minimum requirements for telecommunication infrastructure of data centers and computer rooms including single tenant enterprise data centers and multi-tenant Internet hosting data centers. The topology proposed in TIA-942-A is intended to be applicable to any size data center. When more specific requirements for mission-critical operations are not available, this standard can be consulted by mission-critical operators of other buildings with similar IT operations using critical equipment loads presented in Table C.8.

Uptime Institute-Data Center Tier Standard defines four tiers of requirements to data centers:

- Tier I: lacks redundant IT equipment, with 99.671% availability, maximum of 1729 min annual downtime per year.
- Tier II: adds redundant infrastructure—99.741% availability (1361 min).
- Tier III: adds more data paths, duplicate equipment, and that all IT equipment must be dual-powered (99.982%, 95 min).

Table C.8 Examples of critical equipment loads

Space description	Load, W/ft^2	
	Brigade operations/ brigade and battalion HQ (UFC 4-140-01)[a]	Command and control facilities (UFC 4-140-03)[b]
Sensitive compartmented information facility (SCIF)	5.98	4.7
Signal intelligence	2.36	11.5
Sensitive compartmented information facility server room	51.85	97
Geospatial intelligence	2.93	4.0
Emergency operations center (open office)	15.58	
Network operations centers (open office)	1.31	5.8
Audio/visual server room	39.87	
Server room (emergency operations center)	40.58	
Special technical operations facility		3.1
Server room (operations center)		21.1
Server room (NOC)		95.5
Special technical operations, video teleconferencing		2.0
Telecom entrance/equipment room		73.9
Secret Internet protocol router network room		54.2
Nonclassified Internet protocol router network room		55.3

[a]HQDA (2015b)
[b]HQDA (2012)

- Tier IV: all cooling equipment is independently dual-powered; adds fault-tolerance (99.995%, 26 min).

Spaces listed in Table C.6 can be attributed to facilities with class 3 electric systems and Tier II or Tier III requirements. For more information about such requirements, consult with mission operators.

Although the public power distribution system is fairly reliable in most developed countries, studies have shown that even the best utility systems are inadequate to meet the needs of mission-critical applications. Most organizations, when faced with the likelihood of downtime, and data processing errors caused by utility power, choose to implement a UPS system that implements electrical power conditioning between the public power distribution system and their mission-critical loads (McCarthy and Avelar 2016).

UPS configurations found in the market today are many and varied; there are five that are most commonly applied. These five include (1) capacity, (2) isolated redundant, (3) parallel redundant, (4) distributed redundant, and (5) system plus system. The tiers described in the Uptime Institute paper (Turner et al. 2001) encompass the five UPS architectures listed in Table C.9 and illustrated in Figs. C.2, C.3, C.4, C.5, C.6, C.7, and C.8.

Table C.9 Scale of power availability for UPS configurations

Tier class	Configuration	Scale of power availability
Tier I	Capacity (N[a])	1 = lowest
Tier II	Isolated redundant (N+1)[b]	2
	Parallel redundant (N+1)	3
Tier III	Distributed redundant	4
Tier IV	System plus system (2N, 2N+1)	5 = highest

[a]*N* number of units required to accomplish task
[b]*N+1* required number of components N have one independent backup component (+1)

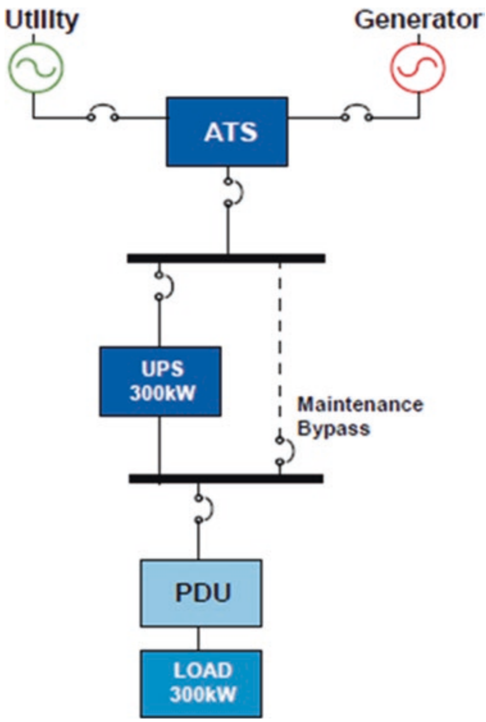


Fig. C.2 Single module "capacity" UPS configuration. (McCarthy and Avelar 2016)

Most *"N" system configurations*, especially under 100 kW, are placed in buildings with no particular concern for the configuration of the overall electrical systems in the building. In general, building electrical systems are designed with an "N" configuration, so an "N" UPS configuration requires nothing more than that to feed it. A common single module UPS system configuration is shown in Fig. C.2.

An *isolated redundant configuration* is sometimes referred to as an "N+1" system; however, it is considerably different from a parallel redundant configuration, which is also referred to as N+1. The isolated redundant design concept does not require a paralleling bus, nor does it require that the modules have to be the same capacity or even from the same manufacturer. In this configuration, there is a main or "primary" UPS module that normally feeds the load. The "isolation" or "secondary" UPS feeds the static bypass of the main UPS module(s). This configuration requires that the primary UPS module has a separate input for the static bypass circuit. This is a way to achieve a level of redundancy for a previously nonredundant configuration without completely replacing the existing UPS. Figure C.3 shows an isolated redundant UPS configuration.

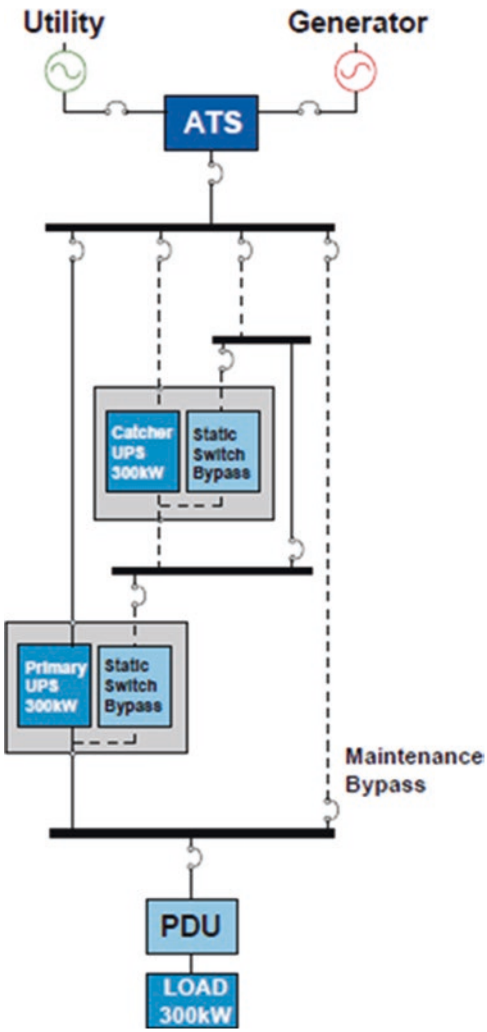


Fig. C.3 Isolated redundant UPS configuration. (McCarthy and Avelar 2016)

The secondary UPS can also be used to extend the run time of the primary UPS, switching from primary to secondary as the power delivery of the primary is consumed. Additional UPS capability is available for unexpected generator shutdown.

Parallel redundant configurations allow for the failure of a single UPS module without requiring that the critical load be transferred to the utility source. The intent of any UPS is to protect the critical load from the variations and outages in the utility source. As the criticality of data increases and the tolerance for risk diminishes, the idea of going to static bypass and maintenance bypass is seen as something that needs to be further minimized. N+1 system designs still must have the static bypass capability, and most of them have a maintenance bypass as they still provide critical capabilities. Figure C.4 depicts a typical two module parallel redundant configuration. This figure shows that even though these systems provide protection of a single UPS module failure, there still remains a single point of failure in the paralleling

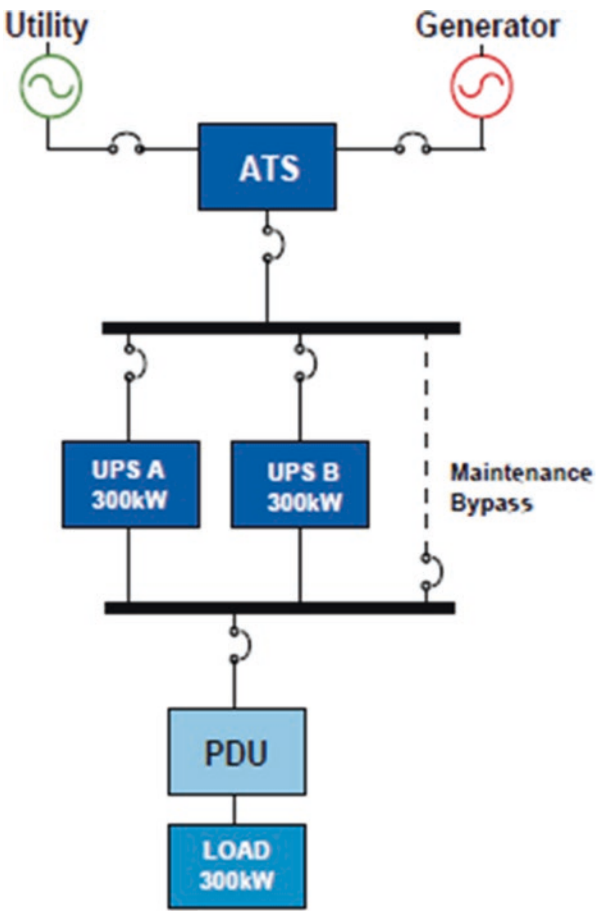


Fig. C.4 Parallel redundant (N+1) UPS configuration. (McCarthy and Avelar 2016) bus. As with the capacity design configuration, a maintenance bypass circuit is an important consideration in these designs to allow the UPS modules to be shut down for maintenance periodically. The paralleling bus can be duplicated for an alternate path of transmission for paralleling bus failure.

Distributed redundant configurations, also known as tri-redundant, are commonly used in the large data center market today especially within financial organizations. This design was developed in the late 1990s in an effort by an engineering firm to provide the capabilities of complete redundancy without the cost associated with achieving it. The basis of this design uses three or more UPS modules with independent input and output feeders. Figures C.5, C.6, and C.7 illustrate a 300-kW load with three different distributed redundant design concepts. Figure C.5 shows three UPS modules in a distributed redundant design that could also be termed a "catcher system." In this configuration, module 3 is connected to the secondary input on each static transfer switches (STS) and would "catch" the load upon the failure of either primary UPS module. In this catcher system, module 3 is typically unloaded.

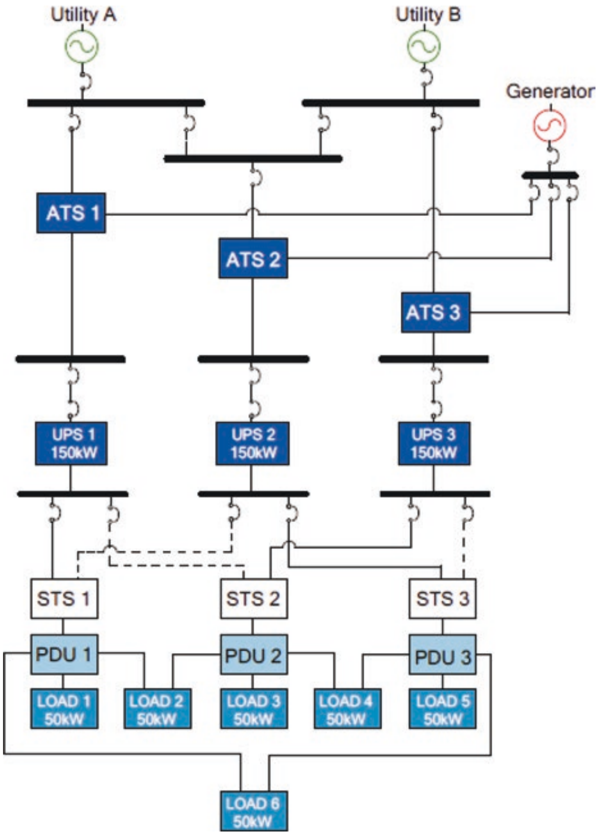


Fig. C.5 Distributed redundant "catcher" UPS configuration. (McCarthy and Avelar 2016)

Figure C.6 shows a distributed redundant design with three STS and the load evenly distributed across the three modules in normal operation. The failure on any one module would force the STS to transfer the load to the UPS module feeding its alternate source.

Figure C.7 depicts design typically known as a tri-redundant and uses no STSs.

"System plus system," "isolated parallel," "multiple parallel bus," "double-ended," "2(N+1)," "2N+2," "[(N+1) + (N+1)]," and "2N" are all nomenclatures that refer to variations of this configuration. With this design, it now becomes possible to create UPS systems that may never require the load to be transferred to the utility power source. These systems can be designed to wring out every conceivable single point of failure. However, the more single points of failure that are eliminated, the more expensive this design will cost to implement.

Most large system plus system installations are located in standalone, especially designed buildings. It is not uncommon for the infrastructure support spaces (UPS, battery, cooling, generator, utility, and electrical distribution rooms) to be equal in size to the data center equipment space or even larger. This is the most reliable, and

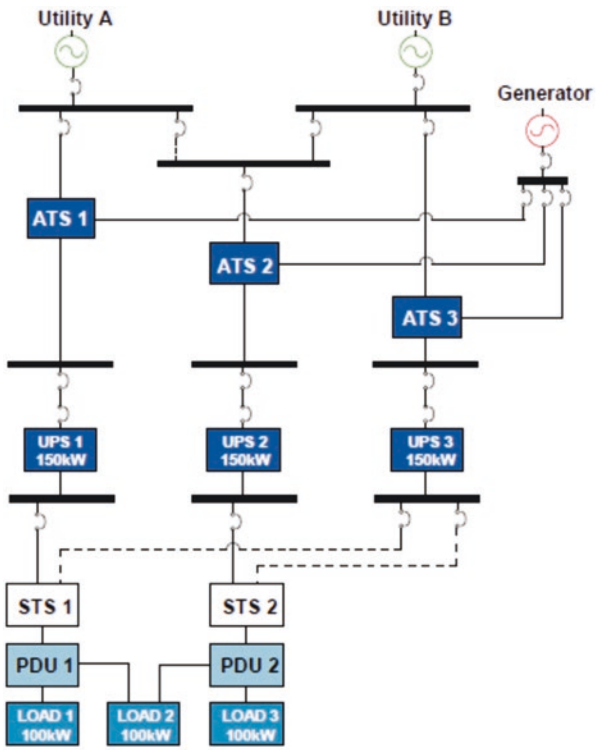


Fig. C.6 Distributed redundant UPS configuration with static transfer switch (STS). (McCarthy and Avelar 2016)

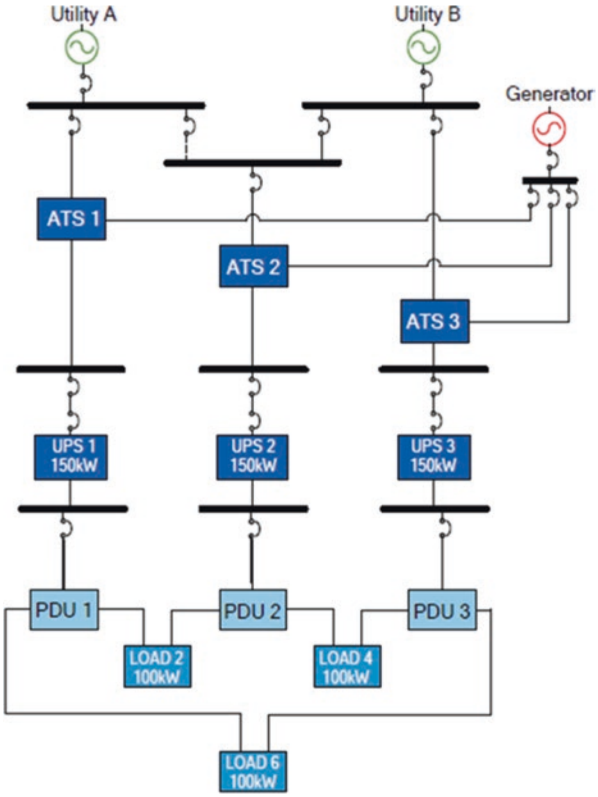


Fig. C.7 Tri-redundant UPS configuration (no STS). (McCarthy and Avelar 2016)

most expensive, design in the industry. It can be very simple or very complex depending on the engineer's vision and the requirements of the owner.

Although a name has been given to this configuration, the details of the design can vary greatly, and this, again, is in the vision and knowledge of the design engineer responsible for the job. The 2(N+1) variation of this configuration, as illustrated in Fig. C.8, revolves around the duplication of parallel redundant UPS systems.

The considerations for selecting the appropriate configuration are:

- Cost/impact of downtime
- Budget
- Types of loads (single- vs. dual-corded)
- Types of IT architecture
- Risk tolerance
- Availability of alternate recovery sites
- Availability performance
- Reliability performance

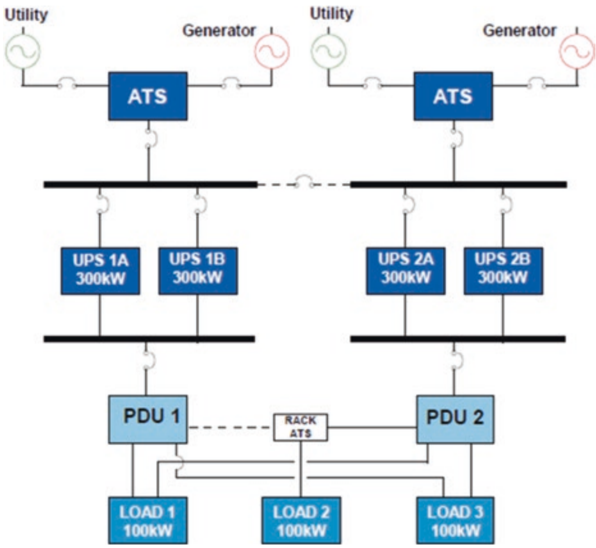


Fig. C.8 2(N+1) UPS configuration. (McCarthy and Avelar 2016)

- Maintainability performance
- Maintainability support performance

The last four bullets can be rolled up into a term called dependability. For more information, please refer to McCarthy and Avelar (2016).

C.5.2.2 Healthcare Facilities

Per NFPA 99 (NFPA 2018a), healthcare facilities include, but are not limited to, hospitals, nursing homes, limited care facilities, clinics, medical and dental offices, and ambulatory healthcare centers. This definition applies to normal, regular operations and does not pertain to facilities during declared local or national disasters. Patient care spaces in healthcare facilities are described using the following four categories (NFPA 99, paragraph 4.1):

Category 1 Space. Space in which failure of equipment or a system is likely to cause major injury or death of patients, staff, or visitors

Category 2 Space. Space in which failure of equipment or a system is likely to cause minor injury to patients, staff, or visitors

Category 3 Space. Space in which the failure of equipment or a system is not likely to cause injury to patients, staff, or visitors but can cause discomfort

Category 4 Space. Space in which failure of equipment or a system is not likely to have a physical impact on patient care

In addition to space categories, equipment and systems are classified similar to the ones described above. From the perspective of risk, healthcare facilities are classified and designed using the NFPA 101 (NFPA 2018b) occupancy classifications.

Per NFPA 99 (NFPA 2018a), the authority having jurisdiction shall be cognizant of the requirements of a healthcare facility with respect to its uniqueness for continued operation in an emergency. These requirements are based on **emergency management categories** (NFPA 99 paragraph 12.3) of the healthcare facility:

Category 1: Those inpatient facilities that remain operable to provide advanced life support services to injured responders and disaster victims. These facilities manage the existing inpatient load as well as plan for the influx of additional patients as a result of an emergency.

Category 2: Those inpatient or outpatient facilities that augment the critical mission. These facilities manage the existing inpatient or outpatient loads but do not plan to receive additional patients as a result of an emergency or do not plan to remain operable should essential utilities or services be lost.

The above set of categories defined by NFPA 99 (paragraph 4.1) along with NFPA 70 (NFPA 2020) allow the narrowing down of the scope of mission-critical areas and systems serving these areas, where patients may be subjected to invasive procedures and connected to line-operated, electro-medical devices, which need to be given priority in the wake of disaster that seriously overtaxes or threatens to seriously overtax the routine capabilities of a healthcare facility. These areas typically include (per UFC 4-510-01 [NAVFAC 2016]):

- Operating rooms
- Surgical delivery rooms (for C-section) and labor and delivery rooms
- Cystoscopy operating rooms
- Maxillofacial surgery
- Recovery (surgery and labor recovery beds)
- Coronary care units (patient bedrooms)
- Intensive care unit (ICU) (patient bedrooms)
- Emergency care units (treatment, trauma, and urgent care rooms and cubicles)
- Labor rooms (including stress test and preparation)
- Nursery intensive care unit (NICU) (birth bedrooms)
- Cardiac catheterization
- Angiographic exposure
- Hyperbaric chamber
- Hypobaric chamber
- Special procedure rooms (as identified on a project-by-project basis by the user)

According to NFPA 99 (2018a), the following *essential utilities and systems* shall plan for the following utilities during an emergency, as applicable:

- Electricity
- Potable water
- Non-potable water
- Wastewater
- HVAC
- Fire protection

- Fuel for building operations
- Fuel for essential transportation
- Medical gas and vacuum
- Information technology

The facility shall identify the resource capability shortfalls from 96 h of sustainability and determine if mitigation activities are necessary and feasible. Resources needed in an emergency could include medical, surgical, and pharmaceutical resources; water; fuel; staffing; food; and linen.

Today's healthcare facilities, because of their increasing size and complexity, have become more and more dependent upon safe, adequate, and reliable electrical systems. New types of sophisticated diagnostic and treatment equipment, using microprocessors or computers, come on the market. Many of these items are sensitive to electrical disturbances, and some require a very reliable power source. Invasive medical procedures such as cardiac catheterization make electrical safety extremely important. Moreover, new medical and surgical procedures are constantly being developed, and new technologies are being used. Modern facilities use robotics, telemedicine, picture archiving and communications systems (PACS), and the mixing of diagnostic and treatment modalities (i.e., surgical procedures combined with various types of medical imaging). In addition to the special safety and reliability requirements, healthcare facilities have unique life safety and communication requirements, because patients are generally unable to care for themselves or evacuate in the event of an emergency (IEEE 2007)

Electrical power to healthcare facilities (Fig. C.9) is provided by primary utility normal sources along with alternate power sources connected to distribution

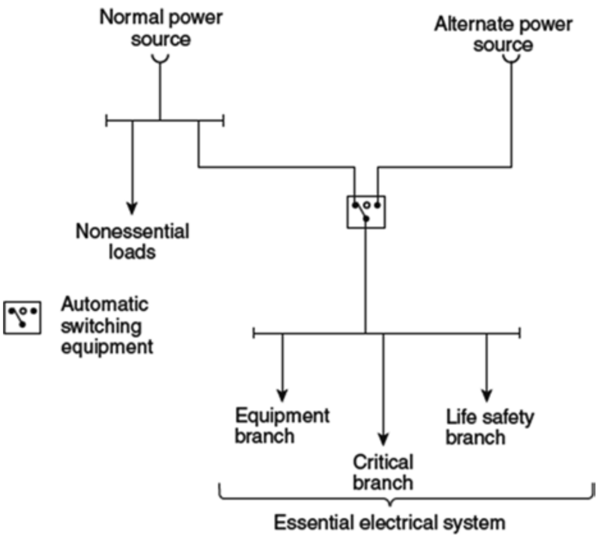


Fig. C.9 Example of a hospital one-line traditional diagram. (Courtesy NFPA 70 [2020]) systems and ancillary equipment, designed to ensure continuity of electrical power to designated areas and functions of a healthcare facility during disruption of normal power sources and also to minimize disruption within the internal wiring system. Power from primary sources is provided by two primary service feeders, each serving one end of a double-ended substation or to a selector switch serving a multi-ended network substation. Each feeder shall be able to carry the full facility demand, plus 20% spare load growth at 100% demand. Service feeders shall be connected to different power sources, if available, and to two differently routed distribution system feeders. Where two power sources are not available, the service feeders may be connected to two different sections of a true loop system (NAVFAC 2016).

Alternative power can be provided by UFC 4-510-01 (NAVFAC 2016) and NFPA 110 (2016):

- **Prime Power Class** generator sets expected to provide power on a continuous basis, i.e., in excess of 4000 h annually or in excess of 40,000 h during the initial 10 years of operation, to serve as the sole or primary source of power
- **Standby Power Class** generator sets expected to provide power on a standby basis for a significant number of hours each year, i.e., between 1000 and 4000 h annually or between 10,000 and 40,000 h during the initial 10 years of operation
- **Emergency Power Class** generator sets expected to provide power on an emergency basis for a short period of time, i.e., less than 1000 h annually or less than 10,000 h during the initial 10 years of operation

While power from primary sources is provided both to essential and nonessential loads (Fig. C.9), alternative power is provided primarily to essential loads by essential electrical system, which are comprised of three branches: **life safety branch**, **critical branch**, and **equipment branch**. The generating equipment used for essential electrical system shall be either reserved exclusively for such service or normally used for other purposes of peak demand control, internal voltage control, load relief for the external utility, or cogeneration. If normally used for such other purposes, two or more sets shall be installed, such that the maximum actual demand likely to be produced by the connected load of the life safety and critical branches, as well as medical air compressors, medical-surgical vacuum pumps, electrically operated fire pumps, jockey pumps, fuel pumps, and generator accessories, shall be met by a multiple generator system, with the largest generator set out of service (per NFPA 99 [2018a]) (see Fig. C.9).

Life safety branch serves systems such as fire alarms, mass notification annunciating and signaling, fire suppression, and emergency lighting. Many systems in the life safety branch are required by various building codes (NFPA 99 [2018a], paragraph 6.4).

Critical branch serves systems and equipment that are essential in success of the mission. Loss of electrical power to the critical branch can result in partial or total mission failure.

Equipment branch serves as the emergency, or backup, electrical power source. It can also be considered as a critical branch because the equipment branch provides electrical power to both the life safety branch and the critical branch. The design for resiliency of the equipment branch matches the critical and life safety branch requirements**.**

A critical branch supplies power for task illumination, fixed equipment, select receptacles, and select power circuits serving areas and functions related to patient care that are automatically connected to alternate power sources by one or more transfer switches during interruption of the normal power source.

According to NFPA 99 (2018a), essential electrical systems shall have a minimum of the following two independent sources of power: a normal source generally supplying the entire electrical system and one or more alternate sources for use when the normal source is interrupted. Where the normal source consists of generating units on the premises, the alternate source shall be either another generating set or an external utility service.

The generating equipment used shall be either reserved exclusively for such service or normally used for other purposes of peak demand control, internal voltage control, load relief for the external utility, or cogeneration. If normally used for such other purposes, two or more sets shall be installed, such that the maximum actual demand likely to be produced by the connected load of the life safety and critical branches, as well as medical air compressors, medical-surgical vacuum pumps, electrically operated fire pumps, jockey pumps, fuel pumps, and generator accessories, shall be met by a multiple generator system, with the largest generator set out of service (not available). The alternate source of emergency power for illumination and identification of means of egress shall be the essential electrical system. The alternate power source for fire protection signaling systems shall be considered the essential electrical system.

Essential electrical system power sources shall be classified as Type 10, Class X, Level 1 generator sets per NFPA 110 (2016). The life safety and critical branches shall be installed and connected to the alternate power source so that all functions specified for the life safety and critical branches are automatically restored to operation within 10 s after interruption of the normal source.

C.5.2.3 Energy Requirements for Food Storage

During a power outage, critical areas in dining facilities and food storage areas are those with refrigerators and freezers. The food in the refrigerator during a power outage should be safe as long as power is out no more than 4 h. The door should be kept closed as much as possible. A full freezer will hold its temperature for about 48 h (24 h if half-full) (USDA 2013, n.d.).

Table C.10 provides exemplary power requirements to selected military critical facilities. All these facilities require emergency generators (stationary or mobile/rented). Facilities that have no tolerance to power disruption and have equipment requiring G3 or G4 class of power stability and level of the frequency, voltage, and waveform characteristics use UPS.

Table C.10 Examples of power requirements to selected military critical facilities

Facility	Critical energy requirement, kW	UPS			Generator				
		Make/model	Battery type	Run time, min	Make/model	RatedkW/kVA	% rated load	Fuel type	Run time, hrs.
NEC	80	Powerware	Gel cell	15	Elliot	200/250	40	Diesel	50
Installation operation center	32	Powerware	Gel cell	15	Cummins	80/100	40	Diesel	24
Land mobile radio repeater	10	Emerson Liebert	Lead-acid	30	Generac	35/44	28	Diesel	67
Pumping station	100	No			Cummins	175/220	57	Diesel	72
Dining facility	196	No			Generac	230/287	85	Diesel	30
Communications hub	11	APS Smart UPS	Lead-acid	15	Cummins	60/75	18	Diesel	30
Fitness center	70	No			Rental				
Hospital	2300	No			Motor Turbine Union	2400/30,000	96	Diesel	96
Sewer lift station	12	No			Kohler	50/64	25	Diesel	72
Garrison HQ	46	Desk-side APS Smart UPS	Lead-acid	15	Generac	230/287	20	Diesel	30
HQ network	11	APC Smart	Lead-acid	15	Generac	18/75	60	Natural Gas (NG)	Indefinite
Radio relay station	2	No			Onan	20/25	10	Propane	120
Community center	30	No			Rental				
Server center	450	Powerware	Gel cell	15	2 Kohler	750/938	60	Diesel	50
Fire station	15	No			Generac	30/37	33	Diesel	55
Police station		Desk-side APS Smart UPS	Lead-acid	15	Kohler	18/18	83	NG+LP	150
Commissary	324	No			Onan	30/37		NG	Indefinite

Appendix D. Requirements for Building Thermal Conditions Under Normal and Emergency Operations in Extreme Climates

D.1 Introduction

This Appendix provides recommendations on thermal and moisture parameters (air, temperature, and humidity content) in different types of buildings under normal and emergency operation conditions in extreme climate condition, e.g., cold/arctic (USDOE climate zones 6–8) and hot and humid (USDOE climate zones 0–2a). Three scenarios are considered under normal operating conditions, when the building/space is occupied, temporarily (2–5 days), unoccupied, and unoccupied long term (i.e., hibernated). These thermal parameters are necessary to achieve one or several of the following purposes:

- To perform required work in a building in a safe and efficient manner
- To support processes housed in the building
- To provide conditions required for a long-term integrity of the building and building materials

Many emergency conditions may occur in the life of a building. Discussion presented in this Appendix is limited to the following emergency conditions: interruptions of fuel, steam, hot or chilled water, and electrical service leading to the interruption of space conditioning for the building.

During an emergency situation, requirements of thermal parameters for different categories of buildings or even parts of the building may change. When the operation of normal heating, cooling, and humidity control systems is limited or unavailable, mission-critical areas can be conditioned to the level of thermal parameters required to support the ability of personnel who perform mission-critical operations but not to the level of their optimal comfort conditions. Beyond these threshold (***habitable***) levels, effective execution of critical missions is not possible, and mission operators have to be moved into a different location. These threshold limits of thermal parameters may be in a broader range compared to those required for thermal comfort but not to exceed levels of heat and cold stress thresholds. However, special process requirements (e.g., with IT and communication equipment, critical hospital spaces, etc.) should be given a priority if they are more stringent. Broader ranges of air temperatures and humidity levels in building spaces surrounding mission-critical areas may be used, but they need to be limited to prevent excessive thermal losses/gains and moisture transfer through walls and apertures not designed with thermal and air/vapor barriers. Finally, noncritical standalone buildings can be hibernated, but necessary measures should be taken, and the thermal environment should be maintained (at the ***sustainability threshold level***) when possible to prevent significant damage to these buildings before they can be returned back to their normal operation.

D.2 Normal (Blue Sky) Operating Conditions

Under normal operating conditions, for any given building, factors like building envelope insulation and airtightness, ventilation rates, thermostat setpoints, plug loads, and lighting levels have a significant impact on building energy consumption and cost. These factors pertain irrespective of the climate, whether arctic or hot/humid.

It is important that engineers and operations and maintenance (O&M) personnel design for and use appropriate rates and setpoints to maintain these thermal conditions, which provide occupant comfort, health, and productivity and which minimize energy usage in normal operation conditions and make thermal systems more resilient during emergency operation. Setting these rates and setpoints can be as much an art as a science, but a number of standard references can be used to help in the operation of the building. The following references provide guidance on the suggested values.

Thermal requirements include criteria for thermal comfort and health and process needs and criteria for preventing the freezing of water pipes, growth of mold and mildew, and other damage to the building materials or furnishings. Under normal operating conditions, code compliant buildings are presumed to be free of mold and mildew problems; if these conditions do occur, they become matters for O&M intervention.

Thermal comfort and health criteria primarily involve the temperature and humidity conditions in the building. Too high a temperature means that occupants are uncomfortably hot. Too low a temperature means that occupants are uncomfortably cold. The wrong humidity (rooms typically do not have humidistats) means that occupants feel damp or sweaty or too dry. Thermal comfort is defined by ASHRAE Standard 55, *Thermal Environmental Conditions for Human Occupancy*, the latest version of which was published in 2017 (ASHRAE 2017a) and is available from ASHRAE.

The following dry bulb room air temperatures and relative humidity values (IMCOM 2010) are within the ASHRAE Standard 55 (ASHRAE 2017a) range and should not be exceeded:

Cooling Period The dry bulb temperature (DBT) in occupied spaces should not be set below 70 °F (21 °C) with the relative humidity (RH) maintained below 60%. When the space is unoccupied during a short period of time, the room thermostat should be reset to 85 °F (29 °C) with the RH maintained below 70%. In spaces unoccupied for an extended period of time, temperature should not be controlled, but the building air RH should be maintained below 70%.

Heating Period RH of *all* building air should be maintained below 50% and above 30% at all times (unless otherwise required for health reasons at hospitals or daycare facilities or required by processes). Examples of DBT in occupied spaces not to be exceeded are:

- Barracks and other living quarters: 70 °F (21 °C) Monday through Friday from 0500 to 2200 and 65 °F (18.3 °C) from 2200 to 0500. Temperature settings for barracks Saturday and Sunday 70 °F (21 °C) from 0600 to 2200 and 65 °F (18.3 °C) from 2200 to 0600.
- Offices, warehouses, etc., where personnel work in a seated or standing position involving little or no exercise: 70 °F (21 °C) during working hours and not more than 55 °F (12.8 °C) during nonworking hours.
- Childcare facilities: 72 °F (22.2 °C) during working hours.
- When the space is unoccupied during a short period of time, the room thermostat should be set back to 55 °F (12.7 °C). In spaces unoccupied for an extended period of time, temperature should be controlled at 40 °F (5 °C).

Process-related criteria include temperature and humidity needed to perform the process housed in the building (e.g., spaces with IT and communications equipment, critical hospital areas, industrial process [painting, printing, etc.]). While new design guidance for computer systems indicates a much higher tolerance for high temperatures than previously thought, there are specialized electronic and laboratory equipment that have fairly tight temperature and humidity requirements for protection from damage caused by electrostatic discharge. Archival storage of important documents also involves relatively tight tolerances for temperature and humidity.

Many mission-critical facilities or dedicated spaces within these facilities (e.g., emergency operation centers, sensitive compartmented information facilities [SCIFs], network operations centers [NOCs], network enterprise centers [NECs]) house computer systems and associated components, such as telecommunications and storage systems. Environmental requirements for spaces with IT and communications equipment may vary depending on type of equipment or manufacturers. According to ASHRAE (2005), there are six standard classes of thermal requirements.

Class A1. Typically, a datacom facility with tightly controlled environmental parameters (dew point [DP], temperature, and RH) and mission-critical operations, including those housing servers and data storage

Class A2/A3/A4. The types of products typically designed for use in an information technology space with some control of environmental parameters (DP, temperature, and RH) are volume servers, storage products, personal computers, and workstations. Among these three classes, A2 has the narrowest temperature and moisture requirements, and A4 has the widest environmental requirements.

Class B. Typically an office, home, or transportable environment with a little control of environmental parameters (temperature only), including personal computers, workstations, and printers.

Class C. Typically a point of sale or light industrial environment with weather protection.

Classes A3 and A4 do not have special requirements to be considered.

In addition to four classes of requirements for IT and communications equipment facilities discussed above, there are also requirements for Network Equipment-Building System (NEBS) offices housing switches, routers, and similar equipment with some control of environmental parameters (DP, temperature, and RH). Table D.1 lists the recommended and allowable conditions for Class A1, Class A2, and NEBS environments.

Healthcare facilities represent another group of mission-critical facilities. Per NFPA 99 (2018a), healthcare facilities include, but are not limited to, hospitals, nursing homes, limited care facilities, clinics, medical and dental offices, and ambulatory health care centers. This definition applies to normal, regular operations and does not pertain to facilities during declared local or national disasters. Patient care spaces in healthcare facilities are described using the following four categories:

Category 1 Space. Space in which failure of equipment or a system is likely to cause major injury or death of patients, staff, or visitors

Category 2 Space. Space in which failure of equipment or a system is likely to cause minor injury to patients, staff, or visitors

Category 3 Space. Space in which the failure of equipment or a system is not likely to cause injury to patients, staff, or visitors but can cause discomfort

Category 4 Space. Space in which failure of equipment or a system is not likely to have a physical impact on patient care

Table D.1 Recommended and allowable conditions for Classes A1-A4 and NEBS environments

	ClassA1/ClassA2 (ASHRAE 2019)		NEBS (ASHRAE 2005)	
Conditions	Allowable level	Recommended level	Allowable level	Recommended level
Temperature control range		64.4–80.6 °F (18–27 °C)	41–104 °F (5–40 °C)	65–80 °F (18–27 °C)
A1	59–89.6 °F (15–32 °C)			
A2	50–95 °F (10–35 °C)			
Maximum temperature rate of change	9 °F/h [36 °F/h][a] (5 °C/h [20 °C/h])		2.9 °F/h (1.6 °C/h)	
RH control range		15.8–59 °F DP (−9) –15 °C DP and 60% RH	5–85% 82 °F (28 °C) Max DP	Max 55%
A1	10.4 °F (−12 °C) DP and 8% RH to 62.6 °F (17 °C) DP and 80% RH			
A2	10.4 °F (−12 °C) DP and 8% RH to 69.8 °F(21 °C) DP and 80% RH			

[a]9 °F/h (5 °C/h) for tape storage, 36 °F/h (20 °C/h) for all other IT equipment, and not more than 9 °F (5 °C/h) in any 15 min period of time

Table D.2 lists examples of requirements (ASHRAE 2017b) to thermal environment in spaces included in categories 1 and 2.

Army guidelines (IMCOM 2010) provide the following recommendations for space air temperatures for "industrial" spaces during the heating period:

- Issue and similar rooms: 60 °F (15.5 °C).
- Special process rooms, such as paint shops and drying rooms: 80 °F (26.6 °C) allowed or the one required by the process.
- Shops, hangars, and other buildings where employees work in a standing position or exercise moderately, such as sorting or light packing or crating: 60 °F (15.5 °C) during the day; 40 °F (4.4 °C) during night time.
- Shops, warehouses, and the like, where employees do work involving considerable exercise, such as foundries, heavy packing, crating, and stacking, or where heat is required to protect material or installed equipment from freezing: 40 °F (4.4 °C). EXCEPTION: Localized heat, not to exceed 55 °F (13 °C), may be furnished in areas where the work requires medium or light personnel activity.
- Heat is not permitted in warehouse areas that do not contain material or equipment requiring protection from freezing or condensation and where warehousing of stored goods is the only operation. Heat for the prevention of condensation on stored machinery and material will be supplied after a thorough survey of all conditions and the approval of managers.
- Buildings other than those specified above will not be heated to temperatures higher than 65 °F (18 °C) without approval (in writing) from managers.
- The environmental conditions (temperature and humidity) maintained in indoor spaces determine not only the comfort of the occupants of those spaces but also the long-term condition of the building itself. Historically, only the DBT of indoor spaces was controlled to achieve comfortable indoor conditions for the occupants. Little attention was given to control the moisture/humidity in the spaces. As a result, many existing Army buildings have exhibited mold/mildew problems.

Table D.2 Thermal environment requirements for selected spaces in medical facilities

Space	T °F	T °C	RH, %
Class B and C operating rooms	68–75	20–24	30–60
Operating/surgical cystoscopic rooms	68–75	20–24	30–60
Delivery room	68–75	20–24	30–60
Critical and intensive care	70–75	21–24	30–60
Wound intensive care (burn unit)	70–75	21–24	40–60
Radiology	70–75	21–24	Max 60
Class A operating/procedure room	70–75	21–24	20–60
X-ray (surgery/critical care and cath)	70–75	2124	Max 60
Pharmacy	70–72	21–22	Max 60

Arctic Buildings Eliminating mold growth from surfaces of buildings requires year-round control of both the DBT and the DP temperature (or air RH) in the indoor spaces in hot/humid climates. In arctic climates, even those humidified up to 30% RH indoors should not exhibit mold problems given the low temperature and vapor pressure outdoors. Preliminary transient hygrothermal analysis of common arctic building wall and roof assemblies shows no risk of mold growth except for atypical unwise assemblies. The use of insulating materials in wall and roof assemblies presents strong assurance of good moisture performance.

Temperature may be set back in arctic buildings during short- and long-term periods, provided measures are taken to prevent pipe bursting. See below. This may require keeping the interior of the building heated to 50 °F (10 °C). Setting back temperature does not present a mold risk in arctic climates. Of course, outdoor air to the building should be shut off during unoccupied periods.

Buildings in Hot/Humid Climates There are many conditions that permit mold growth on interior building surfaces in hot/humid climates. When buildings were constructed without attention to airtightness, with indoor air pressures negative, and with vinyl wall coverings, mold growth on the back side of the interior wallboard was widespread. This condition was recognized and remedied in practice. Under normal conditions, with indoor humidity maintained below 70%, mold growth should not occur on interior building surfaces. Temperature setback for the short and long term should be done carefully. Indoor humidity should not be allowed to rise above 70%. In particular, short cycling of direct expansion (DX) units should be avoided. (Short-cycling permits lowered cooling loads to be met with little or no humidity removal.)

Mold growth occurs in buildings even with moderate average air RH when cold spots exist on poorly insulated supply air ducts and chilled water pipes, supply air diffusers, building envelope elements that are poorly insulated and not airtight, areas with thermal bridges, etc. Careful design and operation of the building envelope and the HVAC, ventilation, and exhaust systems is required to eliminate the potential for mold growth in Army buildings. Maintaining ALL the air inside the building above the DP will reduce potential moisture-related problems. According to the ASHRAE Humidity Control Design Guide (Harriman et al. 2001), the suggested DP limits that meet both health and mold problems requirements are <57 °F (<14 °C) in summer and >35 °F (>2 °C) in winter.

It is important that designers and O&M personnel design and maintain the building and HVAC systems to satisfy all three categories of requirements. In most of cases, thermal comfort requirements satisfy the process. Preventing moisture-related problems requires special attention to the design and building operation. Energy conservation should not be achieved at expense of health, occupant's well-being, and building sustainability. Certain strategies and technologies can minimize or eliminate premium energy use.

D.3 Emergency (Black Sky) Operating Conditions

Depending on the emergency situation, the objective for any mission-critical area of the given building is to maintain mission-critical operations as long as it is necessary or technically possible. The objective for other, noncritical building areas and stand-alone buildings is to minimize the damage to the asset. It is assumed that building processes will be kept only in mission-critical areas and that non-mission-critical activities will be discontinued. In the mission-critical areas/buildings, operations will continue, and processes will require people with critical skills and thought processes. While under normal circumstances, building environmental controls are designed and operated to create a thermoneutral environment conducive to optimal employee thermal environment discussed in the section under blue sky operating condition. However, if the building environmental controls should fail for any reason, the thermal environment may change in such a way as to no longer be optimal for workers needing their critical skills to perform their jobs. The section below describes threshold indoor environmental conditions beyond which human physical and mental skills can no longer be maintained.

Under black sky operations, efforts should be made to maintain thermal environment to prevent significant damage to both mission-critical and non-mission-critical buildings before they can be returned back to their normal operation. This may include reducing ventilation requirements; controlling maximum humidity levels using available technologies with a minimum fuel consumption; allowing maximum daylight; keeping plug loads on; and lowering lighting levels. In cooling constraint conditions, use window shades to minimize solar gains, reduce plug loads, and keep lighting at a minimum level.

Threshold Conditions for Human Environment While cold and hot stress environmental conditions are well defined for jobs performed outdoors (NIOSH 2016, ACGIH 2018), there is not much information available for such conditions when jobs are performed indoors. This section addresses the potential thermal "inflection point" when the person can no longer physiologically and/or behaviorally compensate for the thermal stress while the job is based on the following assumptions and considerations:

1. The building environmental control systems fail and cannot be restored over a period of hours to days.
2. The occupants of the building must stay in that building to perform their jobs (i.e., cannot leave to move to more comfortable conditions).
3. The building occupants do not have access to clothing that can provide anything more than minimal protection against thermal challenges regardless of whether those challenges are cold or hot conditions (at most a clothing insulation [Clo] $\leq$ 1.0).
4. The building occupants are generally healthy with the normal physiological responses to deviations in environmental conditions.

5. The workers remain inside the building and perform minimal physical work (nearly at rest, 1.2–1.5 MET).[1] At this minimal workload, the metabolic heat produced will be minimal (slightly above that produced at rest).
6. Factors such as convection and direct radiation from the sun will be considered negligible.
7. Air movement in the building occupied zone is below 0.7 ft/min (0.2 m/min), and as such, there is little convective heat transfer.
8. Buildings is lit using either fluorescent or LED lighting, which results in a negligible radiant heat from lighting fixtures.
9. The building environmental conditions will be affected as a result of the function of the HVAC system in an indoor setting, and the environmental stressors are the dry air temperature (Dry Bulb or T_{db}) and humidity or wet bulb temperature (T_{wb}) with other environmental factors such as air velocity and radiant heat being negligible.

Humans have evolved the ability to maintain a stable internal (core) temperature (T_{core}) in the face of environmental thermal extremes through physiological, biophysical, and behavioral means. Maintenance of a stable T_{core} involves a tight balance between heat gain and heat loss to the environment during exposure to either cold or hot environments. A detailed discussion of the physiological and behavioral responses to thermal extremes is beyond the scope of the present work. However, note that, although there are strong physiological and behavioral mechanisms for maintaining T_{core}, these can be overcome under severe thermal stress—especially if that thermal burden is prolonged. The following discussion will focus on the physiological responses to cold and heat stress as the result of the prolonged failure of the building HVAC system in a building situated in a hot and humid locale.

Physiological Response The physiological responses, and the rate and magnitude that they occur, will depend on the rate and magnitude of the change in the environmental temperature and, to a greater (hot temperature) or lesser (cold temperature) extent, the RH of the air. The rate of change in the building environment in which environmental controls have failed will depend on the insulating properties of the building, i.e., the rate and magnitude of the change in temperature and RH. The physiological responses will also depend to a large extent on the degree of personal insulation (clothing) surrounding the worker during exposure to an increase in environmental temperature.

A "normal" core body temperature, T_{core}, is considered to be 98.6 °F (37 °C). It is at this temperature that optimal physiological function occurs. The physiological consequences (i.e., ΔT_{core}) from a decrease or an increase in environmental temperature can potentially be severe. If the physiological responses to environmental

[1] A MET, or "metabolic equivalent of task," is a ratio of an individual's working metabolic rate relative to resting metabolic rate.

temperature changes (and the ability to maintain T_{core}) are unsuccessful, then T_{core} will change (either decrease or increase); if the change is large enough, then normal function will be compromised.

For example, a T_{core} of 100.4 °F (38 °C) is considered the onset of hyperthermia. At T_{core} >100.4 °F (38 °C), one becomes symptomatic. Physiological/psychological signs and symptoms of hyperthermia are:

- Feelings of subjective discomfort due to heat
- Sweating (leading to loss of body fluid that must be replaced by drinking fluids)
- Increased heart rate from decrease in body fluids
- Increased perception of thirst (*not* a good indicator of the level of dehydration)
- Dark colored urine (indicating dehydration)
- Heat cramps
- Altered cognitive function
- Dizziness or lightheadedness (especially getting up from seated position)
- If prolonged exposure to severe enough heat, heat exhaustion

A core temperature T_{core} of 96.8 °F (36 °C) is considered the onset of hypothermia. At T_{core} < 95 °F (35 °C), one becomes symptomatic. Physiological/psychological signs and symptoms of hypothermia are:

- Extreme discomfort.
- Numbness (tactile sensitivity, manual dexterity decreases).
- Shivering.
- Skin vasoconstriction (blanching).
- Cold becomes a distraction.
- Muscle stiffness.
- Cognitive changes (confusion, apathy, loss of attention, reduced memory capacity, etc.).
- Loss of sensory information (blurred vision).
- Cardiovascular effects.
- Loss of consciousness.

It is important to understand that probably the first line of defense against heat is behavioral, that is, removal of outer clothing that can create an insulative layer that may decrease heat transfer to the environment under hot conditions or under high metabolic rates (i.e., high level of physical activity). With this strategy, a human being may even perform strenuous (high metabolic rate) activities in a cold (41 °F [5 °C]) environment but be “exposed” to a microenvironment (the layer of air that exists between the surface of the skin and the inner surface of the clothing) that is the equivalent to hot temperatures (86 °F [30 °C]) that can potentially cause heat stress and illness (Parsons 2003). Nevertheless, working in hot, and especially humid, environments has demonstrable effects on humans even if wearing relatively light clothing.

The first line of defense against cold is clothing that creates an insulative layer that protects humans from cold environments. With this strategy, a human being may perform activities in a cold (41 °F [5 °C]) environment but be exposed to a microenvironment (the layer of air that exists between the surface of the skin and the inner surface of the clothing) that is the equivalent to a mild temperature (~71.6 °F [~22 °C]). Nevertheless, working in cold environments has demonstrable effects on humans even if they are wearing relatively warm clothing.

Thermal discomfort often becomes a distraction to the person experiencing it and hence can affect performance of the so-called "time on task" by increasing the time spent not working and addressing the thermal discomfort. The degree of distraction is affected by whether the person can leave the environment or somehow change the environment (changing a thermostat setting) to improve the thermal comfort. If the person has no control over an uncomfortable thermal environment, the degree of distraction or time off task will increase. The distraction occurs as the result of a physiological change, e.g., decrease or increase in T_{sk}, which then results in the focus of attention on that change rather than on the task before them. Distraction is also modulated by motivation such that a more strongly motivated person may be less distracted by cold stimulus that a less motivated person exposed to the same stimulus. In addition, if the person exposed to a cold stimulus perceives that they have no control over the environment and the consequence of not performing the work is high enough, then the cold environment will be less distracting from the necessary work. As can be seen from the previous discussion, the issue of distraction on cognition and job performance is complex.

A compilation of the effects of temperature resulting in the decline in the ability to perform light work (1.2 MET) while wearing light clothing (0.6 clo) has been described in detail elsewhere (Parsons 2003; Wargocki and Wyon 2017). The literature indicates that when indoor temperature increased from ~75 °F (24 °C) to 77 °F (25 °C) or decreases from 60.1 °F (16 °C) to 51 °F (10 °C), the rate of accidents increases sharply by 40%, manual dexterity rapidly declines by 20%, and speed and sensitivity of fingers decline by 50%—all of which would fit the scenario in the present work and would suggest that the ability of workers to perform critical tasks is significantly impaired at temperatures below 60.8 °F (16 °C). Conversely, in workers performing sedentary work (1 MET) while wearing normal indoor clothing (1.0 clo), as the ambient temperature increased from ~75 °F (24 °C) to 77 °F (25 °C), the rate of accidents rose sharply by 50%. In addition, as the ambient temperatures increased from 68 to 86 °F (20 to 30 °C), mental performance decreased by 40%, and finally, as the ambient temperature increased from 61 to 80.1 °F (20 to 27 °C), the work rate declined sharply (by 55%) (Parsons 2003). The frequency of industrial accidents increased to almost 140% as the temperature decreased from 68 °F to ~50 °F (20 °C to ~10 °C), indicating that cold temperatures had a significant effect on workers' ability to perform their tasks safely. The decline in manual dexterity begins at a T_{sk} of 53.6–60.8 °F (12–16 °C). Tactile sensitivity declines steeply below 46 °F (8 °C).

These data show that the ambient temperature can significantly affect the ability of workers to perform tasks if the exposure lasts long enough. Therefore, in emergency situations, reducing indoor air temperature in spaces with mission-critical buildings operation below 60.8 °F (16 °C) (ACGIH 2018) or increasing above ~75 °F (24 °C) and increasing Wet Bulb Globe Temperature (WBGT) above 87.8 °F (31 °C [ACGIH 2017]) is not recommended since it will impair the performance of mission operators.

Arctic Buildings Under Emergency Conditions Arctic climates present low risk of mold growth on building surfaces. Mold does not grow at low temperatures. In addition, arctic outdoor vapor pressures are very low, so without humidification, indoor RH will be quite low. Mold growth depends greatly on the sensitivity of a surface to growth, and surfaces made of organic materials such as wood products and paper facings present the sole possibilities in arctic climate—not metal, concrete, or masonry. Preliminary modeling studies, using humidification at 30%, in climate zones 6, 7, and 8, show surface RH remaining at 65% or below, while mold requires surface RH above 85% in most cases.

Aside from water problems associated with roof or plumbing leaks, the greatest risk of mold growth may be from cold thermal bridges in humidified buildings. Thermal bridges may be identified using infrared (IR) thermography. Typically, in a well-insulated building, the coldest surface facing the interior will be the window surface. It is unlikely that interior temperatures at thermal bridges will be lower than the window surface temperature. Consequently, in an arctic building, the risk of interior mold growth is negligible in a building that shows no window condensation, and the presence of window condensation indicates the importance of lowering the indoor humidification.

In arctic climates, if building climate control is suspended in the short or long term, then mold growth is unlikely to occur. Normally, downward drift of temperature will occur with suspension of the operation of the air handler. This means that the indoor air temperature will decline as a function of the outdoor air temperature, the thermal insulation, the airtightness of the building, and the heat storage by the contents of the building. Also, during a heating period, the outdoor absolute humidity will be lower than the indoor absolute humidity, so it will drift downward at a rate governed primarily by the airtightness of the envelope. Under most conditions, the downward drift of absolute humidity will be much more rapid than the downward drift of DBT, and as a consequence, the indoor RH will be low during the drift period. The downward drift of absolute humidity is considered rapid because, with each air change, assuming full mixing, the absolute humidity difference between indoors and out is halved. Absolute humidity equilibrium with outdoors would be achieved in a matter of hours. The downward drift of temperature would be relatively slow given the low heat content of air, the thermal resistance in the envelope, and the heat storage in interior materials. It would be measured typically in days.

Modeling has provided preliminary estimates of the temperature decay rate of arctic buildings in case of a utility interruption. For a building with average thermal resistance of R-20 (all sides), with an air tightness of 0.25 cfm (0.0001 m^3/s) per 75 sq ft (7 m^2), and which contains, in envelope and contents, 100 lb/sq ft (0.05 kg/cm^2) of envelope, the decay half-life is approximately 1 week. By doubling the thermal resistance or the mass of contents, or by halving the air leakage, the half-life is doubled to 2 weeks. By halving the thermal resistance or the content mass, or by doubling the air leakage measure, the half-life of temperature decay is reduced to 3–4 days. Of course, different parts of the building will perform differently.

Pipe Burst Protection In cold and Arctic climates, hydronic heating systems typically use a glycol/water solution as the heating system fluid (Winfield et al. 2021). To reduce the risk of freezing of water pipes or wet sprinkler systems, pipes should be located in interior walls or plumbing chases. Pipes in exterior walls should be avoided. However, in the emergency situation when heat supply to the building is interrupted, the indoor air temperature can drop significantly. Research at the University of Illinois has illustrated the mechanism by which water pipes burst when surrounded by cold temperatures. Cold air temperatures cause the temperature of water in pipes to decline. Water temperature may decline below 32 °F (0 °C), often to 25 °F (–4 °C). With continued cold temperatures, ice nucleates in the water, raising the temperature of the two-phase mix to 32 °F (0 °C). With continued cold temperatures, ice begins to grow on the pipe wall, growing inward; the rate of ice growth depends on several factors such as air temperature, pipe thermal conductivity, water circulation, and effect of the air film surrounding the pipe. Through this entire process, before the formation of blockage, the pipe system is not put at risk, and with rising air temperatures, the system will recover to the original condition with no ill effects.

If the ice grows inward to the point of blockage, then water pressure effects become important. The blockage can grow along the length of the pipe and act like a piston. Piston action toward the water source will generally have no ill effect, in the absence of a backflow preventer. But piston action toward the remaining liquid water confined downstream will cause the water pressure to rise. Pipe rupture or fitting failure will occur once the water pressure reaches a sufficiently high level.

There are several means to prevent pipe bursting due to freezing:

1. Avoid subzero air temperatures at the pipe.
2. Drain the water from the pipe system. Compressed air may be used for systems that do not drain entirely by gravity.
3. Provide pressure relief at any at-risk portion of the pipe system. A single pressure relief valve is usually sufficient to protect a clustered fixture group. A ballcock assembly in a typical toilet serves as a pressure relief device (which explains the greater likelihood of hot water rupture during freeze events).

4. Provide air expansion (e.g., using water hammer arresters) to protect piping systems where the slight water leakage from pressure relief valves is undesirable, such as in wet fire suppression systems.

It is particularly important to avoid individual sites of particularly cold temperature along the pipe length, as these are preferred sites for blockage to initiate. Such sites will occur at interruptions in pipe insulation (often at fittings such as elbows) and at air leaks in the envelope, where moving air can reduce the air film thermal resistance.

Buildings in Hot/Humid Climates Under Emergency Conditions Mold growth is more widespread on building surfaces in hot humid climates than in cold climates because mechanical cooling may chill surfaces to temperatures close to the DP of the indoor air. Therefore surfaces, rather than air, must become the focus of any understanding of mold growth and the attendant health risks.

Mold only grows on surfaces that retain sufficient moisture over time. But not all moisture is equally available to support mold growth. In some materials, moisture is tightly bound to the surface and cannot be used by mold. In other materials, the moisture is easily accessed to support microbial growth. The most reliable moisture-related metric that governs growth is the surface water activity (i.e., equilibrium relative humidity [ERH]) at the surface of the material in question. Water activity can also be described as a measurement of the bioavailability of moisture in a material. It is in fact a measurement of the difference in water vapor pressure between the fungal cell and the moisture in the surface on which it is located. Therefore, criteria should focus on the more reliable risk indicator of surface water activity.

For most building professionals, the term "water activity" will be new and unfamiliar. The confusion comes from the assumption that RH in the air is the same as RH at the surface. Therefore, a short explanation is needed, to clear up the confusion built up over the last 40 years about the relationship between RH, moisture content, and microbial (mold) growth risk.

The greater the mass of water vapor in the air, the greater the risk of absorption and persistent dampness when surfaces become cool. The indoor air DP is a reliable measurement of the mass of water vapor available for absorption and therefore potentially available to support microbial growth.

The RH in the air is rarely the same as RH at the surface. This is particularly true near cold supply air diffusers. In buildings, the indoor DP stays high over months whenever alternating current (AC) systems are turned off. The persistent high DP allows excessive moisture absorption and mold growth on the surfaces of acoustic ceiling tiles near supply air diffusers. Keeping the indoor DP below 60 °F (15.6 °C) greatly reduces the amount of indoor humidity available to support mold growth. This maximum is a design requirement for systems in mechanically cooled buildings (ASHRAE Standard 62.1-2019: Ventilation and Indoor Air Quality [ASHRAE 2019b]).

To model the effect of an emergency shutdown of air handling equipment in a building in a hot humid climate, it is first necessary to select the extreme DP outdoor conditions. The DP at extreme outdoor conditions in hot/humid climates within the CONUS is below 80%, which is the critical surface ERH for the onset of mold growth on most building materials. So the building goes from a mold-safe indoor ERH and decays to a mold-unsafe ERH. However, the decay process itself may contain conditions for mold growth. Infiltration may bring the indoor absolute humidity to outdoor absolute humidity level in a matter of hours, but the indoor temperature will drift upward to outdoor temperature in a matter of days. So, for several days, the building may see conditions of ERH well in excess of 80%, and mold growth could be expected.

If the sole concern following a power or fuel outage was mold prevention on interior surfaces, one effective strategy would be to open the building as fully as possible to the outdoors so that the interior surfaces and contents were brought to outdoor temperatures as quickly as possible. However, those with concerns for continued use of the building following outage or with concerns for security may argue that the building should remain closed.

A more effective method to allow the building to come to outdoor conditions would be to provide auxiliary dehumidification or auxiliary heating. The aim for either of these strategies would be to keep the indoor DP below 60 °F (15.6 °C).

D.4 Thermal Requirements for Unoccupied Spaces

Requirements for temperatures and RH discussed above are developed for occupied spaces (Table D.3). Many buildings are not occupied at night or on weekends. Some military facilities including barracks, administrative buildings, and dining facilities may be unoccupied for an extended period of time due to training and deployment. So, one of energy conservation strategies may be to set back temperatures for

Table D.3 Requirements to DBT and RH for occupied and unoccupied facilities to reduce the risk of moisture-related problems

Occupancy/use	DP (setpoint) not to exceed	Maximum dry bulb temp (setpoint)	Minimum dry bulb temp (setpoint)
Occupied	60 °F (15.6 °C)	75 °F (24 °C)	70 °F (21 °C)
Unoccupied (Short term)	60 °F (15.6 °C)	85 °F (29 °C)	55 °F (13 °C)
Unoccupied (Long term)	60 °F (15.6 °C)	No Max	40 °F (4 °C)
Critical Equipment	60 °F (15.6 °C) or equip requirement if less	Equip max allowed	Equip min allowed

heating or set up for cooling. One source of guidance on setback or setup temperatures is ANSI/ASHRAE/IESNA Standard 90.1-2004 *Energy Standard for Buildings Except Low-Rise Residential Buildings*. Standard 90.1-2007 does not regulate thermostat setbacks or setups, but it does regulate the capabilities of thermostats installed in buildings. Section 6.4.3.3.2 of Standard 90.1-2004, *Setback Controls*, requires that heating systems in all parts of the United States outside of Miami, FL, and the tropical islands (i.e., climate zones 2–8) must have a capability to be set back to 55 °F (13 °C). Heating systems in zone 1 are assumed to have minimal usage and therefore no need of setbacks. Cooling systems in hot dry areas (zones 1b, 2b, and 3b) must have the capability to be set up to 90 °F (32 °C). However, cooling systems in hot and humid climates (zones 1a, 2a, and 3a) are not required to have cooling setbacks due to potential for moisture problems. It is wasteful to cool facilities left unoccupied for an extended period of time, which are located in hot and humid climates. Significant energy savings can be achieved without damage to building materials and furnishings if a combination of measures related to the building envelope and HVAC maintains the requirements for ALL the air inside the building.

D.5 Recommendations

Requirements for thermal environmental condition in buildings are set to achieve the following purposes:

- To perform the required work in a building in a safe and efficient manner
- To support processes housed in the building
- To provide conditions required for a long-term integrity of the building and building materials

Buildings are designed to meet these three sets of requirements in normal (blue sky) operating condition. Thermal comfort requirements are defined by ASHRAE Standard 55, *Thermal Environmental Conditions for Human Occupancy* (ASHRAE 2017b). Different processes housed in the building (e.g., spaces with IT and communications equipment, critical hospital areas, industrial process [painting, printing, etc.]) may have broader or narrower ranges for air temperature and RH than those for human comfort. In normal operation conditions, environmental requirements based on sustainability of building envelope assemblies and furnishing are not a limiting factor given that the building envelope air barrier and vapor protection are designed to avoid mold growth and water accumulation within the building assembly. For cold and Arctic climate requirements to the building envelope, see Axelarris et al. (2021).

During an emergency (black sky) situation, requirements of thermal parameters for different categories of buildings or even parts of the building may change. When normal heating, cooling, and humidity control system operation is limited or not available, mission-critical areas can be conditioned to the level of thermal parameters required for supporting agility of personnel performing mission-critical operation, but not to the level of their optimal comfort conditions. Beyond these threshold (habitable) levels, effective execution of a critical mission is not possible, and mission operators have to be moved into a different location. These threshold limits of thermal parameters may be in a broader range compared to that required for thermal comfort, but not to exceed levels of heat and cold stress thresholds: in a heating mode, air temperature in spaces with mission-critical operations should be maintained above 60.8 °F (16 °C) [ACGIH 2018], and in a cooling mode, the WBGT should be below 87.8 °F (31 °C [ACGIH 2017]).

Special process requirements (e.g., with IT and communication equipment, critical hospital spaces, etc.) should be given a priority if they are more stringent. Broader ranges of air temperatures and humidity levels in building spaces surrounding mission-critical areas may be used, but they need to be limited to prevent excessive thermal losses/gains and moisture transfer through walls and apertures not designed with thermal and air/vapor barriers.

In arctic climates, building envelope assemblies are not a limiting factor regarding how indoor climate must be maintained during short- or long-term outages of indoor climate control, unless water piping cannot be drained or otherwise protected against freezing.

In cases where utility supply is interrupted and the building air handler is disabled, the indoor temperature will decay to the outdoor temperature. The rate of decay has been field-tested and modeled (Oberg et al. 2021; Liesen et al. 2021); results show that the time it takes for indoor air temperature to reach a threshold (habitable) level or a building sustainability level will range from few hours to several days depending on thermal resistance, airtightness, and the mass of the building envelope and contents in the building.

In hot/humid climates, mold growth on interior surfaces is a serious risk, with both short- and long-term interruption of climate control. Prevention of microbial growth requires maintaining the indoor DP temperature below 60 °F (15.6 °C) typically requiring the use of auxiliary equipment. Table D.4 gives the indoor requirements to avoid damage to building materials and furnishings.

Finally, noncritical stand-alone buildings can be hibernated, but necessary measures should be taken, and the thermal environment should be maintained, when possible, to prevent significant damage to these buildings before they can be returned back to their normal operation. Tables D.5, D.6, D.7, and D.8 list recommendations for thermal environmental conditions for buildings located in both cold and hot and humid climates, for normal and emergency situations.

Table D.4 Indoor requirements to avoid damage to building materials and furnishings

Arctic climate	≥40 °F (4.4 °C) dry bulb, where water piping is at risk
Hot/humid climate	≤60 °F (15.6 °C) DP, to avoid mold growth

Table D.5 Recommended thermal conditions for buildings located in cold/Arctic climate: normal (blue sky) operations

	Space occupancy						
	Occupied			Unoccupied (short term)			
	Normal operations (regular business hours)			Unoccupied for a short time period (e.g., Few days)		Unoccupied for extended period of time (e.g., weeks) Building freezing/not freezing	
Type of requirement	DP	Maximum dry bulb temp	Minimum dry bulb temp	DP	Minimum dry bulb temp	Humidity not to exceed	Minimum dry bulb temp
Human comfort	< 63 °F (17.2 °C)[a]	82 °F (27.8 °C)[a]	68 °F (20 °C)[a]	<63[a]	55 °F (12.7 °C)[d]	N/A	
Process driven	Process specific—see examples in Tables D.1 and D.2			Process specific—see examples in Tables D.1 and D.2 (unless specified otherwise)		N/A	
	Humidity not to exceed	Minimum dry bulb temp		Humidity not to exceed	Minimum dry bulb Temp	Humidity not to exceed	Minimum dry bulb temp
Building sustainment	80%[c]	40 °F (4.4 °C)[b]		<80%[c]	40 °F (4.4 °C)[b]	80%[c]	40 °F (4.4 °C), or N/A if drained

[a]ASHRAE Standard 55 (2017b)
[b]To prevent water pipe rupture, with factor of safety
[c]To prevent interior surface mold growth, with no factor of safety
[d]To prevent long time recovery and significant energy losses
[e]ACGIH (2001) TLV, thermal stress recommendations
[f]ASHRAE Standard 62.1 (ASHRAE 2019b)

Table D.6 Recommended thermal conditions for buildings located in cold/Arctic climate: emergency (black sky) operations

Scenario type of requirement	Emergency (black sky) space occupancy: Mission-critical operation		Tertiary space (non-mission-critical bordering mission-critical space)		Hibernated: can be unoccupied for extended period of time (from days to weeks) building freezing/not freezing	
	DP	Minimum dry bulb temp	Humidity not to exceed	Minimum dry bulb temp	Humidity not to exceed	Minimum dry bulb temp
Human comfort	<63 °F (17.2 °C)[a]	>60 °F (16 °C)[e]	N/A		N/A	
Process driven	Process specific—see examples in Tables D.1 and D.2		N/A		N/A	
	Humidity not to exceed	Minimum dry bulb temp	Humidity not to exceed	Minimum dry bulb temp		
Building sustainment	80%[c]	40 °F (4.4 °C)[b]	80%[3]	40 °F (4.4 °C)[b] 55 °F (12.7 °C)[d]	80%[c]	N/A 40 °F (4.4 °C)[b] or N/A if drained

[a]ASHRAE Standard 55 (2017b)
[b]To prevent water pipe rupture, with factor of safety
[c]To prevent interior surface mold growth, with no factor of safety
[d]To prevent long time recovery and significant energy losses
[e]ACGIH (2001) TLV, thermal stress recommendations
[f]ASHRAE Standard 62.1 (ASHRAE 2019b)

Table D.7 Recommended thermal conditions for buildings located in hot and humid climate: normal (blue sky) operations

	Space occupancy						
	Occupied			Unoccupied (short term)		Unoccupied (long term/hibernated)	
	Normal operations (regular business hours)			Unoccupied for a short time period (e.g., Few days)		Unoccupied for Extended Period of Time (e.g., Weeks) Building Freezing/ Not Freezing	
Type of requirement	Humidity not to exceed	Maximum dry bulb temp	Minimum dry bulb temp	Humidity bot to exceed	Maximum dry bulb temp	DP not to exceed	Maximum dry bulb temp
Human comfort	60%[a]	82 °F (27.7 °C)[a]	68 °F (20 °C)[a]	70%[d]	85 °F (29 °C)[d]	N/A	
Process driven	Process specific—see examples in Tables D.1 and D.2			Process specific—see examples in Tables D.1 and D.2 (unless specified otherwise)		N/A	
	DP	RH		Humidity not to exceed	DP	DP	RH
Building sustainment	≤60 °F (15.6 °C)[c, f]	<70%[c]		<70%[c]	<60 °F (15.6 °C)[c, f]	≤60 °F (15.6 °C)[c, f]	<70%[c]

[a]ASHRAE Standard 55 (2017b)
[b]To prevent water pipe rupture, with factor of safety
[c]To prevent interior surface mold growth, with no factor of safety
[d]To prevent long time recovery and significant energy losses
[e]ACGIH (2001) TLV, thermal stress recommendations
[f]ASHRAE Standard 62.1 (ASHRAE 2019b)

Table D.8 Recommended thermal conditions for buildings located in hot and humid climate: emergency (black sky) operations

	Space occupancy					
	Mission-critical		Tertiary space around mission-critical		Hibernated can be unoccupied for extended period of time (from days to weeks)	
Type of requirement	WBGT		WBGT		WBGT	
Human activity broad range	<87.8 °F (31 °C)^{e}		NA		N/A	
Process driven	Process specific—see examples in Tables D.1 and D.2		N/A (unless specified otherwise)		N/A	
	DP	RH	DP	RH	DP	RH
Building sustainment	≤60 °F (15.6 °C)^{c,f}	<70%^{c}	≤60 °F (15.6 °C)^{c,f}	<70%^{c}	≤60 °F (15.6 °C)^{c,f}	<70%^{c}

[a] ASHRAE Standard 55 (2017b)
[b] To prevent water pipe rupture, with factor of safety
[c] To prevent interior surface mold growth, with no factor of safety
[d] To prevent long time recovery and significant energy losses
[e] ACGIH (2001) TLV, thermal stress recommendations
[f] ASHRAE Standard 62.1 (ASHRAE 2019b)

Appendix E. Best Practices of Energy System Architecture

E.1 Introduction

The library of energy system architecture templates in this appendix comprises more than 50 examples for different use cases depicting energy system designs for different climate zones or fuels, for densely populated communities and small, remote communities, and for communities with or without critical buildings. The examples are organized in five main categories and two subcategories referring to spatial location and the energy types that are supplied to the buildings (see Table E.1).

Each template is identified by a four-digit number. For example, Template 4.3.1.1 shows an energy system example suitable for remote locations (4), where energy generation is located at the community level (3) and buildings are supplied with power and heating (1). The last digit counts the number of examples in this subcategory. Table E.2 gives an overview on the number of templates in the different categories.

The main elements that make up the energy system of a community are represented in the schematic by symbols, with different spatial parts of the energy system being displayed by boxes.[2] Figure E.1 shows an example for a simple district heating system with CHP, boilers, and heat storage.

The two boxes on the left show energy inputs from outside the boundaries of the community. While the upper left box shows different types of grids that supply the community (e. g. electricity, gas, district heating, district cooling), the lower box is

Table E.1 Categorization of energy system architecture templates

No.	Main category		Subcategory 1 spatial location of generation/storage		Subcategory 2 building supplied from the outside with…		No. of template
1	Solutions for generation within the community	1	At the individual building level	1	Power + heating	1	First example for this system type
2	Best practice examples	2	At the building cluster level	2	Power + cooling	2	Second example
3	Generation outside the community	3	At the community level	3	Power	3	
4	Solutions for remote locations (islands)	4	Combined	4	Power + heating + cooling	…	
5	Systems with electrical enhancement					x	

[2] Electrical power. Natural gas building level can also be included, but with a lower level of detail.

Table E.2 List of templates

	Spatial location of generation	Building supplied from the outside with…	Number of examples for this system type
1.	Solutions for generation with the community		
1.1.3.	Generation at building level	Power	4 examples
1.2.1	Generation at building cluster level	Power + heating	1 example
1.2.4	Generation at building cluster level	Power + heating + cooling	4 examples
1.3.1	Generation at community level	Power + heating	3 examples
1.3.2	Generation at community level	Power + cooling	1 example
1.3.4	Generation at community level	Power + heating + cooling	8 examples
1.4.1	Generation at combination of spatial levels	Power + heating	2 examples
1.4.2	Generation at combination of spatial levels	Power + cooling	2 examples
1.4.4.	Generation at combination of spatial levels	Power + heating + cooling	2 examples
2.	Best practice examples		
2.3.1	Generation at community level	Power + heating	3 examples Gram (Denmark) University of British Columbia (CAN) Qaanaaq (Greenland)
2.3.4	Generation at community level	Power + heating + cooling	5 examples: Taarnby District Copenhagen (Denmark) Favrholm (Denmark) Campus Denmark Techn. University (Denmark) University of California Davis CNPRC University of Texas Austin Medical Community
2.4.1	Generation at combination of spatial levels	Power + heating	Smart Thermal Loop University of Melbourne (AUS)
2.4.4	Generation at combination of spatial levels	Power + heating + cooling	Greater Copenhagen (Denmark)
3.	Generation outside the community		
3.0.4.1	Generation outside the community (= 0)	Power + heating + cooling	1 example
4.	Solutions for remote locations		

(continued)

Table E.2 (continued)

	Spatial location of generation	Building supplied from the outside with…	Number of examples for this system type
4.3.1	Generation at community level	Power + heating	3 examples
4.3.4	Generation at community level	Power + heating + cooling	2 examples
4.4.1	Generation at combination of spatial levels	Power + heating	3 examples
5.	Solutions with electrical enhancement		
5.1.4.	Generation at building level	Power + heating + cooling	1 example
5.2.1	Generation at building cluster level	Power + heating	1 example
5.2.4	Generation at building cluster level	Power + heating + cooling	1 example
5.3.1	Generation at community level	Power + heating	1 example
5.3.4	Generation at community level	Power + heating + cooling	3 examples
5.4.3	Generation at combination of spatial levels	Power	2 examples

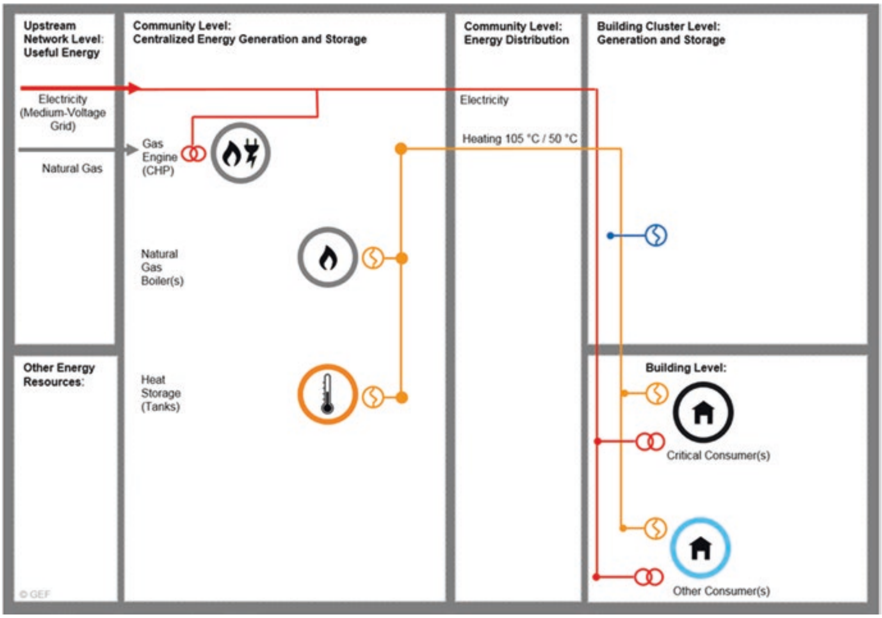


Fig. E.1 Thermal energy system architecture

used to illustrate input of energy resources that are not grid bound (e.g., fuel oil, diesel, biomass, solar radiation, wind, ambient heat, etc.).

The four remaining boxes contain system components within the community:

- **Centralized Energy Generation and Storage at Community Level.** In this box, different generation equipment like boilers, combined heat and power generation (CHP), electric chillers, and tanks for storing hot or chilled water are represented by symbols. Colored circles are used to illustrate fuel input into the equipment (grey = gas, red = electricity, green = biomass). Colors also indicate energy output of each element (red = electricity, yellow = heat, blue = cool). Figure E.2 lists symbols for the most important technology elements that can be included in an energy system design.
- **Energy Distribution at Community Level.** This box shows the grids that exist within the community to supply the buildings. Grid types include electricity, steam, heating (hot water supply), or cooling. Supply and return temperatures can be specified. Gas grids—which may exist within the community to supply buildings—are not represented to keep the schematic simple.
- **Building Cluster Level**. Many—especially larger—energy systems have distributed the generation equipment to several locations, serving building clusters.
- **Building Level.** In the energy system schematic, buildings are included, but with a lower level of detail, showing the network connections and—in case of decentralized supply options—components like decentral boilers, chillers, or emer-

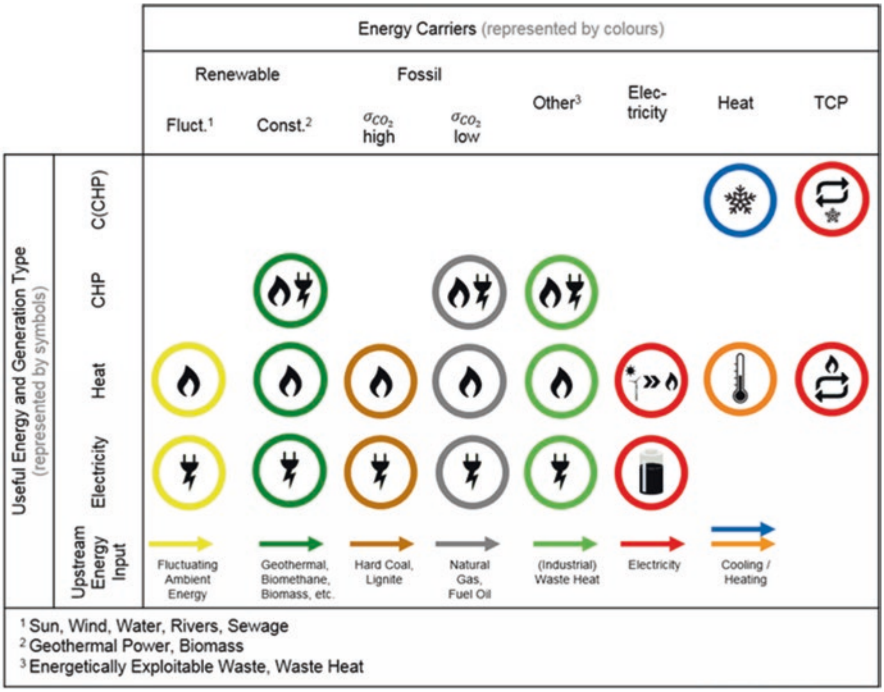


Fig. E.2 Symbols for energy system description

gency generators. Details of the equipment with the buildings (e.g., HVAC details) are not illustrated. Mission-critical buildings are represented by a black symbol (higher resilience to “black sky” conditions required); other consumers are represented by a blue symbol (building functions need only be maintained in “blue sky” conditions). All critical buildings are fitted with a dedicated building-level backup generator to serve critical loads when utility power is unavailable.

The different types of technologies are represented in Fig. E.2 by symbols for generation equipment for power, heat, and cooling used in the schematics and the fuels used in the thermal energy systems represented by colors.

In the rows, components are grouped according the useful energy they can provide and the generation type (power, heating, CHP, and combined cool, heat, and power [CCHP]). In the columns, the equipment is grouped according to energy carriers. Renewable energy sources are grouped into fluctuating and constantly available sources and fossil fuels into high and low CO_2 fuels.

Figure E.3 shows additional symbol depicting electrical elements within the architectures.

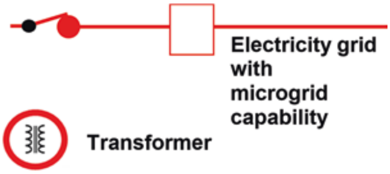
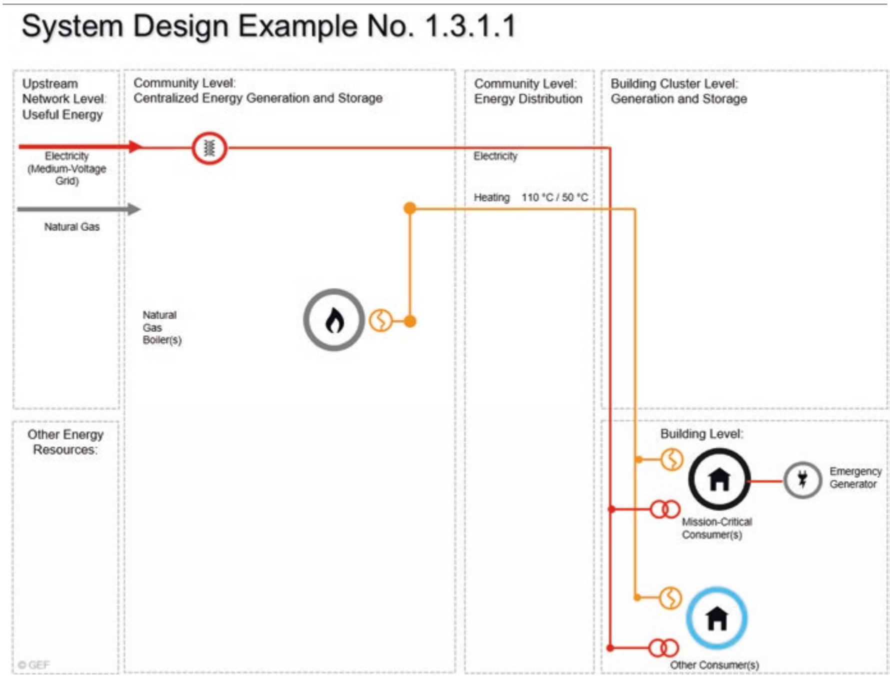
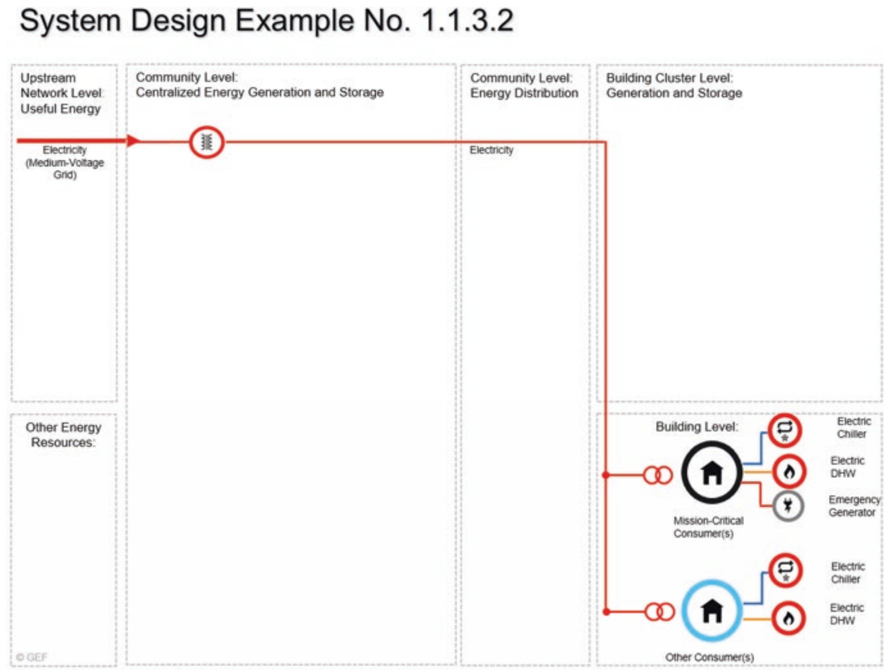


Fig. E.3 Symbols for systems with microgrids

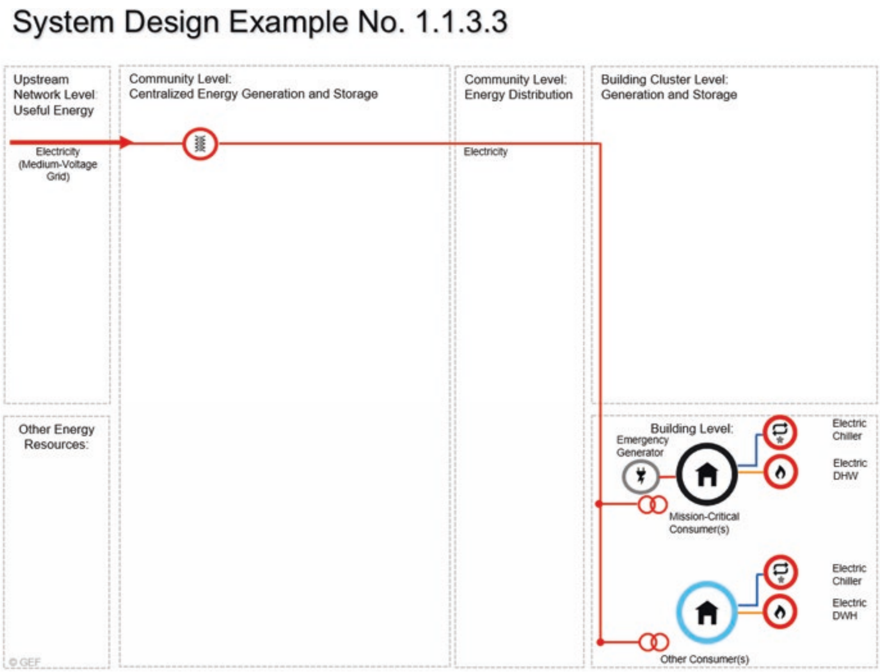
E.2 Solutions for Energy Generation Within the Community



Solutions for generation within the community Nomenclature: 1.1.3.1 Example No. 1	Location of generation at… Building level	Buildings to be supplied from the outside with … Power
Description	Gas boilers in individual buildings	
Central equipment	Small gas boilers	
Capabilities	Reliable heat supply	
Applications	Communities with low heat density	
Advantages	Low-cost equipment, low complexity, little maintenance, emergency power generation for mission-critical buildings	
Disadvantages	No renewables, gas grid necessary, no redundancy for heat, no electricity generation on campus for additional resiliency against power grid failure, local heat storage is expensive	

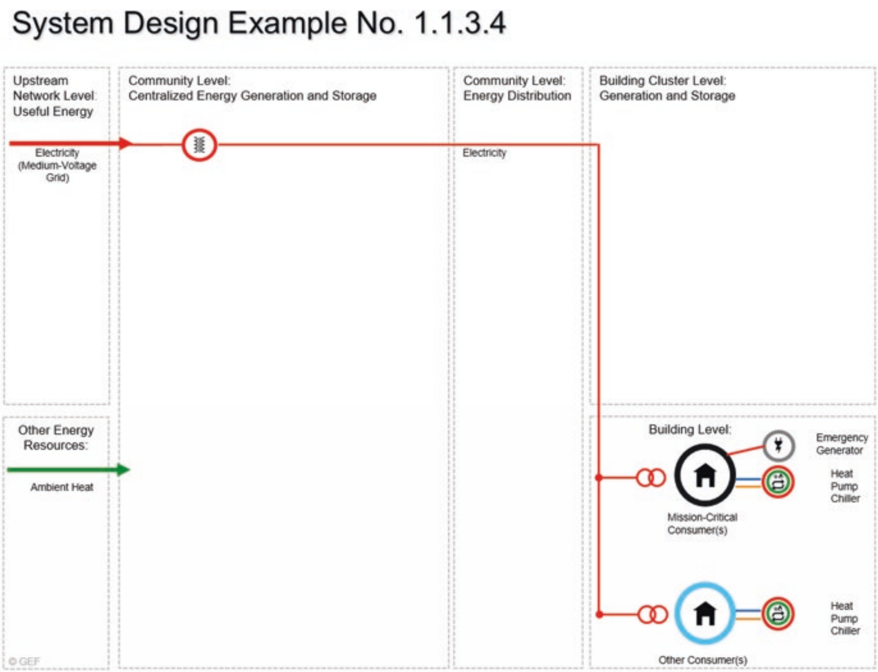


Solutions for generation within the community Nomenclature: 1.1.3.2 Example No. 2	Location of generation at… Building level	Buildings to be supplied from the outside with… Power
Description	Electric chillers in individual buildings	
Central equipment	Small electric chillers	
Capabilities	Reliable cooling supply	
Applications	Communities with low cool density	
Advantages	Low-cost equipment, low complexity, little maintenance, emergency power generation for mission-critical buildings	
Disadvantages	No renewables, no redundancy for cooling, no electricity generation, no electricity generation on campus for additional resiliency against power grid failure, no demand response	



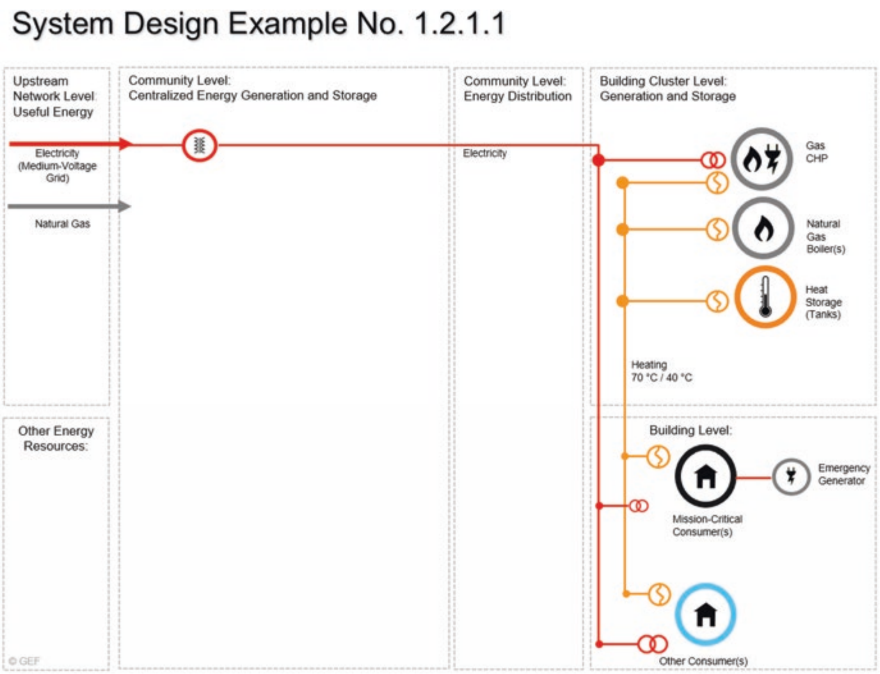
Solutions for generation within the community Nomenclature: 1.1.3.3 Example No. 3	Location of generation at… Building level	Buildings to be supplied from the outside with… Power

Description	Electric chillers and electric instant heaters in individual buildings
Central equipment	Small electric chillers, instant electric heater for DHW
Capabilities	Reliable cooling and DHW supply
Applications	Communities with low cool and heat density
Advantages	Low-cost equipment, low complexity, little maintenance, no gas grid necessary, emergency power generation for mission-critical buildings and—depending on size of emergency equipment—also for electrically generated heat and cool in mission-critical buildings
Disadvantages	No renewables, no redundancy for heat and cooling, no electricity generation



Solutions for generation within the community Nomenclature: 1.1.3.4 Example No. 4	Location of generation at… Building level	Buildings to be supplied from the outside with… Power

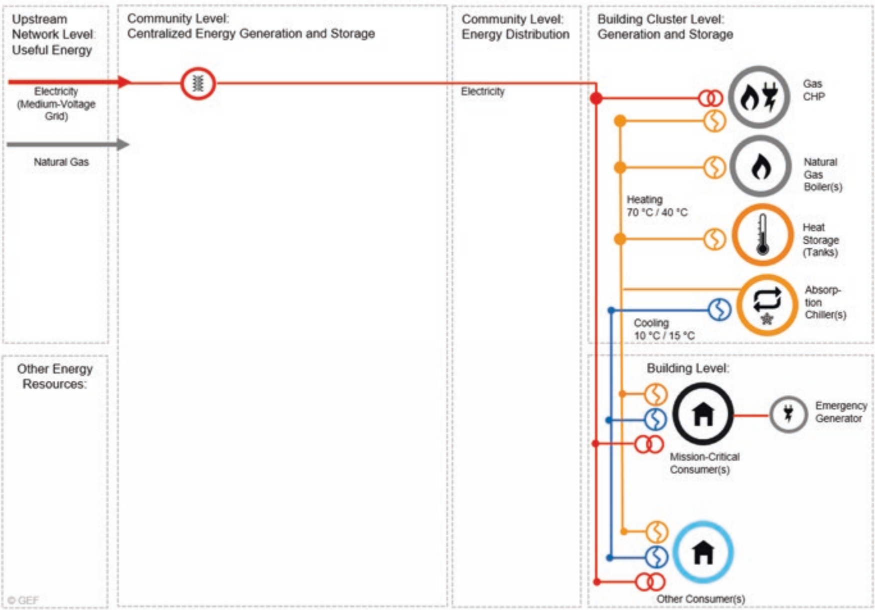
Description	Electric heat pumps in individual buildings
Central equipment	Heat pumps
Capabilities	Reliable heat supply
Applications	Communities with low heat density
Advantages	Low complexity, renewable energy (ambient heat), no gas grid necessary, emergency power generation for mission-critical buildings and—depending on size of emergency equipment—also for electrically generated heat and cool in mission-critical buildings
Disadvantages	No redundancy for heat, no electricity generation, no demand response



Solutions for generation within the community Nomenclature: 1.2.1.1 Example No. 1	Location of generation at… Building cluster level	Buildings to be supplied from the outside with… Power + heat

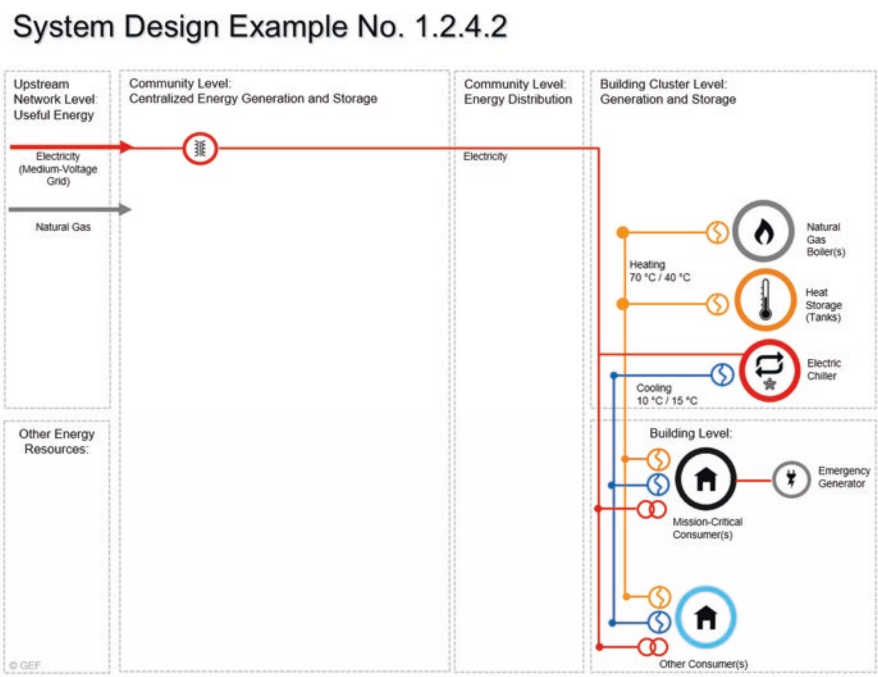
Description	Gas CHP and gas boiler in building cluster
Central equipment	Gas engine and gas boiler
Capabilities	Reliable heat supply, onsite generation of electricity, can supply buildings with high-temperature hot water
Applications	Building clusters with at least medium heat density
Advantages	Cogeneration of power and heat at cluster level for improved resiliency for power (own generation) and heat (n+1), heat storage provides peak shaving for heat and additional resilience, low supply temperature would allow integration of many types of renewables, emergency power generation for mission-critical buildings improves resiliency against grid failure further, CHP power capacity
Disadvantages	No renewables, gas grid necessary

System Design Example No. 1.2.4.1



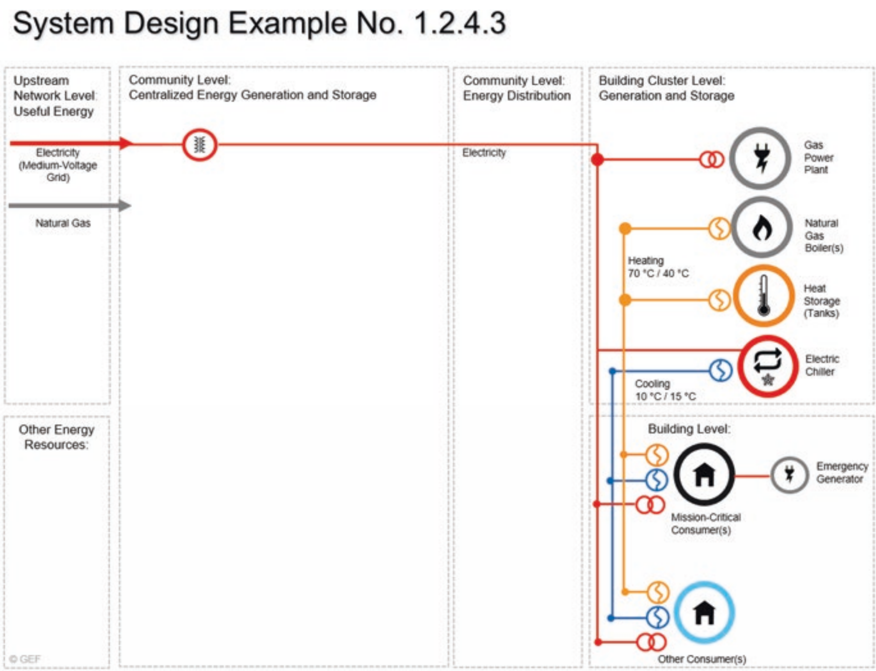
Solutions for generation within the community Nomenclature: 1.2.4.1 Example No. 1	Location of generation at… Building cluster level	Buildings to be supplied from the outside with… Power + heat + cooling

Description	Gas CHP, gas boiler, and absorption chiller in building cluster
Central Equipment	Gas CHP and absorption chiller
Capabilities	Reliable cooling and heat supply, onsite generation of electricity, can supply buildings with high-temperature hot water
Applications	Building clusters with at least medium heat density
Advantages	(n+1) redundancy for heat and cooling at the cluster level, heat storage provides peak shaving for heat and cold and additional resilience, CHP operation in summer to provide power plus cooling with absorption chillers, low supply temperature would allow integration of many types of renewables, emergency power generation for mission-critical buildings, CHP power capacity
Disadvantages	No renewables, gas grid necessary



Solutions for generation within the community Nomenclature: 1.2.4.2 Example No. 2	Location of generation at… Building cluster level	Buildings to be supplied from the outside with … Power + heat + cooling

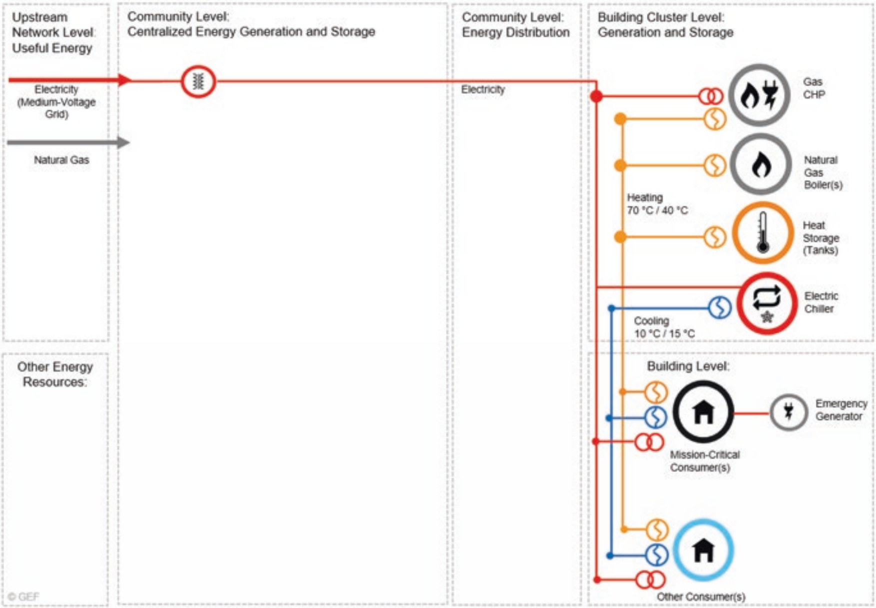
Description	Gas boiler and chiller in building cluster
Central equipment	Gas boiler and electric chiller
Capabilities	Reliable cooling and heat supply, can supply buildings with high-temperature hot water
Applications	Building clusters with at least medium heat density
Advantages	Low complexity, (n+1) redundancy for heat at the cluster level, heat storage provides peak shaving for heat and additional resilience, low supply temperature would allow integration of many types of renewables, emergency power generation for mission-critical buildings
Disadvantages	No renewables, no electricity generation, gas grid necessary



Solutions for generation within the community Nomenclature: 1.2.4.3 Example No. 3	Location of generation at… Building cluster level	Buildings to be supplied from the outside with… Power + heat + cooling

Description	Gas power plant in building cluster
Central equipment	Gas power plant, gas boiler, and electric chiller
Capabilities	Reliable cooling and heat supply, onsite generation of electricity, can supply buildings with high-temperature hot water
Applications	Building clusters with at least medium heat density and higher heat, cooling, and power requirement
Advantages	Generation of power at the cluster level, (n+1) redundancy for heating and cooling at the cluster level, heat storage provides peak shaving for heat and additional resilience, low supply temperature would allow integration of many types of renewables, emergency power generation for mission-critical buildings
Disadvantages	No renewables, gas grid necessary, cogeneration of heat and power would increase efficiency

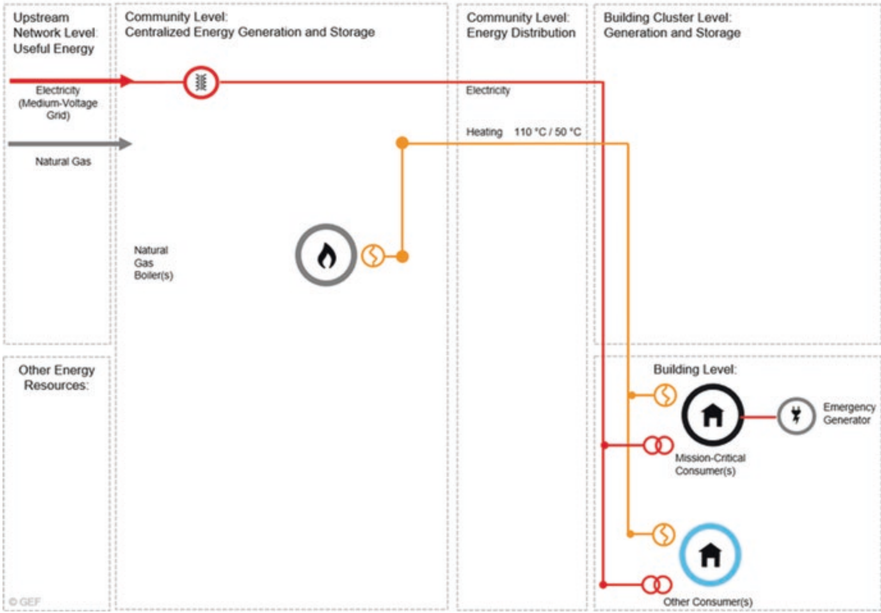
System Design Example No. 1.2.4.4



Solutions for generation within the community Nomenclature: 1.2.4.4 Example No. 4	Location of generation at… Building cluster level	Buildings to be supplied from the outside with… Power + heat + cooling

Description	Gas CHP and chiller in building cluster
Central equipment	Gas engine, gas boiler, and electric chiller
Capabilities	Reliable cooling and heat supply; onsite generation of electricity, could (generally) supply buildings with high-temperature hot water
Applications	Building clusters with at least medium heat density
Advantages	Low complexity, cogeneration of power and heat, heat storage provides peak shaving for heat and additional resilience, low supply temperature would allow integration of many types of renewables, (n+1) redundancy at cluster level for heating and cooling, emergency power generation for mission-critical buildings
Disadvantages	No renewables, gas grid necessary

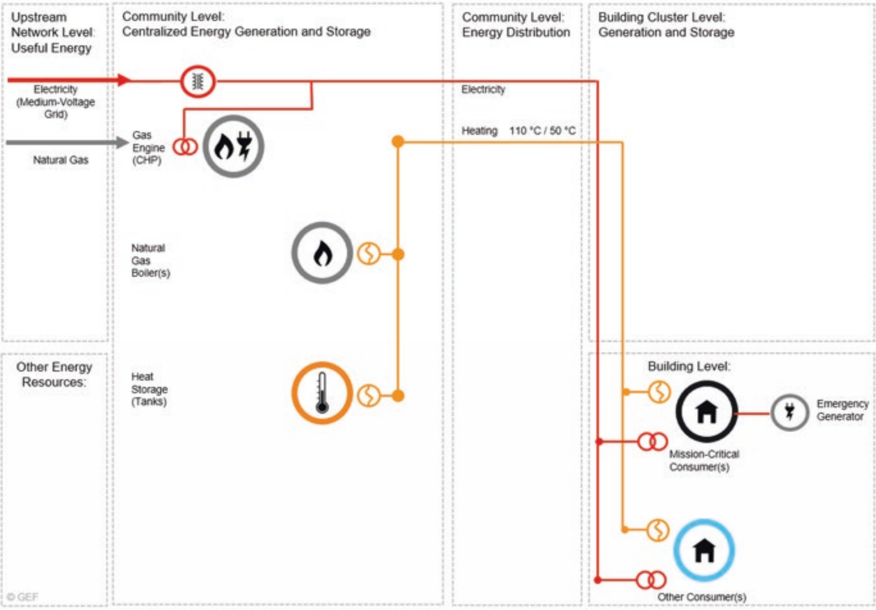
System Design Example No. 1.3.1.1



Solutions for generation within the community Nomenclature: 1.3.1.1 Example No. 1	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heat

Description	Gas boiler in community
Central equipment	Gas boiler
Capabilities	Reliable heat supply, can supply buildings with high-temperature hot water
Applications	Communities with at least medium heat density and no need for local electricity generation except for emergency
Advantages	Very low complexity, (n+1) redundancy at community level for heating, emergency power generation for mission-critical buildings
Disadvantages	Gas grid necessary

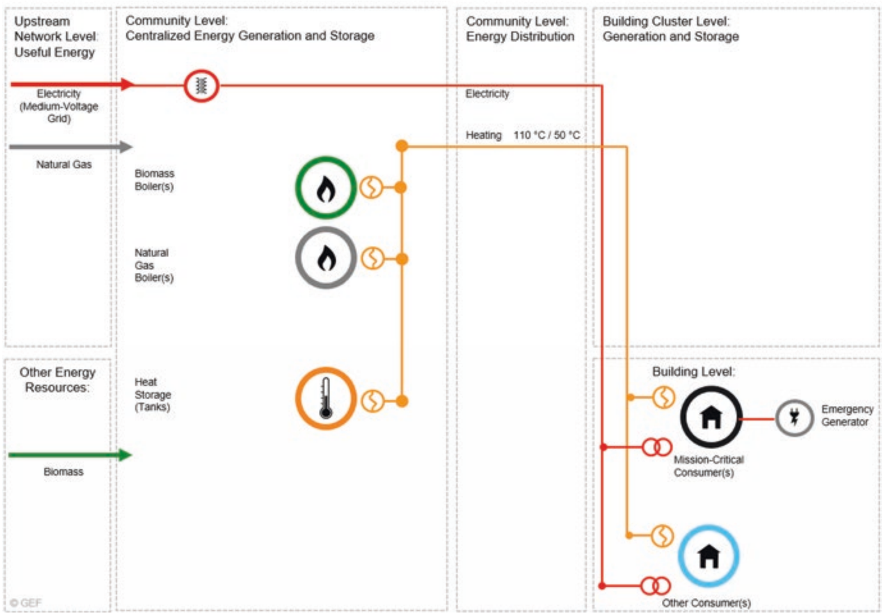
System Design Example No. 1.3.1.2



Solutions for generation within the community Nomenclature: 1.3.1.2 Example No. 2	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heat

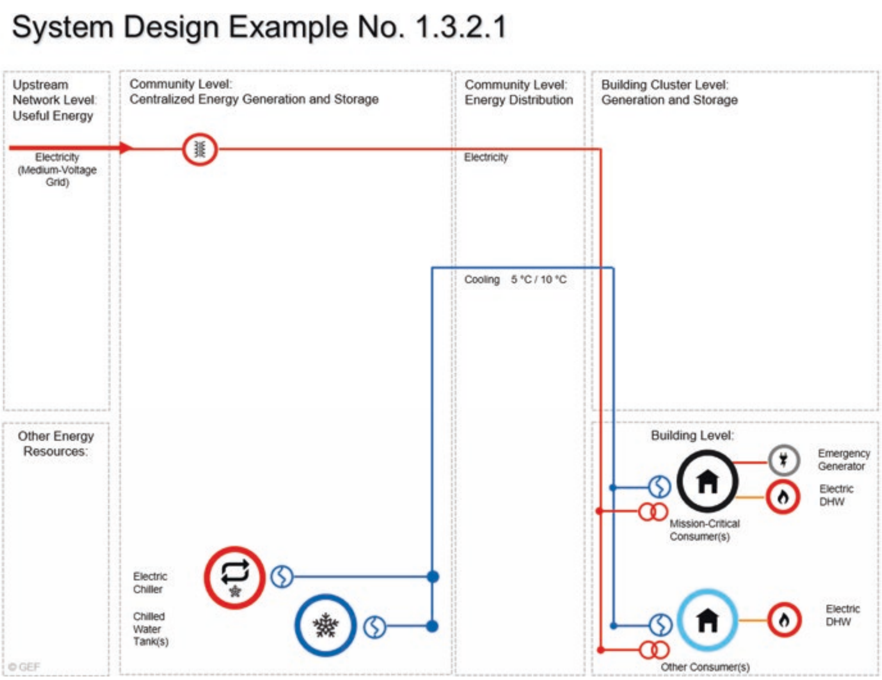
Description	Gas CHP and gas boiler in community
Central equipment	Gas CHP unit and gas boiler
Capabilities	Reliable heat supply, can supply buildings with high-temperature hot water
Applications	Communities with at least medium heat density
Advantages	Low complexity, heat storage provides peak shaving for heat and additional resilience, (n+1) redundancy at community level for heating, emergency power generation for mission-critical buildings
Disadvantages	Gas grid necessary

System Design Example No. 1.3.1.3



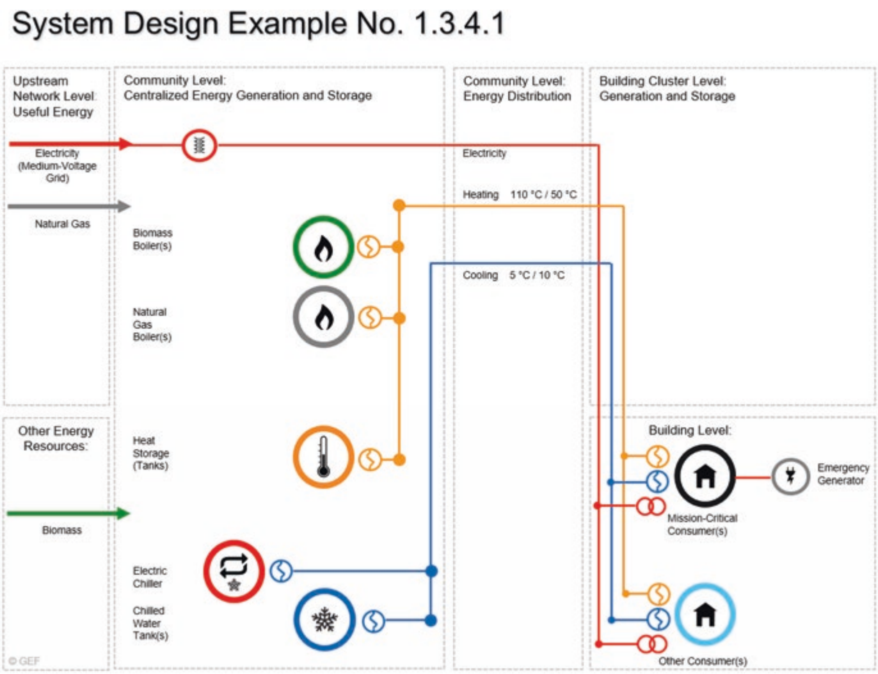
Solutions for generation within the community Nomenclature: 1.3.1.3 Example No. 3	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heat

Description	Biomass and gas boiler in community
Central equipment	Biomass and gas boiler
Capabilities	Reliable heat supply, can supply buildings with high-temperature hot water
Applications	Communities with at least medium heat density and no need for local electricity generation except for emergency
Advantages	Low complexity, renewable energy, heat storage provides peak shaving for heat and additional resilience, (n+1) redundancy at community level for heating, emergency power generation for mission-critical buildings
Disadvantages	Gas grid necessary



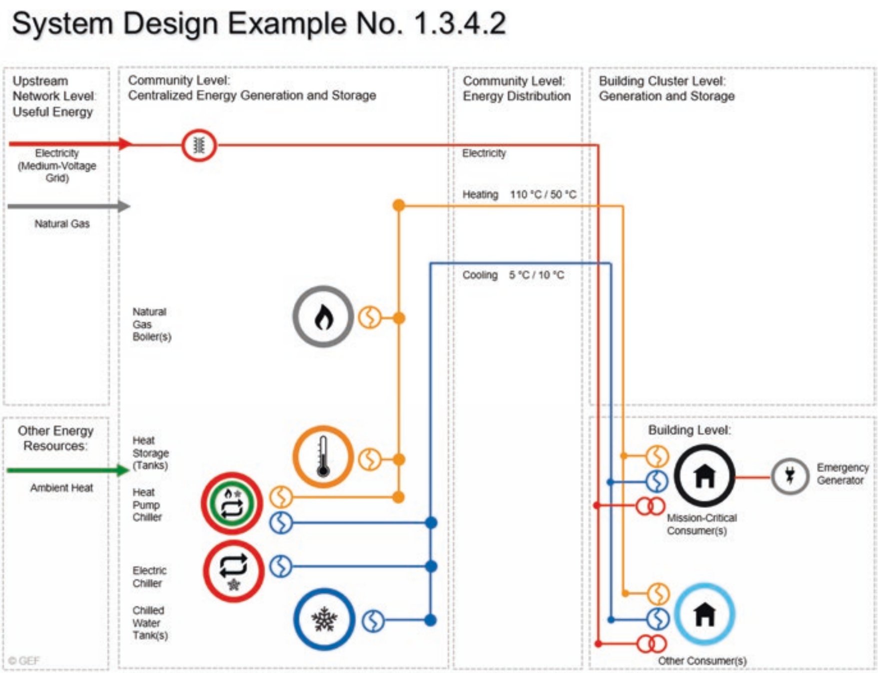
Solutions for generation within the community Nomenclature: 1.3.2.1 Example No. 1	Location of generation at… Community + building level	Buildings to be supplied from the outside with… Power + cooling

Description	Electric chiller in community, electric DHW at building level
Central equipment	Electric chiller, decentral electric DHW
Capabilities	Reliable cooling supply
Applications	Communities with at least medium cool density and no need for local electricity generation except for emergency
Advantages	Low complexity, no gas grid necessary, cool storage provides peak shaving, demand response and additional resilience, (n+1) redundancy for cooling, emergency power generation for mission-critical buildings
Disadvantages	No renewables



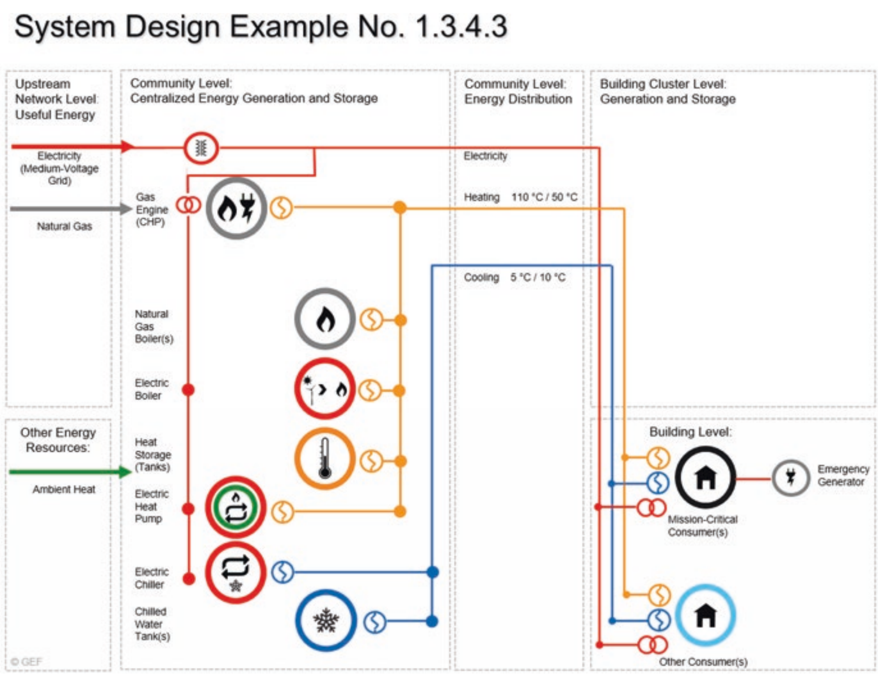
Solutions for generation within the community Nomenclature: 1.3.4.1 Example No. 1	Location of generation at… community level	Buildings to be supplied from the outside with… Power + heat + cooling

Description	Biomass boiler and electric chiller in community
Central equipment	Biomass and gas boiler, electric chiller
Capabilities	Reliable cooling and heat supply, can supply buildings with high-temperature hot water
Applications	Communities with at least medium heat density and no need for local electricity generation except for emergency
Advantages	Renewable energy, (n+1) redundancy at community level for heating and cooling, storage provides peak shaving for heat and cold and additional resilience, emergency power generation for mission-critical buildings
Disadvantages	Gas grid necessary



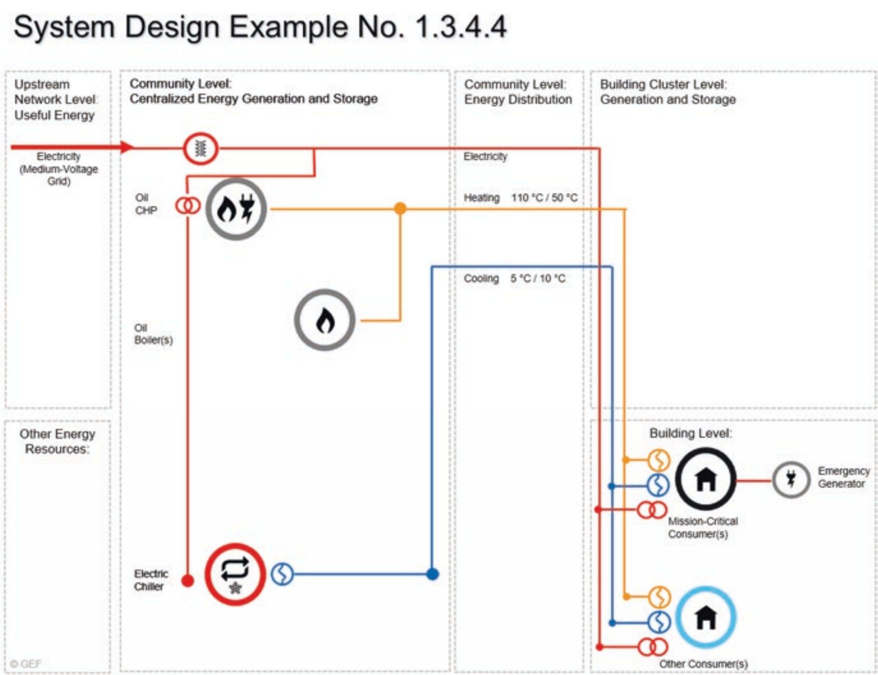
Solutions for generation within the community Nomenclature: 1.3.4.2 Example No. 2	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heat + cooling

Description	Heat pump, gas boiler, and electric chiller in community
Central equipment	Heat pump, gas boiler, and electric chiller
Capabilities	Reliable cooling and heat supply, can supply buildings with high-temperature hot water
Applications	Communities with low or medium cooling and heat density
Advantages	Share of renewable heat, storage provides peak shaving and demand response for heat and cold and additional resilience, (n+1) redundancy at community level for heating and cooling, emergency power generation for mission-critical buildings
Disadvantages	Gas grid necessary, no electricity generation



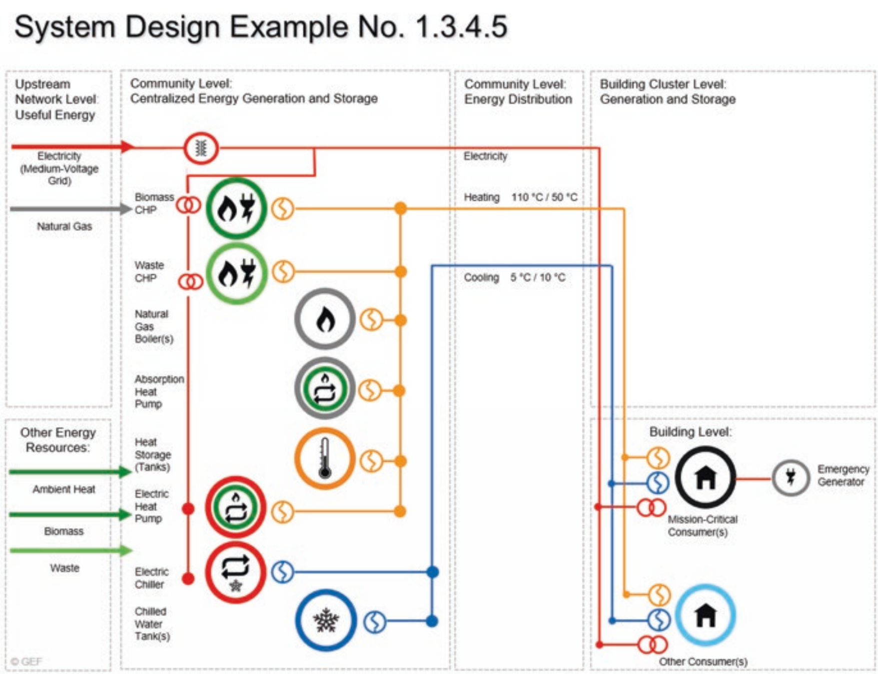
Solutions for generation within the Community Nomenclature: 1.3.4.3 Example No. 3	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heat + cooling

Description	Gas CHP, heat pump, gas boiler, electric boiler, and electric chiller in community
Central equipment	Gas engine, heat pump, gas boiler, electric boiler, and electric chiller
Capabilities	Reliable cooling and heat supply; onsite generation of electricity, can supply buildings with high-temperature hot water
Applications	Communities with at least medium cooling and heat density
Advantages	Renewable energy, cogeneration of power and heat, storage provides peak shaving for heat and cold and additional resilience, (n+1) redundancy at community level for heating and cooling, heat pump and electric boilers can provide demand response to power grid (important with high shares of fluctuating renewables)
Disadvantages	Gas grid necessary, high complexity



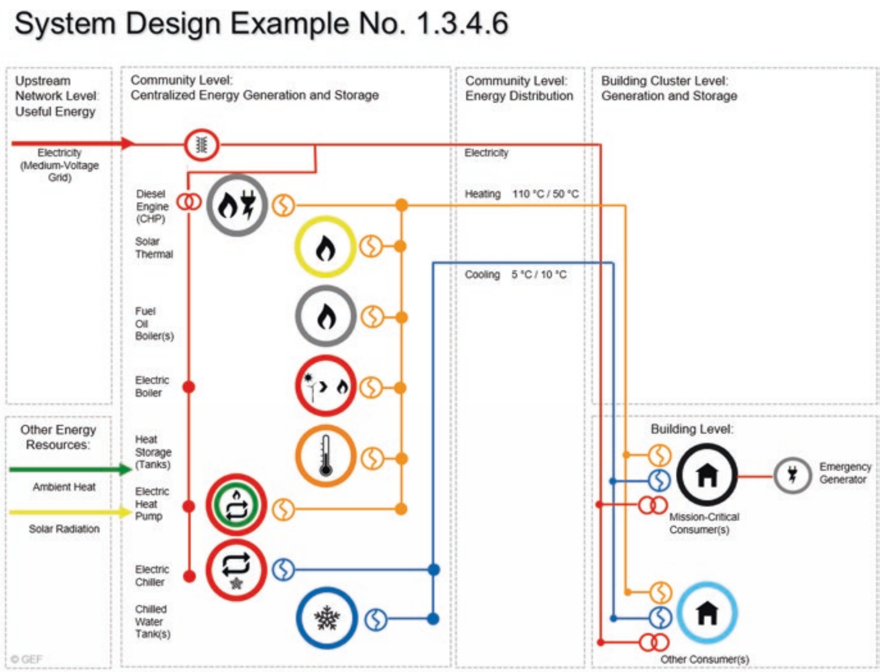
Solutions for generation within the community Nomenclature: 1.3.4.4 Example No. 4	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heat + cooling

Description	Oil CHP, fuel oil boiler, and electric chiller in community
Central equipment	Oil engine, fuel oil boiler, and electric chiller
Capabilities	Reliable cooling and heat supply, onsite generation of electricity, can supply buildings with high-temperature hot water
Applications	Communities with at least medium cooling and heat density
Advantages	Low complexity, cogeneration of power and heat, no gas grid necessary, (n+1) redundancy at community level for heating and cooling
Disadvantages	No renewables



Solutions for generation within the community Nomenclature: 1.3.4.5 Example No. 5	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heat + cooling

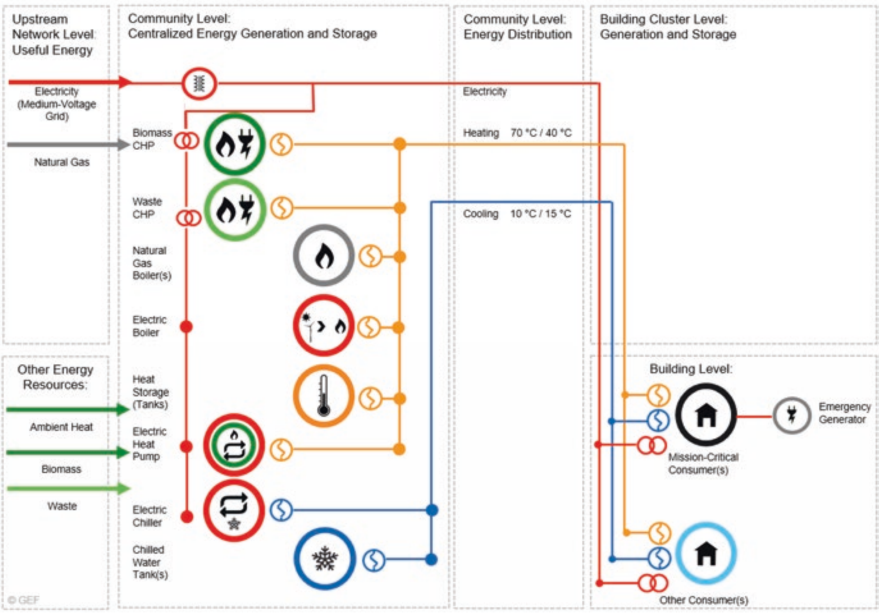
Description	Biomass and waste CHP, heat pump, gas boiler, and electric chiller in community
Central equipment	Biomass and waste CHP unit, electric and absorption heat pump, gas boiler, electric boiler, and electric chiller
Capabilities	Reliable cooling and heat supply, onsite generation of electricity, can supply buildings with high-temperature hot water
Applications	Communities with medium and high cooling and heat density
Advantages	Renewable energy, cogeneration of power and heat, storage provides peak shaving for heat and cold and additional resilience, (n+1) redundancy at community level for heating and cooling
Disadvantages	Gas grid necessary, high complexity



Solutions for generation within the community Nomenclature: 1.3.4.6 Example No. 6	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heat + cooling

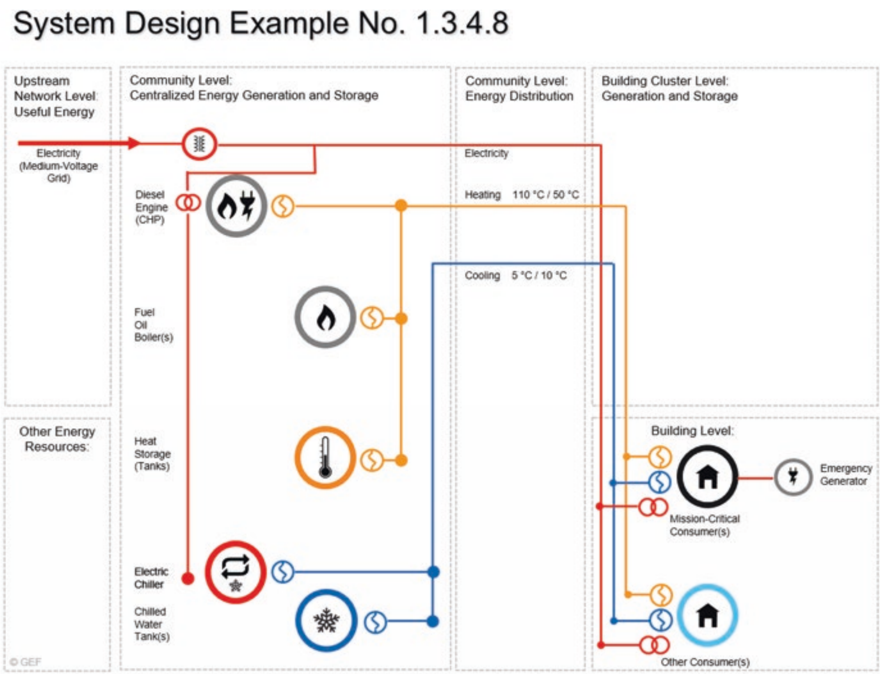
Description	Diesel CHP, heat pump, gas boiler, solar thermal, electric boiler, and electric chiller in community
Central equipment	Biomass and waste CHP unit, heat pump, gas boiler, electric boiler, and electric chiller
Capabilities	Reliable cooling and heat supply, onsite generation of electricity, can supply buildings with high-temperature hot water
Applications	Communities with at least medium cooling and heat density
Advantages	Renewable energy, cogeneration of power and heat, storage provides peak shaving for heat and cold and additional resilience, no gas grid necessary, (n+1) redundancy at community level for heating and cooling, emergency power at building level for mission-critical buildings
Disadvantages	High complexity

System Design Example No. 1.3.4.7



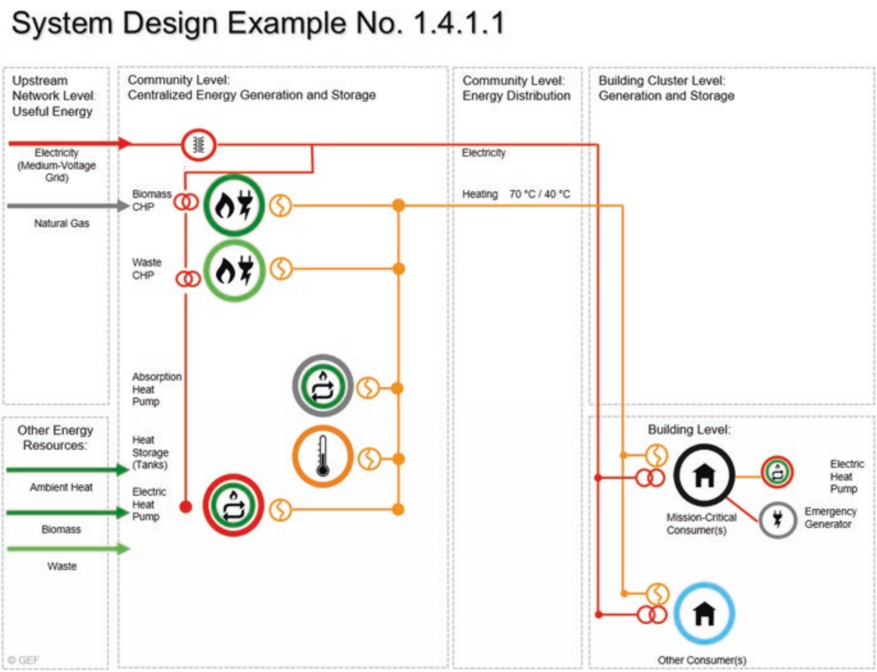
Solutions for generation within the community Nomenclature: 1.3.4.7 Example No. 7	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heat + cooling

Description	Biomass and waste CHP, heat pump, gas boiler, electric boiler, and electric chiller in community
Central equipment	Biomass and waste CHP unit, heat pump, gas boiler, electric boiler, and electric chiller
Capabilities	Reliable cooling and heat supply, onsite generation of electricity, can supply buildings with high-temperature hot water
Applications	Communities with medium and high cooling and heat density
Advantages	Renewable energy, cogeneration of power and heat, storage provides peak shaving for heat and cold and additional resilience, low supply temperature would allow integration of many types of renewables, (n+1) redundancy for heating and cooling, heat pumps and electric boilers can provide demand response to power grids (important with high shares of fluctuating renewables), emergency power generation for mission-critical buildings
Disadvantages	High complexity, gas grid necessary



Solutions for generation within the community Nomenclature: 1.3.4.8 Example No. 8	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heat + cooling

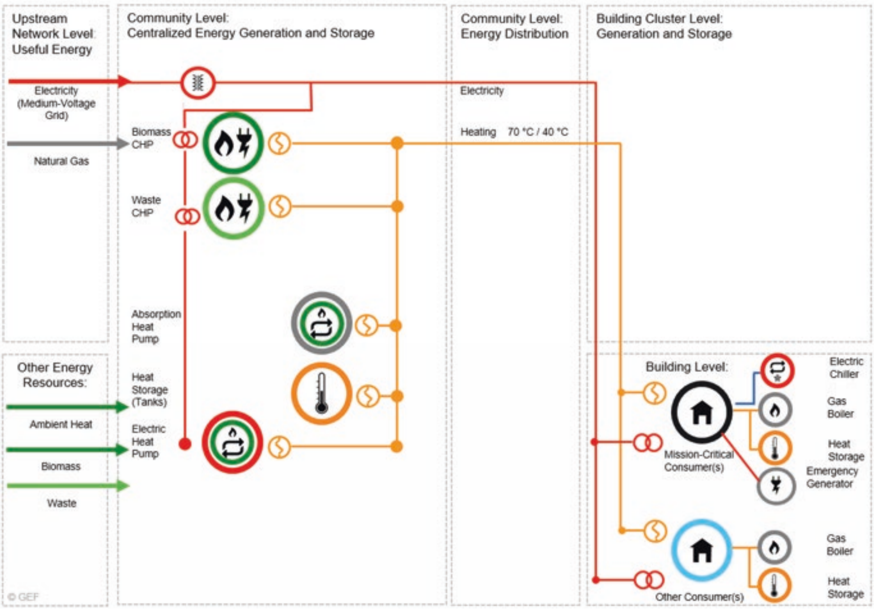
Description	Diesel CHP, fuel oil boiler, and electric chiller in the community
Central Equipment	Diesel engine, fuel oil boiler, and electric chiller
Capabilities	Reliable cooling and heat supply, onsite generation of electricity, can supply buildings with high-temperature hot water
Applications	Communities with at least medium cooling and heat density
Advantages	Low complexity, cogeneration of power and heat, no gas grid necessary, storage provides peak shaving for heat and cold and additional resilience, (n+1) redundancy for heating and cooling, emergency power generation for mission-critical buildings
Disadvantages	No renewables



Solutions for generation within the community Nomenclature: 1.4.1.1 Example No. 1	Location of generation at… Community + building level	Buildings to be supplied from the outside with… Power + heat

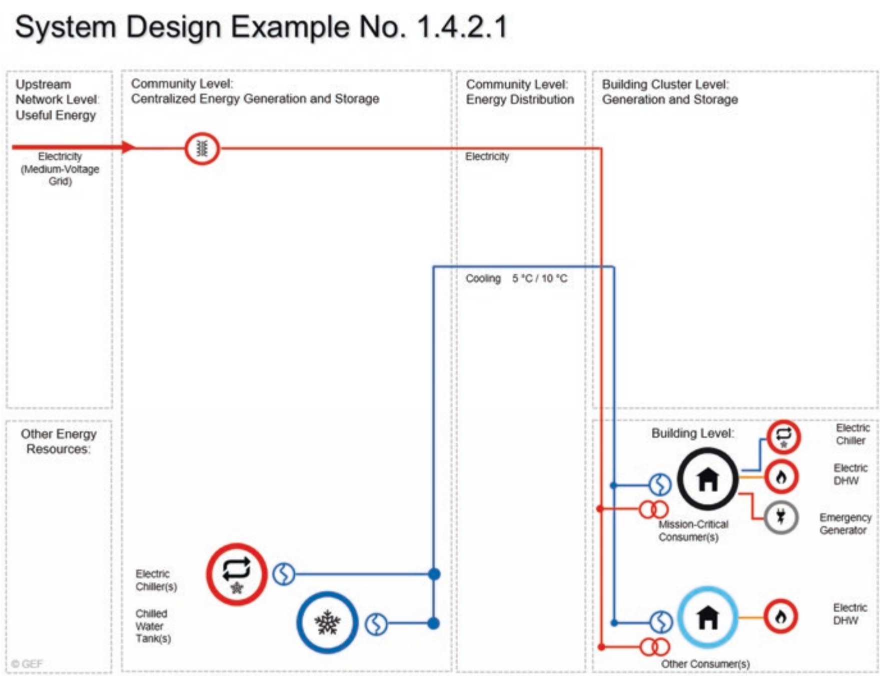
Description	Biomass and waste CHP, heat pump in community
Central equipment	Biomass and waste CHP unit, heat pump (absorption + electric)
Capabilities	Reliable heat supply, onsite generation of electricity, could (generally) supply buildings with high-temperature hot water
Applications	Communities with medium and high heat density
Advantages	Renewable energy, cogeneration of power and heat, heat storage provides peak shaving for heat and additional resilience, low supply temperature allows integration of many types of renewables, (n+1) redundancy for heating, emergency power generation for mission-critical buildings, additional resilience for heating via heat pump in mission-critical buildings
Disadvantages	Gas grid necessary, costs for additional resilience equipment

System Design Example No. 1.4.1.2



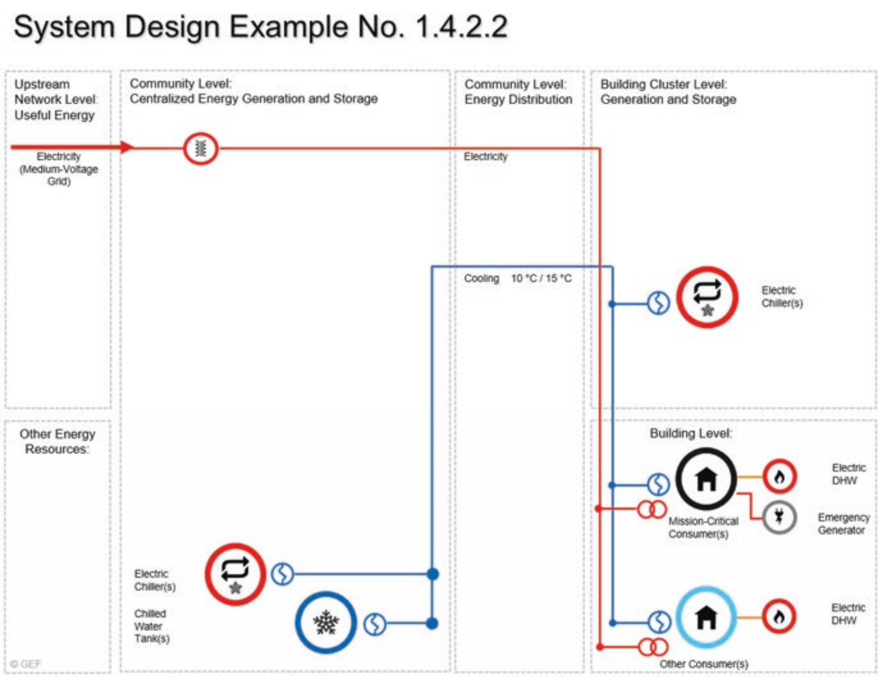
Solutions for generation within the community Nomenclature: 1.4.1.2 Example No. 2	Location of generation at… Community + building level	Buildings to be supplied from the outside with… Power + heating

Description	Largely renewable heat generation supplemented with peak load boilers in the buildings, decentral chillers for mission-critical buildings
Central equipment	Renewable CHP and heat pumps (electric + absorption)
Capabilities	Reliable heat supply, onsite generation of electricity, can supply buildings with high-temperature hot water
Applications	Communities with at least medium heat density
Advantages	Large share of renewables, cogeneration of power and heat, (n+1) redundancy for heating within the grid, heat storage provides peak shaving for heat and additional resilience, emergency power generation for mission-critical buildings, low supply temperature allows integration of many types of renewables, additional resilience for heating and cooling via boilers and chillers in individual buildings
Disadvantages	Complex system, gas grid necessary, higher cost because of high level of resilience



Solutions for generation within the community Nomenclature: 1.4.2.1 Example No. 1	Location of generation at… Community + building level	Buildings to be supplied from the outside with… Power + cooling

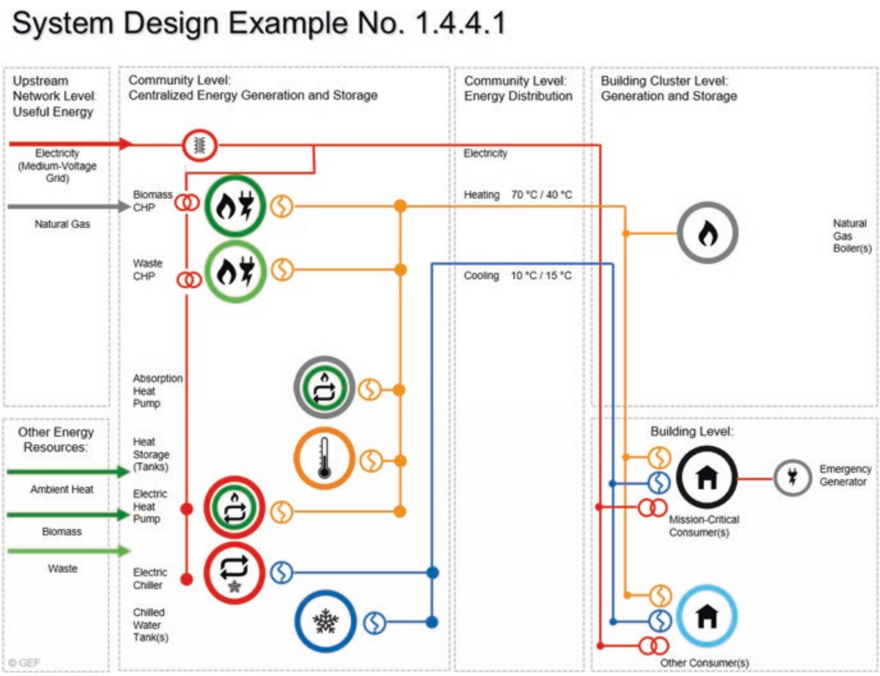
Description	Electric chillers in community and building level, decentral electric DHW
Central equipment	Electric chillers
Capabilities	Reliable cooling supply
Applications	Communities and clusters with low or medium cool density
Advantages	Low complexity, no gas grid necessary, at least (n+1) redundancy for cooling, cool storage provides peak shaving for cooling and additional resilience, emergency power generation for mission-critical buildings
Disadvantages	No renewables, no electricity generation



Solutions for generation within the community Nomenclature: 1.4.2.2 Example No. 2	Location of generation at… Community + building cluster + building level	Buildings to be supplied from the outside with… Power + cooling

Description	Electric chillers in community and building cluster
Central equipment	Electric chillers
Capabilities	Reliable cooling supply
Applications	Communities and clusters with low or medium cool density
Advantages	Low complexity, no gas grid necessary, at least (n+1) redundancy for cooling, cool storage provides peak shaving for cooling and additional resilience, emergency power generation for mission-critical buildings
Disadvantages	No renewables, no electricity generation

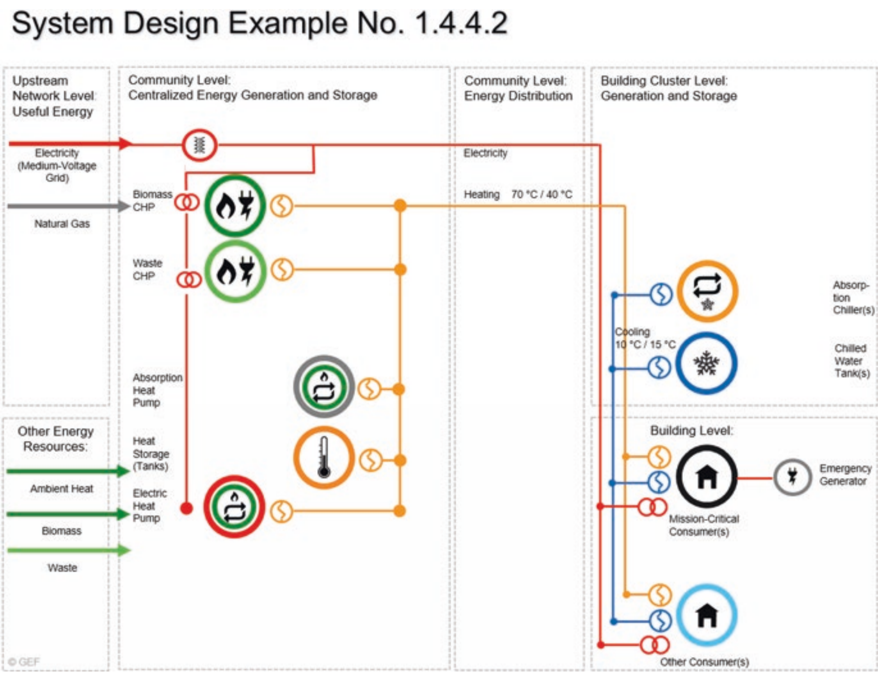
System Design Example 1.4.4.1



Solutions for generation within the community Nomenclature: 1.4.4.1 Example No. 1	Location of generation at… Community + build. cluster level	Buildings to be supplied from the outside with… Power + heat + cooling

Description	Biomass and waste CHP, heat pump, chiller in community, and gas boiler in building cluster
Central equipment	Biomass and waste CHP unit, heat pump (absorption + electric), chiller, and gas boiler
Capabilities	Reliable cooling and heat supply, onsite generation of electricity, could (generally) supply buildings with high-temperature hot water
Applications	Communities with high and medium heat density
Advantages	Renewable energy, cogeneration of power and heat, low supply temperature allows integration of many types of renewables, (n+1) redundancy for heating and cooling, storage provides peak shaving for heat and cold and additional resilience, emergency power generation for mission-critical buildings
Disadvantages	Gas grid necessary, high complexity

System Design Example 1.4.4.1

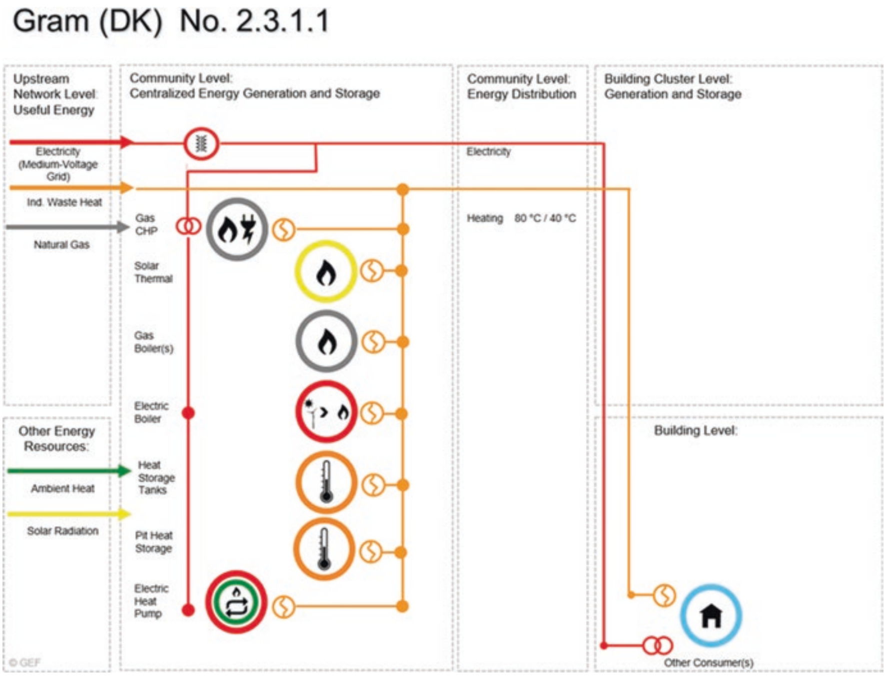


Solutions for generation within the community Nomenclature: 1.4.4.2 Example No. 2	Location of generation at… Community + build. cluster level	Buildings to be supplied from the outside with… Power + heat + cooling

Description	Biomass and waste CHP, heat pump in community, and chiller in building cluster
Central equipment	Biomass and waste CHP unit, heat pump (absorption + electric), and absorption chiller
Capabilities	Reliable cooling and heat supply, onsite generation of electricity, can supply buildings with high-temperature hot water
Applications	Communities with high and medium heat density
Advantages	Renewable energy, cogeneration of power and heat, low supply temperature allows integration of many types of renewables, (n+1) redundancy for heating and cooling, heat and cool storage provides peak shaving for heat and additional resilience, emergency power generation for mission-critical buildings
Disadvantages	Gas grid necessary, high complexity

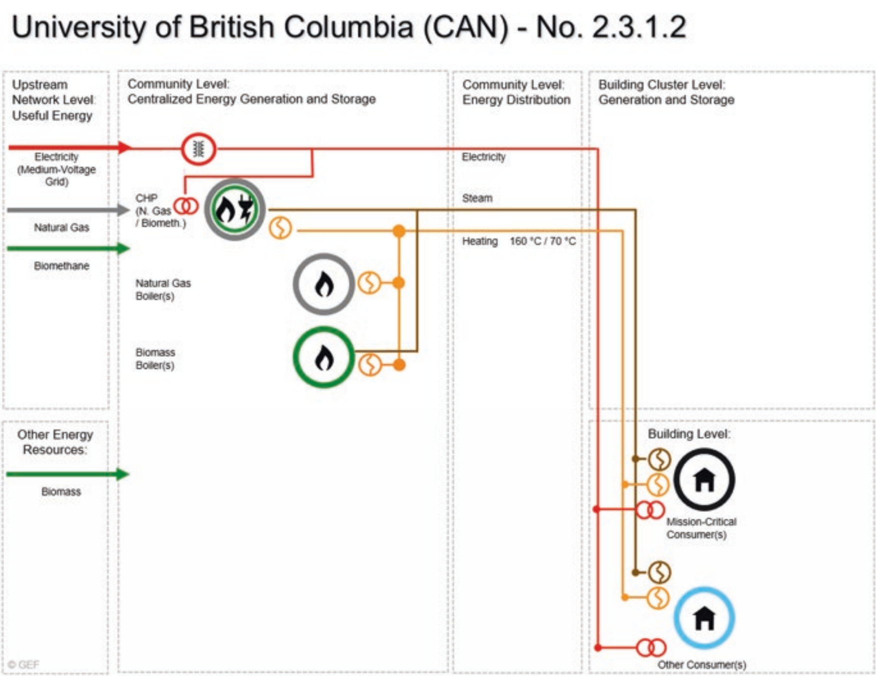
E.3 Best Practice Examples

Best Practice: Gram (DK) No. 2.3.1.1



Solutions for generation within the community Nomenclature: 2.3.1.1 Example No. 1	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heating

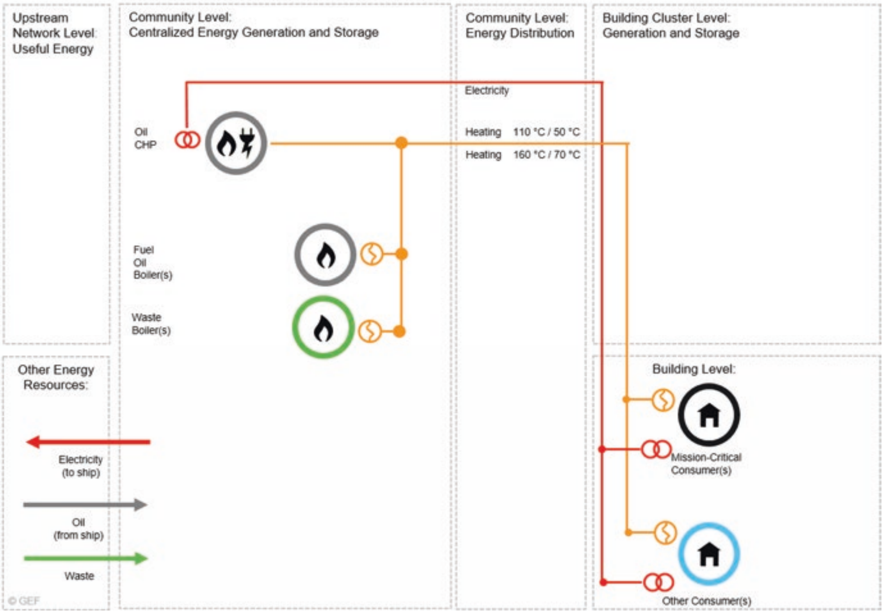
Description	Gram is a good case showing how a district heating system can function as a virtual battery offering huge demand response to the power grid. The system is also integrating industrial waste heat from outside the community
Central Equipment	Large-scale solar heating, pit thermal energy storage, electric boiler, heat pump, gas engine, gas boiler
Capabilities	Solar heating is contributing with around 60% of the annual district heating demand, as it is operating together with a pit thermal energy storage. The other units can also use the storage to better integrate renewable energy in the entire energy system
Applications	Small communities (cities) with available space for solar heating and a pit thermal energy storage
Advantages	Renewable energy, flexibility, tax independent, virtual battery
Disadvantages	High investment costs, solar availability



Solutions for generation within the community Nomenclature: 2.3.1.2 Example No. 2	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heating/steam

Description	Natural gas, biomethane and biomass for CHP, and boiler at community level
Central equipment	Biomass and natural gas boilers, gas CHP unit
Capabilities	Reliable cooling and heat supply, onsite generation of electricity, can supply buildings with high-temperature hot water and steam
Applications	Communities with high and medium heat density
Advantages	Renewable energy, cogeneration of power and heat, (n+1) redundancy for heating at community level
Disadvantages	Gas grid necessary

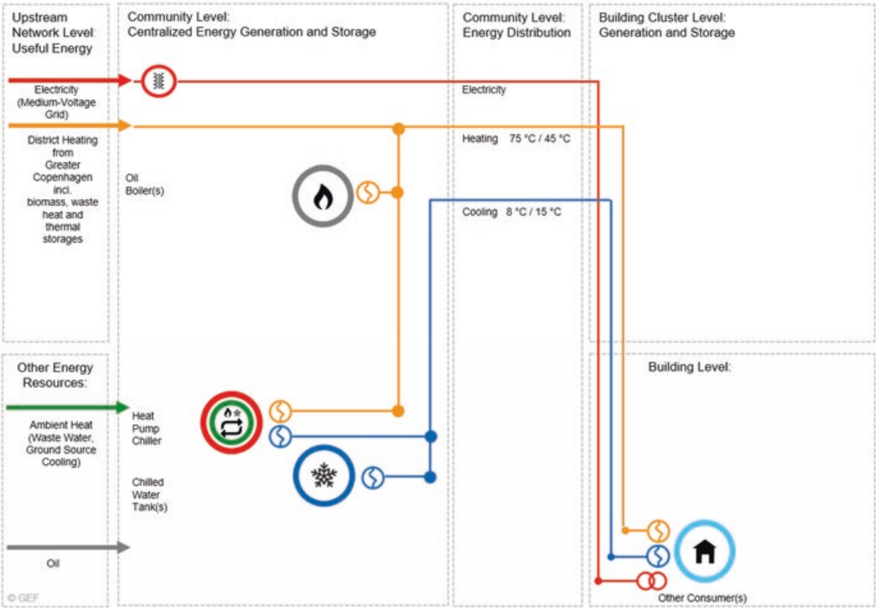
Quanaaq (Greenland) No. 2.3.1.3



Solutions for generation within the community Nomenclature: 2.3.1.3 Example No. 3	Location of generation at… Community level	Buildings to be supplied from the outside with … Power + heating

Description	Qaanaaq is a small settlement located near Thule Air Base in Greenland. The energy system was developed with district heating to efficiently make use of the excess heat from the CHP. It is typical for these remote settlements. Waste boilers are an option for some of the settlements
Central Equipment	CHP, boilers
Capabilities	High use of free excess heat from the oil CHP in the district heating network
Applications	Small Arctic settlements
Advantages	Energy efficient, saves oil, which is the only energy source that can be transported by ship to the settlement, reliable and low cost compared to building-level boilers, and steam district heating trench can be used to keep other service lines from freezing. Open for use of any renewable energy source and waste heat due to low temperature
Disadvantages	

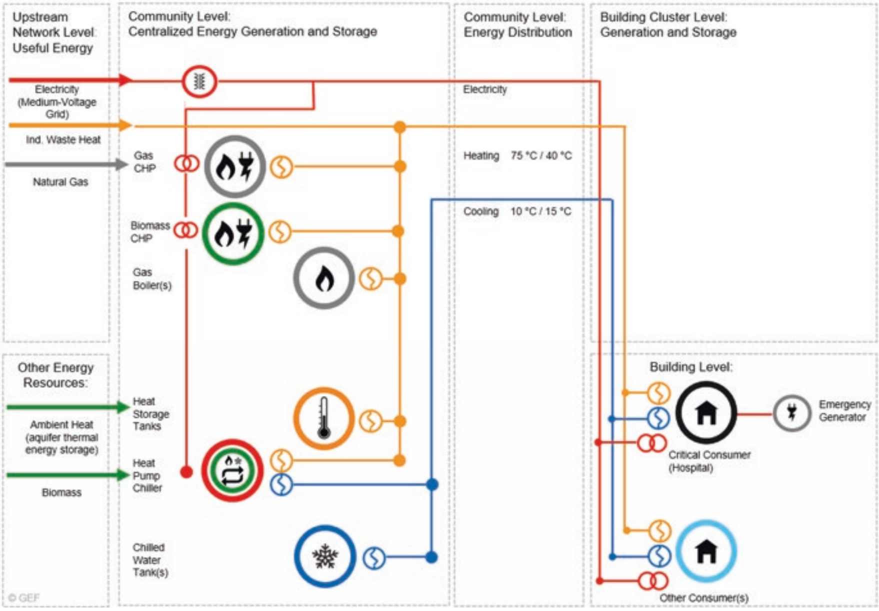
Taarnby District, Copenhagen (DK) No. 2.3.4.1



Solutions for generation within the community Nomenclature: 2.3.4.1 Example No. 1	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heating + cooling

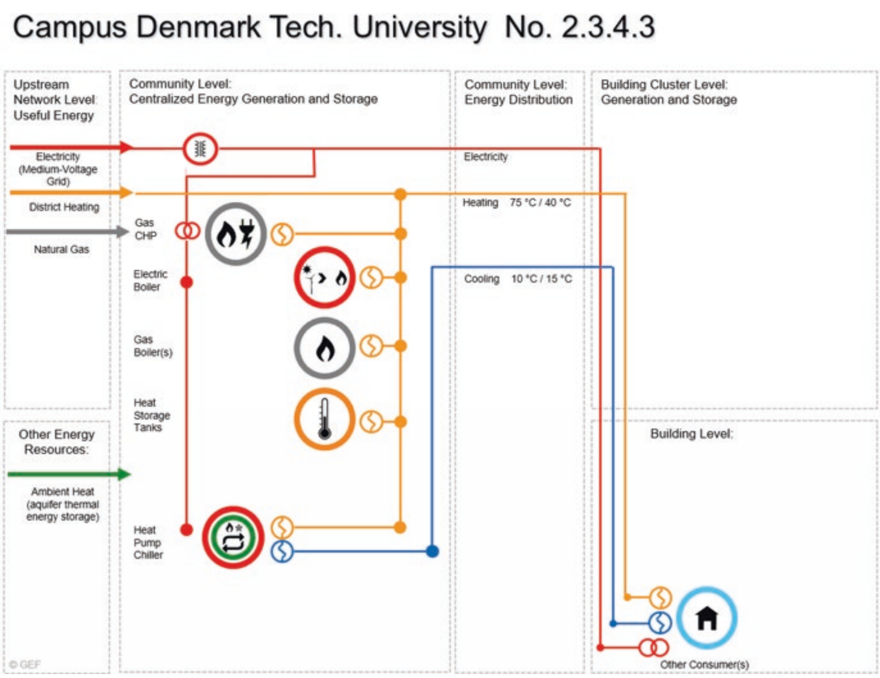
Description	A district cooling system supplying offices and aquariums integrated into district heating system of the local community, which is integrated in Greater Copenhagen
Central equipment	Heat pump, cooling storage, DH&C integration, district cooling, heat exchanger from wastewater Ground source cooling aquifer thermal energy storage (ATES) is planned for a second stage, For an example, see Favrholm (below)
Capabilities	Energy efficiency, integration of electricity, district heating and cooling, ATES, and heat from wastewater
Applications	Small district cooling clusters with connection to district heating systems
Advantages	Energy efficiency, low operational costs, innovative solution The public utility ensures optimal in-house coordination between district heating and cooling (DHC), wastewater, and location of the energy plant at the wastewater treatment plant
Disadvantages	Coordination with consumers in new urban development

Favrholm (DK) No. 2.3.4.2



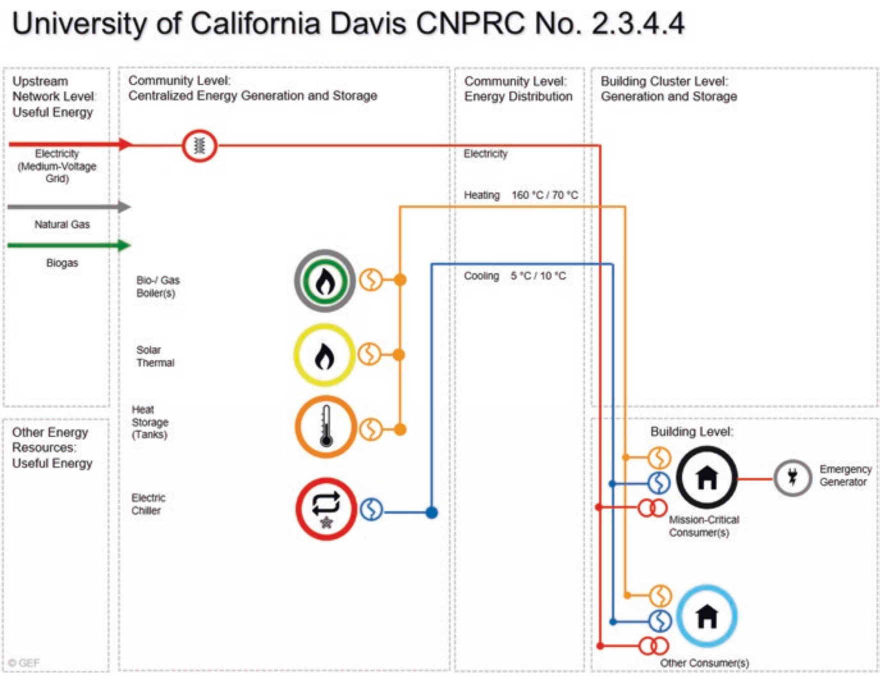
Solutions for generation within the community Nomenclature: 2.3.4.2 Example No. 2	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heating + cooling

Description	Favrholm is a local community in Denmark that is connected to the district heating system in Hillerød. Development of district cooling in clusters for new buildings is planned, and contract is signed with the largest customer, a new hospital
Central Equipment	Heat pump, cooling storage, ATES
Capabilities	Energy efficiency, integration
Applications	Small district cooling clusters with connection to district heating systems
Advantages	Energy efficiency, low operational costs, innovative solution, cooling is planned for extension to pharmaceutical campus, efficient coordination as the public utility is operating all facilities in the city-wide DHC cluster
Disadvantages	Coordination between utility and individual consumers (not a single-owner campus)



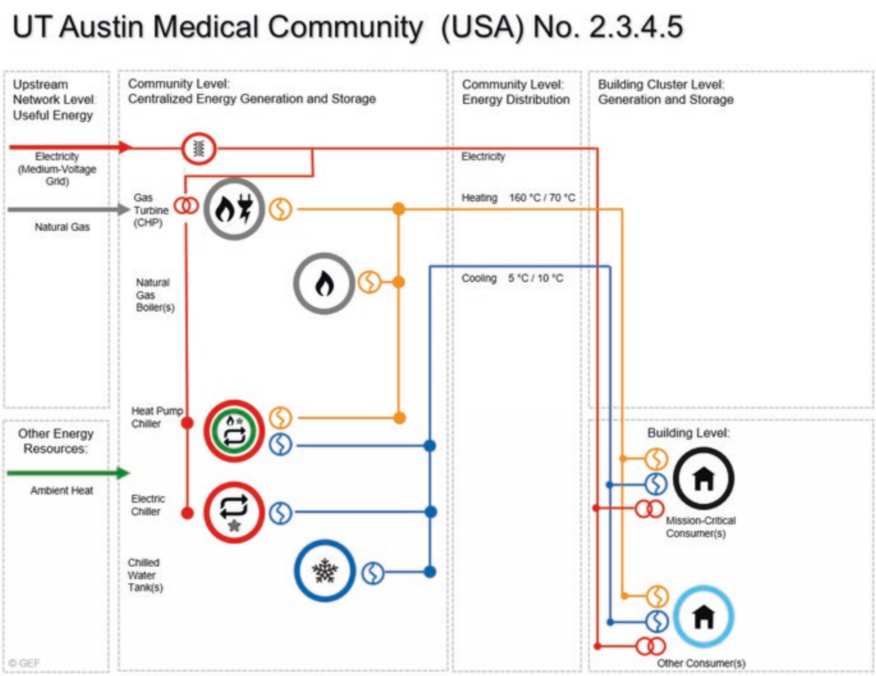
Solutions for generation within the community Nomenclature: 2.3.4.3 Example No. 3	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heating + cooling

Description	DTU are operating their own campus energy system with district heating and district cooling and are connected to the larger district heating system in Copenhagen
Central equipment	Heat pump, heat storage, gas CHP, gas boiler, flue gas condensation
Capabilities	Energy efficiency, integration
Applications	Campus areas
Advantages	Supply of heating and cooling via thermal networks
Disadvantages	Complexity



Solutions for generation within the community Nomenclature: 2.3.4.4 Example No. 4	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heating + cooling

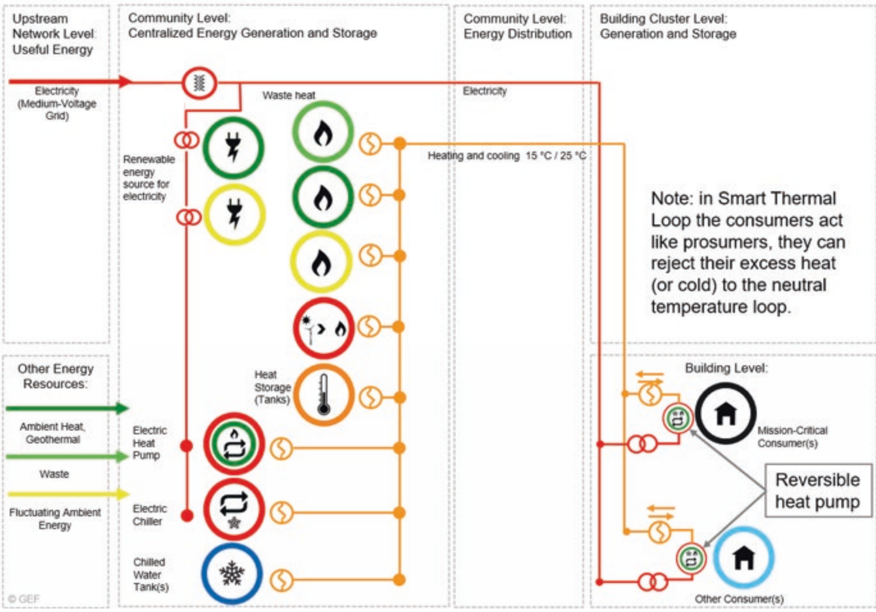
Description	Natural gas and biomethane boilers and solar thermal community level for heating, electrical cool
Central equipment	Gas/biogas boiler, solar thermal, electric chillers
Capabilities	Reliable cooling and heat supply, can supply buildings with high-temperature hot water and low-temperature chilled water
Applications	Communities with high and medium heat and cool density
Advantages	Renewable energy, (n+1) redundancy for heating and cooling at community level, heat storage provides peak shaving for heat and additional resilience, emergency power generation for critical buildings
Disadvantages	Gas grid necessary



Solutions for generation within the C community Nomenclature: 2.3.4.5 Example No. 5	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heating + cooling

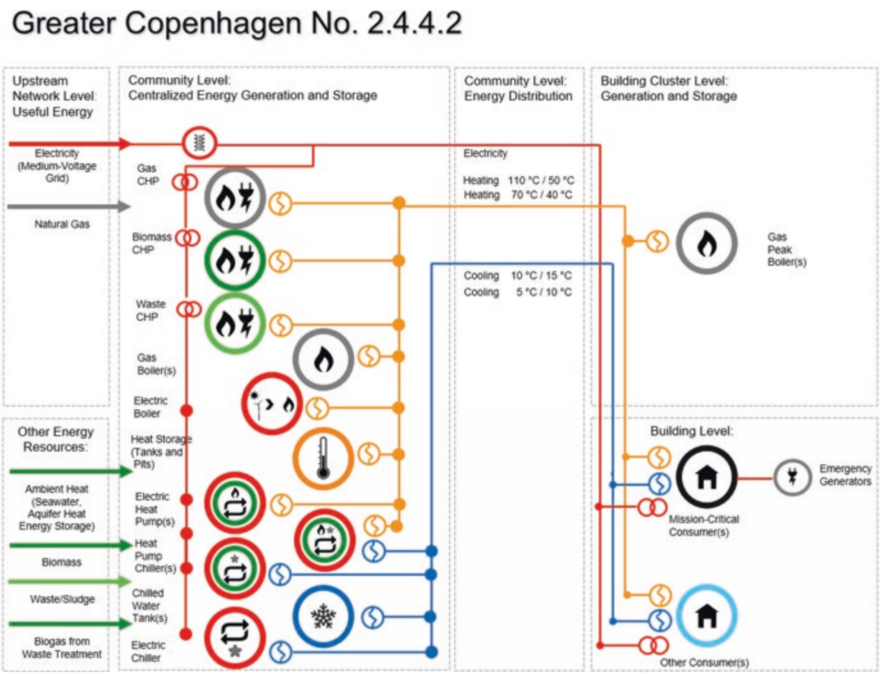
Description	Gas CHP, heat pump for heat + cool and chiller in community
Central equipment	Gas turbine, gas boilers, heat pump, electric chillers
Capabilities	Reliable cooling and heat supply, onsite generation of electricity, can supply buildings with high-temperature hot water and low-temperature chilled water
Applications	Communities with high and medium heat and cool density
Advantages	Renewable energy, cogeneration of power and heat, (n+1) redundancy for heating and cooling, cool storage provides peak shaving for cooling and additional resilience
Disadvantages	Gas grid necessary, higher complexity

Smart Thermal Loop (Australia) No. 2.4.1.1



Solutions for generation within the community Nomenclature: 2.4.1.1 Example No. 1	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heating/cooling

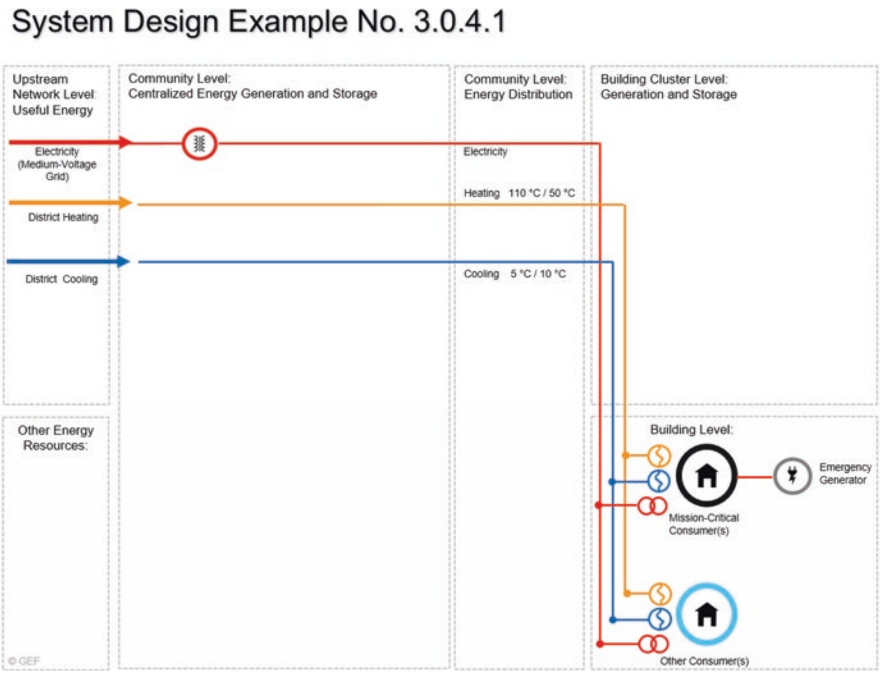
Description	Reversible heat pump of each individual building is connected to STL (both source and sink of heat); consumers act as prosumers; they can reject their excess heat (or cold) to STL. This concept has been developed as part of an energy master planning process for a campus of the University of Melbourne
Central equipment	Control room, energy piles, storage tanks, top up heat conversion/generation units (depending on the demand), e.g., chillers, heat pumps, solar thermal, and so on, onsite electricity generation (optional)
Capabilities	Reliable heating and cooling supply by ultra-low-temperature network
Applications	Communities with simultaneous heating and cooling energy needs with at least medium load (heating and cooling) density
Advantages	Integration of local renewable energy sources (RES), water saving, harvesting low-grade heat, pier to pier heat exchange, peak shaving
Disadvantages	High complexity



Solutions for generation within the community Nomenclature: 2.4.4.2 Example No. 2	Location of generation at… Community + build. cluster level	Buildings to be supplied from the outside with… Power + heating + cooling

Description	The district heating system in Greater Copenhagen
Central equipment	Biomass CHP, waste CHP, boilers, heat pump, thermal storage, electric boilers
Capabilities	Large-scale district heating system integrating many producers via a single market Varmelast.dk
Applications	Large cities
Advantages	Flexibility, energy efficiency, renewable energy integration
Disadvantages	Complexity

E.4 Generation Outside the Community

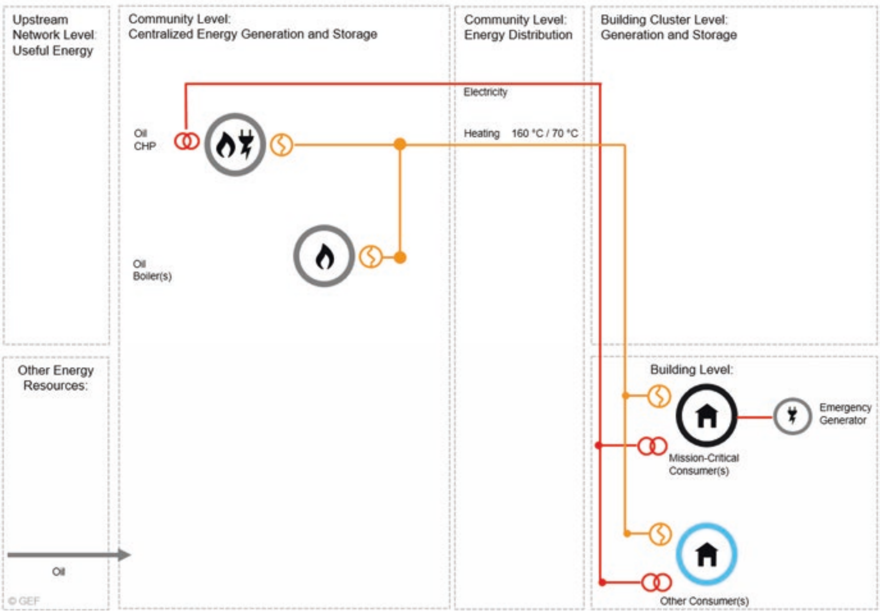


Solutions for generation within the community Nomenclature: 3.0.4.1 Example No. 1	Location of generation at… Upstream network level	Buildings to be supplied from the outside with… Power + heat + cooling

Description	Supply via upstream network (power, heat, and cooling), no generation within community
Central equipment	None
Capabilities	Reliable cooling and heat supply
Applications	Communities with high and medium heat density
Advantages	No equipment for heat or cooling generation needed on site, no space, staff, or finance requirements for such equipment, (n+1) redundancy for heating and cooling (provided by upstream supplier) v, emergency power generation for mission-critical buildings
Disadvantages	Dependence on upstream grids for heating and cooling

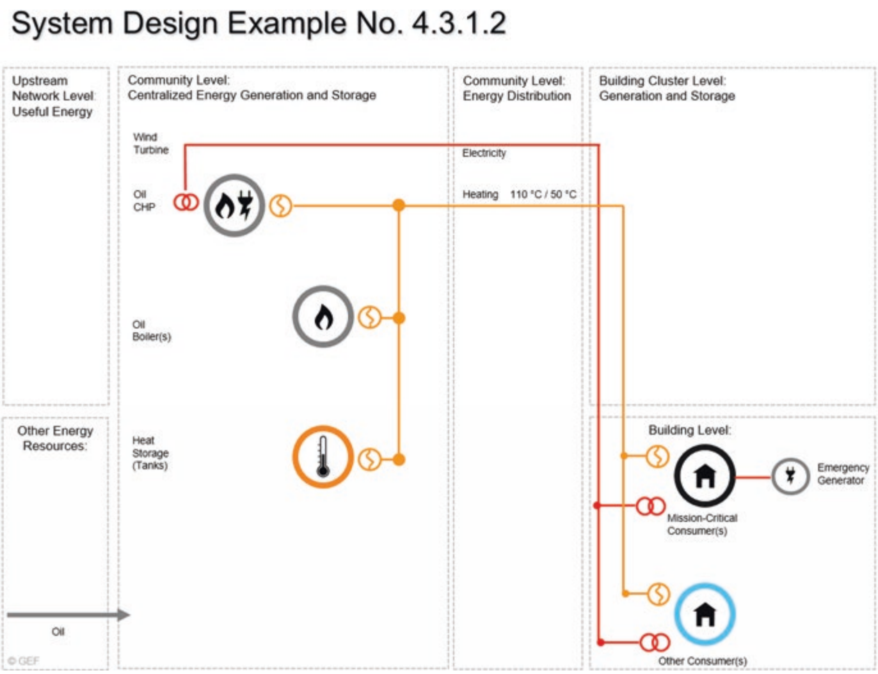
E.5 Solutions for Remote Locations

System Design Example No. 4.3.1.1



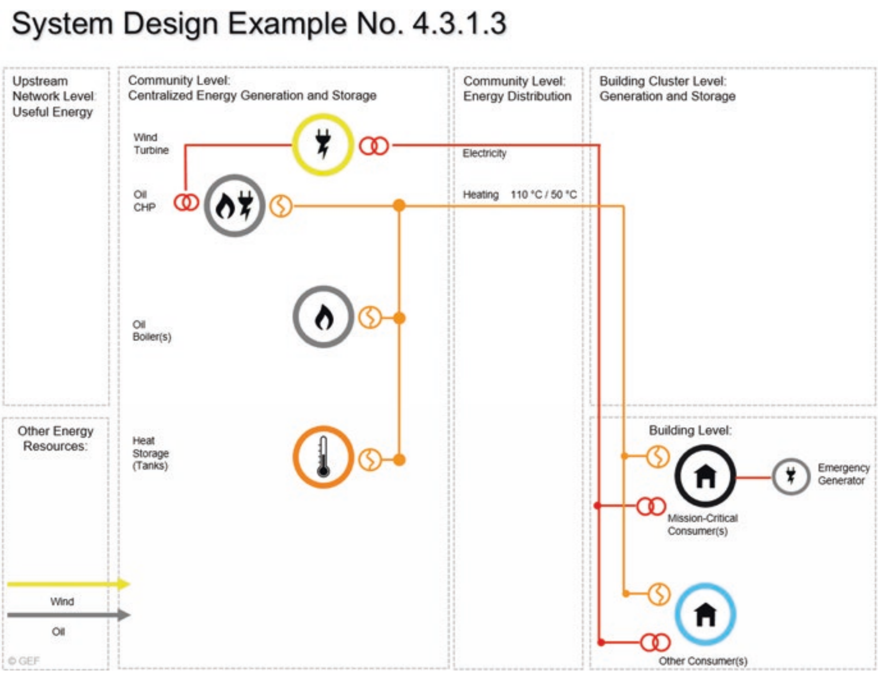
Solutions for generation within the community Nomenclature: 4.3.1.1 Example No. 1	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heat

Description	Island system without need for upstream supply grids, oil CHP, and fuel oil boiler in community
Central equipment	Oil engine, fuel oil boiler
Capabilities	Reliable heat supply, onsite generation of electricity, can supply buildings with high-temperature hot water
Applications	Communities with at least medium heat density
Advantages	Low complexity, cogeneration of power and heat, no gas grid necessary, (n+1) redundancy for heating, emergency power generation for mission-critical buildings
Disadvantages	No renewables



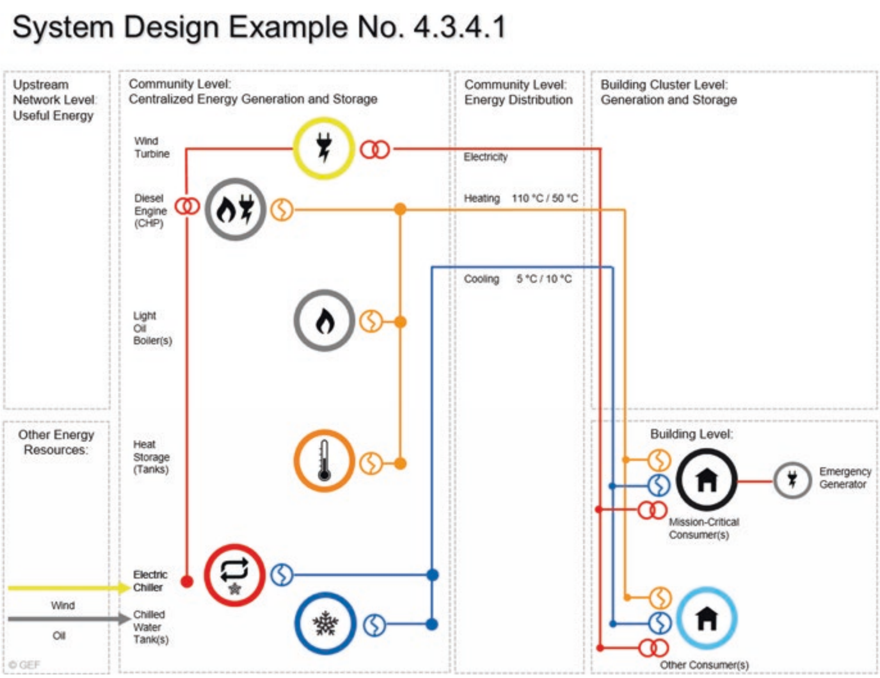
Solutions for generation within the community Nomenclature: 4.3.1.2 Example No. 2	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heat

Description	Island system without need for upstream supply grids, oil CHP, and fuel oil boiler in community
Central equipment	Oil engine, fuel oil boiler
Capabilities	Reliable heat supply, onsite generation of electricity, can supply buildings with high-temperature hot water
Applications	Communities with at least medium heat density
Advantages	Low complexity, cogeneration of power and heat, no gas grid necessary, (n+1) redundancy for heating, emergency power generation for mission-critical buildings
Disadvantages	No renewables



Solutions for generation within the community Nomenclature: 4.3.1.3 Example No. 3	Location of generation at …. community level	Buildings to be supplied from the outside with… Power + heat

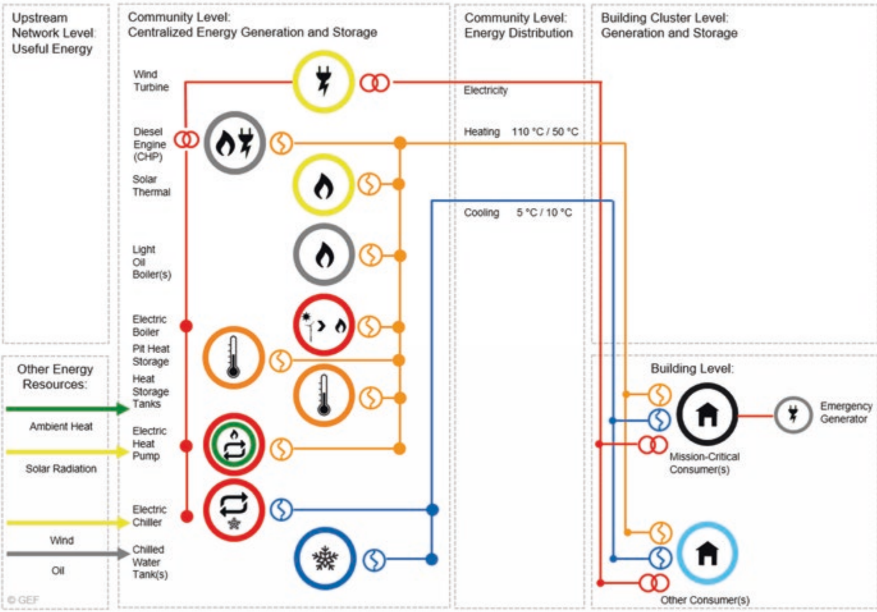
Description	Island system without need for upstream supply grids, wind turbine, oil CHP, and fuel oil boiler in community
Central equipment	Oil engine, fuel oil boiler, wind turbine
Capabilities	Reliable heat supply, onsite generation of fossil and renewable electricity, can supply buildings with high-temperature hot water
Applications	Communities with at least medium heat density
Advantages	Low complexity, cogeneration of power and heat, own electricity use, no gas grid necessary, (n+1) redundancy for heating, heat storage provides peak shaving for heat and additional resilience, emergency power generation for mission-critical buildings
Disadvantages	Wind power needs to be carefully sized when integrated into the islanded power system



Solutions for generation within the community Nomenclature: 4.3.4.1 Example No. 1	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heat + cooling

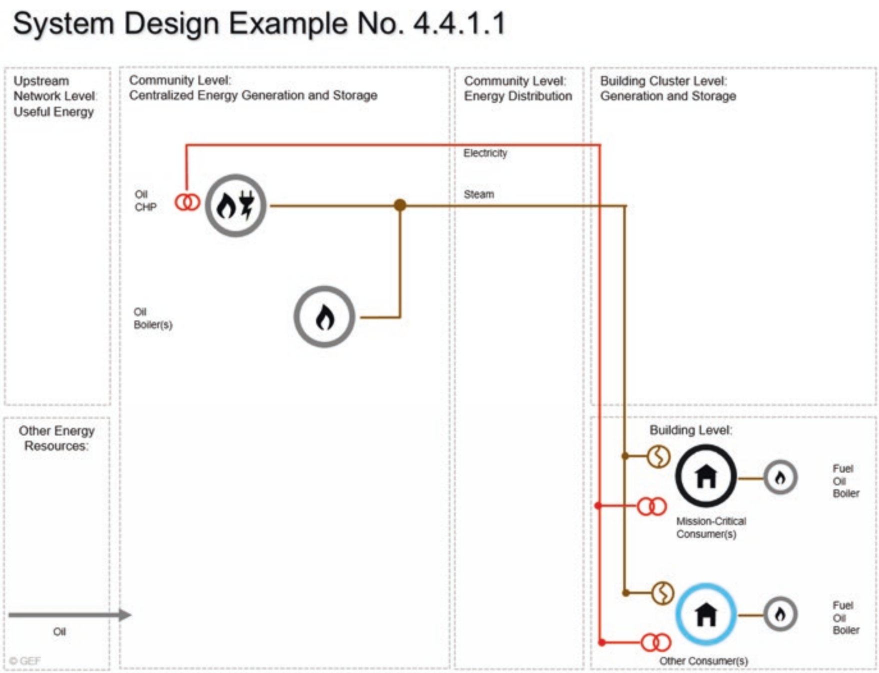
Description	Wind turbine, oil CHP, light oil boiler, and chiller in community
Central equipment	Oil engine, light oil boiler, wind turbine, chiller
Capabilities	Reliable cooling and heat supply, onsite generation of fossil and renewable electricity, can supply buildings with high-temperature hot water
Applications	Communities with at least medium heat and cool density
Advantages	Renewable energy, cogeneration of power and heat, own electricity use, no gas grid necessary, (n+1) redundancy for heating and cooling, heat and cool storage provides peak shaving for heat and cold and additional resilience, emergency power generation for mission-critical buildings
Disadvantages	Wind power needs to be carefully sized when integrated into the islanded power system

System Design Example No. 4.3.4.2



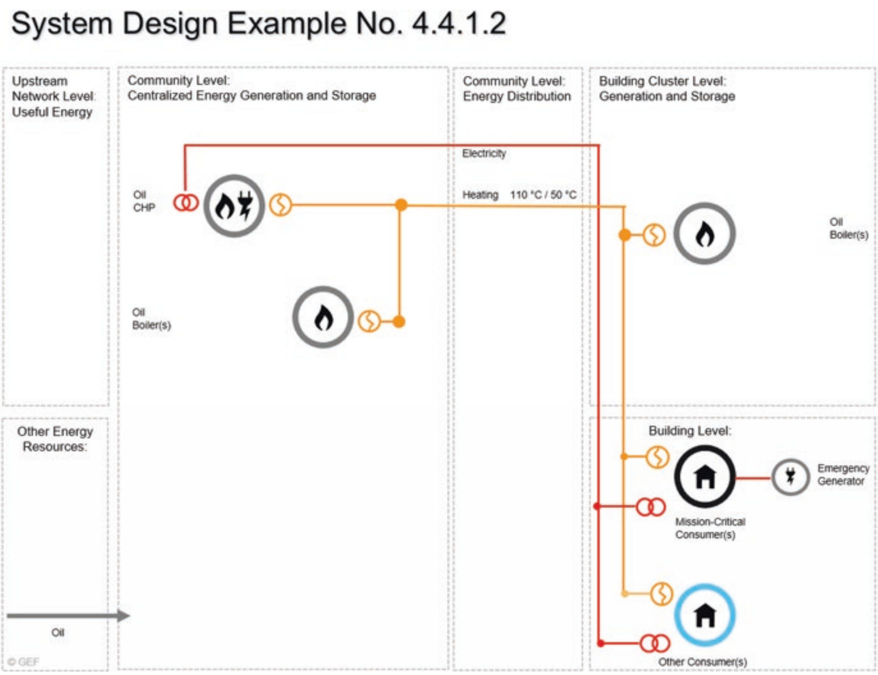
Solutions for generation within the community Nomenclature: 4.3.4.2 Example No. 2	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heat + cooling

Description	Island system without need for upstream supply grids, wind turbine, diesel CHP, oil + electric boiler, solar thermal, heat pump, pit heat storage, and chiller in community
Central equipment	Diesel engine, oil and electric boiler, wind turbine, solar thermal, heat pump, pit heat storage, and chiller
Capabilities	Reliable cooling and heat supply, onsite generation of fossil and renewable electricity, can supply buildings with high-temperature hot water
Applications	Communities with at least medium heat and cool density
Advantages	Cogeneration of power and heat, own electricity use, no gas grid necessary, (n+1) redundancy for heating and cooling, heat and cool storage provides peak shaving for heat and cold and additional resilience, electric boilers, heat pumps and chillers together with storage can provide demand response to balance the fluctuating renewables in the power grid, emergency power generation for mission-critical buildings
Disadvantages	High complexity



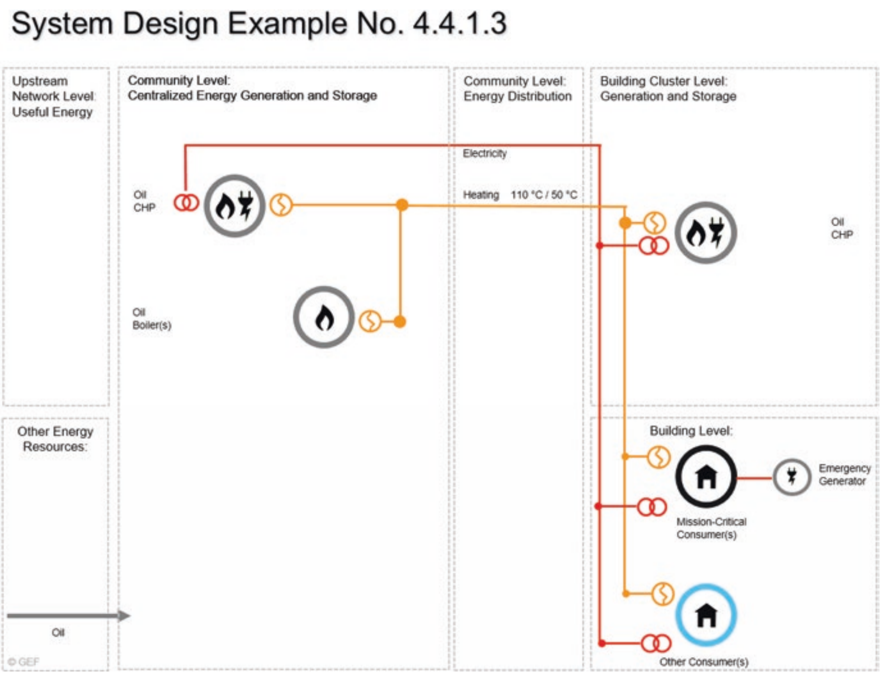
Solutions for generation within the community Nomenclature: 4.4.1.1 Example No. 1	Location of generation at …. Community + building level	Buildings to be supplied from the outside with… Power + steam/heat

Description	Island system without need for upstream supply grids, oil CHP, oil boiler in community, and individual building
Central equipment	Oil engine, small and big fuel oil boiler(s)
Capabilities	Reliable heat supply, onsite generation of fossil and renewable electricity, can supply buildings with high-temperature hot water or steam
Applications	Communities with at least medium heat density
Advantages	Low complexity, no gas grid necessary, cogeneration of power and heat independent of upstream grids, (n+1) redundancy for heating
Disadvantages	No renewables, high supply temperature



Solutions for generation within the community Nomenclature: 4.4.1.2 Example No. 2	Location of generation at… Community + build. cluster level	Buildings to be supplied from the outside with… Power + heat

Description	Island system without need for upstream supply grids, oil CHP, and oil boiler in community
Central equipment	Oil engine, fuel oil boiler
Capabilities	Reliable heat and power supply, onsite generation of fossil and renewable electricity, can supply buildings with high-temperature hot water
Applications	(Island) communities with at least medium heat density
Advantages	Cogeneration of power and heat at the community level, (n+1) redundancy for heating, no gas grid necessary, emergency power generation for mission-critical buildings
Disadvantages	No renewables

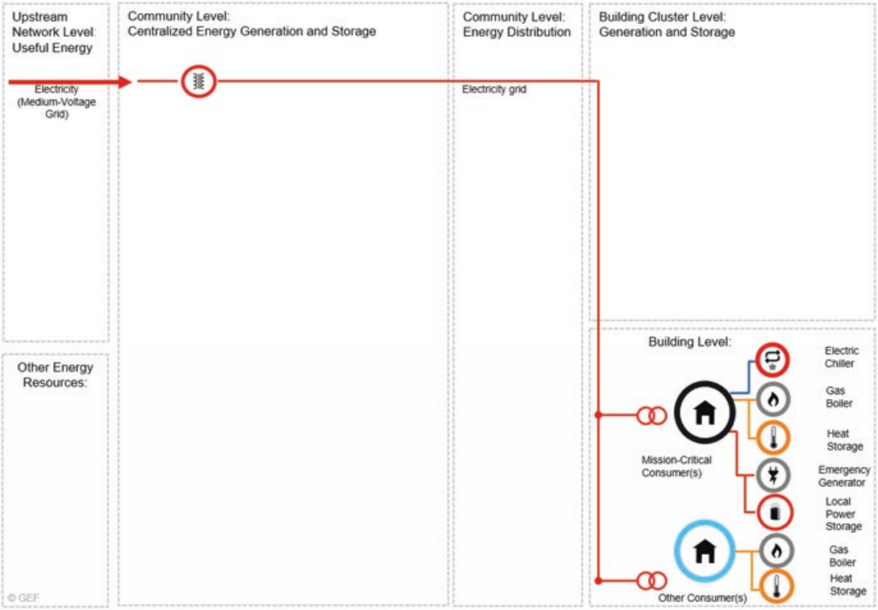


Solutions for generation within the community Nomenclature: 4.4.1.3 Example No. 3	Location of generation at… Community + build. cluster level	Buildings to be supplied from the outside with… Power + heating

Description	Island system without need for upstream supply grids oil CHP, oil boiler in community and building clusters
Central equipment	Oil engine, fuel oil boilers
Capabilities	Reliable heat and power supply, onsite generation of fossil and renewable electricity, can supply buildings with high-temperature hot water
Applications	(Island) communities with at least medium heat density
Advantages	No upstream power or gas grid necessary, cogeneration of power and heat,, improved resiliency for heat and power through CHP on community and on cluster level, emergency power generation for mission-critical buildings
Disadvantages	No renewables

E.6 Systems with Electrical Enhancements

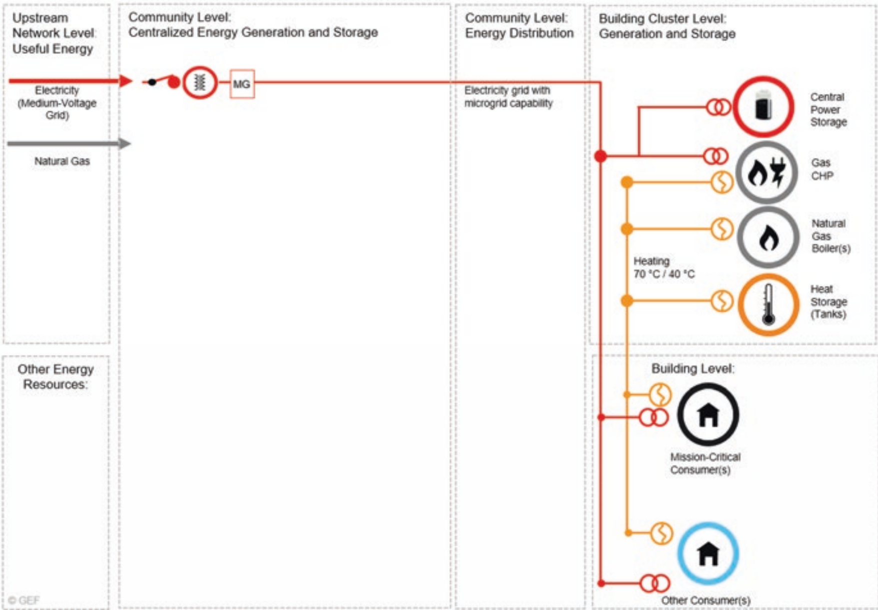
System Design Example No. 5.1.4.1



Solutions for generation within the community Nomenclature: 5.1.4.1 Example No. 1	Location of generation at… Building level	Buildings to be supplied from the outside with… Power

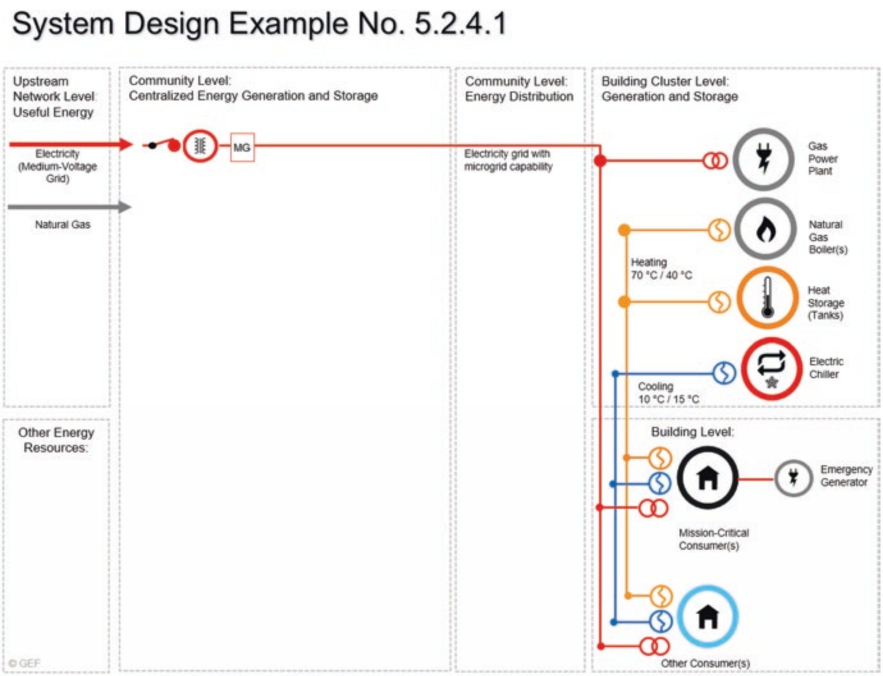
Description	Gas boiler and electric chillers and in individual buildings Critical buildings equipped with a local power storage in addition to emergency generator
Central equipment	Gas boiler, small electric chillers, power storage at building level
Capabilities	Reliable heat and cooling and supply, improved electrical resilience for critical buildings
Applications	Communities with low cool and heat density and need for resilient power supply in critical buildings
Advantages	Low-cost thermal equipment, low complexity, little maintenance, emergency power generation for mission-critical buildings and—depending on size of emergency equipment—also for electrically generated heat and cool in mission-critical buildings
Disadvantages	No renewables, no redundancy for heat and cooling, no onsite electricity generation for increased independence

System Design Example No. 5.2.1.1



Solutions for generation within the community Nomenclature: 5.2.1.1 Example No. 1	Location of generation at… Building cluster level	Buildings to be supplied from the outside with… Power + heating

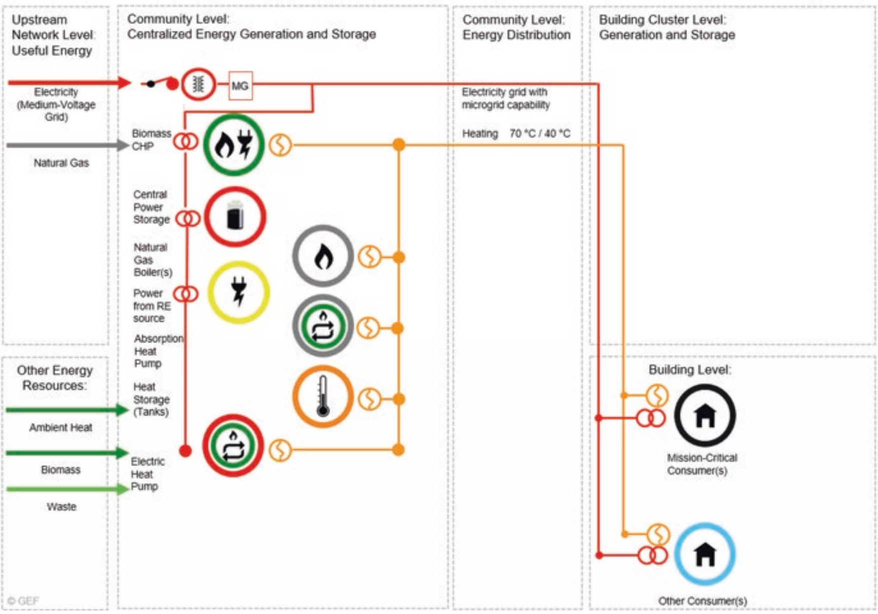
Description	Gas CHP, gas boiler, and power storage in building cluster microgrid at community level
Central equipment	Gas engine, gas boiler, power storage
Capabilities	Reliable heat supply, supply buildings with high-temperature hot water, onsite generation of electricity, improved electrical resilience for all buildings
Applications	Building clusters with at least medium heat density and need for resilient power supply when utility power is unavailable
Advantages	Cogeneration of power and heat at cluster level for improved resiliency for power (own generation) and heat (n+1), heat storage provides peak shaving for heat and additional resilience, low supply temperature would allow integration of many types of renewables, power supply via microgrid when utility power is unavailable, CHP power capacity and power storage at cluster level improves resiliency against grid failure further
Disadvantages	No renewables, gas grid necessary, additional complexity and cost for microgrid capability



Solutions for generation within the community Nomenclature: 5.2.4.1 Example No. 1	Location of generation at… Building cluster level	Buildings to be supplied from the outside with… Power + heating + cooling

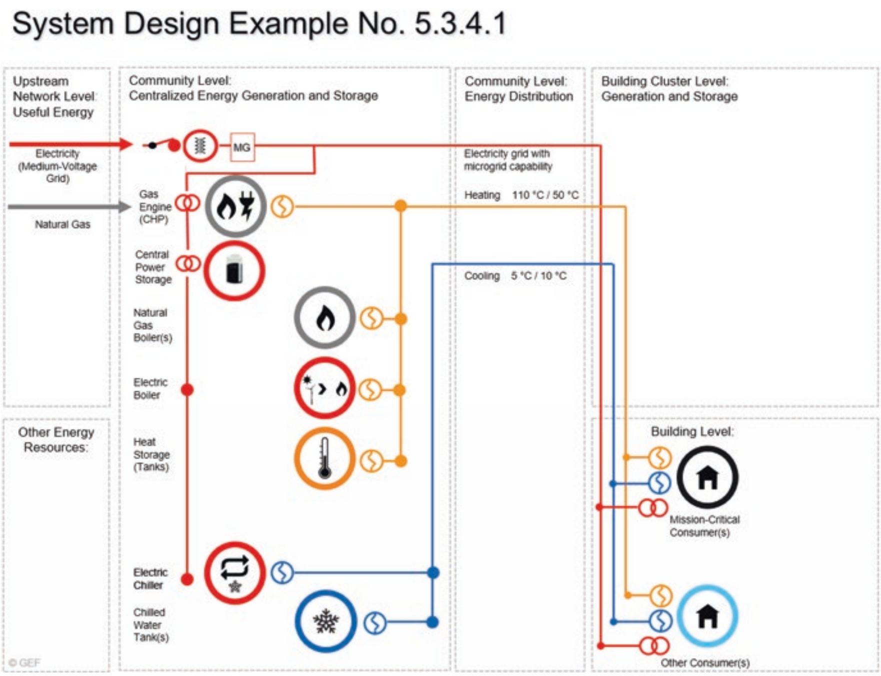
Description	Gas CHP plant, gas boiler and electric chiller in building cluster microgrid at community level
Central equipment	Gas CHP plant, gas boiler, and electric chiller
Capabilities	Reliable cooling and heat supply, can supply buildings with high-temperature hot water, onsite generation of electricity, improved electrical resilience for all buildings
Applications	Building clusters with at least medium heat density and need for resilient power supply when utility power is unavailable
Advantages	Generation of heat and power at the cluster level, (n+1) redundancy for heating and cooling at the cluster level, heat storage provides peak shaving for heat and additional resilience, low supply temperature would allow integration of many types of renewables, highly resilient power supply
Disadvantages	No renewables, gas grid necessary, additional complexity and cost for microgrid capability

System Design Example No. 5.3.1.1



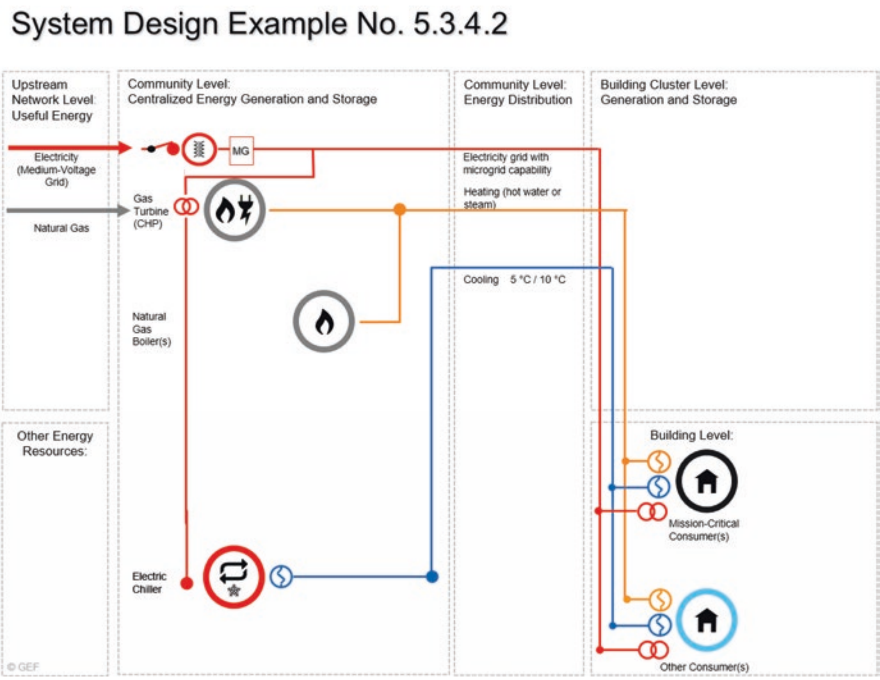
Solutions for generation within the community Nomenclature: 5.3.1.1 Example No. 1	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heating

Description	Biomass CHP, gas boilers, heat pump in community microgrid at community level, central power storage
Central equipment	Biomass CHP unit, heat pump (absorption + electric), renewable power generation, central power storage
Capabilities	Reliable heat supply, can supply buildings with high-temperature hot water, onsite generation of electricity, improved electrical resilience for all buildings
Applications	Communities with high and medium heat density and need for resilient power supply when utility power is unavailable
Advantages	Renewable energy, cogeneration of power and heat, low supply temperature allows integration of many types of renewables, (n+1) redundancy for heating, heat storage provides peak shaving and additional resilience, heat pumps can provide demand response to fluctuating renewable power generation, highly resilient power supply
Disadvantages	Gas grid necessary, high complexity, additional complexity and cost for microgrid capability



Solutions for generation within the community Nomenclature: 5.3.4.1 Example No. 1	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heating + cooling

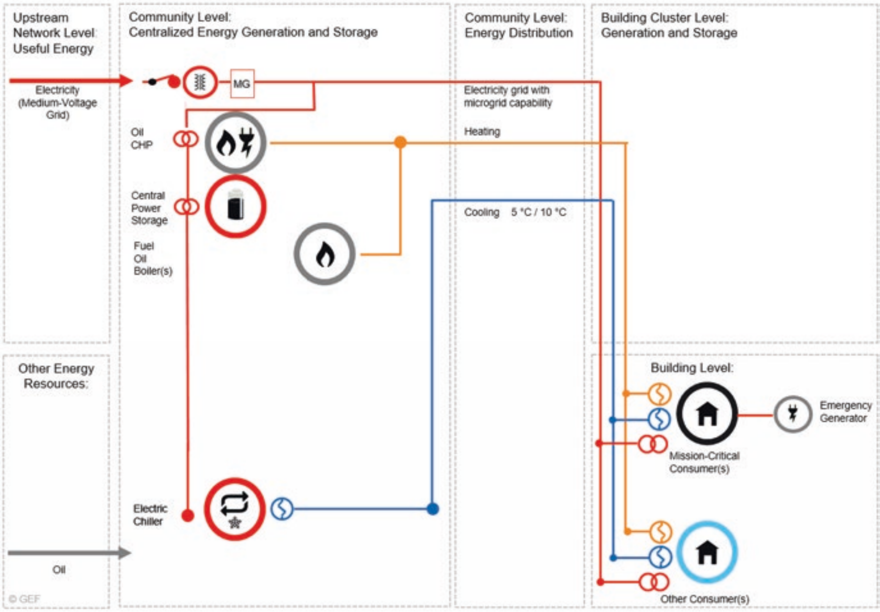
Description	Gas CHP, gas boilers, electric boilers in community microgrid at community level, central power storage
Central equipment	Gas CHP unit, boilers (gas + electric), storage (heat, cool, power), electric chillers
Capabilities	Reliable cooling and heat supply, can supply buildings with high-temperature hot water, onsite generation and storage of electricity, improved electrical resilience for all buildings
Applications	Communities with high and medium heat density and need for resilient power supply when utility power is unavailable
Advantages	Cogeneration of power and heat, (n+1) redundancy for heating and cooling, heat and cool storage provides peak shaving and additional resilience, electric boiler can provide demand response power (important with high shares of fluctuating renewables), highly resilient power supply
Disadvantages	Gas grid necessary, high complexity, additional complexity and cost for microgrid capability



Solutions for generation within the community Nomenclature: 5.3.4.2 Example No. 2	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heating + cooling

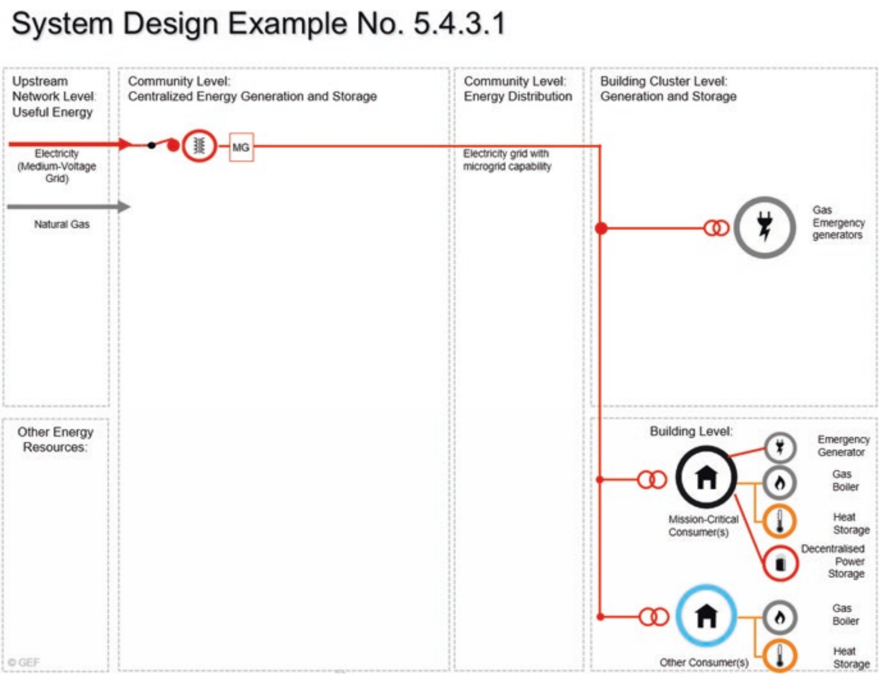
Description	Gas CHP, gas boiler, electric chiller in community microgrid at community level
Central equipment	Gas engine, gas boiler, and electric chiller
Capabilities	Reliable cooling and heat supply, can supply buildings with high-temperature hot water, onsite generation of electricity, improved electrical resilience for all buildings
Applications	Communities with at least medium cooling and heat density and need for resilient power supply when utility power is unavailable
Advantages	Low complexity, cogeneration of power and heat, (n+1) redundancy for heating and cooling, highly resilient power supply
Disadvantages	No renewables, gas grid necessary, additional complexity and cost for microgrid capability

System Design Example No. 5.3.4.3



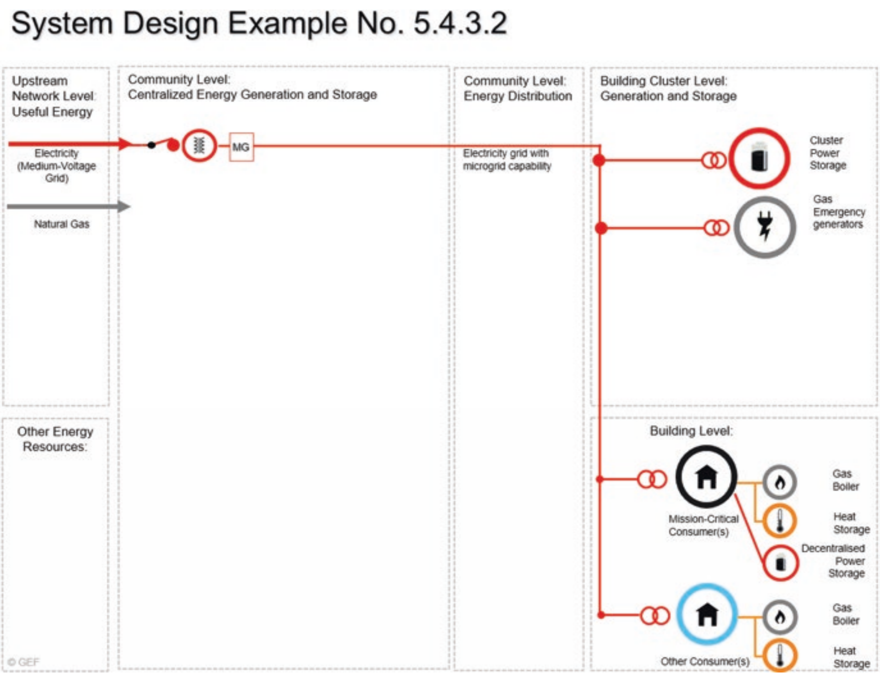
Solutions for generation within the community Nomenclature: 5.3.4.3 Example No. 3	Location of generation at… Community level	Buildings to be supplied from the outside with… Power + heating + cooling

Description	Oil CHP, light oil boiler, electric chiller in community microgrid at community level, central power storage
Central equipment	Oil CHP, light oil boiler, electric chiller, and central power storage
Capabilities	Reliable cooling and heat supply, can supply buildings with high-temperature hot water, onsite generation of electricity and storage, improved electrical resilience for all buildings
Applications	Communities with at least medium cooling and heat density and need for resilient power supply when utility power is unavailable
Advantages	Low complexity, cogeneration of power and heat, no gas grid necessary, (n+1) redundancy for heating and cooling, highly resilient power supply
Disadvantages	No renewables, additional complexity and cost for microgrid capability



Solutions for generation within the community Nomenclature: 5.4.3.1 Example No. 1	Location of generation at …. Building cluster + build. level	Buildings to be supplied from the outside with… Power

Description	Gas boiler and heat storage in individual buildings microgrid at community level, emergency generator at cluster level, local power storage for critical buildings
Central equipment	Gas boiler, heat storage, local power storage at building level, emergency generator at cluster level
Capabilities	Reliable cooling and heat supply, can supply buildings with high-temperature hot water, onsite generation of electricity, improved electrical resilience for all buildings and even more so for critical buildings
Applications	Communities with low cool and heat density and need for resilient power supply when utility power is unavailable
Advantages	Low-cost thermal equipment, low complexity, little maintenance, emergency power for all buildings and more so for critical buildings
Disadvantages	No renewables, no redundancy for heat, only emergency onsite electricity generation, additional complexity and cost for microgrid capability



Solutions for generation within the community Nomenclature: 5.4.3.2 Example No. 2	Location of generation at… Building cluster level	Buildings to be supplied from the outside with… Power

Description	Gas boiler and heat storage in individual buildings, microgrid at community level, emergency generator and storage at cluster level, local power storage for critical buildings
Central equipment	Gas boiler, heat storage, local power storage at building level, emergency generator and storage at cluster level
Capabilities	Reliable cooling and heat supply, can supply buildings with high-temperature hot water, onsite generation and storage of electricity, improved electrical resilience for all buildings and even more so for critical buildings
Applications	Communities with low cool and heat density and need for resilient power supply when utility power is unavailable
Advantages	Low-cost thermal equipment, low complexity, little maintenance, emergency power generation for mission-critical buildings and—depending on size of emergency equipment—also for electrically generated heat and cool in mission-critical buildings
Disadvantages	No renewables, no redundancy for heat and cooling, only emergency onsite electricity generation, additional complexity and cost for microgrid capability

Appendix F. Technologies Database

F.1 Electrical System

F.1.1 CHP and Condensing Power Plants

CHP plants are considered to be very important since, as cogeneration facilities, they are highly efficient at generating both heat and power.

All power plants generate heat, which either is lost when it is expelled at low temperatures in cooling towers or in seawater, or which can be recovered for use in heating or other processes. This appendix describes all the various types of cogeneration CHP power plants in this category. To analyze the cost of generating heat from power plants, it is important to compare technologies that generate power only to CHPs, for each fuel. The advantage of recovering and using this otherwise wasted energy from an engine that generates waste heat at a useful temperature for heating is that this "found" heat is cost free.

Similarly, the fuel cost of extracting heat from an extraction plant is equal to the cost of the lost electricity when the plant is on operation; this cost depends on both temperatures, boiler load, and heat load. In CHP plants that can only generate heat and power in a fixed ratio like an engine or a back-pressure plant, the cost of heat is equal to the total fuel costs minus the value of the generated electricity.

In general, it is necessary to simulate the energy system, e.g., with EnergyPro based on load and electricity price profiles, to analyze the optimal mode of operation, the cost of generating one more MWh heat, or the cost of generating one more MWh electricity (Fig. F.1).

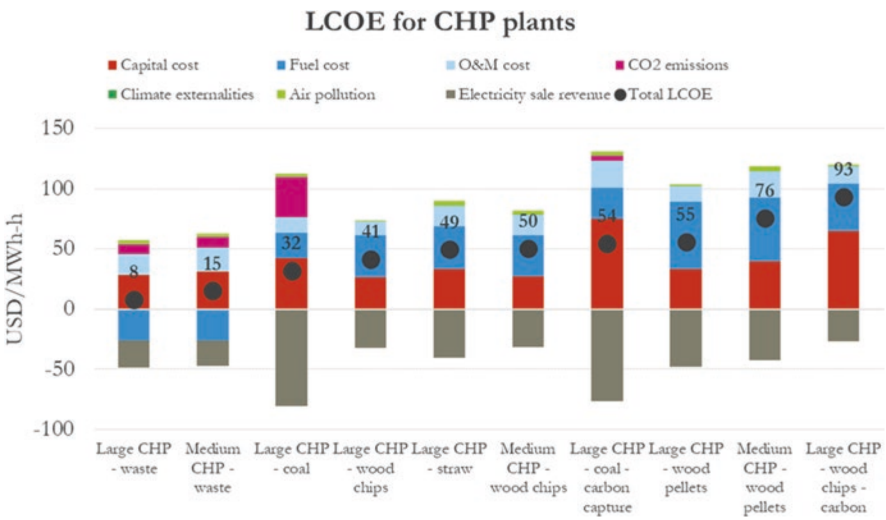


Fig. F.1 LCOE for CHP plants, gas engine

Therefore, the description of power plants in this category will be simplified by assuming that electricity, which is generated in combined production with one fuel (e.g., gas), would otherwise be generated with the best available technology at a power-only plant. The advanced integration of CHP plants into the energy system will be analyzed in the discussion of energy systems (in Sect. F.2).

A gas engine used in the cogeneration of heat and power drives an electricity generator for the power production. Such systems can achieve an electrical efficiency of up to 45–48%. The engine coolant (engine cooling, lube oil, and turbocharger intercooling) and the hot exhaust gas can be used for heat generation, e.g., for district heating or low-pressure steam.

In district heating systems with low return temperatures, both sensible and latent heat in the exhaust gas can be recovered by using a condensing cooler as the final cooling of the flue gases; such systems can achieve a total efficiency of approx. 96–98%. If heat pumps are applied for extra cooling of the exhaust gas system, the system can achieve another 5–7% higher efficiency. The flue gas heat pumps can be electrical or absorption type.

Two combustion concepts are available for spark ignition engines, lean-burn and stoichiometric combustion engines. Lean-burn engines have a high air/fuel ratio. This reduces the combustion temperature and hence the NOx emission. The engines can be equipped with oxidation catalysts for CO reduction.

In stoichiometric combustion engines, the amount of air is (theoretically) just sufficient to achieve complete combustion. For this technology, the NOx emission must be reduced in a three-way catalyst. These engines are usually in the lowest power range (<150 kWe).

A pre-chamber lean-burn combustion system is a common technology for engines with a bore size typically larger than 200 mm. This technology helps to maximize electrical efficiency and increases combustion stability along with low NOx emissions.

Another ignition technology used in dual-fuel engines combines dual-fuel engine (diesel-gas) with pilot oil injection in a gas engine that, instead of using spark plugs, uses a small amount of light oil (1–6%) to ignite the air-gas mix by compression (as in a diesel engine). Dual-fuel engines can often operate on diesel oil alone as well as on gas with pilot oil for ignition (Table F.1).

Table F.2 lists nominal investment by capacity for a spark ignition engine using biogas or natural gas; Fig. F.2 shows nominal investment by capacity for a spark ignition engine using natural gas; and Fig. F.3 shows nominal investment by capacity for a spark ignition engine using biogas (Tables F.3 and F.4).

F.1.1.1 Gas Turbine Combined Cycle

Main components of combined cycle gas turbine (CC-GT) plants include a gas turbine, a steam turbine, a gear (if needed), a generator, and a heat recovery steam generator (HRSG)/flue gas heat exchanger.

The gas turbine and the steam turbine may drive a shared generator. In practice, the two turbines might drive separate generators. Although the single-shaft

Table F.1 Technical and economic assumptions for spark ignition engines and micro-gas turbines

Technology		Spark ignition engine (natural gas)	Spark ignition engine (biogas)	Micro-gas turbine
	Unit			
Energy/technical data				
Generation capacity for one unit	MW	5	5	0.1
Electricity efficiency (condensation mode for extraction plants), net	%	47	43	27
Electricity efficiency, (condensation mode for extraction plants), net, annual average	%	45	41	27
C_b coefficient (50 °C/100 °C)		0.95	0.86	0.66
C_v coefficient (50 °C/100 °C)		–	–	–
Forced outage	%	3	3	5
Planned outage	Weeks per year	0.8	1	2
Technical lifetime	Years	25	25	15
Construction time	Years	1	1	0.5
Space requirement	1000 m^2/MW_{th} heat output	0.04	0.04	0.04
Plant dynamic capabilities				
Primary regulation	% per 30 s	30	30	30
Secondary regulation	% per minute	30	30	30
Minimum load	% of full load	50	50	50
Warm startup time	Hours	0.05	0.05	0.05
Cold startup time	Hours	0.3	0.3	0.3
Environmental data				
SO_2	Degree of desulphurization %	0	0	0
NO_x	g per GJ fuel	60	100	100
CH_4	g per GJ fuel	315	300	300
N_2O	g per GJ fuel	0.6	1	1
Financial data (USD)				
Nominal investment	MUSD (million US dollar) per MW	1.15	1.15	3.24
—of which equipment	%	0.64	0.64	1.8
—of which installation	%	0.51	0.51	1.44
Fixed O&M	USD/MW/year	10920	10920	-
Variable O&M	USD/MWh	6.05	8.4	12

Table F.2 Nominal investment by capacity for a spark ignition engine using biogas or natural gas

Technology	Unit	Spark ignition engine								
Rated power	MWh	1	2	3	4	5	10	15	20	25
Nominal investment	MUSD/MWh	3.55	2.18	1.64	1.34	1.15	0.71	0.53	0.44	0.37
—of which equipment	MUSD/MWh	1.97	1.21	0.91	0.75	0.64	0.39	0.30	0.24	0.21
—of which installation	MUSD/MWh	1.58	0.97	0.73	0.60	0.51	0.31	0.24	0.19	0.17

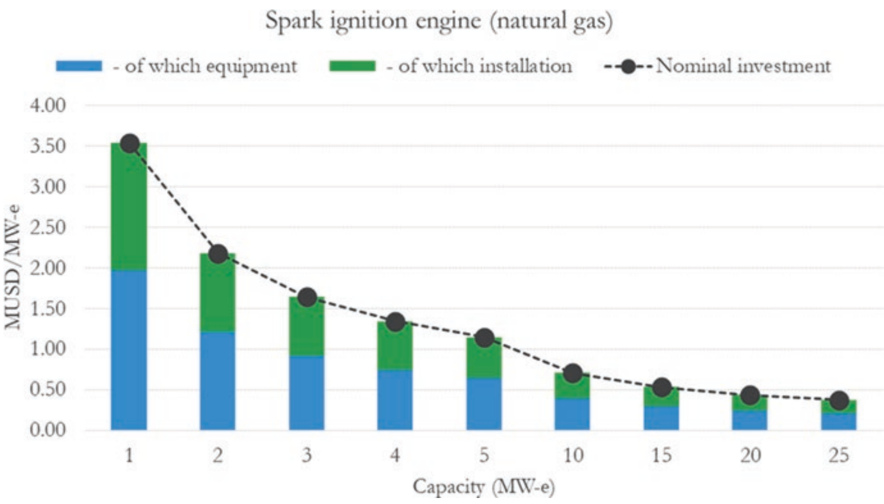


Fig. F.2 Nominal investment by capacity for a spark ignition engine using natural gas

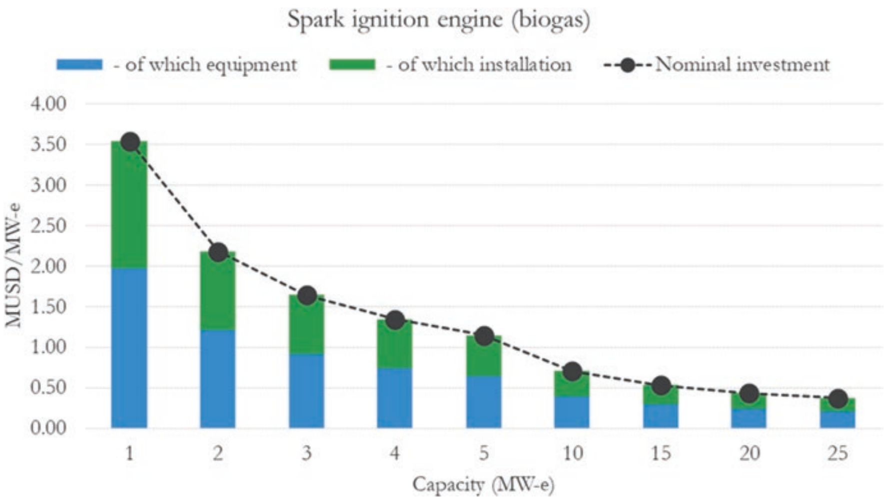


Fig. F.3 Nominal investment by capacity for a spark ignition engine using biogas

configuration contributes higher reliability, the multi-shaft configuration has a slightly better overall performance.

The condenser is cooled by the return water from the district heating network. Since this water is afterward heated by the flue gas from the gas turbine, the condensation temperature can be fairly low.

Although overall energy efficiency depends on the flue gas stack temperature, electricity efficiency depends on the district heating flow temperature (and on the equipment technical characteristics and on ambient conditions). Plants that do not

Table F.3 Microturbine performance characteristics and capital and O&M costs

Technology		Micro-gas turbine[a]				
System		1	2	3	4	5
	Unit					
Performance characteristics						
Rated power	kW	65	200	250	333	1000
Parasitic load for gas compressor	kW	4	10	8	10	50
Net electric power	kW	61	190	242	323	950
Fuel input	MMBtu/hr, HHV	0.84	2.29	3.16	3.85	11.43
Useful thermal	MMBtu/hr	0.39	0.87	1.20	1.60	4.18
Power to heat ratio		0.53	0.75	0.69	0.69	0.77
Electric efficiency	%, HHV	24.7	28.4	26.1	28.7	28.3
Thermal efficiency	%, HHV	46.9	38.0	38.0	41.6	36.6
Overall efficiency	%, HHV	71.6	66.3	64.0	70.2	64.9
Capital and O&M costs						
Net electric power	kW	61	190	242	323	950
Complete microturbine package	$/kW	2120	2120	1830	1750	1710
Construction and installation	$/kW	1100	1030	870	800	790
Installed cost	$/kW	3220	3150	2700	2560	2500

[a]Note: Performance characteristics are average values and are not intended to represent a specific product. Performance characteristics summarize technical performance characteristics for microturbine CHP systems ranging in size from 65 to 1000 kW. The values in the table are based on systems connected to low-pressure (<5 psig) natural gas. Microturbines typically require an inlet fuel. Costs are average values and are not intended to represent a specific product. Available microturbines offer basic interconnection and paralleling

Table F.4 Reciprocating engine performance characteristics and capital and O&M costs

Technology		Reciprocating engine[a]				
System		1	2	3	4	5
	Unit					
Performance characteristics						
Net electric power	kW	100	633	1141	3325	9341
Fuel input	MMBtu/hr, HHV	1.15	6.26	10.37	27.73	76.06
Useful thermal	MMBtu/hr	0.61	2.84	4.46	10.69	26.60
Power to heat ratio		0.56	0.76	0.87	1.06	1.20
Electric efficiency	%, HHV	29.6%	34.5%	37.6%	40.9%	41.9%
Thermal efficiency	%, HHV	53.2%	45.3%	43.0%	38.6%	35.0%
Overall efficiency	%, HHV	82.8%	79.8%	80.6%	79.5%	76.9%
Capital and O&M costs						
Net electric power (kW)	kW	100	633	1141	3325	9341
Engine type		Rich burn	Lean-burn	Lean-burn	Lean-burn	Lean-burn
Engine and generator, including heat recovery and emission control	$/kW	1650	1650	1380	1080	900
Construction and Installation	$/kW	1250	1190	990	720	530
Total installed cost	$/kW	2900	2840	2370	1800	1430
Total O&M cost	¢/kWh	2.4	2.1	1.9	1.6	0.9

[a]Note: Costs are average values and are not intended to represent a specific product

have the option to sell district heating may cool the condenser using sea/river/lake water or a cooling tower.

With the application of heat pumps for extra cooling of the exhaust gas, the system can reach even higher total fuel efficiency. Depending on priorities, the flue gas heat pumps can be electrical or absorption type.

The HRSG is defined by its number of pressure levels, each of which produces steam for the steam turbine. Small-, medium-, and large-scale units usually have one or two steam pressure stages, whereas very large units may have three steam pressure stages. Steam is fed to the turbine both at the inlet and at a later stage between the two adjacent steam turbine sections; this is one of the special features of steam turbines in CC-GT.

Plants that can shift between condensation mode (power only) and back-pressure mode (power and district heat) include a so-called extraction steam turbine. Such turbines are not available in small sizes, and dual-mode plants are therefore only feasible in the large scale.

The power generated by the gas turbine is typically two to three times the power generated by the steam turbine. An extraction steam turbine shifting from full condensation mode at sea temperature to full back-pressure mode at district heat return temperature will typically lose about 10% of its electricity generation capacity. For example, a 40 MW gas turbine combined with a 20 MW steam turbine (condensation mode) loses 2 MW or 3% of the total generating capacity (60 MW). Table F.5 summarizes the technical and economic assumptions for a gas turbine. Table F.6 lists and Fig. F.4 shows nominal investment for gas turbine (combined cycle, extraction plant); Table F.7 lists and Fig. F.5 shows nominal investment for gas turbine (combined cycle, back-pressure).

Gas Turbine Simple Cycle

The major components of a simple cycle (or open cycle) gas turbine power unit are a gas turbine, a gear (when needed), and a generator. For cogeneration (combined heat and power production), a flue gas heat exchanger (hot water or steam) is also installed.

If applying heat pumps for extra cooling of the exhaust gas, even higher total fuel efficiency can be reached. Depending on priorities, the flue gas heat pumps can be electrical or absorption type.

Simple cycle gas turbines can be used for preheating the feed water of steam power plants. There are in general two types of gas turbines:

1. Industrial turbines (also called heavy duty)
2. Aeroderivative turbine

Industrial gas turbines differ from aeroderivative turbines in the way that the frames, bearings, and blading are of heavier construction. Additionally, industrial gas turbines have longer intervals between services compared to the aeroderivatives.

Aeroderivative turbines benefit from higher efficiency than industrial ones, and the most service demanding module of the aeroderivative gas turbine can normally be replaced in a couple of days, thus keeping a high availability.

Table F.5 Technical and economic assumptions for a gas turbine (combined cycle, extraction, and back-pressure)

Technology	Unit	Gas turbine (combined cycle, extraction plant)	Gas turbine (combined cycle, back-pressure)
Energy/technical data			
Generation capacity for one unit	MW	300	300
Electricity efficiency (condensation mode for extraction plants), net	%	59	51
Electricity efficiency, (condensation mode for extraction plants), net, annual average	%	56	48
C_b coefficient (50 °C/100 °C)		1.8	1.3
C_v coefficient (50 °C/100 °C)		0.15	–
Forced outage	%	3	3
Planned outage	Weeks per year	2.3	2.3
Technical lifetime	Years	25	25
Construction time	Years	2.5	2
Space requirement	1000 m^2/MW_{th} heat output	0.02	0.025
Plant dynamic Capabilities			
Primary regulation	% per 30 s	–	–
Secondary regulation	% per minute	15	15
Minimum load	% of full load	40	40
Warm startup time	Hours	1	1
Cold startup time	Hours	2.5	2.5
Environmental data			
SO_2	Degree of desulphurization %	0	0
NO_x	g per GJ fuel	15	15
CH_4	g per GJ fuel	1.5	1.5
N_2O	g per GJ fuel	1	1
Financial data (USD)			
Nominal investment	MUSD per MW	1.03	1.52
—of which equipment	%	0.76	1.12
—of which installation	%	0.27	0.40
Fixed O&M	USD/MW/year	32,816	32,816
Variable O&M	USD/MWh	4.93	4.93

Table F.6 Nominal investment for gas turbine (combined cycle, extraction plant)

Technology	Unit	Gas turbine (combined cycle, extraction plant)								
Electric capacity	MW_e	100	150	200	250	300	350	400	450	500
Nominal investment	$MUSD/MW_e$	2.22	1.67	1.37	1.17	1.03	0.93	0.84	0.78	0.72
—of which equipment	$MUSD/MW_e$	1.64	1.24	1.01	0.87	0.76	0.68	0.62	0.57	0.53
—of which installation	$MUSD/MW_e$	0.58	0.44	0.36	0.31	0.27	0.24	0.22	0.20	0.19

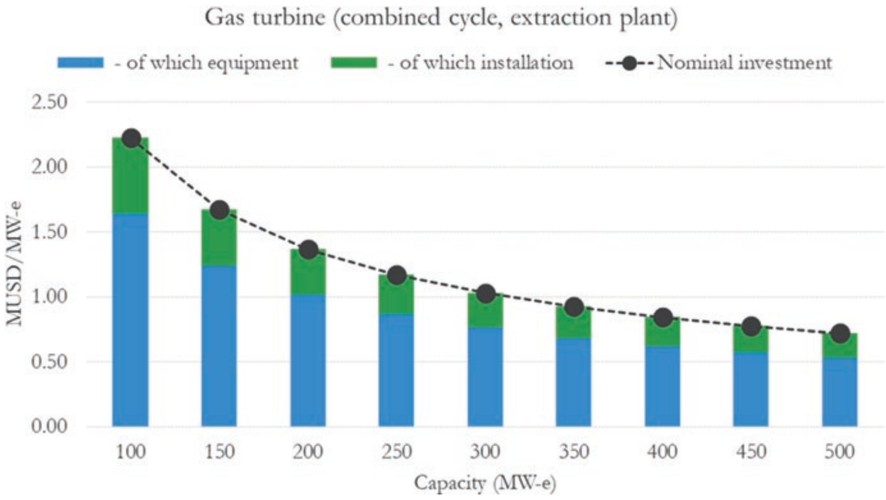


Fig. F.4 Nominal investment for gas turbine (combined cycle, extraction plant)

Table F.7 Nominal investment for gas turbine (combined cycle, back-pressure)

Technology	Unit	Gas turbine (combined cycle, back-pressure)								
Electric capacity	MW_e	100	150	200	250	300	350	400	450	500
Nominal investment	$MUSD/MW_e$	3.29	2.47	2.02	1.73	1.52	1.37	1.25	1.15	1.07
—of which equipment	$MUSD/MW_e$	2.42	1.82	1.49	1.27	1.12	1.01	0.92	0.84	0.78
—of which installation	$MUSD/MW_e$	0.87	0.66	0.54	0.46	0.40	0.36	0.33	0.30	0.28

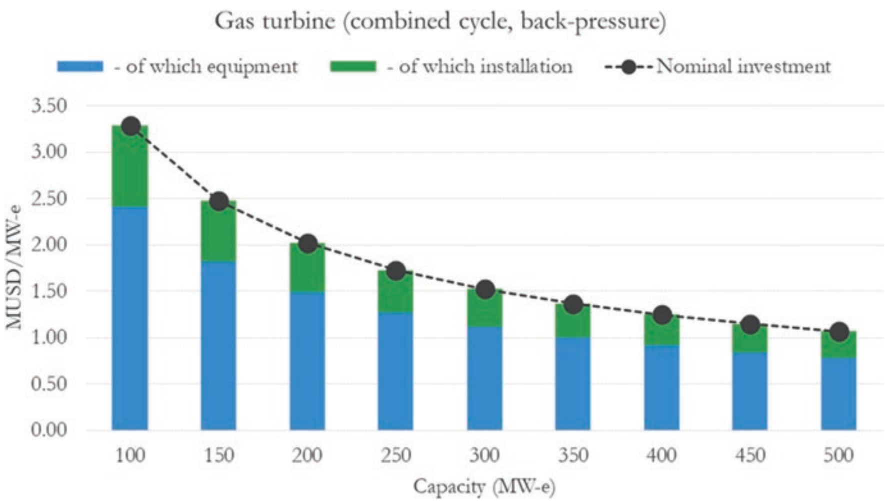


Fig. F.5 Nominal investment for gas turbine (combined cycle, back-pressure)

Gas turbines can be equipped with compressor intercoolers where the compressed air is cooled to reduce the power needed for compression. The use of integrated recuperators (preheating of the combustion air) to increase efficiency can also be made by using air/air heat exchangers—at the expense of an increased exhaust pressure loss. Gas turbine plants can have direct steam injection in the burner to increase power output through expansion in the turbine section (Cheng Cycle).

Small (radial) gas turbines below 100 kW_e are now on the market, the so-called microturbines. These are often equipped with preheating of combustion air based on heat from gas turbine exhaust (integrated recuperator) to achieve reasonable electrical efficiency (25–30%).

Table F.8 lists the technical and economic assumptions for a simple cycle gas turbine. Table F.9 lists (and Fig. F.6 shows) the nominal investment for a simple cycle gas turbine (large back-pressure). Table F.10 lists (and Fig. F.7 shows) the nominal investment for a simple cycle gas turbine (small and medium back-pressure). Table F.11 shows gas turbine performance characteristics and capital and O&M costs.

F.1.1.2 Biomass CHP

Energy conversion in CHP or heating-only plant (HOP) of biomass is the combustion of woodchips from forestry and/or from wood industry, wood pellets, or straw. The main technical differences between the two are the electricity production, which is produced in a CHP but not a HOP, and the resulting necessary operating temperatures. Figure F.8 shows an example of one such facility, the Avedøre power plant.

CHP production from biomass has been used in an increasing scale for many years in Denmark using different technologies. The typical implementation is combustion in a biomass boiler feeding a steam turbine. The energy output from the boiler is either hot water to be used directly for district heating or it could be (high-pressure) steam to be expanded through a turbine.

Application of flue gas condensation for further energy generation is customary at biomass fired boilers, except at small plants below 1–2 MW_{th} input due to the additional capital and O&M costs. Plants without flue gas condensation should only use fuels with less than 30% moisture content.

Table F.8 Technical and economic assumptions for a simple cycle gas turbine

Technology	Unit	Gas turbine (simple cycle, large, back-pressure)	Gas turbine (simple cycle, small and medium, back-pressure)
Energy/technical data			
Generation capacity for one unit	MW	80	25
Electricity efficiency (condensation mode for extraction plants), net	%	42	37
Electricity efficiency, (condensation mode for extraction plants), net, annual average	%	40	35
C_b coefficient (50 °C/100 °C)		0.96	0.73
C_v coefficient (50 °C/100 °C)		-	-
Forced outage	%	2	2
Planned outage	Weeks per year	3	2.8
Technical lifetime	years	25	25
Construction time	years	1.5	1.5
Space requirement	1000 m^2/MW_{th} heat output	0.02	0.04
Plant dynamic capabilities			
Primary regulation	% per 30 s	0	0
Secondary regulation	% per minute	20	20
Minimum load	% of full load	23	23
Warm startup time	Hours	0.23	0.23
Cold startup time	Hours	0.5	0.5
Environmental data			
SO_2	Degree of desulphurization %	0	0
NO_x	g per GJ fuel	15	15
CH_4	g per GJ fuel	1.5	1.5
N_2O	g per GJ fuel	1	1
"			
Nominal investment	MUSD per MW	0.66	0.82
—of which equipment	%	0.50	0.61
—of which installation	%	0.20	0.25
Fixed O&M	USD/MW/year	21840	21840
Variable O&M	USD/MWh	4.93	6.05

Table F.9 Nominal investment for a simple cycle gas turbine (large back-pressure)

Technology	Unit	Gas turbine (simple cycle, large, back-pressure)						
Electric capacity	MW_e	40	55	70	85	100	115	130
Nominal investment	$MUSD/MW_e$	1.13	0.90	0.76	0.67	0.59	0.54	0.49
—of which equipment	$MUSD/MW_e$	0.81	0.64	0.54	0.48	0.42	0.38	0.35
—of which installation	$MUSD/MW_e$	0.32	0.26	0.22	0.19	0.17	0.15	0.14

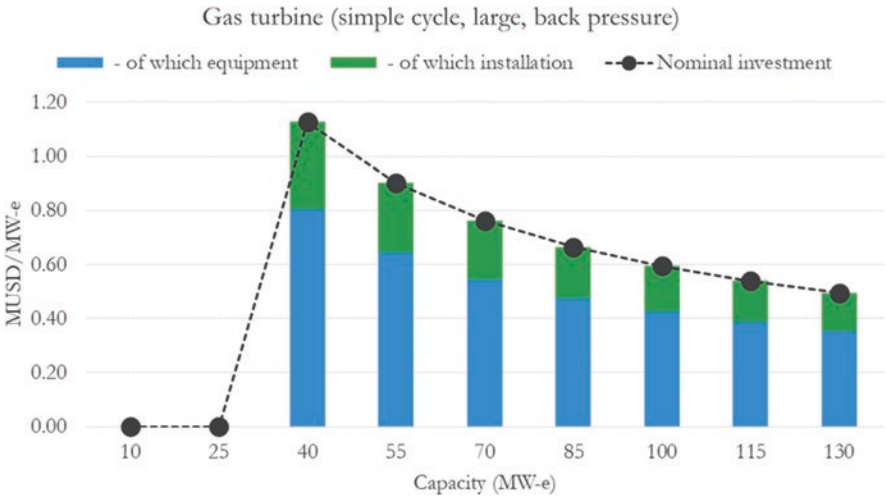


Fig. F.6 Nominal investment for a simple cycle gas turbine (large back-pressure)

Table F.10 Nominal investment for a simple cycle gas turbine (small and medium back-pressure)

Technology	Unit	Gas turbine (simple cycle, small and medium, back-pressure)		
Electric capacity	MW_e	10	25	40
Nominal investment	$MUSD/MW_e$	1.63	0.86	0.62
—of which equipment	$MUSD/MW_e$	1.16	0.61	0.44
—of which installation	$MUSD/MW_e$	0.47	0.25	0.18

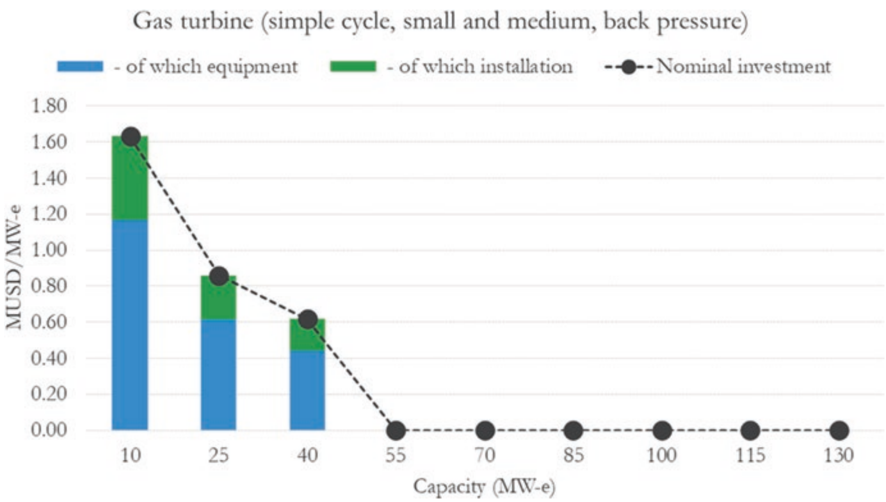


Fig. F.7 Nominal investment for a simple cycle gas turbine (small and medium back-pressure)

Table F.11 Gas turbine performance characteristics and capital and O&M costs

Technology		Gas turbine[a]					
System	Unit	1	2	3	4	5	6
Performance characteristics							
Nominal electric power	kW	3515	4600	7965	11,350	21,745	43,069
Net electric power	kW	3304	4324	7487	10,669	20,440	40,485
Fuel input	MMBtu/hr, HHV	47.5	59.1	87.6	130.0	210.8	389.0
Useful thermal	MMBtu/hr	19.6	25.2	36.3	52.2	77.4	133.8
Power to heat ratio		0.58	0.58	0.70	0.70	0.90	1.03
Electric efficiency	%, HHV	23.7	25.0	29.2	28.0	33.1	35.5
Thermal efficiency	%, HHV	41.1	42.7	41.4	40.2	36.7	34.4
Overall efficiency	%, HHV	64.9	67.6	70.6	68.2	69.8	69.9
Capital and O&M costs							
Net electric power	kW	3304	4324	7487	10,669	20,440	40,485
Combustion turbine	$/kW	908	860	683	619	563	477
Emission control	$/kW	208	174	126	92	74	65
Balance of plant	$/kW	899	712	455	389	276	231
Construction and Installation	$/kW	1305	1072	753	698	562	503
Total installed cost	$/kW	3320	2817	2017	1798	1474	1276
Total O&M cost	¢/kWh	1.3	1.3	1.2	1.2	0.9	0.9

[a]Special site requirements, emissions control requirements, and prevailing labor rates. The table shows estimated capital costs for six representative gas turbine CHP systems used in typical applications. As indicated, there are economies of scale, with installed costs declining from $3320/kW for a 3.3 MW system to $1276/kW for a 40 MW system. Routine maintenance practices include online running maintenance, predictive maintenance, plotting trends, performance testing, vibration analysis, and preventive maintenance procedures. Typically, routine inspections are required every 4000 h to ensure that the turbine is free of excessive vibration. Costs are average values and are not intended to represent a specific product

Fig. F.8 Avedøre power plant

F.1.1.3 Wood Chips CHP (Tables F.12, F.13, F.14, and F.15 and Figs. F.9, F.10, and F.11)

Table F.12 Technical and economic assumptions for a wood-chip CHP

Technology	Unit	Large wood chips CHP (600 MW feed, back-pressure)	Medium wood chips CHP (80 MW feed, back-pressure)	Small wood chips CHP (ORC, 20 MW feed, back-pressure)
Energy/technical data				
Generation capacity for one unit	MW_e	176.9	23.1	2.9
Electricity efficiency, net, name plate	%	29.5	28.9	14.3
Electricity efficiency, net, annual average	%	28	27.4	13.5
Heat efficiency, net, name plate	%	82.2	82.1	97.3
Heat efficiency, net, annual average	%	83.6	83.5	98.1
Additional heat potential with heat pumps	% of thermal input	1.9	2	2
C_b coefficient (40 °C/80 °C)		0.36	0.35	0.15
C_v coefficient (40 °C/80 °C)		1	1	1
Forced outage	%	3	3	3
Planned outage	Weeks per year	3	3	3
Technical lifetime	Years	25	25	25
Construction time	Years	5	2.5	1
Space requirement	1000 m^2/MW_e	0.08	0.2	0.7
Plant dynamic capabilities				
Primary regulation	% per 30 s	2	NA	NA
Secondary regulation	% per minute	4	4	10
Minimum load	% of full load	45	20	20
Warm startup time	Hours	2	2	0.25
Cold startup time	Hours	12	8	0.5
Environmental data				
SO_2	Degree of desulphurization %	98	98	98
NO_x	g per GJ fuel	24	72	63
CH_4	g per GJ fuel	2	2	11
N_2O	g per GJ fuel	8	1	1
Particles	g per GJ fuel	0.3	0.3	0.3
Financial data (USD)				
Nominal investment	MUSD per MW	4.08	4.30	7.84

(continued)

Table F.12 (continued)

Technology	Unit	Large wood chips CHP (600 MW feed, back-pressure)	Medium wood chips CHP (80 MW feed, back-pressure)	Small wood chips CHP (ORC, 20 MW feed, back-pressure)
—of which equipment	%	2.46	2.69	4.48
—of which installation	%	1.61	1.61	3.36
Fixed O&M	USD/MW/year	109,312	172,032	323,568
Variable O&M	USD/MWh	4.26	4.26	8.74
Technology-specific data				
Steam reheat		None	None	None
Flue gas condensation		Yes	Yes	Yes
Combustion air humidification		Yes	Yes	Yes
Nominal investment	MUSD/MW fuel input	1.12	1.19	1.04
—of which equipment		0.73	0.80	0.65
—of which installation		0.39	0.39	0.39
Fixed O&M	USD/MW input/year	32,256	49,693	46,144
Variable O&M	USD/MWh input	1.23	1.23	1.23
Fuel storage-specific cost in excess of 2 days	MUSD/MW input/storage day	0.01	0.015	0.02

Table F.13 Nominal investment for a large wood chips CHP (600 MW feed, back-pressure)

Technology	Unit	Large wood chips CHP (600 MW feed, back-pressure)		
Electric capacity	MW_e	150	200	250
Nominal investment	$MUSD/MW_e$	4.58	3.74	3.20
—of which equipment	$MUSD/MW_e$	2.77	2.26	1.93
—of which installation	$MUSD/MW_e$	1.81	1.48	1.27

Table F.14 Nominal investment for a medium wood chips CHP (80 MW feed, back-pressure)

Technology	Unit	Medium wood chips CHP (80 MW feed, back-pressure)		
Electric capacity	MW_e	15	20	25
Nominal investment	$MUSD/MW_e$	5.82	4.76	4.07
—of which equipment	$MUSD/MW_e$	3.64	2.97	2.54
—of which installation	$MUSD/MW_e$	2.18	1.78	1.53

Table F.15 Nominal investment for a small wood chips CHP (20 MW feed, back-pressure)

Technology	Unit	Small wood chips CHP (ORC, 20 MW feed, back-pressure)		
Electric capacity	MW_e	5	7.5	10
Nominal investment	$MUSD/MW_e$	5.35	4.03	3.30
—of which equipment	$MUSD/MW_e$	3.06	2.30	1.88
—of which installation	$MUSD/MW_e$	2.29	1.73	1.41

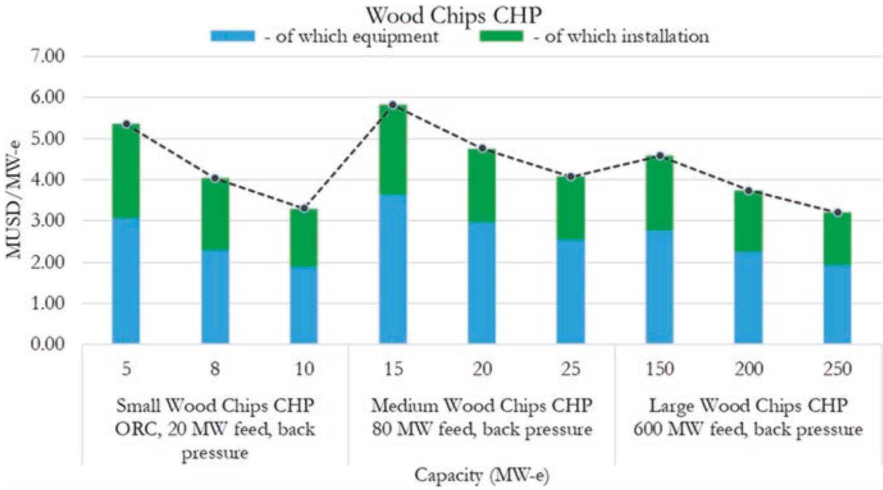


Fig. F.9 Nominal investment for a wood chips CHP (20, 80, 600 MW feed, back-pressure)

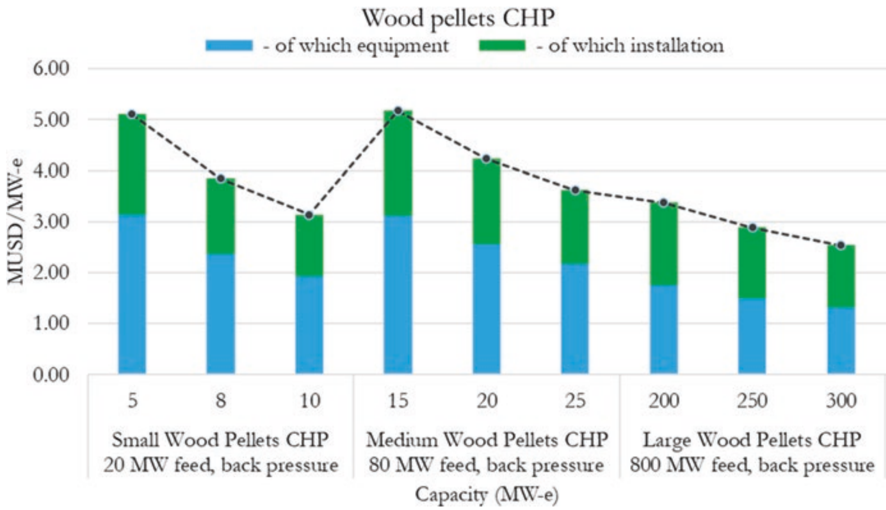


Fig. F.10 Nominal investment for wood pellets CHP (20, 80, 800 MW feed, back-pressure)

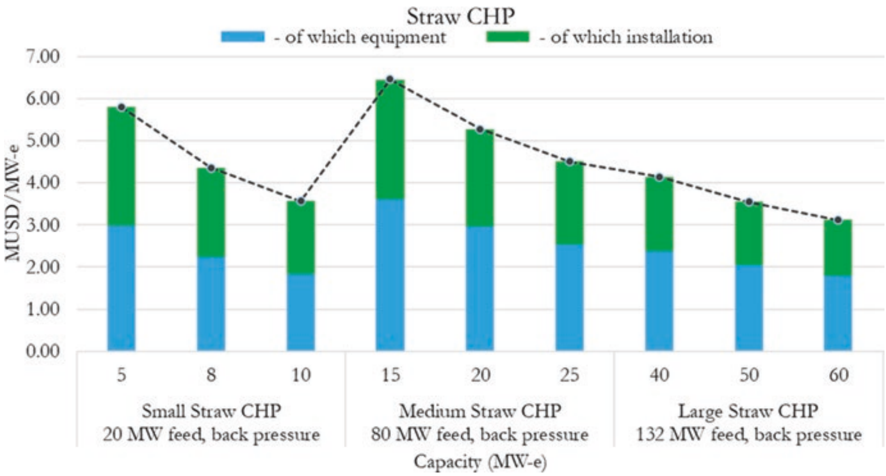


Fig. F.11 Nominal investment for straw CHP (20, 80, 132 MW feed, back-pressure)

F.1.1.4 Wood Pellets CHP (Tables F.16, F.17, F.18, and F.19)

Table F.16 Technical and economic assumptions for a large wood pellet CHP (back-pressure)

Technology	Unit	Large wood pellets CHP, 800 MW feed, back-pressure	Medium wood pellets CHP, 80 MW feed, back-pressure	Small wood pellets CHP, 20 MW feed, back-pressure
Energy/technical data				
Generation capacity for one unit	MW	261.2	24.1	3
Electricity efficiency, net, name plate	%	32.6	30.2	15.1
Electricity efficiency, net, annual average	%	31	28.6	14.4
Heat efficiency, net, name plate		63.9	66.5	82.2
Heat efficiency, net, annual average		65.5	68	83
Additional heat potential with heat pumps		1.7	1.7	1.7
C_b coefficient (40 °C/80 °C)		% of thermal input	0.45	0.18
C_v coefficient (40 °C/80 °C)			1	1
Forced outage	%	3	3	3

(continued)

Table F.16 (continued)

Technology	Unit	Large wood pellets CHP, 800 MW feed, back-pressure	Medium wood pellets CHP, 80 MW feed, back-pressure	Small wood pellets CHP, 20 MW feed, back-pressure
Planned outage	Weeks per year	3	3	3
Technical lifetime	Years	25	25	25
Construction time	Years	1	1	1
Space requirement	1000 m^2/MW_e	0.06	0.19	0.5
Plant dynamic capabilities				
Primary regulation	% per 30 s	2	NA	NA
Secondary regulation	% per minute	4	10	10
Minimum load	% of full load	15	15	20
Warm startup time	Hours	2	0.25	0.25
Cold startup time	Hours	12	8	0.5
Environmental data				
SO_2	Degree of desulphurization %	98.3	98.3	98.3
NO_x	g per GJ fuel	21	62	54
CH_4	g per GJ fuel	0	0	0
N_2O	g per GJ fuel	1	1	1
Particles	g per GJ fuel	0.3	0.3	0.3
Financial data (USD)				
Nominal investment	MUSD per MW	2.8	3.72	7.3
—of which equipment	%	1.46	2.24	4.48
—of which installation	%	1.34	1.48	2.82
Fixed O&M	USD/MW/year	71,680	142,352	309,008
Variable O&M	USD/MWh	1.79	1.90	3.81
Technology-specific data				
Steam reheat		None	None	None
Flue gas condensation		Yes	Yes	Yes
Combustion air humidification		Yes	Yes	Yes
Nominal investment	MUSD/MW fuel input	0.84	1.03	1.04
—of which equipment		0.47	0.66	0.68
—of which installation		0.37	0.37	0.36
Fixed O&M	USD/MW input/year	23,408	42,896	46,704
Variable O&M	USD/MWh input	0.57	0.57	0.57
Fuel storage-specific cost in excess of 2 days	MUSD/MW input/storage day	0.002	0.003	0.004

Table F.17 Nominal investment for a small wood pellets CHP (20 MW feed, back-pressure)

Technology	Unit	Small wood pellets CHP, 20 MW feed, back-pressure		
Electric capacity	MW_e	5	7.5	10
Nominal investment	$MUSD/MW_e$	5.11	3.85	3.14
—of which equipment	$MUSD/MW_e$	3.13	2.36	1.93
—of which installation	$MUSD/MW_e$	1.97	1.49	1.22

Table F.18 Nominal investment for a medium wood pellets CHP (80 MW feed, back-pressure)

Technology	Unit	Small wood pellets CHP, 80 MW feed, back-pressure		
Electric capacity	MW_e	15	20	25
Nominal investment	$MUSD/MW_e$	5.18	4.24	3.62
—of which equipment	$MUSD/MW_e$	3.12	2.55	2.18
—of which installation	$MUSD/MW_e$	2.06	1.68	1.44

Table F.19 Nominal investment for a large wood pellets CHP (800 MW feed, back-pressure)

Technology	Unit	Small wood pellets CHP, 80 MW feed, back-pressure		
Electric capacity	MW_e	200	250	300
Nominal investment	$MUSD/MW_e$	3.38	2.89	2.54
—of which equipment	$MUSD/MW_e$	1.76	1.50	1.32
—of which installation	$MUSD/MW_e$	1.62	1.39	1.22

F.1.1.5 Straw CHP (Table F.20, F.21, F.22, and F.23)

Table F.20 Technical and economic assumptions for a straw CHP (20–132 MW feed, back-pressure)

Technology	Unit	Large straw CHP (132 MW feed, back-pressure)	Medium straw CHP (80 MW feed, back-pressure)	Small straw CHP (20 MW feed, back-pressure)
Energy/technical data				
Generation capacity for one unit	MW_e	40.7	24.4	3
Electricity efficiency, net, name plate	%	30.9	30.5	15
Electricity efficiency, net, annual average	%	29.3	29	14.2
Heat efficiency, net, name plate	%	67.9	67.7	84.2
Heat efficiency, net, annual average	%	69.5	69.3	85
Additional heat potential with heat pumps	% of thermal input	1.7	1.7	1.7

(continued)

Table F.20 (continued)

Technology	Unit	Large straw CHP (132 MW feed, back-pressure)	Medium straw CHP (80 MW feed, back-pressure)	Small straw CHP (20 MW feed, back-pressure)
C_b coefficient (40 °C/80 °C)		0.45	0.45	0.18
C_v coefficient (40 °C/80 °C)		1	1	1
Forced outage	%	3	4	4
Planned outage	Weeks per year	3	4	4
Technical lifetime	Years	25	25	25
Construction time	Years	3	2.5	1
Space requirement	1000 m^2/MW_e	0.2	0.3	1
Plant dynamic capabilities				
Primary regulation	% per 30 s	2	NA	NA
Secondary regulation	% per minute	4	4	10
Minimum load	% of full load	40	40	50
Warm startup time	Hours	2	2	0.25
Cold startup time	Hours	8	8	0.5
Environmental data				
SO_2	Degree of desulphurization %	96.4	96.4	96.4
NO_x	g per GJ fuel	67	70	72
CH_4	g per GJ fuel	0	0	11
N_2O	g per GJ fuel	1	1	1
Particles	g per GJ fuel	0.3	0.3	0.3
Financial data (USD)				
Nominal investment	MUSD per MW_e	4.10	4.59	8.29
—of which equipment	%	2.35	2.58	4.26
—of which installation	%	1.75	2.02	4.03
Fixed O&M	USD/MW_e/year	139,888	167,888	356,384
Variable O&M	USD/MWh_e	2.13	2.24	4.48
Technology-specific data				
Steam reheat		None	None	None
Flue gas condensation		Yes	Yes	Yes
Combustion air humidification		Yes	Yes	Yes
Nominal investment	MUSD/MW fuel input	1.20	1.30	1.14
—of which equipment		0.74	0.80	0.65
—of which installation		0.46	0.50	0.49
Fixed O&M	USD/MW input/year	43,120	51,296	53,424
Variable O&M	USD/MWh input	0.67	0.67	0.67
Fuel storage-specific cost in excess of 2 days	MUSD/MW input/storage day	0.063	0.068	0.078

Table F.21 Nominal investment for a small straw CHP (20 MW feed, back-pressure)

Technology	Unit	Small straw pellets CHP, 20 MW feed, back-pressure		
Electric capacity	MW_e	5	7.5	10
Nominal investment	$MUSD/MW_e$	5.80	4.36	3.57
—of which equipment	$MUSD/MW_e$	2.98	2.24	1.83
– of which installation	$MUSD/MW_e$	2.82	2.12	1.74

Table F.22 Nominal investment for a medium straw CHP (80 MW feed, back-pressure)

Technology	Unit	Medium straw pellets CHP, 80 MW feed, back-pressure		
Electric capacity	MW_e	15	20	25
Nominal investment	$MUSD/MW_e$	6.46	5.28	4.51
– of which equipment	$MUSD/MW_e$	3.62	2.96	2.53
– of which installation	$MUSD/MW_e$	2.83	2.32	1.98

Table F.23 Nominal investment for a large straw CHP (132 MW feed, back-pressure)

Technology	Unit	Large straw pellets CHP, 132 MW feed, back-pressure		
Electric capacity	MW_e	40	50	60
Nominal investment	$MUSD/MW_e$	4.15	3.55	3.12
– of which equipment	$MUSD/MW_e$	2.38	2.04	1.79
– of which installation	$MUSD/MW_e$	1.77	1.51	1.33

F.1.1.6 Waste CHP

Waste-to-energy (WtE) plants incinerate waste and produce energy. HOPs produce only heat, while CHPs also produce electricity. The flue gas condensation technology was introduced at WtE plants in Denmark in 2004 and has been installed in every new built WtE line in Denmark since 2007. It recovers the heat of condensation of the flue gas content of water vapor. The heat is recovered as low-temperature heat and thereby increases the energy efficiency by additional 10–25% points for mixed waste.

The fuels used in WtE plants include mainly municipal solid waste (MSW) and other combustible nonrecyclable wastes. Biomass may be used mainly for starting up and closing down. Some plants in Denmark feed green waste from gardens and parks and challenging forest residues such as tree trunks. In addition, imported refuse-derived fuel (RDF) may be used as fuel. Other fuels include gas oil[3] or natural gas for burners, which are mainly used for startup.

The fuel waste is characterized as a heterogeneous product that has large variation in physical appearance, heating value, and chemical composition. The heating value of the waste fed to the furnace is a result of controlled mixing of available waste sources fed to the bunker of the WtE facility. It is usually in the range 7–15 MJ/

[3] A range of intermediates and finished petroleum products, generally in the diesel or VGO range of distillation.

kg, typically averaging 10–11 MJ/kg, referring to the lower heating value (LHV). For instance, in the WtE facility owned by Amager Resource Center (ARC) in the Copenhagen area in 2014, the heating value varied from 8 to 11 MJ/kg, with an average of 9.5 MJ/kg. At the time, ARC had about 50% waste from trade and industry, which is a high ratio in Denmark.

Table F.24 lists data that illustrate the heating value trend at Vestforbrænding I/S—the largest MSW plant in Denmark, located in the Copenhagen area.

The heating value of the waste received at the WtE plants may be affected by increased focus on recycling, which on one hand may divert organic waste with relatively low heating value and on the other hand divert plastics, paper, and wood with relatively high heating value. Many Danish WtE plants are importing RDF waste with relatively high heating value. Table F.25 lists the technical and economic assumptions for a WtE CHP. Table F.26 lists (and Fig. F.12 shows) the nominal investment for a small waste-to-energy CHP (35 MW feed, back-pressure). Table F.27 lists (and Fig. F.13 shows) the nominal investment for a medium waste-to-energy

Table F.24 Trend of the heating value at Vestforbrænding I/S

Year	2011	2012	2013	2014	2015
MJ/kg	10.32	10.30	9.80	10.0	10.4

Table F.25 Technical and economic assumptions for a WtE CHP

Technology	Unit	Large waste-to-energy CHP (220 MW feed, back-pressure)	Medium waste-to-energy CHP (80 MW feed, back-pressure)	Small waste-to-energy CHP (35 MW feed, back-pressure)
Energy/technical data				
Generation capacity for one unit	MW_e	51.2	18.4	7.9
Incineration capacity (fuel input)	tonnes/h	74.7	27.2	11.9
Electricity efficiency, net, name plate	%	23.3	23	22.6
Electricity efficiency, net, annual average	%	22.1	21.9	21.4
Heat efficiency, net, name plate	%	78.1	78	78.5
Heat efficiency, net, annual average	%	79.3	79.1	79.6
Additional heat potential with heat pumps	% of thermal input	4.1	4.1	4.1
C_b coefficient (40 °C/80 °C)		0.3	0.3	0.29
C_v coefficient (40 °C/80 °C)		1	1	1

(continued)

Table F.25 (continued)

Technology	Unit	Large waste-to-energy CHP (220 MW feed, back-pressure)	Medium waste-to-energy CHP (80 MW feed, back-pressure)	Small waste-to-energy CHP (35 MW feed, back-pressure)
Forced outage	%	1	1	1
Planned outage	Weeks per year	2.4	2.9	3.3
Technical lifetime	Years	25	25	25
Construction time	Years	3	2.5	2.5
Space requirement	1000 m^2/MW_e	0.8	1.6	2.5
Plant dynamic capabilities				
Primary regulation	% per 30 s	5	5	NA
Secondary regulation	% per minute	10	10	10
Minimum load	% of full load	20	20	20
Warm startup time	Hours	0.5	0.5	0.5
Cold startup time	Hours	2	2	2
Environmental data				
SO_2	Degree of desulfurization %	99.8	99.8	99.8
NO_x	g per GJ fuel	56	56	67
CH_4	g per GJ fuel	0.1	0.1	0.1
N_2O	g per GJ fuel	1	1	1
Particles	g per GJ fuel	0.3	0.3	0.3
Financial data (USD)				
Nominal investment	MUSD per MW	9.43	11.00	12.66
– of which equipment	%	5.26	6.16	7.28
– of which installation	%	4.17	4.84	5.38
Fixed O&M	USD/MW/year	210,896	296,576	463,232
Variable O&M	USD/MWh	27.78	28.00	28.67
Technology-specific data				
Steam reheat		None	None	None
Flue gas condensation		Yes	Yes	Yes
Combustion air humidification		No	No	No
Nominal investment	MUSD/MW fuel input	2.04	2.35	2.64
– of which equipment	MUSD/MW fuel input	1.23	1.43	1.65
– of which installation	MUSD/MW fuel input	0.81	0.92	1.0
Fixed O&M	USD/MW input/year	49,168	68,320	104,608
Variable O&M	USD/MWh input	6.5	6.5	6.5
Nominal investment	USD/(tonne/year)	753	866	973
Fixed O&M	USD/tonne	18	25	38
Variable O&M	USD/tonne	19	19	19

Table F.26 Nominal investment for a small waste-to-energy CHP (35 MW feed, back-pressure)

Technology	Unit	Small waste-to-energy CHP (35 MW feed, back-pressure)					
Electric capacity	MW_e	15	20	25	40	50	60
Nominal investment	$MUSD/MW_e$	8.08	6.61	5.65	4.07	3.48	3.06
– of which equipment	$MUSD/MW_e$	4.65	3.80	3.25	2.34	2.00	1.76
– of which installation	$MUSD/MW_e$	3.43	2.81	2.40	1.73	1.48	1.30

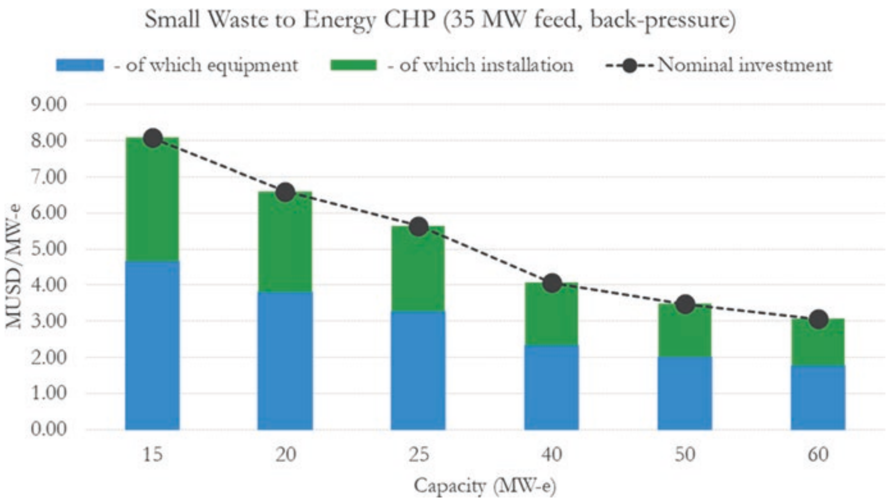


Fig. F.12 Nominal investment for a small waste-to-energy CHP (35 MW feed, back-pressure)

Table F.27 Nominal investment for a medium waste-to-energy CHP (80 MW feed, back-pressure)

Technology	Unit	Medium waste-to-energy CHP (80 MW feed, back-pressure)		
Electric capacity	MW_e	15	20	25
Nominal investment	$MUSD/MW_e$	12.69	10.37	8.87
– of which equipment	$MUSD/MW_e$	7.11	5.81	4.97
– of which installation	$MUSD/MW_e$	5.58	4.56	3.90

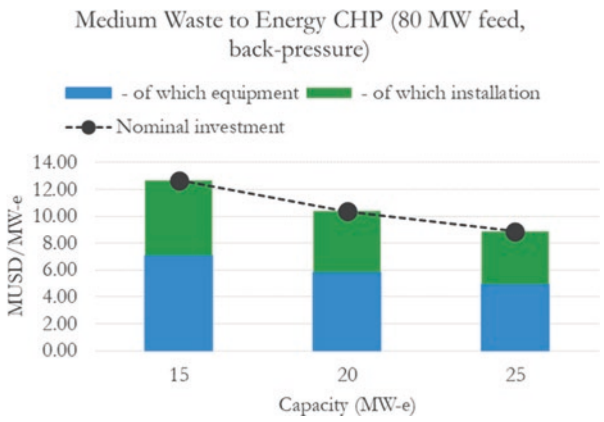


Fig. F.13 Nominal investment for a medium waste-to-energy CHP (80 MW feed, back-pressure)

Table F.28 Nominal investment for a large waste-to-energy CHP (220 MW feed, back-pressure)

Technology	Unit	Large waste-to-energy CHP (220 MW feed, back-pressure)		
Electric capacity	MW_e	40	50	60
Nominal investment	$MUSD/MW_e$	11.21	9.59	8.44
– of which equipment	$MUSD/MW_e$	6.26	5.35	4.71
– of which installation	$MUSD/MW_e$	4.95	4.24	3.73

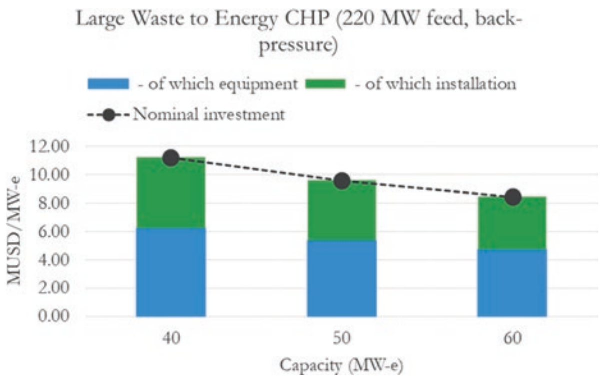


Fig. F.14 Nominal investment for a large waste-to-energy CHP (220 MW feed, back-pressure)

CHP (80 MW feed, back-pressure). Table F.28 lists (and Fig. F.14 shows) the nominal investment for a large waste-to-energy CHP (220 MW feed, back-pressure).

F.1.2 Electricity Storage

F.1.2.1 Electric Batteries

Several technologies are either available or being developed for storing electricity. Table F.29 lists a classification of some of these technologies regarding their capacities and discharge times.

The battery technology with the broadest base of applications today is the lithium-ion battery, used, e.g., in laptop computers and electric vehicles. The ability of lithium-ion batteries to economically serve electric utility applications has not yet been demonstrated, except for some ancillary service provisions to independent system operators. Three main battery types are most relevant for large-scale electricity storage:

- Advanced lead-acid batteries
- NaS (sodium sulfur) batteries
- Flow batteries, in particular:
  - Vanadium redox (VRB)
  - Zinc-bromine (ZnBr)

Table F.29 Technical and economic assumptions for sodium sulfur (NaS) and vanadium redox battery (VRB)

Technology		Sodium sulfur	Vanadium redox
	Unit	2020	2020
Energy/technical data			
Storage capacity	MWh	100	
Generating capacity	MW	10	10
Charge/discharge ratio			
Cell efficiency	%		
System efficiency, DC to DC, net	%		
System efficiency, AC to AC, net	%		
Lifetime in full charge-discharge cycles			
Technical lifetime	Years	15	
Construction time	Months	6–8	6–8
Financial data (USD)			
Specific investment, storage capacity	kUSD/MWh	152	57
Specific investment, output capacity	MUSD/MW	2	1.23
Fixed O&M	USD/MW/year	57,120	60,480
Variable O&M	USD/MWh	6	3.14

The lead-acid battery is one of the oldest and most developed battery technologies. A lead-acid battery is an electrical storage device that uses a combination of lead plates or grids and an electrolyte, consisting of a diluted sulfuric acid to convert electrical energy into potential chemical energy and back again.

The sodium sulfur (NaS) battery is a high-temperature (~300 °C) battery system that consists of a molten sulfur positive electrode and a molten sodium negative electrode separated by a solid ceramic electrolyte.

During discharge, positive sodium ions flow through the electrolyte, and electrons flow in the external circuit of the battery, producing about 2 V. This process is reversible. Flow batteries use an active element in a liquid electrolyte that is pumped through a membrane similar to a fuel cell to produce an electrical current.

The system's power rating is determined by the size and number of membranes, and the runtime (hours) is based on the volume of electrolyte pumped through the membranes. Pumping in one direction produces power from the battery, and reversing the flow charges the system.

The vanadium redox battery (VRB) is based on vanadium as the only element and is based on the reduction and oxidation of the different ionic forms of vanadium. Energy can be stored indefinitely in a liquid—very low self-discharge. The zinc-bromine (ZnBr) battery is based on cells with two different electrolytes flowing past carbon-plastic composite electrodes in two compartments separated by a microporous polyolefin membrane. For batteries to be practically applied in the utility grid, reliable power conversion systems (PCSs) that convert AC power to battery DC and back to AC are needed. Table F.29 lists the technical and economic assumptions for the sodium sulfur (NaS) and vanadium redox battery (VRB).

F.1.2.2 Pumped Hydro Storage

For bulk electricity storage in utility grids, pumped hydropower plants dominate, with approximately 100 GW in service around the globe.

A typical pumped hydro storage (PHS) consists of two water reservoirs (lakes), tunnels that convey water from one reservoir to another, a reversible pump turbine, a motor-generator, transformers, and transmission connection. The amount of stored electricity is proportional to the product of the volume of water and the height between the reservoirs. For example, storing 1000 MWh requires an elevation change of 300 m (984 ft) and a water volume of about 1.4 million m^3 (49 million ft^3).

A new PHS, including dams, has high capital expenditures and a long construction time. If an existing hydro plant is upgraded to become a PHS, the investment per installed MW is significantly lower, and the construction time is between 2 and 3 years.

With this technology, electricity is basically stored as potential energy. Other ways of storing electricity as potential energy may have similar characteristics. Table F.30 lists the technical and economic assumptions for a pumped hydro storage.

Table F.30 Technical and economic assumptions for a pumped hydro storage

Technology	Unit	Pumped hydro storage 2020
Energy/technical data		
Generating capacity	MW	10–1000
Total efficiency net	%	70–80
Technical lifetime	years	50
Construction time	years	2–3
Financial data (USD)		
Investment, pump part	MUSD/MW	0.07
Investment, total, greenfield part	MUSD/MW	4.5
Fixed O&M 1–2% of investment	USD/MW/year	10,080
Variable O&M	USD/MWh	Depends on power price

F.1.3 Electric Network

Electricity from power plants, wind turbines, and solar cells is transported from manufacturer to consumer through the grid. The main electricity transmission network consisting of 400 kV and 150/132 kV transmission lines is owned and operated by the national TSO. The underlying distribution networks are operated and owned by local distribution companies. At European level, efforts are being made to integrate all countries in Europe into one single electricity market. This means that the market areas must be even more closely connected to electrical transmission lines. The European electricity network can be seen here: https://www.entsoe.eu/Documents/Publications/maps/Map_Continental-Europe-2.pdf.

In any electrical system, a "player" is required for the overall stability of the network—which means that both import and export, as well as frequency and voltage, must remain within agreed limits. This player is called the system-responsible company or transmission system operator (TSO). To ensure that the balance between purchase and sale of electricity is constantly maintained, selected players in the electricity market have the status of "balance-responsible player." All production, consumption, and trade of electricity must be affiliated with a balance-responsible player. In practice, this role can be transferred to other balancing actors. For example, if the electricity vendor is not solely responsibility for the balance, the balance is guaranteed through a purchase agreement with another balance-responsible player. Liberalization of the electricity sector introduced competition between manufacturers and suppliers. These players act together in the wholesale market. Due to its status as a natural monopoly, the transmission network is not competitive.

Among the many advantages of a liberalized electricity market, a principal benefit is that electricity is always produced at the lowest cost and that transmission capacity between market areas is implicitly allocated, i.e., electricity flows from high-price areas to low-price areas.

F.1.3.1 Electric Transmission Network

The electricity systems of the future will presumably change from a centralized system with conventional thermal condensing, and CHP plants, to a decentralized system based on wind and solar power and smaller CHP plants. To ensure a high security of supply, when domestic conventional production capacity is reduced, and to develop a common European electricity market, new power cables are built. The increased electricity consumption from heat pumps, electric boilers, data centers, and electric vehicles must be covered by higher output from renewable energy production.

We believe that we will see the following trends:

- Large central power plants are decommissioned, mothballed, or converted to biomass with reduced power capacity.
- Wind turbines and solar cells gradually replace the conventional power plants.
- The number of individual heat pumps and large-scale heat pumps and electric boilers increases and enables a more flexible electricity consumption.
- Electrification of the transport sector is currently stagnant but will occur.
- New transmission lines will be built, and the existing ones expanded.

Table F.31 lists the technical and economic assumptions for electric main distribution cables.

F.1.3.2 Electric Distribution Network

The electric distribution networks are typically owned and operated by a local distribution system operator (DSO). The DSOs are monopolies and are subject to a nonprofit regulation. Most countries also benchmark the DSOs against each other to reduce operating costs for the benefit of consumers. Table F.32 lists the technical and economic assumptions for electric distribution in rural areas. Table F.33 lists parameters pertaining to underground high-voltage distribution.

F.1.3.3 Microgrid

A microgrid is a localized group of electricity sources and loads that normally operates connected to and synchronous with the traditional wide area synchronous grid (microgrid) but can also disconnect to "island mode"—and function autonomously as physical or economic conditions dictate. In this way, a microgrid can effectively integrate various sources of distributed generation (DG), especially RES—renewable electricity, and can supply emergency power, changing between island and connected modes.

Control and protection are challenges to microgrids. A very important feature is also to provide multiple end-use needs such as heating, cooling, and electricity at the same time since this allows energy carrier substitution and increased energy efficiency due to waste heat utilization for heating, DHW, and cooling purposes (cross-sectoral energy usage).

Table F.31 Technical and economic assumptions for electric main distribution cables

Technology	Unit	Energy transport, electric main distribution line
Energy/technical data		
Energy losses, lines 1–20 MW	%	0.3
Energy losses, lines 20–100 MW	%	0.3
Energy losses, lines above 100 MW	%	0.3
Energy losses, stations [Type 1]	%	0.2
Energy losses, stations [Type 2]	%	N/A
Auxiliary electricity consumption	% energy transmitted	N/A
Technical lifetime	Years	40
Typical load profile	–	0.45
Construction time	Years	1.5
Financial data (USD)		
Investment costs; single line, 0–50 MW	USD/MW/m	6.7
Investment costs; single line, 50–100 MW	USD/MW/m	4.4
Investment costs; single line, 100–250 MW	USD/MW/m	3.5
Investment costs; single line, 250–500 MW	USD/MW/m	N/A
Investment costs; single line, 500–1000 MW	USD/MW/m	N/A
Investment costs; single line, above 1000 MW	USD/MW/m	N/A
Reinforcement costs	USD/MW	17,696
Investment costs; [type 1] station	USD/MW	85,120
Investment costs; [type 2] station	USD/MW	5013
Investments, percentage installation	%	0.47
Investments, percentage materials	%	0.65
Fixed O&M	USD/MW/km/year	24.4055
Variable O&M	USD/MWh/km	N/A

Table F.32 Technical and economic assumptions for electric distribution in rural areas

Technology	Unit	Energy transport, electricity distribution, rural areas	Energy transport, electricity distribution, suburban areas	Energy transport, electricity distribution, city	Energy transport, electricity distribution, new developed areas
Energy/technical data					
Energy losses, lines	%	5.25	3.00	2.25	3.00
Energy losses, stations	%	1.13	1.13	1.13	1.13
Auxiliary electricity consumption	% energy delivered	N/A	N/A	N/A	N/A
Technical lifetime	Years	40.00	40.00	40.00	40.00
Typical load profile	–	0.44	0.48	0.50	0.48
—Residential	–	0.44	0.48	0.50	0.48
—Commercial	–	0.44	0.48	0.50	0.48
Construction time	Years	1.00	1.00	1.00	1.00

(continued)

Table F.32 (continued)

Technology	Unit	Energy transport, electricity distribution, rural areas	Energy transport, electricity distribution, suburban areas	Energy transport, electricity distribution, city	Energy transport, electricity distribution, new developed areas
Financial data (USD)					
Distribution network costs, rural	USD/ MWh/year	194	431	409	194
Investment costs; service line, 0–20 kW	USD/unit	587	1608	2407	587
Investment costs; service line, 20–50 kW	USD/unit	1581	4515	6292	1581
Investment costs; service line, 50–100 kW	USD/unit	1773	4752	6467	1773
Investment costs; service line, above 100 kW	USD/unit	4194	10,154	13,587	4194
Investment costs; single line, 0–50 kW	USD/m	N/A	N/A	N/A	N/A
Investment costs; single line, 50–250 kW	USD/m	N/A	N/A	N/A	N/A
Investment costs; single line, 100–250 kW	USD/m	40	N/A	N/A	40
Investment costs; single line, 250 kW–1 MW	USD/m	40	84	129	40
Investment costs; single line, 1 MW–5 MW	USD/m	46	90	134	46
Investment costs; single line, 5 MW–25 MW	USD/m	99	143	189	99
Investment costs; single line, 25 MW–100 MW	USD/m	N/A	N/A	N/A	N/A
Reinforcement costs	USD/MW	12,880	12,880	12,880	12,880
Investment costs type 1 station	USD/MW	75,600	42,560	42,560	42,560
Investment costs type 2 station	USD/MW	N/A	N/A	N/A	N/A
Investments, percentage installation (cables)	%	0.69	0.90	0.96	0.90
Investments, percentage materials (cables)	%	0.43	0.22	0.16	0.22
Investments, percentage installation (stations)	%	0.25	0.16	0.06	0.16
Investments, percentage materials (stations)	%	0.87	0.96	1.06	0.96
Fixed O&M	USD/MW/ year	1798	2961	0	1500
Variable O&M	USD/ MWh	N/A	N/A	N/A	N/A

Table F.33 Underground high-voltage distribution

Underground high-voltage distribution[a]		MW. power (1000 ft^2) area [A] ampacity	
Wire		Voltage, phase	
Wire size (sets)	Cost	5 KV range	15 KV range
FOUR LOOPS 8@500 KCMIL	$510/LF	N/A	32 (6400) [1480]
TWO LOOPS 4@500 KCMIL	$300/LF	N/A	16 (3200) [740]
ONE LOOP 2@500 KCMIL	$150/LF	2.4 (490) [375]	8 (1600 each) [370 each]
ONE LOOP 2@350 KCMIL	$145/LF	2 (410) [315]	6.7 (1340 each) [310 each]
ONE LOOP 2@250 KCMIL	$140/LF	1.7 (340) [260]	5.6 (1120 each) [260 each]
RADIAL 500 KCMIL	$90/LF	2.4 (480) [375]	8 (1600) [370]
RADIAL 350 KCMIL	$85/LF	2 (400) [315]	6.7 (1340) [310]
RADIAL 250	$80/LF	1.7 (340) [260]	5.6 (1120) [260]
RADIAL 4/0	$75/LF	1.5 (300) [235]	5.2 (1040) [240]
RADIAL 2/0	$72/LF	1.2 (240) [185]	4 (800) [185]
RADIAL 1/0	$70/LF	1 (200) [160]	3.5 (700) [165]
RADIAL #1	$68/LF	0.9 (180) [140]	3.1 (620) [145]
RADIAL #2	$66/LF	0.8 (160) [125]	2.8 (560) [130]

[a]Cables installed in UG duct bank, concrete encased ducts, three each; manhole every 500 ft; cost includes cable, duct, and trench excavation, backfill, and surface repair; cost does not include high-voltage switch at each point of use ($40,000–$50,000 each), manhole or pull box, splicing, and termination; cable is single conductor, copper shielded, 100% insulation level high-voltage cable; each duct contains 3 H.V. cables and a ground conductor sized per NEC; prices shown are the

(continued)

Table F.33 (continued)

construction costs for direct buried wire, including trench excavation, backfill, and moderate pavement repair. For total project cost, add A–E fees, testing, contingencies, etc. This chart is intended to be used for obtaining an initial estimate of required wire size and cost. Actual system design must be based on values obtained specifically for the project. For radial systems, building area power usage is estimated at 5 W/ft^2 (53.8 W/m^2). For loop systems, building area power usage is estimated at 3 W/ft^2 (32.3 W/m^2) (central plant loads not included)

Figures F.15, F.16, F.17, F.18, F.19, F.20, and F.21 illustrate microgrids in different configurations:[4]

- Microgrid with centralized emergency generators and a building-level backup
- Microgrid with centralized emergency generators and a centralized storage
- Microgrid with centralized emergency generators and CHP
- Microgrid with centralized emergency generators, RE sources, and a centralized storage
- Microgrid with centralized emergency generators
- Microgrid with decentralized emergency generators and CHP
- Microgrid with decentralized emergency generators

Table F.34 lists microgrid characteristics; Table F.35 lists microgrids components; and Tables F.36, F.37, F.38, and F.39 list equipment costs (1/4, 2/4, 3/4, and 4/4, respectively). All data below are provided by US Army Corps of Engineers.

F.1.4 Renewable Energy

F.1.4.1 Solar PV

A solar cell is a semiconductor component that generates electricity when exposed to light. For practical reasons, several solar cells are typically interconnected and laminated to (or deposited on) a glass pane to obtain a mechanical ridged and weathering protected solar module. The photovoltaic (PV) modules are typically 1–2 m^2 in size and have a power density in the range 100–210 Wp pr. m^2. They are sold with a product guarantee of typically 2–5 years, a power warranty of minimum 25 years, and an expected lifetime of more than 30 years.

PV modules are characterized according to the type of absorber material used:

Crystalline silicon (c-Si): the most widely used substrate material is made from purified solar-grade silicon and comes in the form of mono- or multi-crystalline silicon *wafers*. Currently more than 90% of all PV modules are wafer-based divided between multi- and mono-crystalline with a 60:40 share of the market size (this division is expected to level out toward a 50:50 ratio over the coming years). This technology platform is expected to dominate the world market for decades due to significant cost and performance advantages.

[4] Source: Wikipedia Undated(c); Anderson et al. (2017).

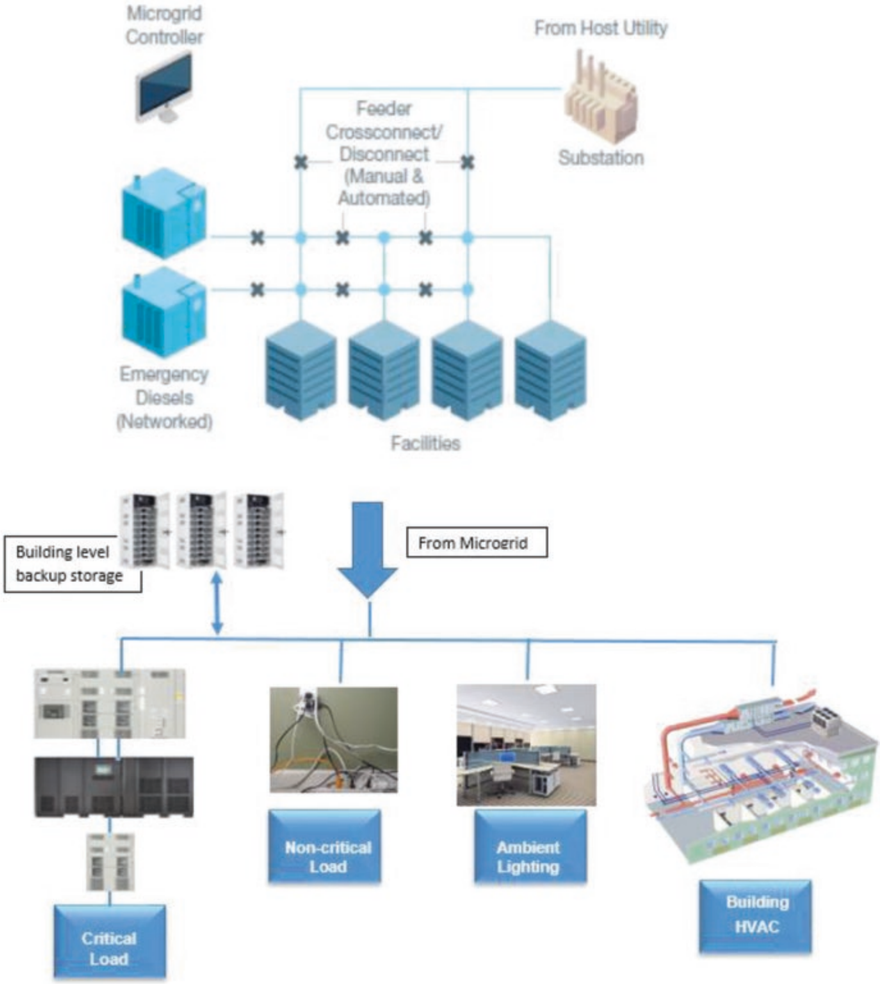


Fig. F.15 Microgrid with centralized emergency generators and a building-level backup

Thin film solar cells: where the absorber can be an amorphous/microcrystalline layer of silicon (a-Si/μc-Si), cadmium telluride (CdTe), or copper indium gallium (di)selenide (CIGS). These semiconductor materials are deposited on the top cover glass of the solar module in a micrometer thin layer. Tandem junction and triple junction thin film modules are commercially available. In these modules, several layers are deposited on top of each other to increase the efficiency.

Monolithic III-V solar cells: that are made from compounds of group III and group V elements (Ga, As, In, and P), often deposited on a Ge substrate. These materials can be used to manufacture highly efficient multi-junction solar cells that are mainly used for space applications or in concentrated photovoltaic (CPV) systems. CPV mainly uses the direct beam component of the solar irradiation. Dye-

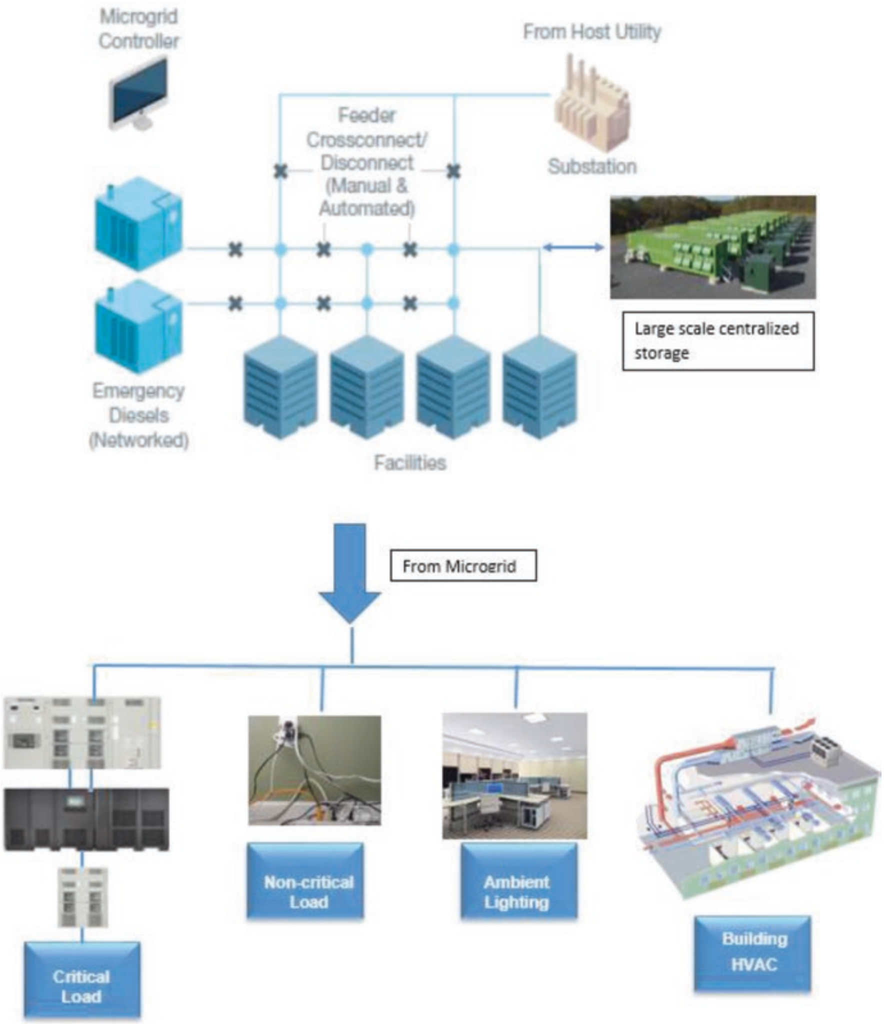


Fig. F.16 Microgrid with centralized emergency generators and a centralized storage

sensitized solar cells (DSCs) and polymer/organic solar cells: are emerging technologies where significant research activities are among others currently addressing efficiency and lifetime issues. These cells are expected to develop into commercial products by 2020–2030 but are currently not considered candidates for grid-connected systems. The general view on polymer/organic solar cells has been, and still is, that they are suited for low-demanding applications (typically recharging of batteries) but will face challenge in large-scale, grid-connected installations. Significant R&D achievements in recent years (which have broken the 10% efficiency limit (achieved for small laboratory cells) and

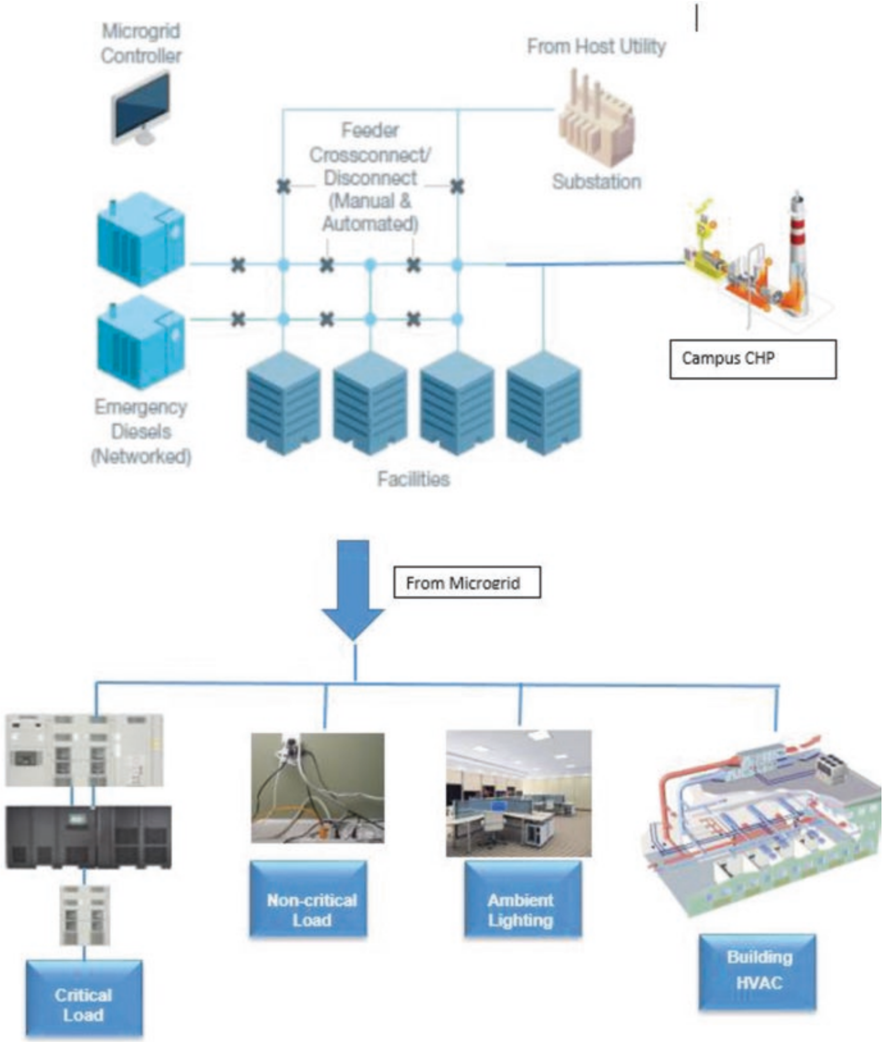


Fig. F.17 Microgrid with centralized emergency generators and CHP plant

demonstrated large-scale power production with a competitive energy payback and prospects for cost competitiveness) have called this view into question.

Perovskite material PV cells. In principle, perovskite solar cells are DSC cells with an organo-metal salt applied as the absorber material. Perovskites can also be used as an absorber in modified (hybrid) organic/polymer solar cells. The potential to apply perovskite solar cells in a multi-stacked cell on, e.g., a traditional c-Si device, provides interesting opportunities. Under lab conditions, perovskite-based solar cells have shown a remarkable progress over the years when rated with respect to efficiency. In 5 years, the efficiency has increased

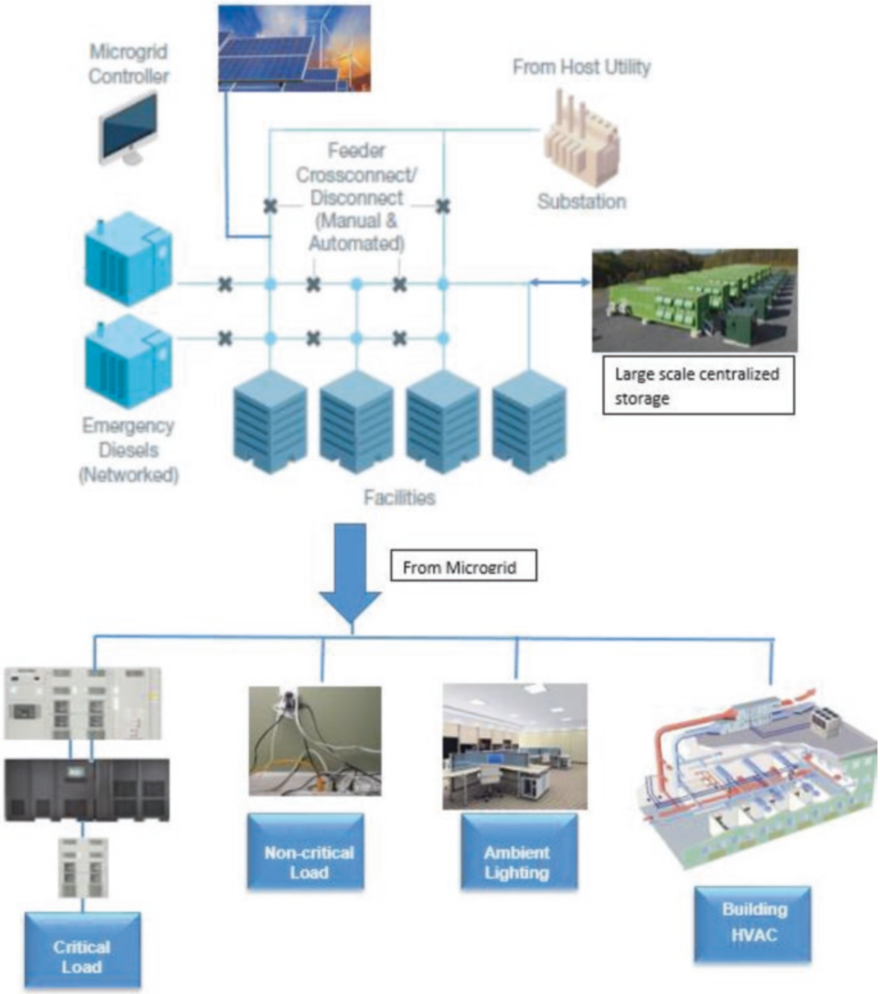


Fig. F.18 Microgrid with centralized emergency generators, RE sources, and a centralized storage

quite significantly from about 5% to almost 20%. The perovskite potential is, however, paired with serious concerns related to their toxicity. The best perovskite absorbers contain soluble organic lead compounds that are toxic and environmentally hazardous at a level that calls for extraordinary precautions. Therefore, the perovskite's health and environmental impact shall be analyzed before they are eventually considered as a viable absorber material in solar cells. Furthermore, challenges in industrial-scale manufacturing have presently not been resolved.

In addition to PV modules, a grid-connected PV system also includes balance of system (BOS) consisting of a mounting system, DC-to-AC inverter(s), cables,

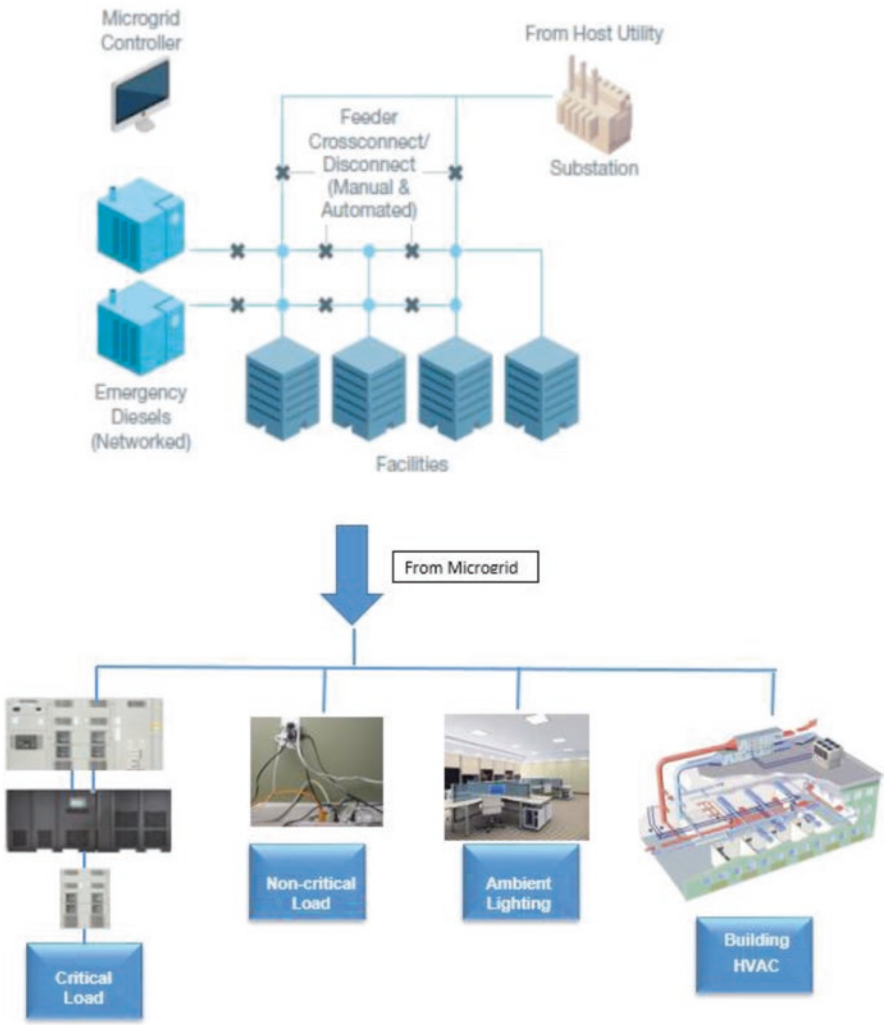


Fig. F.19 Microgrid with centralized emergency generators

combiner boxes, optimizers, monitoring/surveillance equipment, and for larger PV power plants also transformer(-s). Table F.40 lists the technical and economic assumptions for a photovoltaic system. Table F.41 lists (and Fig. F.22 shows) the nominal investment for a small, medium, and large residential photovoltaic system.

Wind Turbine

The typical large onshore wind turbine being installed today is a horizontal axis, three-bladed, upwind, grid-connected turbine using active pitch, variable speed, and yaw control to optimize generation at varying wind speeds.

Wind turbines work by capturing the kinetic energy in the wind with the rotor blades and transferring it to the drive shaft. The drive shaft is connected either to a

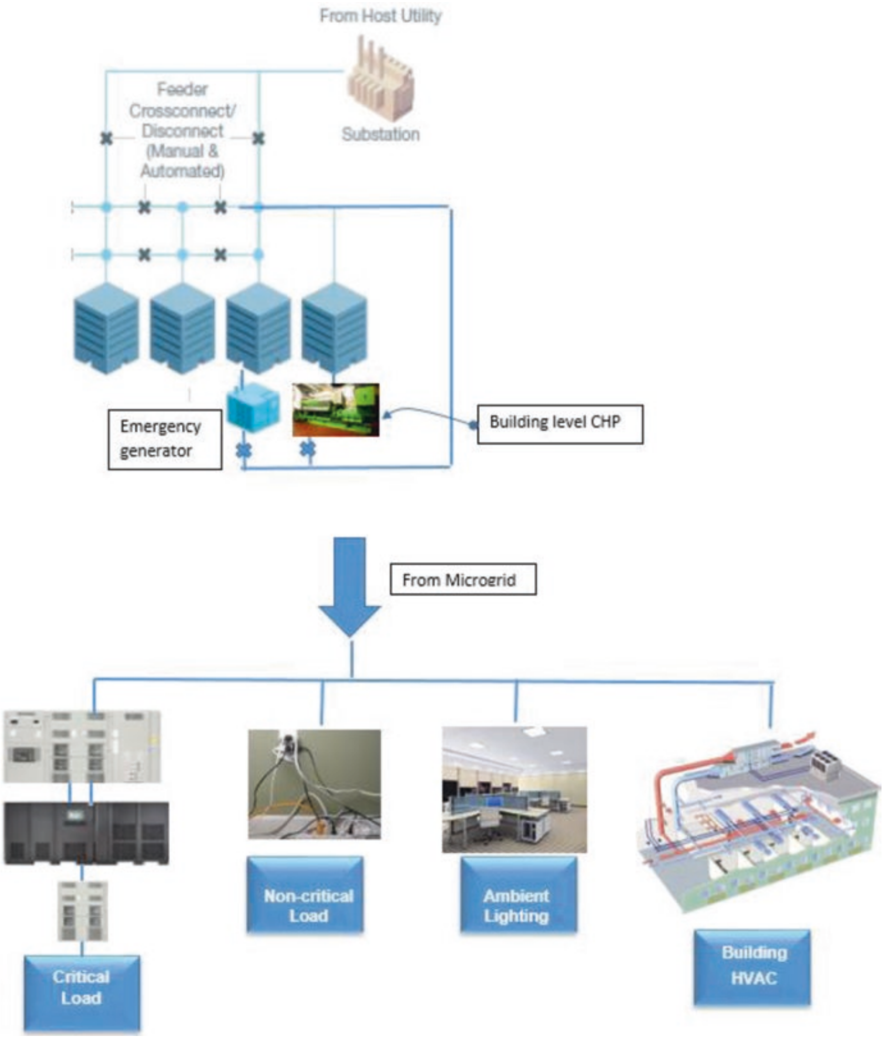


Fig. F.20 Microgrid with decentralized emergency generators and CHP

speed-increasing gearbox coupled with a medium- or high-speed generator or to a low-speed, direct-drive generator. The generator converts the rotational energy of the shaft into electrical energy. In modern wind turbines, the pitch of the rotor blades is controlled to maximize power production at low wind speeds and to maintain a constant power output and limit the mechanical stress and loads on the turbine at high wind speeds.

Wind turbines are designed to operate within a wind speed range bounded by a low “cut-in” wind speed and a high “cut-out” wind speed. When the wind speed is below the cut-in speed, the energy in the wind is too low to be used. When the wind reaches the cut-in speed, the turbine begins to operate and produce electricity. As

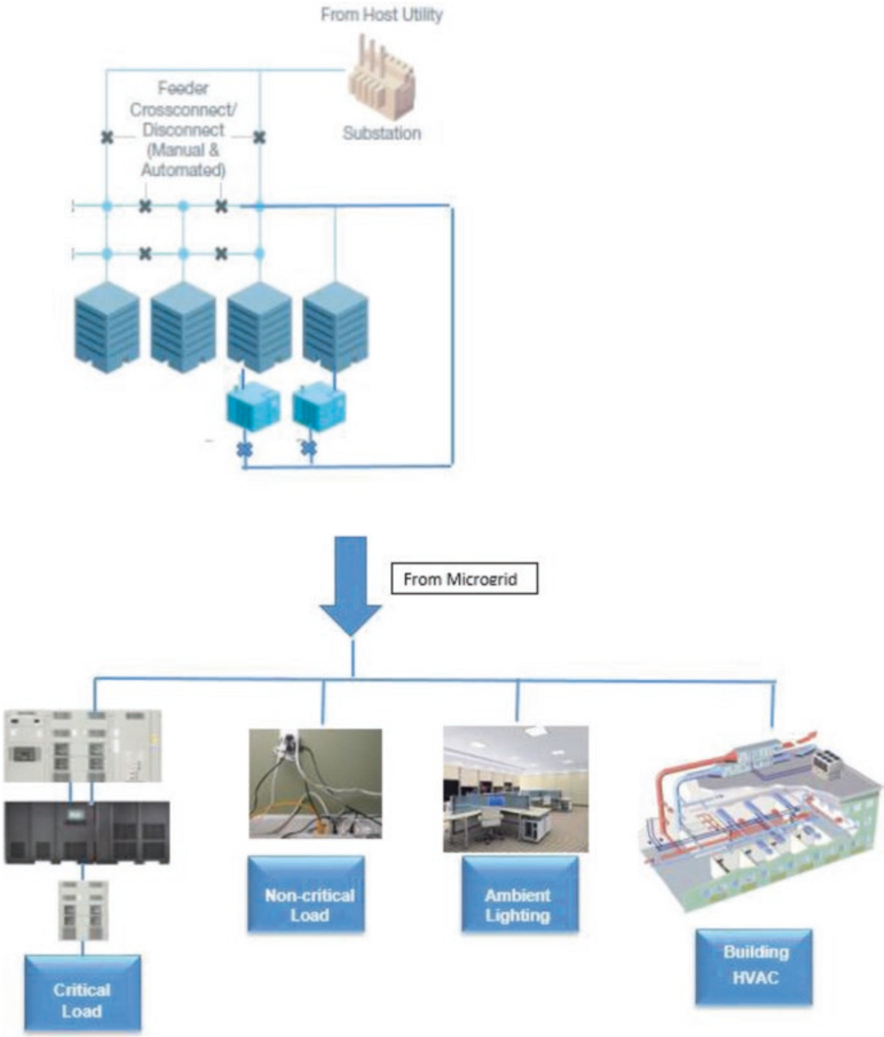


Fig. F.21 Microgrid with decentralized emergency generators

the wind speed increases, the power output of the turbine increases, and at a certain wind speed, the turbine reaches its rated power. At higher wind speeds, the blade pitch is controlled to maintain the rated power output. When the wind speed reaches the cut-out speed, the turbine is shut down or operated in a reduced power mode to prevent mechanical damage.

Onshore wind turbines can be installed as single turbines, clusters, or in larger wind farms.

Commercial wind turbines are operated unattended and are monitored and controlled by a SCADA system.

Table F.34 Microgrid characteristics

Architecture name	Description	Microgrid?	Must contain	May contain	Capabilities	Applications	Advantages	Disadvantages
Base case	Dedicated building-level backup generators serve critical loads when utility power is unavailable	USDOE – No IEEE—Yes	Building-level control, building-level backup generators	Various power sources such as photovoltaic, energy storage	Dedicated generators to critical loads	Basic critical load backup power	None – base case	Lack of redundancy, if backup generation source fails or there is a lack of fuel, the building will lose power
Central power plant (base loading)	A central plant serves installation loads or supplements utility power service installation loads	No	Distribution-level control, Distribution-level CUP	Various power sources such as photovoltaic, energy storage	Offset installation power consumption	Installation-scale power production	Provides a portion of primary power which can result in less electric cost	Centralized plants are costly and must be competitive with utility provider to be sustainable; if centralized plant is lost, then the associated buildings served will be lost since it is a single point of failure
Central backup generators	A backup generator plant connected at the distribution level serves critical loads when utility power is not available.	USDOE – No IEEE—Yes	Distribution-level control, distribution-level backup Generator plant	Distribution- and building-level remote controlled disconnect switch, various power sources such as photovoltaic, energy storage	More efficiency backup power with more flexibility that dedicated building generators	More efficient and reliable critical load backup power for multiple facilities. Typically seen when multiple critical buildings are located geographically close to one another	Less expensive than central plant for installation loads. May be less expensive than backup generators at individual facilities	Like central plant, one backup generator plant is a single point of failure; unlike central plant, it only picks up power when utility power is unavailable
Islandable central plants	A central utility plant serves installation loads and can operate islanded from utility power	Yes	Control system and network, distribution-level control, distribution-level CUP	Distribution-level backup generators, various power sources such as photovoltaic, energy storage	Islandable power for large installation loads, offset installation power consumption	Installation-scale power production and support for power outage ride-through	Can provide all of primary power if competitive with utility and consolidates backup power requirements at one location so may be less expensive and easier to maintain than distributed generators spread across the service area and can operate in parallel with the utility	Even more expensive than that of the central plant since additional generation is needed and paralleling switchgear to operate the system in parallel with the utility. Has the same disadvantages of being a single point of failure if central plant is lost

(continued)

Table F.34 (continued)

Architecture name	Description	Microgrid?	Must contain	May contain	Capabilities	Applications	Advantages	Disadvantages
Distribution-level microgrid	Generation resources connected to the distribution system at medium voltage serve installation loads and can operate islanded from utility power	Yes	Control system and network, distribution-level control	Distribution-level CUP, D-L backup generators, D-L solar, D-L energy storage	Improved efficiency, runtime, flexibility, and resiliency through integration of multiple types of generation for backup power	Integration of multiple large resources into backup power service for critical loads. Typically done when installation has multiple substations	Generators connected along distribution at medium voltage instead of at individual facilities are easier to operate, since they are not necessarily centralized, may avoid single point of failure issues, may be less costly than central plant installations, but may not be as efficient; generation resources decoupled from individual facilities relieve the necessity to keep backup generators at individual facilities	Since generation is distributed, the cost for control infrastructure is high as well as the complexity of the controls themselves, even though a larger variety of sizes of power sources make the matching load to generation more optimized and efficient; the larger the number of spares are needed, since electrical power can flow in bidirectional instead of unidirectional which is typically seen in distribution systems, the protection scheme becomes more complex and costly
Distributed microgrid	Generation resources connected at the distribution level and building level serve installation loads and can operate islanded from utility power	Yes	Control system and network, distribution-level control	Distribution-level CUP, D-L backup generators, D-L solar, D-L energy storage, building-level controls, B-L generators, B-L solar, B-L energy storage, B-L CHP	Improved efficiency, runtime, flexibility, and resiliency through integration of multiple types of generation for backup power	Integration of multiple generation resources, including backup generators previously dedicated to individual buildings, into backup power service for critical loads. Typically done at facilities with dedicated building generators with grid paralleling capability	Adds benefit relative to distribution only generation resources of using building-level generators as well so may be less expensive; as with distribution resources, less efficient than central plants	Same disadvantages as the distribution-level microgrid

Single-building microgrid	Generation resources connected to a single building serve that building's loads and can operate the single building islanded from the distribution system	Yes	Control system and Network, Building-Level Control	B-L Generators, B-L Solar, B-L Energy Storage, B-L CHP	Improved efficiency, runtime, flexibility, and resiliency through integration of multiple types of generation for backup power.	Integrating building-level generation resources into backup power service for the building.	Adds to single building tied backup generator to increase reliability and resilience through redundancy of the additional generation resources	More expensive than building tied backup generation; more complex controls.
Low-voltage microgrid	Multiple single-building microgrids use the low-voltage distribution system to share generation resources and operated islanded from utility power.	Yes	Control system and network, distribution-level control, building-level control	B-L generators, B-L solar, B-L energy storage, B-L CHP, various power sources such as photovoltaic, energy storage	Improved efficiency, runtime, flexibility, and resiliency through integration of multiple types of generation for backup power. Multiple building collaboration further improves flexibility, efficiency, and resiliency	Integrating multiple building-level microgrids to improve redundancy and efficiency for building backup power service. Typically done when buildings are within very close proximity of each other and very low load demand	Adds benefit by using building-level generators and not distribution-level generators so may be less expensive than either distribution-level generators or a combination of both; as with distribution resources, less efficient than central plants	Less expensive than individual facility installations but will have more complex controls since more diverse set of generators needs to be controlled. Since power is being sent along the low-voltage system, larger electrical feeders are needed which increases costs. Buildings need to be closely located to one another to minimize voltage drop and cost of electrical wire

Table F.35 Microgrids components (x—must contain; o—may contain)

	Base case	Central plant	Central backup	Islandable plants	Distribution-level microgrid	Distributed microgrid	Single-building microgrid[a]	Low-voltage microgrid
Control system and network				x	x	x	x	x
Distribution break/switch control		x	x	x	x	x		x
CUP		x		x	o	o		
Distribution backup generators			x	o	o	o		
Distribution solar					o	o		
Distribution energy storage					o	o		
Building-level breaker/switch control	x					o	x	x
Building backup generators	x					o	o	o
Building solar						o	o	o
Building energy storage						o	o	o
Building CHP						o	o	o

[a]Single building microgrid contains one or more of these resources located at a single building

Table F.36 Equipment costs (1/4)

Equipment	Rating	Cost (range) + (range)[a]	Cost format	Reference	Additional cost items
Small diesel generator	30–150 kW	(356–526)	$/kW	Ref (1)[b]	Site prep, installation, testing, commissioning, control programming
Medium diesel generator	150–500 kW	(238–356)	$/kW	Ref (1)[******]	Site prep, installation, testing, commissioning, control programming
Large diesel generator	500 kW–1 MW	(223–238)	$/kW	Ref (1)[******]	Site prep, installation, testing, commissioning, control programming
Extra-large diesel generators	>1 MW	550	$/kW	Ref (4)[c]	Site prep, installation, testing, commissioning, control programming
Small NG generator	7.5–60 kW	(483 –1586)	$/kW	Ref (1)[******]	Site prep, installation, testing, commissioning, control programming
Medium NG generator	60–185 kW	(454–483)	$/kW	Ref (1)[******]	Site prep, installation, testing, commissioning, control programming
Large NG generator	>1 MW	(700–1000)	$/kW	Ref (4)[††††††]	Site prep, installation, testing, commissioning, control programming
Generator belly tank– small gen	<100 kW	N/A – these are included with generator package costs	$/gal	N/A	Including any site provisions
Generator belly tank – medium gen	100–750 kW	N/A – these are included with generator package costs	$/gal	N/A	Including any site provisions
Generator belly tank – large gen	750 kW–2 MW	N/A – these are included with generator package costs	$/gal	N/A	Including any site provisions
Generator belly tank – extra-large gen	>2 MW	N/A – these are included with generator package costs	$/gal	N/A	Including any site provisions
Building-mounted PV array + inverter		(1000–1500)	$/kW	Ref (4)[††††††]	Including wiring, combiner boxes, mounting structure, inverter, building electrical interface
Ground-mounted PV array + inverter		(1000–1500)	$/kW	Ref (4)[††††††]	Including wiring, combiner boxes, mounting structure, inverter, electrical interface

(continued)

Table F.36 (continued)

Equipment	Rating	Cost (range) + (range)[a]	Cost format	Reference	Additional cost items
Carport PV array		600–800	$/kW	Ref (5)[d]	Including wiring, combiner boxes, mounting structure, inverter, electrical interface
PV inverter		400–1000	$/kW	Ref (5)[‡‡‡‡‡‡‡]	Equipment, installations, programming
Generic battery energy storage system			$/kW + $/kWh		Inclusive of all safety systems such as fire suppression that meets code and UFCs
Lithium battery energy storage systems		(1263–2162) + (829–1152)	$/kW + $/MWh	Ref (2)[e]-pg13, 26, 27	Inclusive of all safety systems such as fire suppression that meets code and UFCs
Lead-acid battery energy storage systems		(1278–1763) + (108–1225)	$/kW + $/MWh	Ref (2)[§§§§§§]-pg13, 26, 27	Inclusive of all safety systems such as fire suppression that meets code and UFCs
Flow battery energy storage system		(1715–3650) + (115–167)	$/kW + $/MWh	Ref (2)[§§§§§§]-pg13, 26, 27	Inclusive of all safety systems such as fire suppression that meets code and UFCs
Flywheel energy storage systems		(1300–2000) + (1000–3000)	$/kW + $/kWh	Ref (5)[‡‡‡‡‡‡‡]	Inclusive of all safety systems such as fire suppression that meets code and UFCs
Capacitor energy storage systems			$/kW + $/kWh		Inclusive of all safety systems such as fire suppression that meets code and UFCs
CUP			$/kW		Turn-key power plant cost
Gasifier			$/kW		Turn-key power plant cost
Fuel storage (diesel) above ground		(2–4)	$/gal	Ref (4)[††††††]	Inclusive of civil work, equipment, installation, and commissioning
Fuel storage (NG/propane) above ground		(3–5)	$/gal	Ref (4)[††††††]	Inclusive of civil work, equipment, installation, and commissioning
Fuel storage (JP8) above ground		similar to 27	$/gal		Inclusive of civil work, equipment, installation, and commissioning
Fuel storage (diesel) below ground		Likely 2x aboveground costs	$/gal		Inclusive of civil work, equipment, installation, and commissioning
Fuel storage (NG) below ground		Likely 2x aboveground costs	$/gal		Inclusive of civil work, equipment, installation, and commissioning

Fuel storage (JP8) below ground		Likely 2x aboveground costs	$/gal		Inclusive of civil work, equipment, installation, and commissioning
Small diesel generator	30–150 kW	(356–526)	$/kW	Ref (1)******	Site prep, installation, testing, commissioning, control programming
Medium diesel generator	150–500 kW	(238–356)	$/kW	Ref (1)******	Site prep, installation, testing, commissioning, control programming
Large diesel generator	500 kW–1 MW	(223–238)	$/kW	Ref (1)******	Site prep, installation, testing, commissioning, control programming
Extra-large diesel generators	>1 MW	550	$/kW	Ref (4)††††††	Site prep, installation, testing, commissioning, control programming

[a]Example 1000–1500 + 300–400 for $/kW + $/kWh means range is ($1000–$1500)/kW + ($300 $400)/kWh
[b]Ref (1) RSMeans Electricity Costs 2019
[c]Ref (4) Information from previous Sandia microgrid projects and consultation with manufacturers
[d]Ref (5) Information obtained from online searches
[e]Ref (2) Lazard's Levelized Cost of Storage Analysis—Version 4.0. Retrieval link: https://www.lazard.com/media/450774/lazards-levelized-cost-of-storage-version-40-vfinal.pdf

Table F.37 Equipment costs (2/4)

Equipment	Rating	Cost (range) + (range)[§§§§§]	Cost Format	Reference	Additional cost items
Medium voltage overhead power lines (~15kv)		20	$/ft	Ref (4)[††††††]	Inclusive of civil work, equipment, installation, and commissioning
Medium voltage underground power lines (~15kv)		50	$/ft	Ref (4)[††††††]	Inclusive of civil work, equipment, installation, and commissioning
MV pole-mounted transformer (~15kV/208V)	10–100 kVA	(55–186)	$/kVA	Ref (1)[******]	Inclusive of civil work, equipment, installation, and commissioning
MV pad-mounted transformer (~15kV/208V)	150–3750 kVA	(29–93)	$/kVA	Ref (1)[******]	Inclusive of civil work, equipment, installation, and commissioning
Substation transformers (~69kV/~15kV)		(26–33)	$/kVA	Ref (1)[******]	Inclusive of civil work, equipment, installation, and commissioning
Substation transformers (~115kV/~15kV)		24	$/kVA	Ref (1)[******]	Inclusive of civil work, equipment, installation, and commissioning
Substation breaker (~15kV)		76,890	$/ea.	Ref (1)[******]; oil breaker	Inclusive of civil work, equipment, installation, and commissioning
Pad-mounted breaker (~15kV)		Similar to 41	$/ea.		Inclusive of civil work, equipment, installation, and commissioning
Pole-mounted breaker (~15kV)		Similar to 41	$/ea.		Inclusive of civil work, equipment, installation, and commissioning
Low-voltage breaker (208V)	650–2500 kVA	(960–1850)	$/ea.	Ref (1)[******]	Inclusive of civil work, equipment, installation, and commissioning
MV pole-mounted switch (~15kV)		Similar to 46	$/ea.		Inclusive of civil work, equipment, installation, and commissioning
MV pad-mounted switch (~15kV)		20,915	$/ea.	Ref (1)[******]; manual gang operated switch	Inclusive of civil work, equipment, installation, and commissioning
Multi-way MV pad-mounted switch (~15kV)		Similar to 46	$/ea.		Inclusive of civil work, equipment, installation, and commissioning

Multi-way MV pole-mounted switch (~15kV)		Similar to 46	$/ea.		Inclusive of civil work, equipment, installation, and commissioning
ATS – small generator	<100 kW	5220	$/ea.	Ref (1)[******]	Inclusive of civil work, equipment, installation, and commissioning
ATS – medium generator	100–750 kW	(5220–20,475)	$/ea.	Ref (1)[******]	Inclusive of civil work, equipment, installation, and commissioning
ATS – large generator	750 kW–1.5 MW	(20,475–35,275)	$/ea.	Ref (1)[******]	Inclusive of civil work, equipment, installation, and commissioning
ATS – extra-large generator	>2 MW	>35275	$/ea.	Extrapolation from Ref (1)[******]	Inclusive of civil work, equipment, installation, and commissioning
Motor operator for high-voltage (HV) breaker (69kV)		N/A – these are included with breaker costs	$/ea.		Equipment, installation, test
Motor operator for MV breaker (15kV)		N/A – these are included with breaker costs	$/ea.		Equipment, installation, test
Motor operator for low-voltage (LV) breaker (208kV)		N/A – these are included with breaker costs	$/ea.		Equipment, installation, test
UPS		1000–2000	$/kW	Ref (4)[††††††]	Equipment, installation, test

Table F.38 Equipment costs (3/4)

Equipment	Rating	Cost (range) + (range)[§§§§§]	Cost format	Reference	Additional cost items
Microgrid supervisory controller		700–3000[a]	$/ea.	Ref (5)[‡‡‡‡‡‡]	Including supporting equipment, installation, programming, testing, hardening, and commissioning
Microgrid human machine interface (HMI) terminal		700–3000[*******]	$/ea.	Ref (5)[‡‡‡‡‡‡]	Hardware, software, programming, hardening, test, commissioning
SCADA gateway		400–2000[*******]	$/ea.	Ref (5)[‡‡‡‡‡‡]	Hardware, software, programming, hardening, test, commissioning
SCADA RTU		500–2000[*******]	$/ea.	Ref (5)[‡‡‡‡‡‡]	Hardware, software, programming, hardening, test, commissioning
SCADA programmable logic controller (PLC)		500–2000[*******]	$/ea.	Ref (5)[‡‡‡‡‡‡]	Hardware, software, programming, hardening, test, commissioning
Generator paralleling control		100,000–200,000	$/ea.	Ref (4)[††††††]	Hardware, software, programming, hardening, test, commissioning
Control system to subsystem interface			$/ea.		Physical connection, programming, hardening, test, commissioning
New trenched fiber cable enclosure	1–2 inches	(6.0–12.3)	$/ft	Ref (1)[******]	Inclusive of civil work, equipment, installation, and commissioning
New fiber cable in existing conduit	48 strand	6.2	$/ft	Ref (1)[******]	Inclusive of civil work, equipment, installation, and commissioning
OH pole hung new fiber cable			$/ft		Inclusive of civil work, equipment, installation, and commissioning
Router		1000–50,000[*******]	$/ea.	Ref (5)[‡‡‡‡‡‡]	Equipment, programming, hardening, test, commissioning
Network switch		500–50,000[*******]	$/ea.	Ref (5)[‡‡‡‡‡‡]	Equipment, programming, hardening, test, commissioning
Network firewall		1000–100,000[*******]	$/ea.	Ref (5)[‡‡‡‡‡‡]	Equipment, programming, hardening, test, commissioning
Recommission SCADA after modification			$/ea.		

Cost of these items is largely dependent on the size purchased

Table F.39 Equipment costs (4/4)

Equipment	Rating	Cost (range) + (range)[§§§§§]	Cost format	Reference	Additional cost items
Conventional generation (diesel, gas)		(833–1641)	$/kW	Ref (3)[a] page 26 (utility, commercial, and military microgrids)	
Renewable generation (PV, wind)		(502–663)	$/kW	Ref (3)[†††††††] page 26 (utility, commercial, and military microgrids)	
Energy storage		(248–351)	$/kW	Ref (3)[†††††††] page 26 (utility, commercial, and military microgrids)	
Controls		(48–162)	$/kW	Ref (3)[†††††††] page 26 (utility, commercial, and military microgrids)	
Additional infrastructure (new switches, lines)		(191–459)	$/kW	Ref (3)[†††††††] page 26 (utility, commercial, and military microgrids)	
Soft costs (engineering, construction, commissioning, regulatory)		(102–1655)	$/kW	Ref (3)[†††††††] page 26 (utility, commercial, and military microgrids)	

Ref (3) Phase I Microgrid Cost Study (NREL/TP-5D00-67821; October 2018) https://www.nrel.gov/docs/fy19osti/67821.pdf

Table F.40 Technical and economic assumptions for a photovoltaic system

Technology	Unit	Photovoltaics: small residential systems	Photovoltaics: medium-sized commercial systems	Photovoltaics: large-scale utility systems
Input				
Global horizontal irradiance	kWh/m^2/y	1068	1068	1068
Energy/technical data				
Typical capacity for one installation (plant capacity)	kW	6	100	4000
Typical peak capacity for one installation at STC	kW$_p$	6	110	5400
Energy/technical data—system design				
DC/AC sizing factor (W$_p$/W)	W$_p$/W	1	1	1
Transposition factor for fixed tilt system		1	1	1
Incident angle modifier loss	%	0	0	0
PV system losses and non-STC corrections	%	0	0	0
Inverter loss	%	0	0	0
AC grid losses	%	0	0	0
PV module conversion efficiency	%	0	0	0
Availability	%	1	1	1
Technical lifetime of total system	Years	35	35	35
Inverter lifetime	Years	15	15	15
Output				
Full-load hours	kWh/kW	1043	1129	1420
Peak power full-load hours	kWh/kW$_p$	993	1027	1050
Financial data USD)				
PV module cost	USD/W$_p$	0.35	0.32	0.29
Balance Of plant cost	USD/W$_p$	0.85	0.50	0.05
Specific investment, total system	MUSD/W$_p$	1.20	0.82	0.35
Specific investment, total system	MUSD/MW	1.26	0.90	0.69
Fixed O&M	USD/MW$_p$/y	14336	11648	0
Fixed O&M	USD/MW/y	15053	12813	0.07

Table F.41 Nominal investment for a small, medium, and large residential photovoltaic system

Technology	Unit	Photovoltaic residential systems								
		Small			Medium			Large		
Electric capacity	MW_e	5	10	15	100	200	300	4000	5000	6000
Specific investment, total system	$MUSD/MW_e$	1.44	0.88	0.67	0.90	0.55	0.42	0.69	0.59	0.52

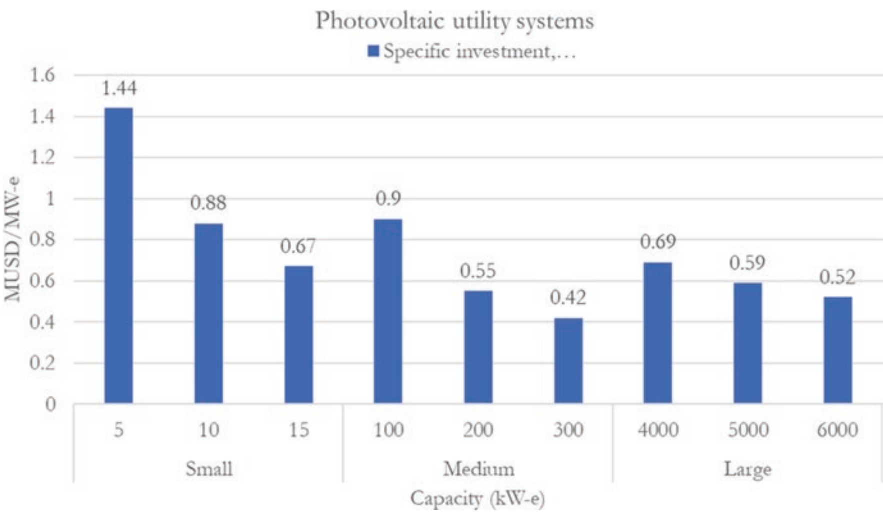


Fig. F.22 Nominal investment for a small, medium, and large residential photovoltaic system

The winning price in the tenders for the offshore wind farms in Denmark has decreased substantially from 2012 to 2016. The same trend has been seen in, e.g., the Netherlands and Great Britain.

There are several reasons for the reduction in the winning bids. The costs of the wind turbine technology itself, as well as for installation, operation, and maintenance, have fallen sharply in recent years. In general, more experience has been gained in this area, making the collaboration between the different players on the market more efficient. Moreover, there are better opportunities for optimizing project plans and the volume of the offshore wind market. In addition, interest rates are low, and technological and economic risks are assessed lower by investors; therefore low returns are accepted, and competition has been increasing. Expectations for the electricity price after expiration of the grant period and other possible income from, e.g., certificates of origin also affect the bid price. Table F.42 lists the technical and economic assumptions for wind turbines. Table F.43 lists (and Fig. F.23 shows) the nominal investment for onshore wind turbine. Table F.44 lists (and Fig. F.24 shows) the nominal investment for large offshore wind turbine. Table F.45 lists (and Fig. F.25 shows) the nominal investment for large offshore wind turbine nearshore.

Table F.42 Technical and economic assumptions for wind turbines

Technology	Unit	Onshore wind turbine	Small wind turbines, grid-connected (<25 kW)	Large wind turbine offshore	Large offshore wind turbine nearshore
Energy/technical data					
Generating capacity for one unit	MW	4.2	0.025	10	10
Average annual full-load hours		3400	1600	4500	4500
Forced outage	%	2.5	3.0	3.0	3.0
Planned outage	%	0.3	0.3	0.3	0.3
Technical lifetime	Years	27	20	27	27
Construction time	Years	1.5	1	2.5	2
Space requirement	1000 m^2/MW	–	0.8	220	220
Regulation ability					
Primary regulation	% per 30 s	–	–	–	–
Secondary regulation	% per minute	–	–	–	–
Financial data					
Nominal investment	MUSD/MW	1.35	4.34	2.69	2.20
—of which equipment	MUSD/MW	0.80	3.83	0.88	0.75
—of which installation	MUSD/MW	0.55	0.51	1.80	1.45
Fixed O&M	USD/MW/year	15,680	106,400	44,866	40,379
Variable O&M	USD/MWh	1.68	–	3.36	2.99
Technology-specific data					
Rotor diameter	m	130	8	190	190
Hub height	m	85	18	115	115
Specific power	W/m^2	316	–	353	353
Average capacity factor	%	39	–	51	51
Average availability	%	97	–	97	97
Specific area coverage	MW/km^2	–	–	4.5	4.5

Table F.43 Nominal investment for onshore wind turbine

Technology	Unit	Onshore wind turbine								
Electric capacity	MW_e	2	3	4	5	6	7	8	9	10
Specific investment, total system	$MUSD/MW_e$	2.26	1.70	1.39	1.19	1.05	0.94	0.86	0.79	0.73
– of which equipment	$MUSD/MW_e$	1.34	1.01	0.82	0.70	0.62	0.56	0.51	0.47	0.43
– of which installation	$MUSD/MW_e$	0.93	0.70	0.57	0.49	0.43	0.39	0.35	0.32	0.30

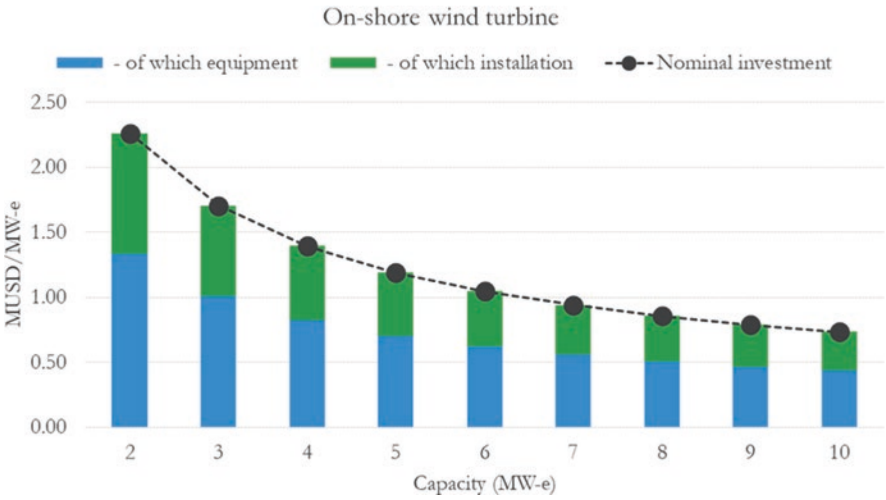


Fig. F.23 Nominal investment for onshore wind turbine

Table F.44 Nominal investment for large offshore wind turbine

Technology	Unit	Large wind turbine offshore								
Electric capacity	MW_e	2	3	4	5	6	7	8	9	10
Specific investment, total system	$MUSD/MW_e$	8.29	6.24	5.10	4.36	3.84	3.45	3.14	2.89	2.69
– of which equipment	$MUSD/MW_e$	2.73	2.06	1.68	1.44	1.27	1.14	1.03	0.95	0.88
– of which installation	$MUSD/MW_e$	5.56	4.18	3.42	2.93	2.58	2.31	2.11	1.94	1.80

Solar PVT

PVT collector is a solar energy device that uses PV as a thermal absorber and produces both electrical and thermal energy. There is a wide variety of PVT module configurations. (Table F.46 lists the characteristics of PVT collectors.) Several previous market surveys have been published. The attention for PVT systems and the number of suppliers is steadily growing.

On one hand, PVT collectors are used in the well-known fields of application of solar thermal energy such as DHW heating, DHW heating with heating support and supply of warm air, e.g., for heating swimming halls. However, non-covered

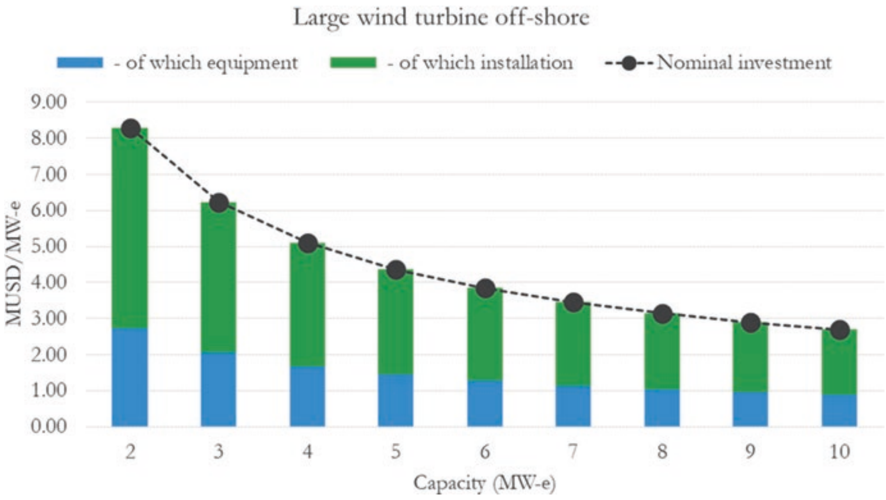


Fig. F.24 Nominal investment for large offshore wind turbine

Table F.45 Nominal investment for large offshore wind turbine nearshore

Technology	Unit	Large offshore wind turbine nearshore								
Electric capacity	MW_e	2	3	4	5	6	7	8	9	10
Specific investment, total system	$MUSD/MW_e$	6.79	5.11	4.18	3.58	3.15	2.83	2.57	2.37	2.20
– of which equipment	$MUSD/MW_e$	2.32	1.74	1.43	1.22	1.07	0.96	0.88	0.81	0.75
– of which installation	$MUSD/MW_e$	4.48	3.37	2.76	2.36	2.08	1.86	1.70	1.56	1.45

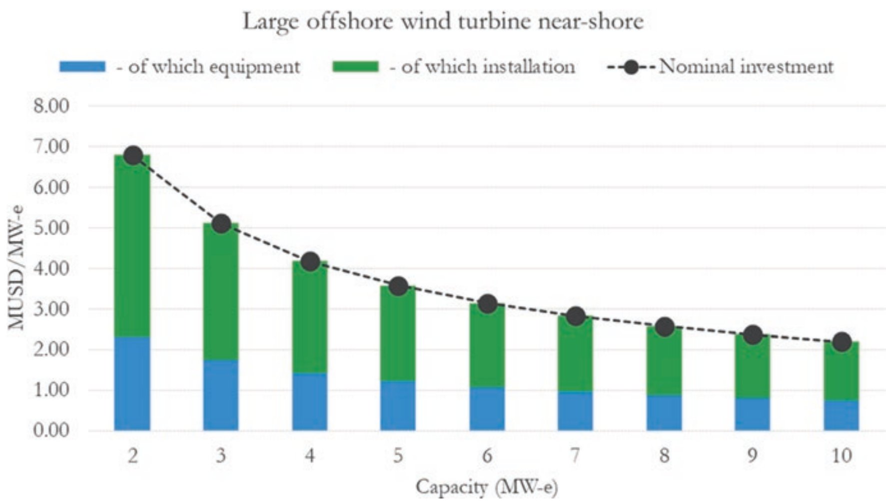


Fig. F.25 Nominal investment for large offshore wind turbine nearshore

Table F.46 Characteristics of PVT collectors

Main characteristics	Renewable heat and electricity generation
Technology interdependencies	Similar to sole solar thermal and photovoltaic installation
Advantages	Compactness and yields, good combination of PVT with heat pump
Disadvantages	Complexity of system design and installation, difficulties in optimization, low economic profitability, and high investment costs
Recommended for	Buildings with a high heat demand throughout the year, e.g., hotels, dormitories, hospitals, pools, residential buildings

liquid-cooled PVT collectors are also used in heat pump systems where their low-temperature heat is primarily used at the source side of the heat pump. In particular, the use for the regeneration of geothermal probes deserves mention. First demonstration projects with PVT ("Hybrid") collectors have been realized since around 2010. One example is the swimming hall of Kümmersbruck with 120 m^2 (1291 ft^2) collector field. There are quite a few projects in Switzerland, where water PVT is increasingly used to regenerate geothermal heat sources and support the heat pump. Examples range from single-family homes to building compounds with hundreds of apartments.

Furthermore, PVT collectors are distinguished by their:

- Electric performance, which can be higher or lower than that of pure PV, depending on operating conditions (temperature).
- Thermal performance, which is similar to that of solar collectors.
- Costs, which are higher than for usual PV systems. As first approximation, one could use the sum of corresponding PV and solar thermal field costs.
- Installation costs, which depend on availability of experienced experts, usually higher than for single purpose, can reach 40% of total costs.

Since there are so many technological solutions, costs vary. Costs are expected to fall, as the technology is still strongly developing.

Monitoring data obtained from existing, operational facilities (Fig. F.26) show that a 5% rise in electric efficiency can be reached and a COP increases by 1.5 (if heat is used as source for heat pump). Table F.47 describes solar PV panel products.

Sources

https://www.seac.cc/wp-content/uploads/2018/01/SEAC_PVTinSHaPeBenchmark_final.pdf

https://www.solarthermalworld.org/sites/gstec/files/news/file/2017-06-01/pvt_switzerland_final.pdf

BMWi (Bundesministerium fur Wirtschaft und Energie [Federal Ministry for Economic Affairs and Energy]). 2018. *Welcome to energieforschung.de, the information portal about funding opportunities and facts about applied energy research.* Web page. http://www.bine.info/publikationen/publikation/solardaecher-doppelt-nutzen/.

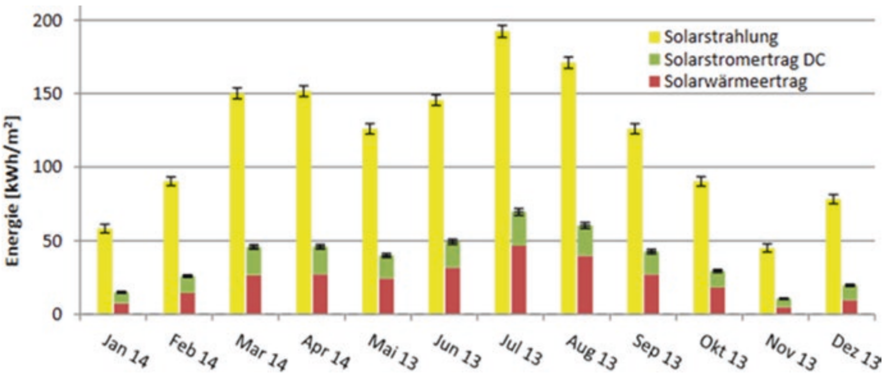


Fig. F.26 Electric efficiency and COP data from existing, operational facilities

Fraunhofer ISE. 2016. *PVTgen2—Optimized PVT Collectors for Combined Electricity and Heat Generation*. Web page. Freiburg, Germany: Fraunhofer ISE. https://www.ise.fraunhofer.de/en/research-projects/pvtgen2.html

IEA (International Energy Agency). 2021. *Application of PVT Collectors*. Web page. Bournens, Switzerland: International Energy Agency, Solar Heating & Cooling Programme, Task 60. http://task60.iea-shc.org/.

F.1.4.2 Fuel Cells

Fuel cells use an electrochemical process to convert the chemical energy in a fuel to electricity. In contrast to reciprocating engines and gas turbines, fuel cells generate electricity without combusting the fuel. The first practical application for fuel cells emerged in the 1950s when fuel cells were used to provide onboard power for spacecraft. Fuel cells continue to be used in space exploration, but over the past few decades, the technology has migrated to other applications, including vehicle transportation and stationary power generation. For stationary power, fuel cells are used for distributed generation (DG, electricity only) and are also configured for CHP. The data in Table F.48 provide an overview of fuel cell operation in CHP applications.

Fuel cells produce direct current electricity through an electrochemical process, much like a standard battery. Unlike a standard battery, a fuel supply continuously replenishes the fuel cell. A single fuel cell element consists of a cathode (positively charged electrode), an anode (negatively charged electrode), and an electrolyte. Hydrogen and oxygen are fed to the anode and cathode, respectively, and chemical reactions occur in the presence of catalysts at the anode and cathode. The chemical reactions generate ions and electrons that produce direct current (DC) electricity and water. The voltage generated from a single fuel cell element is low (< 1 volt DC). For practical applications, over a hundred cells are typically combined (“stacked”) in series to generate voltages in the range of 200–400 volts DC.

Table F.47 Solar PV panel product description

Product name	Capacity (MW)	Size (m^2)	Material	Company	Website	Type
2Power HM 260	260	1.6	mono cSi	PA-ID Process (GE)	http://www.2power-hybrid.com/de/	Flat plate water, insulation
3F Solar One Hybrid—collector	265	1.6	mono cSi	3F Solar (AT)	http://www.3f-solar.at	Flat plate water, insulation
Alius Solar Volthera	260–275	1.6	Poly/ mono cSi	Alius Solar (NL)	http://aliusenergy.nl	Flat plate water, insulation
3S HYBRID 240–900	285	1.6	mono cSi	Meyer Burger (CH)	http://www.meyerburger.com	Flat plate water
Building Energy Hybrid PV/T 2	250	1.6	Poly/ mono cSi	Building Energy (BE)	http://buildingenergy.be	Flat plate water, with/ without insulation
Optisolar PVT-Thermodule 2.0				Optisolar PVT (NL)	http://www.optisolarpvt.nl	Flat plate water, insulation
Solarus Power Collector	250	2.5	cSi	Solarus (NL/SE)	http://www.solarus.com	Concentrating sunlight
Solarduct PV/T	100			Conserval Engineering	http://solarwall.com/en/home.php	Ventilated PV module with heat recovery system for ventilation system

Table F.48 Technical and economic assumptions for fuel cells

Technology	Unit	SOEC (solid oxide electrolyser cell)	LT PEM EC (low-temperature proton exchange membrane electrolyser cell)
Energy/technical data			
Typical total plant size	MW input	1	10
Inputs			
A) Electricity input	% total size	85	100
B) Heat input	% total size	15	0
Outputs			
A) Hydrogen output	% total size	76	58
B) Heat output	% total size	3	0
Forced outage	%		
Planned outage	Weeks per year		
Technical lifetime	Years	20	15
Construction time	Years	0.5	0.5
Financial data (USD)			
Specific investment	MUSD per MW input	2.46	1.23
– of which equipment	%	1.11	0.92
– of which installation	%	1.63	0.37
Fixed O&M	USD per MW input per year	73,920	61,600
Variable O&M	USD per MWh input	0	0
Technology-specific data			
Operating temperature	deg C	750	80
Stack lifetime	Years	5	-
Ramp-up time, linear to full load	Minutes	1	0.03
Ramp-down time, linear to full load	Minutes	1	0.02
Startup time	Minutes	60	0.5

Several electrolytes have been successfully developed, and fuel cells are often categorized by the type of electrolyte or, in some cases, the type of fuel. Six leading fuel cell technologies are alkaline (AFC), direct methanol (DMFC), phosphoric acid (PAFC), proton exchange membrane (PEMFC), molten carbonate (MCFC), and solid oxide (SOFC). Four of these technologies—PAFC, PEMFC, MCFC, and SOFC—have been used for CHP.

In addition to the fuel cell stack, commercially available fuel cells are typically packaged with two other integrated subsystems: a fuel processor and a power conditioner. The fuel processor, or reformer, converts the fuel (e.g., natural gas or biogas) into a hydrogen-rich feed stream for the fuel cell stack. The power conditioner regulates the DC electricity generated from the stack and converts this DC power to AC.

F.1.5 Resiliency

In this category, we collect all the technologies that are of particular important for power system resilience. There are two types of technologies: one group of technologies maintains supply in case of breakdown, and another group of technologies prevents break down.

In this section, we mainly focus on the first group and briefly present the second group.

In the first group, we find an emergency generator, which is installed for generating power in emergency operation only and is therefore not efficient enough for normal power generation, or a UPS battery, which is installed for short-term emergency operation before a generator is started and not for storing electricity.

In the second group, we find underground cables to replace wires above ground both for distribution and transmission at production plants, which deliver both peak and spare capacity as well as large smart electricity consumers and which can be interrupted at any time and can also help balance the grid.

Electricity, in all its forms, is a vital commodity that enables societies and economies to function properly. Disruptions in energy systems have the potential to cause severe impacts, thereby limiting economic and societal development. As such, modern electricity systems must be able to withstand shocks from a wide range of sources, including natural disasters, geopolitical conflicts, and new and emerging threats related to the ongoing digitalization of electricity systems.

The electricity sector faces multiple threats from climate change, in particular from extreme weather events and increasing stress on water resources (see Fig. F.27). Greater resilience to climate change impacts will be essential to the technical viability of the energy sector and its ability to cost-effectively meet the rising energy demands driven by global economic and population growth.

Electricity systems around the world are becoming more interconnected and intelligent. This expansion brings many opportunities but also new challenges as suppliers and governments seek to ensure the security of these systems. To date, cyber-related disruptions to the energy sector have been relatively minor; however,

Fig. F.27 Grid resiliency

Fig. F.28 Emergency generators

cyberattacks are becoming more common, and the issue will only become more important as greater volumes of data are exchanged or stored on servers and with the increasingly rapid development of connected devices.

F.1.5.1 Emergency Generators

An emergency generator (Fig. F.28) is a backup electrical system that operates automatically. Within seconds of a utility outage, an ATS senses the power loss, commands the generator to start, and then transfers the electrical load to the generator. The standby generator begins supplying power to the circuits. After utility power returns, the automatic transfer switch (ATS) transfers the electrical load back to the utility and signals the standby generator to shut off. It then returns to standby mode where it awaits the next outage. To ensure a proper response to an outage, a standby generator runs weekly self-tests. Most units run on diesel, natural gas, or liquid propane gas.

Automatic standby generator systems may be required by building codes for critical safety systems such as elevators in high-rise buildings, fire protection systems, standby lighting, or medical and life support equipment. Residential standby generators are increasingly common, providing backup electrical power to HVAC systems, security systems, and household appliances such as refrigerators, stoves, and water heaters.

Sources

Ericson and Olis (2019)
Wikipedia. Undated(e). Standby Generator. https://en.wikipedia.org/wiki/Standby_generator

F.1.5.2 UPS

A UPS is an electrical apparatus that provides emergency power to a load when the input power source or main power fails. A UPS differs from an auxiliary or emergency power system or standby generator in that it will provide near-instantaneous protection from input power interruptions, by supplying energy stored in batteries, supercapacitors, or flywheels. The on-battery run time of most UPSs is relatively short (only a few minutes) but sufficient to start a standby power source or properly shut down the protected equipment. It is a type of continual power system.

A UPS is typically used to protect hardware such as computers, data centers, telecommunication equipment, or other electrical equipment where an unexpected power disruption could cause injuries, fatalities, serious business disruption, or data loss. UPS units range in size from units designed to protect a single computer without a video monitor (around 200-volt-ampere rating) to large units powering entire data centers or buildings. The world's largest UPS, the 46-megawatt battery electric energy storage system (BESS), in Fairbanks, Alaska, powers the entire city and nearby rural communities during outages (Figs. F.29, F.30, and F.31).

Sources

Eaton (2011)
Wikipedia. Undated(g). *Uninterruptible Power Supply* https://en.wikipedia.org/wiki/Uninterruptible_power_supply

Redundancy – the duplication of critical components or functions of a system with the intention of increasing reliability of the system
N: Only the number of components needed is provided; there is no resilience, and any component failure will cause downtime.

Fig. F.29 Batteries in Fairbanks and Mira Loma

Fig. F.30 Lithium manganese oxide (LMO) + lithium nickel manganese cobalt oxide (NMC) (left) and lithium iron phosphate (LFP) (right)

Fig. F.31 Supercapacitor

N+1: Where the number of components provided is one more than the number (N) of components needed.

2N: Comprises two complete systems, each containing N components, and are run in parallel to hot swap between each other.

2(N+1): Comprises two N+1 systems in parallel. One side can be taken down for maintenance, and the other side will be protected from exposure to the risk of downtime by its own redundant module.

Reliability – the probability that a product or service will operate properly for a specified period of time under design operating conditions without failure.

MTBF— Mean time between failures: average time the equipment performed its intended function between failures.

MTTR—Mean time to repair: average time it takes to repair the failure and get the equipment back into service.

Availability – is the long-term average fraction of time that a repairable component or system is in service and satisfactorily performing its intended function.

$$\text{Availability} = \text{MTBF} / \left(\text{MFBF} + \text{MTTR}\right)$$

$$\left(8760\,\text{h in 1 year of operation}\right)$$

F.1.5.3 Emergency Power System

An emergency power system is an independent source of electrical power that supports important electrical systems on loss of normal power supply. A standby power system may include a standby generator, batteries, and other apparatuses. Emergency power systems are installed to protect life and property from the consequences of loss of primary electric power supply. It is a type of continual power system.

Emergency power systems find uses in a wide variety of settings from homes to hospitals, scientific laboratories, data centers, telecommunication equipment, and ships. Emergency power systems can rely on generators, deep-cycle batteries, flywheel energy storage, or fuel cells.

Emergency power systems (Fig. F.32) were used as early as World War II on naval ships. In combat, a ship may lose the function of its boilers, which power the steam turbines for the ship's generator. In such a case, one or more diesel engines

Fig. F.32 Emergency power system

are used to drive backup generators. Early transfer switches relied on manual operation; two switches would be placed horizontally, in line and the "on" position facing each other. A rod is placed in between. To operate the switch, one source must be turned off, the rod moved to the other side, and the other source turned on.

Sources

FEMA (2014).
Wikipedia. Undated(a). *Emergency Power System* https://en.wikipedia.org/wiki/Emergency_power_system

F.1.5.4 Reliability Technology Data

The sample data provided in Fig. F.33 and Table F.49 originate from Army Technical Manual (TM) 5-698-5, *Survey of Reliability and Availability Information for Power Distribution, Power Generation, and HVAC Components for Commercial, Industrial, and Utility Installations*. The full table is available within the tool database or accessible here: https://www.wbdg.org/ffc/army-coe/technical-manuals-tm/tm-5-698-5.

F.1.5.5 Underground Cables

Statistics indicate that most failures and interruptions due to unforeseen events like hurricanes occur in the power distribution system. Moreover, aboveground or overhead power distribution and high-voltage cables have a negative impact on the environment in cities and in protected natural areas.

Some countries prefer not to use overhead cables and save costs of distribution, whereas other countries prefer to pay additional costs of underground cables to increase the resiliency and avoid the need for backup generators.

Hurricanes are not common in Denmark, but in 1999, a storm destroyed some of the power distribution lines aboveground, and there was a blackout for several days in some regions. Therefore, the Parliament decided that all low-voltage distribution

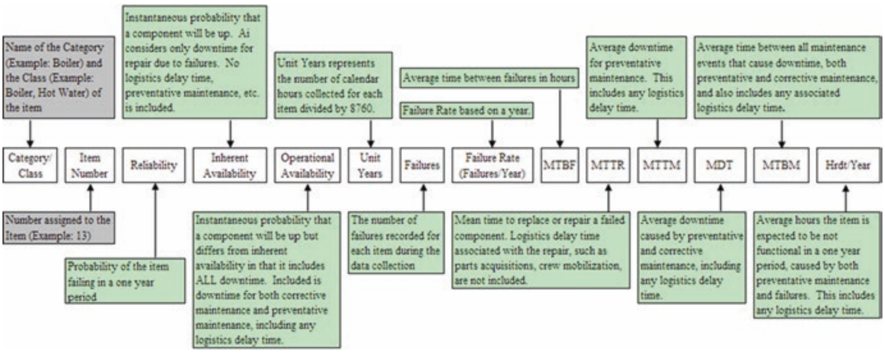


Fig. F.33 Reliability technology data

Table F.49 Reliability technology data

Category/class	Item number	Reliability	Inherent availability	Operational availability	Unit years	Failures	Failure rate (Failures/year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/year
Accumulator	H1-000	0.993467721	0.999993849	0.999884828	1373.3	9	0.00655	1336648	8.22	0.8375	0.88	7638	1.0089
Pressurized	H1-100	0.993913727	0.999992102	0.999841861	982.8	6	0.0061	1434920	11.33	1	0.897	5672	1.3853
Unpressurized	H1-200	0.992345933	0.999998246	0.999992983	390.4	3	0.00768	1140104	2	0	0.421	60005	0.0615
Air compressor	H2-000	0.964395571	0.999966392	0.999377084	799.9	29	0.03625	241630.3	8.12	0.3086	0.326	523	5.4567
Electric	H2-100	0.92680572	0.999919556	0.999207149	315.7	24	0.07601	115246	9.27	0.1602	0.178	224	6.9454
Fuel	H2-200	0.989726301	0.999996935	0.999487902	484.2	5	0.01033	848275.2	2.6	2	2.006	3916	4.486
Air dryer, all types	H4-000	0.997716217	0.999998695	0.999926162	437.4	1	0.00229	3831360	5	1	0.946	12814	0.6468
Air handling unit	H5-000	0.989056337	0.999997032	0.999875595	1817.5	20	0.011	796075.2	2.36	xxx	99.036	796075	1.0898
Non-humid	H5-200	0.989056337	0.999997032	0.999875595	1817.5	20	0.011	796075.2	2.36	xxx	99.036	796075	1.0898
W/o drive	H5-210	0.989056337	0.999997032	0.999875595	1817.5	20	0.011	796075.2	2.36	0	99.036	796075	1.0898
Arrester, lightning	E1-000	0.998679474	0.999999397	0.999999397	1513.5	2	0.00132	6629340	4	0	4	6629340	0.0053
Battery	E2-000	0.993006248	0.999990299	0.999969547	10543.8	74	0.00702	1248161	12.11	0.149	0.217	7140	0.2668
Rechargeable	E2-100	0.993006248	0.999990299	0.999969547	10543.8	74	0.00702	1248161	12.11	0.149	0.217	7140	0.2668
Gel cell-sealed, strings	E2-110	0.980061731	0.999995402	0.999967422	2333.7	47	0.02014	434961.4	2	0	0.152	4660	0.2854
Lead-acid, string	E2-120	0.992563514	0.999972627	0.999968207	3215.3	24	0.00746	1173590	32.13	0	1.023	32190	0.2785
Nickel-cadmium	E2-130	0.999399558	0.999999292	0.999971403	4994.8	3	0.0006	14584865	10.33	0	0.163	5701	0.2505
Blower	H7-000	0.999825378	1	0.999960812	2920.3	0	0.00017	50160988	xxx	0.0692	0.069	1765	0.3433
W/o drive	H7-100	0.999825378	1	0.999960812	2920.3	0	0.00017	50160988	xxx	0	0.069	1765	0.3433
Boiler	H8-000	0.87864221	0.999360697	0.995132436	1113	144	0.12938	67708.83	43.29	3.2844	3.738	768	42.639
Hot water	H8-100	0.959008598	0.999985268	0.999501894	358.4	15	0.04186	209292.8	3.08	1	1.005	2018	4.3634

(continued)

Table F.49 (continued)

Category/class	Item number	Reliability	Inherent availability	Operational availability	Unit years	Failures	Failure rate (Failures/ year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ year
Steam	H8-200	0.842870823	0.99906409	0.993057393	754.6	129	0.17094	51245.58	47.96	3.6062	4.12	593	60.817
High pressure	H8-210	0.928026957	0.999619462	0.991492148	468.6	35	0.07469	117277.7	44.63	3	3.162	372	74.528
Low pressure	H8-220	0.719936234	0.9981544	0.995621239	286.1	94	0.32859	26659.1	49.2	0	116.734	26659	38.357
Bus duct, all types/100ft	E3-000	0.99969629	1	1	1679	0	0.0003	28838917	xxx	xxx	xxx	xxx	0
Cabinet heaters	E4-000	0.99989793	0.999999994	0.999978224	9796.7	1	0.0001	85819128	0.5	1.6476	1.647	75612	0.1908
Forced air flow steam or hot water	E4-100	0.99989793	0.999999994	0.999978224	9796.7	1	0.0001	85819128	0.5	2	1.647	75612	0.1908
Cable, AC per 1000 ft.	E6-000	0.998679301	0.9999989	0.999987359	698411	923	0.00132	6628468	7.29	4.281	4.44	351270	0.1107
Cable, AC, 0–600 V	E6-100	0.998924937	0.99999889	0.999995587	130155	140	0.00108	8143981	9.04	6.3706	6.882	1559723	0.0387
Aboveground	E6-110	0.99990438	0.999999953	0.999995381	62745.1	6	0.0001	91607820	4.33	4.6194	4.616	999358	0.0405
In conduit	E6-111	0.999932074	0.999999938	0.999990264	29442.9	2	0.00007	128959932	8	13	13.01	1336372	0.0853
In trays	E6-112	0.968468243	1	1	15.9	0	0.03204	273411.8	0	0	xxx	xxx	0
No conduit	E6-113	0.999879838	0.999999966	0.999999904	33286.3	4	0.00012	72896904	2.5	0	0.078	816772	0.0008
Below ground	E6-120	0.998014135	0.9999979	0.99999578	67409.9	134	0.00199	4406794	9.25	26.6382	13.768	3262488	0.037
In duct	E6-121	0.999875009	0.999999766	0.999999697	40000.4	5	0.00012	70080729	16.4	1	2.789	9221149	0.0026
In conduit	E6-122	0.997994901	0.999997428	0.999991686	24413.2	49	0.00201	4364479	11.22	88	28.222	3394595	0.0728
Insulated	E6-123	0.973653295	0.999976836	0.999976836	2996.3	80	0.0267	328089.9	7.6	0	7.6	328090	0.2029
Cable, AC, 601–15 kV	E6-200	0.998623048	0.999998903	0.999985474	568256	783	0.00138	6357495	6.98	4.2034	4.333	298329.1	0.1273
Aboveground	E6-210	0.999462309	0.999999477	0.999998712	526182.7	283	0.00054	16287492	8.52	10.5194	9.605	7458512	0.0113

In conduit	E6-211	0.999463225	0.999999476	0.999998707	523356.6	281	0.00054	16315315	8.56	41	16.109	12458162	0.0113
In trays	E6-212	0.997171966	1	1	180.1	0	0.00283	3093176	0	0	xxx	xxx	0
No conduit	E6-214	0.999244433	0.999999655	0.999999655	2646	2	0.00076	11589564	4	0	0.032	92717	0.003
Below ground	E6-220	0.988186203	0.999991725	0.999819915	42072.9	500	0.01188	737117.2	6.1	4.0674	4.131	22937.4	1.5776
In conduit	E6-221	0.997646877	0.999995779	0.999987126	19525.5	46	0.00236	3718331	15.7	211	41.547	3227231	0.1128
In duct	E6-222	0.987125021	1	1	39.4	0	0.01296	676000	0	0	xxx	xxx	0
Insulated	E6-223	0.980031515	0.999988193	0.999674546	22508.1	454	0.02017	434296.5	5.13	4	4.007	12312	2.851
Cable, aerial per 1 mile	E7-000	0.988381339	0.999997295	0.999997259	37478.5	438	0.01169	749570.9	2.03	0.3529	1.907	695576	0.024
Cable, aerial, 0–15 kV	E7-100	0.953928762	0.999990218	0.999990218	6593.7	311	0.04717	185725.9	1.82	0	1.817	185726	0.0857
Cable, aerial >15 kV	E7-200	0.995896395	0.999998806	0.999998762	30884.9	127	0.00411	2130325	2.54	0	2.081	1680443	0.0108
Cable, DC per 100 ft.	E8-000	0.992748496	0.999998338	0.999998338	412.2	3	0.00728	1203640	2	0	0.109	65653	0.0146
Cable, DC, insulated	E8-100	0.992748496	0.999998338	0.999998338	412.2	3	0.00728	1203640	2	0	0.109	65653	0.0146
Cable connection	E5-000	0.999629261	0.999999968	0.999999968	21574.5	8	0.00037	23624073	0.75	xxx	0.75	23624073	0.0003
Below ground, duct ≤600 V, per 1000ft	E5-100	0.999629261	0.999999968	0.999999968	21574.5	8	0.00037	23624073	0.75	xxx	0	23624073	0.0003
Capacitor bank													
Power factor corrector (in kVAR)	E10-000	0.83993744	0.999954142	0.999942075	567.6	99	0.17443	50221.33	2.3	10	2.743	47352	0.5074
Charger, battery	E11-000	0.992621004	0.999999577	0.999986472	270	2	0.00741	1182768	0.5	0	0.133	9816	0.1185
Chiller	H10-000	0.888515818	0.999829779	0.997620632	2021.9	239	0.1182	74109.9	12.62	1.0881	1.164	489	20.843
Absorption	H10-100	0.841986658	0.999769437	0.995132437	430.3	74	0.17199	50932.86	11.74	1	0.653	134	42.639
Centrifugal	H10-200	0.955142622	0.999923928	0.997604888	544.7	25	0.04589	190872.1	14.52	5.2247	5.333	2227	20.981

(continued)

Table F.49 (continued)

Category/class	Item number	Reliability	Inherent availability	Operational availability	Unit years	Failures	Failure rate (Failures/ year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ year
600–1000 tons	H10-220	0.955142622	0.999923928	0.997604888	544.7	25	0.04589	190872.1	14.52	5	5.333	2227	20.981
Reciprocating	H10-300	0.864557699	0.999799791	0.998898189	948.2	138	0.14554	60190.78	12.05	1.5457	1.837	1667	9.6519
Closed	H10-320	0.879941865	0.999809524	0.998734968	680.2	87	0.1279	68491.3	13.05	1	1.662	1314	11.081
W/ drive, 50–200 T	H10-321	0.879941865	0.999809524	0.998734968	680.2	87	0.1279	68491.3	13.05	1	1.662	1314	11.081
Open	H10-330	0.826705884	0.999775088	0.999312485	268	51	0.19031	46031.1	10.35	3	3.611	5252	6.0226
W/o drive,50–200 T	H10-331	0.826705884	0.999775088	0.999312485	268	51	0.19031	46031.1	10.35	3	3.611	5252	6.0226
Rotary	H10-400	0.986993503	0.999964132	0.996197991	76.4	1	0.01309	669120	24	6.0723	6.115	1608	33.305
600–1000 ton	H10-410	0.986993503	0.999964132	0.996197991	76.4	1	0.01309	669120	24	6	6.115	1608	33.305
Screw	H10-500	0.95628669	0.999510164	0.996566046	22.4	1	0.0447	195984	96	1	1.164	339	30.081
>300 tons	H10-520	0.95628669	0.999510164	0.996566046	22.4	1	0.0447	195984	96	1	1.164	339	30.081
Circuit breaker	E12-000	0.999996752	0.999999582	0.999983888	157040.9	52	0	26974078	xxx	1.9167	1.959	121569	0.1411
Fixed (incl. mold case)	E12-200	0.999996551	0.999999899	0.999992732	147880	5	0	25400557	xxx	8.2967	8.376	1152516	0.0637
≤600V, 3ph,≤600 A	E12-210	0.999949237	0.999999892	0.999994177	59096.5	3	0.00005	172561870	18.667	5.9887	6.065	1041621	0.051
Normally closed	E12-211	0.999984307*	1	0.999997443	32498.7	0	0.00002*	558213637*	0	3	3.098	1211442	0.0224
Normally open	E12-212	0.999887215	0.99999976	0.999990187	26597.8	3	0.00011	77665552	18.67	9	8.727	889300	0.086
≤600V, 3ph,>600 A	E12-220	0.999977474	0.999999904	0.99999177	88783.4	2	0.00002	388871412	37.5	10.121	10.208	1240419	0.0721
Normally closed	E12-221	0.999994218*	1	0.999992509	88200.2	0	0.00001*	1514968565*	0	14	13.618	1817962	0.0656,
Normally open	E12-222	0.996576534	0.99998532	0.999880051	583.2	2	0.00343	2554428	37.5	3	3.034	25291	1.0507

Metal clad (drawout)	E12-400	0.998892235	0.999999605	0.99983799	7217.8	8	0.00111	7903437	3.13	2.0569	2.059	12706	1.4192
≤600V, ≤600Amp	E12-410	0.999463921	0.999999633	0.999806833	5594.7	3	0.000536	16336496	6	2.0831	2.086	10797.4	1.6921
Normally closed	E12-411	0.999792091	0.999999858	0.999798004	4809.3	1	0.00021	42129480	6	2	2.019	9998	1.7695
Normally open	E12-412	0.997456731	0.999998256	0.999860901	785.4	2	0.00255	3440004	6	3	2.945	21169	1.2185
≤600V, >600 Amp	E12-420	0.99692414	0.999999508	0.999945386	1623.1	5	0.00308	2843602	1.4	1.7813	1.777	32535.5	0.4784
Normally closed	E12-421	0.998150509	0.999999894	0.999954301	1080.4	2	0.00185	4732057	0.5	1	1.481	32411	0.4003
Normally open	E12-422	0.994487152	0.999998738	0.999927638	542.7	3	0.00553	1584631	2	2	2.372	32785	0.6339
Vacuum	E12-700	0.980129686	0.999975385	0.99985278	1943.2	39	0.02007	436464	10.74	0.4031	0.48	3263	1.2897
<15kV, <600 Amp	E12-710	0.998771968	0.999998878	0.999973208	813.8	1	0.00123	7128984	8	0.0728	0.076	2834.6	0.2347
Normally closed	E12-711	0.997191564	0.999997432	0.999960511	355.6	1	0.00281	3114792	8	0	0.05	1257	0.3459
Normally open	E12-712	0.998887668*	1	0.99998306	458.2	0	0.00111*	7870964*	0	2	1.838	108492	0.1484
<15kV, >600 Amp	E12-720	0.966912133	0.999958456	0.999765999	1129.4	38	0.03365	260345.1	10.82	0.715	0.857	3662.8	2.0499
Normally closed	E12-721	0.976752059	0.999960259	0.999619774	425.1	10	0.02352	372410.4	14.8	1	1.62	4261	3.3308
Normally open	E12-722	0.961020019	0.999957368	0.999854272	704.2	28	0.03976	220321.7	9.39	0	0.492	3377	1.2766
Compressor, refrigerant	H11-000	0.986548811	0.999986587	0.999865676	1255.3	17	0.01354	646853.6	8.68	0.9208	1.011	7527	1.1767
>1 ton	H11-020	0.995193627	0.999998075	0.999907183	1037.8	5	0.00482	1818196	3.5	1	0.925	9968	0.8131
Screw type	H11-100	0.946328222	0.999931777	0.999667651	217.5	12	0.05517	158794	10.83	1	1.154	3471	2.9114
Condensers	H12-000	0.900083857	0.99991381	0.999583534	1102	116	0.10527	83216.68	7.17	4.0979	4.497	10798	3.6482
Double tube	H12-100	0.973573588	0.999992357	0.999758971	298.7	8	0.02678	327087	2.5	3	2.628	10903	2.1114
Propeller-type fans, with coils DX: direct expansion	H12-200	0.733621551	0.999734138	0.999393134	348.7	108	0.30976	28279.77	7.52	3	4.165	6863	5.3161

(continued)

Table F.49 (continued)

Category/class	Item number	Reliability	Inherent availability	Operational availability	Unit years	Failures	Failure rate (Failures/ year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ year
Shell and tube	H12-300	0.998878743	1	0.999614286	454.6	0	0.00112	7808282	xxx	7	7.349	19054	3.3789
Control panel	C4-000	0.994698171	0.999998908	0.999800824	5643.4	30	0.00532	1647876	1.8	4.441	4.406	22119	1.7448
Generator, w/o switchgear	C4-100	0.988952766	0.99999733	0.999980962	1710.4	19	0.01111	788570.5	2.11	1	0.635	33369	0.1668
HVAC/chillers/ AHUs, w/o switchgear	C4-200	0.999848787	1	0.999982209	3372.5	0	0.00015	57926964	xxx	1	1.045	58733	0.1559
Switchgear	C4-300	0.980568763	0.999997149	0.998160003	560.6	11	0.01962	446426.1	1.27	7	7.043	3828	16.118
Convectors	H13-000	0.999913016	1	0.999998481	5862.9	0	0.00009	10070423	xxx	0.0149	0.015	9830	0.0133
Fin tube baseboard	H13-100	0.999913016	1	0.999998481	5862.9	0	0.00009	10070423	xxx	0.0149	0.015	9830	0.0133
Electric	H13-110	0.999582861*	1	0.999999626	1222.4	0	0.00042*	20995811*	0	0	0.005	12702	0.0033
Steam/hot water	H13-120	0.999890105*	1	0.99999818	4640.6	0	0.00011*	79708423*	0	0	0.017	9277	0.0159
Cooling tower	H14-000	0.968333522	0.999702865	0.99717052	839.1	27	0.03218	272229.7	80.89	1.0681	1.192	421	24.786
Atmospheric type, w/o fans, Motors, pumps, valves, etc.	H14-100	0.928543791	0.999247479	0.994184363	323.7	24	0.07414	118158.5	88.92	1	1.137	196	50.945
Evaporative type w/o fans, motors, pumps, valves, etc.	H14-200	0.99419554	0.999988924	0.99904633	515.3	3	0.00582	1504800	16.67	1	1.458	1529	8.3542

Damper assembly	H15-000	0.999971953	0.999999975	0.999990131	18183.5	2	0.00003	31232804	xxx	0.054	0.054	5486	0.0865
Motor operated	H15-100	0.999966919	1	0.999989337	15416.3	0	0.00003	264797694	xxx	0	0.05	4656	0.0934
Pneumatic	H15-200	0.999277503	0.999999835	0.999994555	2767.2	2	0.00072	12120240	2	4	3.882	712955	0.0477
Generator, diesel engine	E18-000	0.589772164	0.998540049	0.993985981	1354.1	715	0.52802	16590.31	24.22	2.0554	2.642	439	52.682
Packaged	E18-100	0.775917369	0.99932981	0.997272882	938.1	238	0.25371	34527.71	23.14	1.1483	1.498	549.4	23.89
250kW–1.5 MW	E18-120	0.775917369	0.99932981	0.997272882	938.1	238	0.25371	34527.71	23.14	1.1483	1.498	549.4	23.89
Continuous	E18-121	0.558396351	0.998287624	0.99692725	266	155	0.58269	15033.8	25.74	1	1.149	374	26.917
Standby	E18-122	0.883822868	0.999742312	0.997409685	672.1	83	0.1235	70932	18.28	2	1.748	675	22.691
Unpackaged	E18-200	0.317735957	0.996759289	0.986574653	416	477	1.14653	7640.415	24.76	3.2103	4.064	303	117.6
750kW–7 MW	E18-210	0.317735957	0.996759289	0.986574653	416	477	1.14653	7640.415	24.76	3.2103	4.064	303	117.6
Continuous	E18-211	0.162719469	0.994801067	0.980739869	180.6	328	1.81573	4824.5	25.08	4	4.997	259	168.71
Standby	E18-212	0.531004159	0.998262059	0.991052357	235.4	149	0.63299	13839.2	24.05	3	3.106	347	78.381
Drive	E14-000	0.978172315	0.999958316	0.999925947	2990.6	66	0.02207	396929	16.55	3.4472	6.218	83966	0.6487
Adjustable speed	E14-100	0.978172315	0.999958316	0.999925947	2990.6	66	0.02207	396929	16.55	3	6.218	83966	0.6487
Evaporator	H18-000	0.995968933	0.999993228	0.999908962	7922.3	32	0.00404	2168739	14.69	0.2565	0.277	3040	0.7975
Direct expansion	H18-100	0.995812835	0.999992633	0.999899263	6911.4	29	0.0042	2087724	15.38	0.2689	0.29	2876	0.8825
Coil	H18-110	0.995812835	0.999992633	0.999899263	6911.4	29	0.0042	2087724	15.38	0	0.29	2876	0.8825
Shell tube	H18-120	0.997036799	0.99999729	0.99997527	1010.9	3	0.00297	2951880	8	0	0.123	4972	0.2166
Fan	H19-000	0.987559807	0.99997161	0.999351118	2396.5	30	0.01252	699780	19.87	4.2211	4.372	6737	5.6842
Centrifugal	H19-100	0.981021428	0.999946483	0.99977044	782.8	15	0.01916	457179.2	24.47	2	2.061	8976	2.0109
Propeller/disc	H19-200	0.989640193	0.999957798	0.999093547	384.1	4	0.01041	841188	35.5	2	1.954	2156	7.9405
Tube axial	H19-300	0.989938879	0.99999087	0.999055744	1087.8	11	0.01011	866290.9	7.91	11	11.375	12047	8.2717
Vane axial	H19-400	0.996408668*	1	1	141.8	0	0.00360*	2434823.*	0	0	xxx	xxx	0
Filter, electrical	E16-000	0.999898973	1	0.999903911	5047.9	0	0.0001	86704894	xxx	0.2894	0.289	3012	0.8417
Tempest	E16-200	0.998510134*	1	1	342.1	0	0.00149*	5875341*	0	0	0	2996424	0
Filter, mechanical	H20-000	0.99989163	1	0.999896927	4705.8	0	0.00011	80829552	xxx	0.2894	0.289	2808	0.9029
Air regulator set.	H20-100	0.999840000*	1	0.999981949	3187.2	0	0.00016*	54745647*	0	0	0.044	2464	0.1581

(continued)

Table F.49 (continued)

Category/class	Item number	Reliability	Inherent availability	Operational availability	Unit years	Failures	Failure rate (Failures/ year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ year
Fuel oil	H20-200	0.999271146*	1	0.999910729	699.5	0	0.00073*	12014494*	0	0	0.486	5442	0.782
Lube oil	H20-300	0.999377566*	1	0.999554311	819.1	0	0.00062*	14069411*	0	1	1.439	3229	3.9042
Fuse	E17-000	0.997969725	1	1	1145.4	0	0.00087	10033704	xxx	xxx	xxx	xxx	0
>5 kV ≤15 kV	E17-200	0.999341365*	1	1	774.1	0	0.00066*	13295858*	0	0	xxx	xxx	0
0–5 kV	E17-100	0.998627456*	1	1	371.3	0	0.00137*	6377929*	0	0	xxx	xxx	0
Generator, gas turbine	E19-000	0.647849145	0.998890863	0.990692798	921.5	400	0.4341	20179.8	22.38	2.1583	2.419	260	81.531
Packaged	E19-100	0.587787144	0.998689955	0.989043771	750.9	399	0.53139	16485.05	21.6	2.1103	2.366	216	95.976
750 kW–7 MW	E19-110	0.587787144	0.998689955	0.989043771	750.9	399	0.53139	16485.05	21.6	2.1103	2.366	216	95.976
Continuous	E19-111	0.177710554	0.994598022	0.983584136	167.9	290	1.7276	5070.6	27.39	1	1.225	75	143.8
Standby	E19-112	0.829472916	0.999868149	0.99061577	583	109	0.18696	46853.7	6.18	4	4.453	475	82.205
Unpackaged	E19-200	0.994155201	0.999775158	0.997950995	170.6	1	0.00586	1494384	336	4.5892	5.146	2512	17.949
750 kW–7 MW	E19-210	0.994155201	0.999775158	0.997950995	170.6	1	0.00586	1494384	336	4.5892	5.146	2512	17.949
Continuous	E19-211	0.994155201	0.999775158	0.997950995	170.6	1	0.00586	1494384	336	5	5.146	2512	17.949
Gauge	C5-000	0.999042094	1	0.999999785	532.2	0	0.00096	9140564	xxx	xxx	xxx	xxx	0.0019
Fluid level	C5-100	0.999042094*	1	0.999999785	532.2	0	0.00096*	9140564*	0	0	xxx	xxx	0.0019
Heat exchanger	H21-000	0.988170294	0.999985962	0.999515055	1512.6	18	0.0119	736120	10.33	0.95	0.976	2012	4.2481
Boiler system	H21-100	0.971835048	0.999998369	0.997231137	210	6	0.02857	306624	0.5	29	28.3	10221	24.255
Lube oil	H21-200	0.996596565	0.99999533	0.99974096	293.3	1	0.00341	2569488	12	7	6.59	25440	2.2692
Radiators	H21-300	0.987545587	0.99997776	0.999934189	877.7	11	0.012533	698976	15.55	0.0999	0.15	2285	0.5765
Small tube	H21-310	0.987545587	0.99997776	0.999934189	877.7	11	0.012533	698976	15.55	0.0999	0.15	2285	0.5765
Water to water	H21-400	0.996130029*	1	0.999861134	131.5	0	0.00388*	2259200*	0	0	0.054	392	1.2165
Heater	E24-000	0.947826981	0.999984168	0.994164558	317.3	17	0.05358	163483.7	2.59	1.2053	1.207	207	51.118

Lube fuel oil/Jkt water	E24-100	0.947826981	0.999984168	0.994164558	317.3	17	0.05358	163483.7	2.59	1.2053	1.207	207	51.118
Electric	E24-110	0.947826981	0.999984168	0.994164558	317.3	17	0.05358	163483.8	2.59	1	1.207	207	51.118
Humidistat	H24-000	0.984575905	0.999998226	0.999998226	643.3	10	0.01554	563551.2	1	0	0.043	24083	0.0155
Inverters all types	E25-000	0.995190512	0.999985691	0.999598793	414.8	2	0.00482	1817016	26	5	5.321	13263	3.5146
Meter	C6-000	0.998913484	0.999993988	0.999993961	16557.7	18	0.00109	8058086	48.44	0.0055	1.182	195743	0.0529
Electric	C6-100	0.999635167	0.999999958	0.999999958	13702.4	5	0.00036	24006614	1	0	0.025	606228	0.0004
Fuel	C6-200	0.946014073	0.999543853	0.999543853	216.2	12	0.0555	157844	72	0	72	157844	3.9958
Water	C6-300	0.999621152	0.99999987	0.999999697	2639.1	1	0.00038	23118360	3	0	0.013	43537	0.0027
Motor-generator set	E27-000	0.975052652	0.999978501	0.993070544	435.4	11	0.02526	346741	7.45	0.8368	0.839	121	60.702
3 phase	E27-100	0.975052652	0.999978501	0.993070544	435.4	11	0.02526	346741	7.45	0.8368	0.839	121	60.702
400 Hz	E27-120	0.995075131	0.999995491	0.999628032	202.6	1	0.00494	1774344	8	3	2.895	7782	3.2584
60 Hz	E27-110	0.957963867	0.999963722	0.987366458	232.9	10	0.04295	203980.8	7.4	1	0.824	65	110.66
Motor starter	E28-000	0.999147052	0.999995416	0.999944527	597.7	1	0.00085	10265882	xxx	0.2442	0.266	4795	0.4859
≤600 V	E28-100	0.998167781*	1	0.999984223	278.1	0	0.00183*	4776705*	0	0	0.081	5161	0.1382
>600 V	E28-200	0.996875738	0.999991427	0.999909983	319.6	1	0.00313	2799480	24	0	0.406	4515	0.7885
Motor, electric	E29-000	0.999032041	0.9999733	0.999930849	27880.2	27	0.00097	9045589	241.52	0.5662	0.921	13318	0.6058
DC	E29-100	0.985531708	0.999031729	0.998182336	754.8	11	0.01457	601071.2	582	0.4228	0.904	497	15.922
Induction	E29-200	0.981918899	0.99999295	0.999724259	712.5	13	0.01825	480090.4	3.38	2.9576	2.967	10761	2.4155
≤600 volts	E29-210	0.988992708	0.999998736	0.999957372	361.4	4	0.01107	791448	1	1	1.336	31344	0.3734
>600 volts	E29-220	0.974689985	0.999986993	0.999484292	351.1	9	0.02564	341709.3	4.44	3	3.311	6420	4.5176
Single phase	E29-300	0.999980411	0.999999987	0.999988267	26034.5	1	0.00002	44718136	xxx	0.6247	0.625	53286	0.1028
≤5 Amp	E29-310	0.999979878*	1	0.999996192	25345.3	0	0.00002*	435342400*	0	0	0.491	128934	0.0334
>5 Amp	E29-320	0.99855021	0.999999503	0.999696847	689.3	1	0.00145	6037872	3	1	0.716	2360	2.6556
Synchronous	E29-400	0.998653401	0.999978284	0.999857033	378.5	2	0.00135	6500894	xxx	2.2088	2.576	18019	1.2524
≤600 volts	E29-410	0.996555656*	1	0.99977758	147.8	0	0.00345*	2538917*	0	2	2	8992	1.9484

(continued)

Table F.49 (continued)

Category/class	Item number	Reliability	Inherent availability	Operational availability	Unit years	Failures	Failure rate (Failures/ year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ year
>600 volts	E29-420	0.991366824	0.999964367	0.999907948	230.7	2	0.00867	1010304	36	3	4.65	50515	0.8064
Engine	E15-000	0.195448823	0.999809717	0.998810724	1154.7	1885	1.63246	5366.145	1.02	2.8441	2.212	1860	10.418
Diesel	E15-100	0.904562026	0.999953538	0.991433654	129.6	13	0.1003	87334.15	4.06	3	3.253	380	75.041
Gas	E15-200	0.16102903	0.999791533	0.999743425	1025.1	1872	1.82617	4796.923	1	1	0.941	3668	2.2476
Pipe	H25-000	0.998585822	0.999998644	0.999685368	13425.9	19	0.00142	6190032	8.39	7.7161	7.719	24533	2.7562
Flex	H25-100	0.981888041	0.999994337	0.999991952	383	7	0.01828	479265	2.71	4	3	372762	0.0705
Non-reinforced	H25-110	0.985560776	0.999994466	0.999990038	206.3	3	0.01454	602290.2	3.33	4	3.6	361374	0.0873
>4 inch	H25-112	0.985560776	0.999994466	0.999990038	206.3	3	0.01454	602290.2	3.33	4	3.6	361374	0.0873
Reinforced	H25-120	0.977618384	0.999994186	0.999994186	176.7	4	0.02264	386996.1	2.25	0	2.25	386996	0.0509
>4 in.	H25-122	0.977618384	0.999994186	0.999994186	176.7	4	0.02264	386996.1	2.25	0	2.25	386996	0.0509
Refrigerant	H25-300	0.99995455	0.99999943	0.999990919	11221	6	0.00005	19273661	xxx	3.0645	3.199	352314	0.0795
<1 inch, per 100 ft.	H25-310	0.999925556*	1	0.999993884	6850.6	0	0.00007*	117668376*	0	4	3.67	600109	0.0536
1–3 inch, per 100 ft.	H25-320	0.998628073	0.999998537	0.999986271	4370.4	6	0.001373	6380800	9.3333	3	2.936	213882	0.1203
Water	H25-400	0.999720116	0.999994706	0.997739077	1821.9	6	0.00028	31294258	xxx	xxx	8.008	3542	19.805
≤2 inch, per 100 ft.	H25-410	0.998834378*	1	1	437.3	0	0.00117*	7510917*	0	0	xxx	xxx	0
>12 inch, per 100 ft.	H25-450	0.939385452*	1	1	8.2	0	0.06253*	140094.1*	0	0	xxx	xxx	0
>2 ≤4 inch, per 100 ft.	H25-420	0.979679275	0.999966994	0.999966994	292.3	6	0.02053	426692	14.08	0	14.083	426692	0.2891
>4 ≤8 inch, per 100 ft.	H25-430	0.998103531*	1	1	268.7	0	0.00190*	4614729*	0	0	xxx	xxx	0

>8 ≤12 inch, per 100 ft.	H25-440	0.999374866*	1	0.994961083	815.6	0	0.00063*	14008611*	0	8	8	1588	44.14
Pressure control assembly	C8-000	0.99309182	0.999995568	0.999938101	721.3	5	0.00693	1263676	5.6	3	3.492	56414	0.5422
Pressure regulator	C9-000	0.999163441	1	0.999993069	609.4	0	0.00084	10467090	xxx	0.5	0.5	72138	0.0607
Hot gas	C9-100	0.999163441*	1	0.999993069	609.4	0	0.00084*	10467090*	0	0	0.5	72138	0.0607
Pump	H26-000	0.993705867	0.999994889	0.999826613	1742.2	11	0.00631	1387387	7.09	0.4204	0.432	2494	1.5189
Centrifugal	H26-100	0.994206434	0.999995523	0.99990345	1376.8	8	0.00581	1507638	6.75	0.3372	0.353	3654	0.8458
Integral drive	H26-110	0.99251545	0.999993654	0.999897429	665.5	5	0.00751	1166025	7.4	1	0.599	5836	0.8985
Without drive	H26-120	0.995791244	0.999997272	0.999909083	711.3	3	0.00422	2076992	5.67	0	0.246	2707	0.7964
Positive displacement	H26-200	0.991821538	0.9999925	0.999537023	365.3	3	0.00821	1066720	8	1	0.526	1135	4.0557
Rectifiers, all types	E32-000	0.995540658	0.999991837	0.998972976	447.5	2	0.00447	1960032	16	3.4491	3.471	3379	8.9967
Sending unit	C13-000	0.999566658	0.999999536	0.999999258	36914.4	16	0.00043	20210622	9.38	0.017	0.045	60956	0.0065
Air velocity	C13-100	0.998867884	0.999998707	0.999997599	6179.6	7	0.00113	7733345	10	0	0.034	14050	0.021
Pressure	C13-200	0.997916028	0.999997883	0.999997089	4314.2	9	0.00209	4199130	8.89	0	0.076	26028	0.0255
Temperature	C13-300	0.999980697*	1	1	26420.6	0	0.00002*	453812471*	0	0	xxx	xxx	0
Control system	C12-000	0.64222125	0.999854564	0.999658784	551	244	0.44282	19782.19	2.88	0.5615	0.855	2505	2.9891
≤1k acquisition points	C12-100	0.777690112	0.999954199	0.999888246	373.9	94	0.25143	34841.1	1.6	1	1.376	12312	0.979
>1k acquisition points	C12-200	0.428800729	0.999644282	0.999174503	177.1	150	0.84676	10345.28	3.68	0	0.771	934	7.2314
Strainer	H27-000	0.99994331	1	0.999916767	8996.1	0	0.00006	15452150	xxx	0.3084	0.308	3705	0.7291
Liquid	H27-200	0.99994331	1	0.999916767	8996.1	0	0.00006	15452150	xxx	0.3084	0.308	3705	0.7291
Coolant	H27-210	0.998861684*	1	0.999333463	447.8	0	0.00114*	7691200*	0	2	1.629	2444	5.8389
Duplex fuel/lube oil	H27-220	0.995679886*	1	0.999861421	117.8	0	0.00433*	2023341*	0	1	0.861	6216	1.214
Fuel oil	H27-230	0.998766615*	1	0.999924447	413.2	0	0.00123Z*	7098023*	0	2	1.709	22625	0.6618

(continued)

Table F.49 (continued)

Category/class	Item number	Reliability	Inherent availability	Operational availability	Unit years	Failures	Failure rate (Failures/ year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ year
Lube oil	H27-240	0.999529759*	1	0.999881981	1084.3	0	0.00047*	18624376*	0	2	1.738	14726	1.0339
Water	H27-250	0.999926442	1	0.999960363	6933	0	0.00007	11908456	xxx	0.1288	0.129	3249	0.3472
≤4 inch	H27-251	0.999920044*	1	0.999999893	6378.3	0	0.00008*	109556141*	0	0	0	3116	0.0009
>4 inch	H27-252	0.999081068*	1	0.999505864	554.7	0	0.00092*	9528423*	0	3	3.168	6411	4.3286
Switch	E34-000	0.993744427	0.999996988	0.999960651	9720.8	61	0.00628	1395966	4.2	1.5333	1.612	40959	0.3447
Automatic transfer	E34-100	0.950118163	0.999976051	0.999857315	1074.9	55	0.05117	171197.6	4.1	7.3553	6.49	45487	1.2499
>600 Amp, ≤600 V	E34-110	0.968631015	0.999994046	0.999809981	690.3	22	0.03187	274853.5	1.64	34	20.891	109941	1.6646
0–600 Amp., ≤600 V	E34-120	0.917774618	0.999943753	0.999942269	384.6	33	0.0858	102093.8	5.74	0	1.28	22165	0.5057
Disconnect	E34-200	0.999846881	0.999999966	0.999961037	3330.5	1	0.00015	57205889	xxx	1.5473	1.547	39694	0.3413
Enclosed	E34-210	0.999398941	0.999999931	0.999928002	1663.2	1	0.0006	14569899	1	1.9055	1.904	26442	0.6307
≤600 V	E34-211	0.999394569*	1	0.999938186	842.1	0	0.00061*	14464658*	0	2	1.991	32214	0.5415
>600 V ≤5 kV	E34-212	0.997942528	1	0.99986723	247.6	0	0.00206	4253270	0	2	2.4	18076	1.1631
>5 kV	E34-213	0.998257804	0.999999801	0.999939288	573.5	1	0.00174*	5023755*	1	2	1.51	24870	0.5318
Fused, DC	E34-220	0.999694154	1	0.999993992	1667.25	0	0.00031	28637459	xxx	0.4769	0.477	79376	0.0526
>600 amp, ≤600 V	E34-222	0.999408178*	1	1	861.5	0	0.00059*	14797364*	0	0	0	314444	0
0–600 amp, ≤600 V	E34-221	0.999367257*	1	0.999987568	805.8	0	0.00063*	13840094*	0	1	0.548	44115	0.1089
Electric, on/off breaker	E34-300	0.999358198	0.999999927	0.99999978	3115.2	2	0.00064	13644684	1	0.0093	0.014	63170	0.0019

Type, non-knife ≤600 V	E34-310	0.999358198	0.999999927	0.99999978	3115.2	2	0.00064	13644684	1	0	0.014	63170	0.0019
Float, electric	E34-400	0.997716932	0.999999478	0.999985388	437.5	1	0.00229	3832560	2	0.1869	0.193	13216	0.128
Manual transfer	E34-500	0.999129111	1	0.999966262	585.4	0	0.00087	10054305	xxx	1.4786	1.479	43826	0.2955
≤600 Amp, ≤600 V	E34-510	0.997919138*	1	0.999952908	244.8	0	0.00208*	4205411*	0	1	1.098	23313	0.4125
>600 Amp, ≤600 V	E34-520	0.998503402*	1	0.999975863	340.5	0	0.00150*	5848894*	0	3	2.88	119317	0.2114
Oil filled	E34-600	0.998241979	1	0.999996849	289.8	0	0.00176	4978494	xxx	8	8	2539032	0.0276
≤5 kV	E34-610	0.998241979*	1	0.999996849	289.8	0	0.00176*	4978494*	0	8	8	2539032	0.0276
Static	E34-800	0.997748999	0.999996656	0.999919287	887.5	2	0.00225	3887220	13	2.039	2.113	26177	0.707
>1000 Amp, ≤600 V	E34-830	0.996326697	0.999989918	0.999739539	271.7	1	0.00368	2380392	24	3	3.584	13759	2.2816
>600 ≤1000 Amp, ≤600 V	E34-820	0.99233672	0.999998244	0.999994731	130	1	0.00769	1138728	2	0	0.078	14789	0.0462
0–600 Amp, ≤600 V	E34-810	0.998950665*	1	0.999999648	485.8	0	0.00105*	8343764*	0	0	0.032	90539	0.0031
Switchgear	E36-000	0.991916417	0.999974462	0.999585725	4558.7	37	0.00812	1079291	27.56	3.449	3.646	8800	3.6291
Bare bus	E36-100	0.989863408	0.999968286	0.999579123	3239	33	0.01019	859808.3	27.27	3.7329	3.993	9486	3.6869
≤600 V, bkrs. not incl.	E36-110	0.990554799	0.999992098	0.999455269	1791.3	17	0.00949	923068.2	7.29	4	4.308	7909	4.7718
>5 kV, bkrs. not incl.	E36-130	0.982216877	0.999995342	0.999839597	780.2	14	0.01794	488208.8	2.27	1	1.296	8079	1.4051
>600 V ≤5 kV, bkrs. not incl.	E36-120	0.997007868	0.999872746	0.999607036	667.4	2	0.003	2923296	372	10	14.27	36314	3.4424
Insulated bus	E36-200	0.999613608	0.999989619	0.999601929	1319.6	4	0.00039	22666917	xxx	2.9046	2.975	7473	3.4871
≤600 V, bkrs not Incl.	E36-210	0.998420947*	1	0.999468794	322.7	0	0.00158*	5543247*	0	3	3.182	5990	4.6534

(continued)

Table F.49 (continued)

Category/class	Item number	Reliability	Inherent availability	Operational availability	Unit years	Failures	Failure rate (Failures/year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/year
>5 kV, bkrs. Not Incl.	E36-230	0.995913049	0.999982547	0.999626621	732.5	3	0.0041	2139024	37.33	14	14.434	38657	3.2708
>600 V ≤5 kV, bkrs. not incl.	E36-220	0.996224761	0.999996546	0.999696028	264.4	1	0.00378	2316000	8	1	0.774	2548	2.6628
Tank	E37-000	0.995965564	0.999991636	0.999971186	1978.9	8	0.00404	2166924	18.13	0.1221	0.172	5955	0.2524
Air	E37-100	0.997280535	0.999997824	0.999996891	734.4	2	0.00272	3216840	7	0.0029	0.01	3078	0.0272
Receiver	E37-110	0.997280535	0.999997824	0.999996891	734.4	2	0.00272	3216840	7	0	0.01	3078	0.0272
Liquid	E37-200	0.995190343	0.999987984	0.999956016	1244.5	6	0.00482	1816952	21.83	0.4276	0.584	13279	0.3853
Day	E37-210	0.994810377	0.99999703	0.999974756	384.4	2	0.0052	1683600	5	0	0.346	13688	0.2211
Fuel	E37-220	0.993549151	0.999955673	0.999872929	309	2	0.00647	1353576	60	1	1.911	15040	1.1131
Water	E37-230	0.996377265	0.999999793	0.999989539	551.1	2	0.00363	2413680	0.5	0	0.128	12221	0.0916
Thermostat	C15-000	0.998319168	0.999999398	0.999997565	6538.9	11	0.00168	5207323	3.14	0.7895	0.969	397782	0.0213
Radiator	C15-100	0.998319168	0.999999398	0.999997565	6538.9	11	0.00168	5207323	3.14	1	0.969	397782	0.0213
Transducer	C16-000	0.99997847	0.999999933	0.999998552	23687.4	42	0.00002	40686583	xxx	0.0183	0.019	13235	0.0127
Flow	C16-100	0.996713345*	1	0.999986736	154.9	0	0.00329*	2660941*	0	0	0.36	27142	0.1162
Pressure	C16-200	0.99747775	0.999999423	0.999987243	791.9	2	0.00253	3468708	2	1	0.72	56402	0.1118
Temperature	C16-300	0.998242572	0.99999995	0.999999026	22740.5	40	0.00176	4980177	0.25	0	0.013	12848	0.0085
Transformer, dry	E38-100	0.999953743	0.999995817	0.999971899	11025.1	19	0.00005	18937280	xxx	3.2263	3.693	131402	0.2462
Air-cooled	E38-110	0.999882198	1	0.999944571	4329	0	0.00012	74357512	xxx	4.2724	4.272	77078	0.4856
≤500 kVA	E38-111	0.999775100*	1	0.99999557	2267.4	0	0.00022*	38946258*	0	4	3.826	863591	0.0388
>1500 kVA ≤3000 kVA	E38-113	0.999393210*	1	0.999745124	840.2	0	0.00061*	14432242*	0	4	4.206	16503	2.2327
>500 kVA ≤1500 kVA	E38-112	0.999582527*	1	0.999987102	1221.4	0	0.00042*	20979011*	0	6	6	465187	0.113

Dry, isolation	E38-120	0.997166548	0.999993113	0.999989567	6696.1	19	0.00284	3087252	21.26	0.9286	2.519	241390	0.0914
Delta Wye, <600 V	E38-121	0.997166548	0.999993113	0.999989567	6696.1	19	0.00284	3087252	21.26	1	2.519	241390	0.0914
Transformer, liquid	E38-200	0.994797669	0.999950735	0.99899058	8819.2	46	0.00522	1679476	82.74	16.9047	17.588	17424	8.8425
Forced air	E38-210	0.989259891	0.999836759	0.996601877	2593	28	0.0108	811246.2	132.43	21.1758	22.066	6494	29.767
≤10,000 kVA	E38-212	0.992879584	0.999797696	0.990915913	419.8	3	0.00715	1225880	248	23	23.677	2606	79.576
≤5,000 kVA	E38-211	0.987452327	0.999994736	0.999987215	1821.5	23	0.01263	693748.2	3.65	1	0.976	76345	0.112
>10,000 kVA ≤50,000 kVA	E38-213	0.99432976	0.999065253	0.98585676	351.7	2	0.00569	1540524	1440	22	23.203	1641	123.89
Non-forced air	E38-220	0.997113141	0.999998203	0.999985412	6226.1	18	0.00289	3030057	5.44	0.76	0.85	58270	0.1278
≤3000 kVA	E38-221	0.998891114	0.999999367	0.999996102	5407.8	6	0.00111	7895436	5	10	8.394	2153301	0.0341
>3000 kVA ≤10000 kVA	E38-222	0.994771048	0.999999402	0.999985038	190.7	1	0.00524	1670904	1	3	2.5	167090	0.1311
>10000 kVA ≤50000 kVA	E38-223	0.982624792	0.999987813	0.999893406	627.6	11	0.01753	499773.8	6.09	1	0.648	6081	0.9338
UPS: uninterruptible power supply	E39-000	0.999078297	0.999998349	0.999951289	553.1	4	0.00092	9499764	xxx	3.8	3.688	75701	0.4267
Rotary	E39-100	0.995983397*	1	0.9998955	126.7	0	0.00402*	2176564*	0	6	6.105	58424	0.9154
Small computer room floor	E39-200	0.990661925	0.999997858	0.99996787	426.4	4	0.00938	933708	2	3	2.667	82996	0.2815
Valve	H28-000	0.999995192	0.999999568	0.999977752	106073.6	183	0	18219692	xxx	0.7962	0.806	36233	0.1949
3-way	H28-100	0.999727982	1	0.999987577	1874.6	0	0.00027	32199388	xxx	0.5165	0.516	41574	0.1088
Diverting/ sequencing	H28-110	0.999257278*	1	0.999999501	686.4	0	0.00074*	11790070*	0	0	0.015	30368	0.0044
Mixing control	H28-120	0.999570876*	1	0.999980689	1188.2	0	0.00043*	20409317*	0	1	1.02	52836	0.1692
Ball	H28-300	0.999807822	0.999999957	0.999999204	2653.5	2	0.00019	45578400	xxx	0.1577	0.164	205708	0.007
Normally closed	H28-310	0.999516658*	1	0.999998106	1054.9	0	0.00048*	18119435*	0	0	0.192	101548	0.0166

(continued)

Table F.49 (continued)

Category/class	Item number	Reliability	Inherent availability	Operational availability	Unit years	Failures	Failure rate (Failures/ year)	MTBF	MTTR	MTTM	MDT	MTBM	Hrdt/ year
Normally open	H28-320	0.998749718	0.999999929	0.999999929	1598.6	2	0.00125	7002036	0.5	0	0.045	636549	0.0006
Butterfly	H28-400	0.998692271	0.999999513	0.999995506	17576.2	23	0.00131	6694253	3.26	0.5539	0.609	135416	0.0394
Normally closed	H28-410	0.991788585	0.999996931	0.999990199	2789.5	23	0.00825	1062421	3.26	1	1.288	131375	0.0859
Normally open	H28-420	0.999965510*	1	0.999996507	14786.8	0	0.00003*	253984565*	0	0	0.476	136206	0.0306
Check	H28-500	0.999742108	0.999999971	0.999980199	3877.1	1	0.00026	33963360	1	1	0.914	46146	0.1735
Control	H28-600	0.999937125	0.999999943	0.99999649	15904	1	0.00006	13931940	8	0.1091	0.111	31599	0.0307
Normally closed	H28-610	0.999922211	0.999999929	0.999997478	12854.8	1	0.00008	112607808	8	0	0.08	31864	0.0221
Normally open	H28-620	0.999832761*	1	0.999992325	3049.3	0	0.00017*	52375670*	0	0	0.234	30528	0.0672
Expansion	H28-700	0.999742991*	1	1	1984.1	0	0.00026*	34080094*	0	0	xxx	xxx	0
Gate	H28-800	0.999827547	0.999999888	0.999999642	17394.5	3	0.00017	50792032	5.67	0.8333	1.135	3174502	0.0031
Normally closed	H28-810	0.999421886	0.999999934	0.999998647	1729.3	1	0.00058	15148344	1	1	0.603	445540	0.0119
Normally open	H28-820	0.999872337	0.999999883	0.999999752	15665.3	2	0.00013	68613876	8	2	2.429	9801982	0.0022
Globe	H28-900	0.99998057	1	0.999921533	26248	0	0.00002	45084720	xxx	0.9954	0.995	12685	0.6874
Normally closed	H28-910	0.999975654*	1	0.999901776	20947.4	0	0.00002*	359802729*	0	1	0.997	10149	0.8604
Normally open	H28-920	0.999903788*	1	0.999999612	5300.5	0	0.00010*	91044470*	0	0	0.4	1031837	0.0034
Plug	H28-A00	0.990331504	0.999997992	0.999997984	15233.3	148	0.00972	901648.3	1.81	0.0476	1.592	789609	0.0177
Normally closed	H28-A10	0.986191497	0.999997832	0.999997819	8845.9	123	0.0139	630001.6	1.37	0	1.174	538126	0.0191
Normally open	H28-A20	0.996093704	0.999998213	0.999998213	6387.4	25	0.00391	2238150	4	0	4	2238151	0.0157
Reducing	H28-B00	0.998490771	1	0.999972616	337.7	0	0.00151	5799905	xxx	0.4939	0.494	18036	0.2399

Makeup Water	H28-B10	0.998490771*	1	0.999972616	337.7	0	0.00151*	5799905*	0	0	0.494	18036	0.2399
Relief	H28-C00	0.998671145	0.999999696	0.999994763	752	1	0.00133	6587760	2	0	0.19	36196	0.0459
Suction	H28-D00	0.998214603	0.999998521	0.999994094	2238.4	4	0.00179	4902090	7.25	1	0.698	118123	0.0517
Valve operator	C17-000	0.992808232	0.999991177	0.999971677	9975.4	72	0.00722	1213674	10.71	1.0564	1.469	51860	0.2481
Electric	C17-100	0.990159307	0.999979209	0.999934083	3640.2	36	0.00989	885794	18.42	1	1.4	21245	0.5774
Hydraulic	C17-200	0.915817948	0.999969884	0.999601804	68.2	6	0.08794	99616	3	2	2.204	5534	3.4882
Pneumatic	C17-300	0.995224402	0.999998361	0.999997541	6266.9	30	0.00479	1829941	3	1	1.776	722345	0.0215
Voltage regulator	E40-000	0.964377637	0.999690405	0.999644857	358.4	13	0.03627	241506.4	74.77	0.3333	2.523	7103	3.111
Static	E40-100	0.964377637	0.999690405	0.999644857	358.4	13	0.03627	241506.5	74.77	0	2.523	7103	3.111
Water cooling coil	H29-000	0.999577258	0.999999879	0.999993176	4730	2	0.00042	20717496	2.5	0.2558	0.26	38084	0.0598
Fan coil unit	H29-100	0.999577258	0.999999879	0.999993176	4730	2	0.00042	20717496	2.5	0	0.26	38084	0.0598

Note:*—Time truncated, chi squared, 60% single-sided confidence interval

xxx—Data not available at time of analysis

The data originates from the report: TM 5-698-5 “Survey of reliability and availability information for power distribution, power generation, and HVAC components for commercial, industrial, and utility installations,” published 22 July 2006; available at: https://www.wbdg.org/ffc/army-coe/technical-manuals-tm/tm-5-698-5 lines and some of the transmission lines be replaced by cables. The largest distribution company SEAS-NVE, which is owned by the consumers, has in the following 12 years invested 300 million USD (285.3 million Euros) in 9,400 km low-voltage cables. Today 98% of the distribution network including 10 kV is cables.

The Netherlands has followed the same strategy, and the power systems in these two countries are among the most reliable according to European statistics.

As regards the transmission lines, these are only in cables in the urban areas and in natural protection areas.

F.1.5.6 Peak and Spare Capacity

One of the advantages of combining the power system with district heating is that power peak plants, e.g., gas-fueled engines or large CHP plants with extraction turbines and heat storage, can be used more efficient by generating heat and power in case of large electricity prices. This has the following advantages:

- The gas-fueled engines are in operation on regular basis for generating heat and power efficiently and are therefore more reliable in case of an emergency breakdown compared to plants.
- The gas engines generate income from sale of heat in case of large electricity prices and corresponding very low heat production costs.
- The gas engines provide peak capacity as they automatically will be put in operation in case of power shortage and corresponding huge prices in the market.
- The large CHP extraction plants can interrupt the heat production on short notice and gain maximal power capacity in case of power shortage, as the heat storage tank will typically have the capacity to provide 8 h of maximal load.
- The large CHP back-pressure plants with a fixed ratio between heat and power can optimize with respect to the power prices and to some extend offer peak capacity.

F.1.5.7 Smart Consumers

Another advantage of combining the power system with DHC is that electric boilers for heating and large heat pumps for heating and/or cooling can be interrupted at any time and even offer regulation services to the power grid, thereby stabilizing the frequency.

The logic is that these large electricity consumers, which can be controlled and monitored, can be interrupted at any time while the system still operates as efficiently when there is a rapid decrease in consumption as when there is an increase in production. Moreover, the plants can be interrupted if there is a sudden lack of capacity in the power grid due to a breakdown.

F.2 District Heating System

F.2.1 Boiler Plants

Boiler plants are the simplest technology, which can be the baseline for all other alternatives in a low-carbon and sustainable energy system. Boiler plants can serve several purposes:

- Backup and peak capacity for heating, e.g., from gas and oil boilers, which can increase the resilience
- Base load capacity for heating from biomass boilers, which use local resources
- Electric boilers, which use low-cost surplus electricity from fluctuating resources and offer services to the power grid, e.g., frequency stabilization
- Process energy in the form of superheated temperature, e.g., 320 °F (160 °C) or steam

It is therefore important to look at the costs for capacity as well as the variable cost of generating energy per MWh. The boiler plants in this database are for supplying low-temperature heating, with supply temperatures below 203–230 °F (95–110 °C). Figure F.34 shows the LCOE for district heating boilers.

Natural Gas Boiler

The fuel is burnt in the furnace section. Heat from the flame is transmitted via radiation (and convection) to the inner walls of the boiler and from there to the water to be heated. After the combustion, the hot flue gases are led through the convection parts of the boiler, and heat is transmitted to the water to be heated.

Shell and flue gas tube-type boilers are the most commonly used type of boilers at Danish district heating plants.

The boiler (Fig. F.35) may be fitted with an external heat exchanger (economizer) to use any remaining heat (including latent heat) in flue gases.

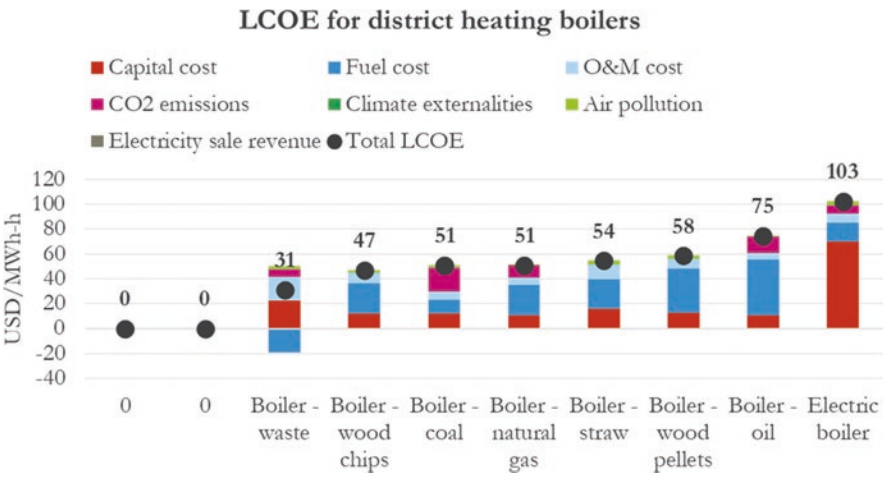


Fig. F.34 LCOE for district heating boilers

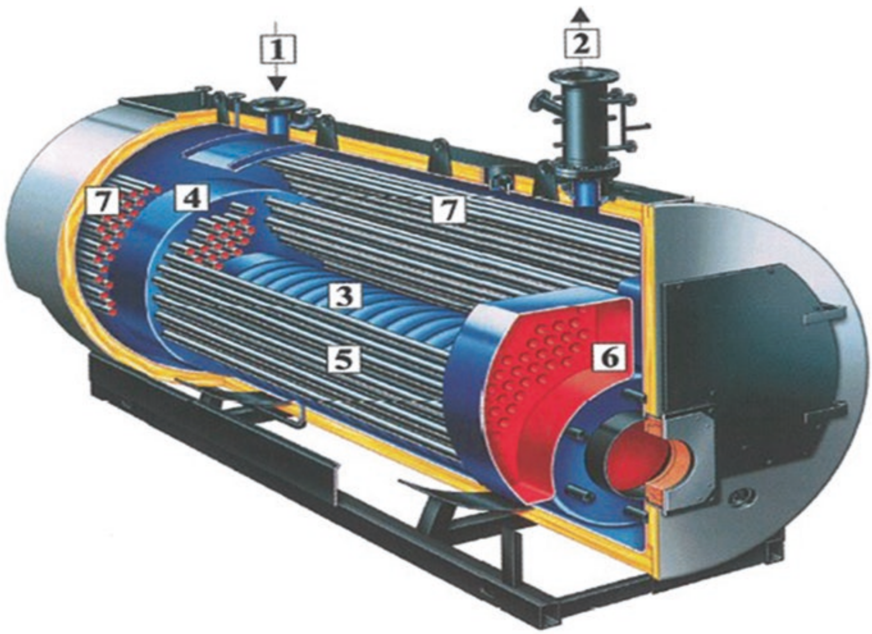


Fig. F.35 Natural gas boiler

Boilers for district heating have been used for decades. Today, many gas-fired district heating boilers are used for peak load or backup capacity. During periods with low electricity prices, gas-fired district heating boilers have accounted for a relatively large part of the district heating production as it has been less feasible to operate the engines at CHP plants.

Figure F.35 shows a typical flue gas tube boiler for the power range 1–20 MW. Combustion takes place in the fire tube (3). Flue gases then pass inside a number of flue gas tubes (5 and 7) transmitting further heat to the boiler water. The water connections (forward/return) are on the top (2 and 1).

Advantages
Gas-fired boilers are a proven and well-known technology. They can be supplied over a wide range of output capacities. Load response is good.

The boilers may also be used for heat extraction at medium or high temperature from waste process air.

Heat pumps, either electrical or absorption, may be added to use flue gas heat, thereby increasing the efficiency of the heat pump.

Disadvantages
When gas boilers are being fueled with diesel or biogas, possibly in combination with natural gas, additional sulfur cleaning may be needed.

Table F.50 lists the technical and economic assumptions for a district heating natural gas boiler. Table F.51 lists the nominal investment by capacity for new

Table F.50 Technical and economic assumptions for a district heating natural gas boiler

Technology	Unit	New condensing boiler	Existing condensing boiler	New non-condensing boiler	Existing non-condensing boiler
Energy/technical data					
Heat generation capacity for one unit (MJ/s)	MJ/s	5	5		
Total efficiency, net, nominal load	%	105	84	84	84
Total efficiency, net, annual average	%	103	82.4	82.4	82.4
Electricity consumption for pumps, etc.	% of heat gen	0.14	0.14	0.14	0.14
Forced outage	%	1	1	1	1
Planned outage	Weeks per year	0.4	0.4	0.4	0.4
Technical lifetime	Years	25		25	
Construction time	Years	0.5		0.5	
Space requirement	1000 m^2 per MJ/s	0.005		0.005	
Plant dynamic capabilities					
Primary regulation	% per 30 s	–	–	–	–
Secondary regulation	% per minute	–	–	–	–
Minimum load	% of full load	15	15	15	15
Warm startup time	Hours	0.1	0.1	0.1	0.1
Cold startup time	Hours	0.4	0.4	0.4	0.4
Environmental data					
SO2	g per GJ fuel	0.3	0.3	0.3	0.3
NOx	g per GJ fuel	9	9	9	9
CH4	g per GJ fuel	3	3	3	3
N2O	g per GJ fuel	1	1	1	1
Financial data (USD)					
Nominal investment	MUSD per MJ/s	0.07	–	0.07	-
of which equipment	MUSD per MJ/s	0.04	–	0.04	-
Of which installation	MUSD per MJ/s	0.03	–	0.03	-
Fixed O&M	USD/MJ/s/year	2184	2730	2184	2730
Variable O&M	USD/MWh	1.23	1.54	1.23	1.54
Of which electricity costs	USD/MWh	0.11	0.14	0.11	0.14
Of which other O&M costs	USD/MWh	1.12	1.40	1.12	1.40

Table F.51 Nominal investment by capacity of new condensing and not condensing natural gas boiler

Technology	Unit	New condensing/not condensing boiler								
Heat capacity	MWh	1	2	3	4	5	10	15	20	25
Nominal investment	MUSD/MWh	0.22	0.14	0.10	0.08	0.07	0.04	0.03	0.03	0.02
– of which equipment	MUSD/MWh	0.14	0.09	0.06	0.05	0.04	0.03	0.02	0.02	0.01
– of which installation	MUSD/MWh	0.08	0.05	0.04	0.03	0.03	0.02	0.01	0.01	0.01

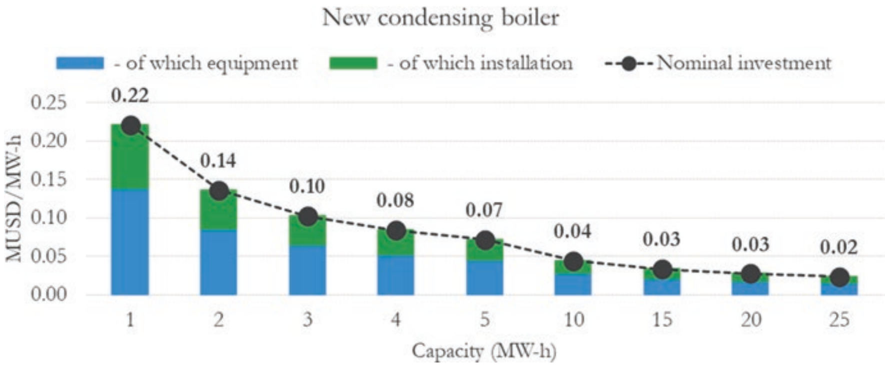


Fig. F.36 Nominal investment by capacity of new condensing natural gas boiler

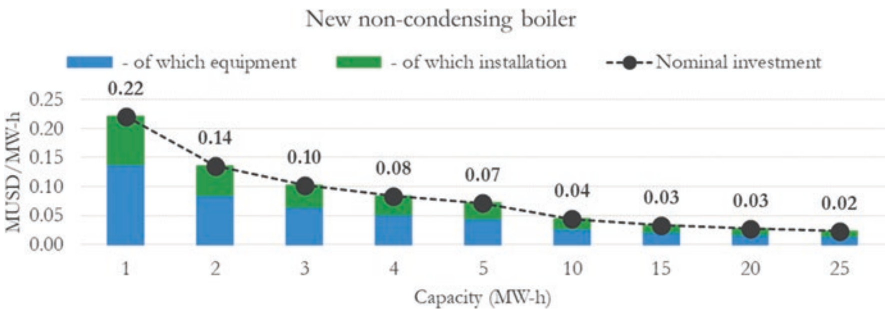


Fig. F.37 Nominal investment by capacity of new non-condensing natural gas boiler

condensing and not condensing natural gas boiler; Figs. F.36 and F.37 show the nominal investment by capacity of new condensing and new non-condensing natural gas boilers, respectively.

Biomass Boiler

A biomass boiler is a boiler fired by woodchips from forestry and/or from wood industry, wood pellets, or straw.

If the moisture content of the fuel is above 30–35%, as with forest woodchips, flue gas condensation should be employed. Thereby the thermal efficiency usually exceeds 100% (based on LHV). The efficiency is primarily determined by the condensation temperature, which is little above the return temperature from the district heating network. In well-designed systems, this return temperature is below 104 °F (40 °C), yielding efficiencies above 105%.

For plants firing woodchips with 45–55% moisture content, the thermal efficiency exceeds 110%. Some plants are equipped with cooling devices for full flue gas condensation, and thermal efficiencies of more than 120% are reached. Flue gas condensation should not be applied to plants below 1–2 MJ/s due to O&M costs. Such plants should only use fuels drier than 30% moisture content.

Straw-fired boilers are normally equipped with a bag filter for flue gas cleaning. Electro filters do not work with straw firing as they do with wood firing. Flue gas condensation is now available also for straw firing but must be combined with a bag filter to hold back calcium chlorine particles from the scrubber. The flue gas condensation raises the efficiency by 5–10% and reduces SO_2 emission to a minimum when the pH value is kept above 6.5–7.0. Whether flue condensation is feasible is much dependent on taxes, e.g., on sulfur.

Wood chips are wood pieces of 0.2 to 2-in. (5 to 50 mm) in the fiber direction, longer twigs (slivers), and a fine fraction (fines). The quality description is based on three types of wood chips: fine, coarse, and extra coarse. The names refer to the size distribution only, not to the quality. The woodchips are often traded in two size qualities, coarse and fine. Other possible fuels are chipped energy crops (e.g., willow and poplar) and chipped park and garden waste.

Wood pellets are made from sawdust, wood shavings, and other residues from sawmills and other wood manufacturers. Pellets are produced in several types and grades as fuels for electric power plants and district heating (low grade) and homes (high grade). Pellets are extremely dense and can be produced with a low humidity content (below 5% for high-grade products) that allows easy handling (incl. long-term storage) and a capacity to be burnt with a high combustion efficiency.

Straw is a waste product from the farming industry. Some of the straw is used in the farming industry, but in general there is a way to produce sustainable energy from the straw. In the future, it may be profitable to use straw to generate biodiesel or substitute oil for generating useful materials instead of plastic, but until this technology has been further developed it makes, since that the energy market support a market for industrial production and handling of straw.

The simple industrialized collection for farming used round bales, but the big bales (500 kg each) are suitable for energy plants. The plant can operate and feed in bales automatically without staff at the plant. It also makes a good business for the local community to generate fuels locally, which was appreciated by the local politicians at the inauguration of this district heating boiler plant. Straw is, however, a difficult fuel. Therefore, it is only acceptable for environmental reasons to use it in or near urban areas in large boiler plants, typically larger than 5 MW.

Table F.52 lists the technical and economic assumptions for wood pellet, wood chip, and straw boilers. Table F.53 lists (and Fig. F.38 shows) the nominal investment by capacity for a wood pellet boiler. Table F.54 lists (and Fig. F.39 shows) the nominal investment by capacity for a wood chip boiler. Table F.55 lists (and Fig. F.40 shows) the nominal investment by capacity for a straw boiler.

Table F.52 Technical and economic assumptions for wood pellet, wood chip, and straw boilers

Technology	Unit	Wood pellet boiler		Wood chip boiler		Straw boiler	
		New boiler	Existing boiler	New boiler	Existing boiler	New boiler	Existing boiler
Energy/technical data							
Heat generation capacity for one unit	MW	6	6	6.9	6.9	6.1	6.1
Total efficiency, net, nominal load	%	100	80	114.9	91.9	102.1	81.7
Total efficiency, net, annual average	%	100	80	114.9	91.9	102.1	81.7
Electricity consumption for pumps, etc.	% of heat gen	1.7	1.4	2.0	1.6	1.7	1.4
Forced outage	%	2.1	1.7	2.3	1.8	2.1	1.7
Planned outage	Weeks per year	3.0	3.0	3	3	4	4
Technical lifetime	Years	3	3	2	2	4	4
Construction time	Years	25	20	25	25	25	25
Space requirement	1000 m^2 per MJ/s	1	–	1	–	1	–
Plant dynamic capabilities		0.2	0.2	0.2	0.2	0.2	0.2
Primary regulation	% per 30 s	NA	NA	NA	NA	NA	NA
Secondary regulation	% per minute	10	10	10	10	10	10
Minimum load	% of full load	40	40	20	20	50	50
Warm startup time	Hours	0.25	0.25	0.25	0.25	0.25	0.25
Cold startup time	Hours	0.5	0.5	0.5	0.5	0.5	0.5
Environmental data							
SO_2	Degree of desulphurization %	98.3	98.3	98	98	96.4	96.4
NO_x	g per GJ fuel	54	54	63	63	72	72
CH_4	g per GJ fuel	0	0	11	11	11	11
N_2O	g per GJ fuel	1	1	3	3	3	3
Particles	g per GJ fuel	–	–	–	–	0.3	0.3
Financial data (USD)							
Nominal investment	MUSD per MJ/s	0.87	–	0.84	–	1.10	–
– of which equipment	MUSD per MJ/s	0.49	–	0.45	–	0.48	–
– of which installation	MUSD per MJ/s	0.38	–	0.39	–	0.62	–
Fixed O&M	USD/MJ/s/year	36960	46200	36064	45080	57456	71820
Variable O&M	USD/MWh	0.56	0.7	1.12	1.4	0.67	0.84
Technology-specific data							
Flue gas condensation		Yes	Yes	Yes	Yes	Yes	Yes
Combustion air humidification		Yes	Yes	Yes	Yes	Yes	Yes

(continued)

Table F.52 (continued)

Technology	Unit	Wood pellet boiler		Wood chip boiler		Straw boiler	
		New boiler	Existing boiler	New boiler	Existing boiler	New boiler	Existing boiler
Nominal investment	MUSD/MW fuel input	0.81	–	0.88	–	1.01	–
– of which equipment		0.49	–	0.52	–	0.49	–
– of which installation		0.31	–	0.37	–	0.52	–
Fixed O&M	USD/MW input/year	37072	–	41552	–	58688	–
Variable O&M	USD/MWh input	2.13	–	3.02	–	2.35	–
– of which electricity costs	USD/MWh	1.57	–	1.79	–	1.68	–
– of which other O&M costs	USD/MWh	0.56	–	1.232	–	0.67	–
Fuel storage-specific cost in excess of 2 days	MUSD/MW Input/storage day	0.004	–	0.02	–	0.078	–

Table F.53 Nominal investment by capacity for a wood pellet boiler

Technology	Unit	Wood pellet boiler								
Heat capacity	MW_h	1	2	3	4	5	10	15	20	25
Nominal investment	$MUSD/MW_h$	3.05	1.88	1.41	1.15	0.99	0.61	0.46	0.37	0.32
– of which equipment	$MUSD/MW_h$	1.73	1.06	0.80	0.65	0.56	0.34	0.26	0.21	0.18
– of which installation	$MUSD/MW_h$	1.32	0.81	0.61	0.50	0.43	0.26	0.20	0.16	0.14

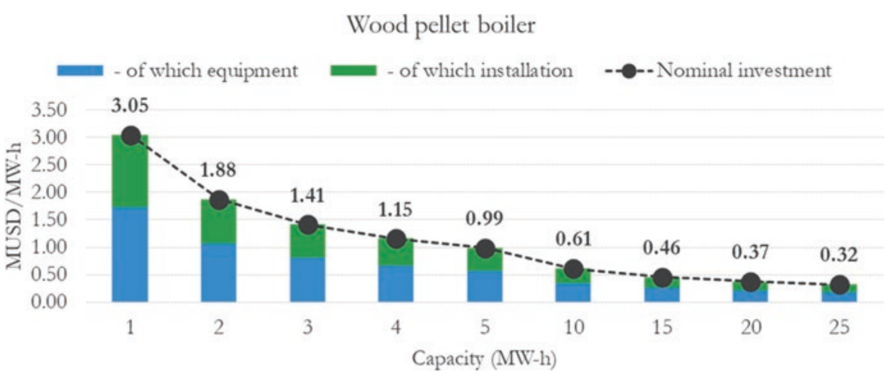


Fig. F.38 Nominal investment by capacity for a wood pellet boiler

Table F.54 Nominal investment by capacity for a wood chips boiler

Technology	Unit	Wood chips boiler								
Heat capacity	MWh	1	2	3	4	5	10	15	20	25
Nominal investment	MUSD/MWh	3.24	1.99	1.50	1.23	1.05	0.65	0.49	0.40	0.34
– of which equipment	MUSD/MWh	1.73	1.07	0.80	0.66	0.56	0.35	0.26	0.21	0.18
– of which installation	MUSD/MWh	1.51	0.93	0.70	0.57	0.49	0.30	0.23	0.19	0.16

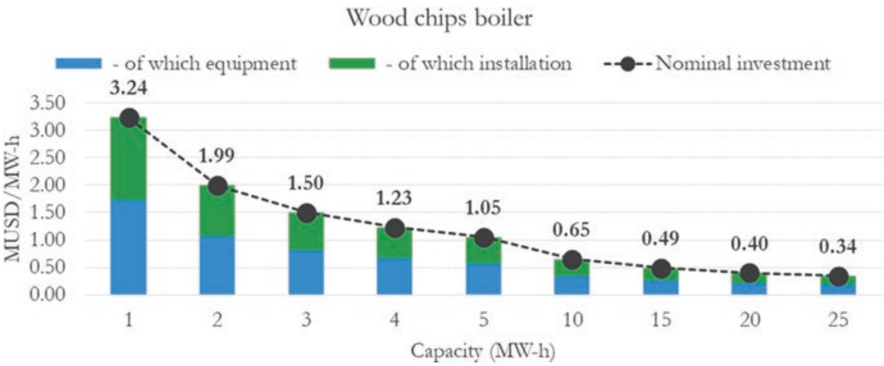


Fig. F.39 Nominal investment by capacity for a wood chips boiler

Table F.55 Nominal investment by capacity for a straw boiler

Technology	Unit	Straw boiler								
Heat capacity	MWh	1	2	3	4	5	10	15	20	25
Nominal investment	MUSD/MWh	3.90	2.40	1.81	1.48	1.26	0.78	0.59	0.48	0.41
– of which equipment	MUSD/MWh	1.71	1.05	0.79	0.65	0.55	0.34	0.26	0.21	0.18
– of which installation	MUSD/MWh	2.19	1.35	1.02	0.83	0.71	0.44	0.33	0.27	0.23

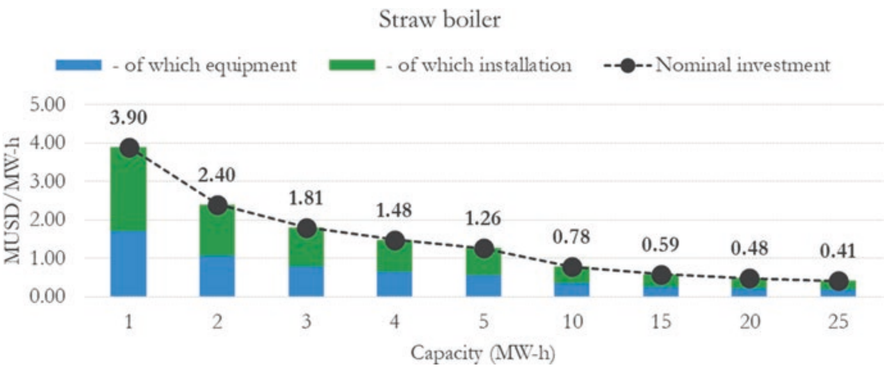


Fig. F.40 Nominal investment by capacity for a straw boiler

Electric Boiler

Electric boilers are devices in the MW size range using electricity to produce hot water or steam for industrial or district heating purposes. They are usually installed as peak load units in the same way as an oil or gas boilers.

The conversion from electrical energy to thermal energy takes place at almost 100% efficiency. The use of this technology should be justified by its systemic advantages. Electric water heaters can be a part of the energy system allowing that uses wind energy and enables efficient use of various thermal energy sources.

Thus, the application of electric boilers in district heating systems is primarily driven by the demand for ancillary services rather than by the demand for heat, although examples of electric boilers that operate in the "on the spot" market can be found.

Generally, two types of electric boilers are available:

- Heating elements using electrical resistance (same principle as a hot water heater in a normal household). Typically, electrical resistance is used in smaller applications up to 1–2 MW. These electric boilers are connected at low voltage (e.g., 400 or 690 V, depending on the voltage level at the onsite distribution board).
- Heating elements using electrode boilers. Electrode systems are used for larger applications. Electrode boilers (larger than a few MW) are directly connected to the medium to high-voltage grid at 10–15 kV (depending on the voltage in the locally available distribution grid).

Table F.56 lists the technical and economic assumptions for an electric boiler. Table F.57 lists (and Fig. F.41 shows) the nominal investment by capacity for an electric boiler.

Waste Boiler

WtE plants incinerate waste and produce energy. HOPs produce only heat, while CHPs also produce electricity.

Contrary to other fuels used for energy generation, waste has a negative price and is received at a gate fee. The primary objective of a waste-to-energy plant is the treatment of waste. The energy produced may be considered a useful by-product although one with an increasing importance for the future energy system with extensive use in district heating systems with high-power production from wind.

The total energy production from a WtE boiler can be varied by adjusting the fuel feed, although WtE facilities run at full load most of the time if the district heating demand allows together with additional cooling opportunities. Operation of WtE CHP unit as power only may not be financially attractive, and often CHP facilities are constructed so that operation at power only is not physically possible, as the necessary cooling facilities are not in place. The heat production can be changed also by starting or stopping the flue gas condensation.

Yet, for smaller-scale plants, a HOP may be a better solution than a CHP plant due to economic reasons.

Table F.58 lists the technical and economic assumptions for a waste boiler. Table F.59 lists (and Fig. F.42 shows) the nominal investment by capacity for a waste boiler.

Table F.56 Technical and economic assumptions for an electric boiler

Technology	Unit	Electric boiler
Energy/technical data		
Heat generation capacity for one unit	MW	5.0
Total efficiency, net, nominal load	%	99.0
Total efficiency, net, annual average	%	99.0
Electricity consumption for pumps etc.	% of heat gen	0.5
Forced outage	%	1.0
Planned outage	Weeks per year	0.2
Technical lifetime	Years	20.0
Construction time	Years	0.5
Regulation ability		
Primary regulation	% per 30 s	100.0
Secondary regulation	% per minute	100.0
Minimum load	% of full load	
Warm startup time	Hours	
Cold startup time	Hours	
Financial data (USD)		
Nominal investment, 400/690 V; 1–5 MW	MUSD per MW	0.17
– of which equipment	MUSD per MW	0.13
– of which installation	MUSD per MW	0.04
Nominal investment, 10/15 kV; >10 MW	MUSD per MW	0.08
– of which equipment	MUSD per MW	0.07
– of which installation	MUSD per MW	0.01
Fixed O&M	USD/MW/year	1198
Variable O&M	USD/MWh input	1.01
– of which electricity costs	USD/MWh	0.34
– of which other O&M costs	USD/MWh	0.56
Technology-specific data		
Startup costs	USD/MW/startup	0.0

Table F.57 Nominal investment by capacity for an electric boiler

Technology	Unit	Electric boiler								
Heat capacity	MWh	1	2	3	4	5	10	15	20	25
Nominal investment	MUSD/MWh	0.54	0.33	0.25	0.20	0.17	0.08	0.06	0.05	0.04
– of which equipment	MUSD/MWh	0.41	0.26	0.19	0.16	0.13	0.07	0.05	0.04	0.04
– of which installation	MUSD/MWh	0.12	0.08	0.06	0.05	0.04	0.01	0.01	0.01	0.01

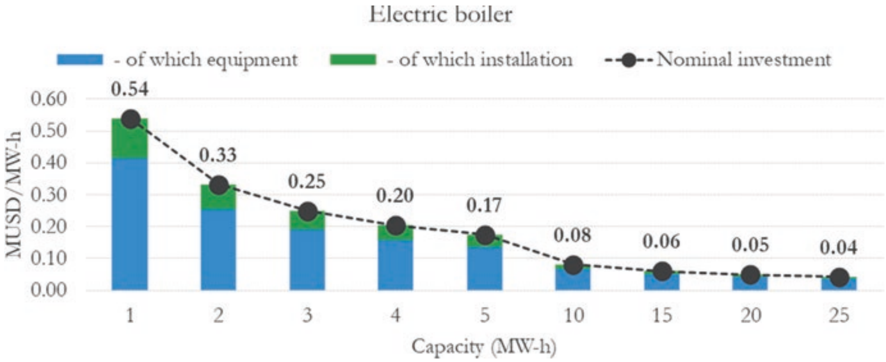


Fig. F.41 Nominal investment by capacity for an electric boiler

Table F.58 Technical and economic assumptions for a waste boiler

Technology	Unit	Waste boiler
Energy/technical data		
Heat generation capacity for one unit	MW	36.6
Incineration capacity (fuel input)	tonnes/h	11.9
Total heat efficiency, net, ref. LHV, name plate	%	104.7
Total heat efficiency, net, ref. LHV, annual average	%	104.7
Additional heat potential with heat pumps	% of thermal input	4.1
Auxiliary electricity consumption	% of heat gen	2.6
Forced outage	%	1.0
Planned outage	Weeks per year	2.9
Technical lifetime	Years	25.0
Construction time	Years	2.0
Space requirement	1000 m^2/MW_{th} heat output	0.6
Regulation ability		
Primary regulation	% per 30 s	NA
Secondary regulation	% per minute	1.0
Minimum load	% of full load	70.0
Warm startup time	Hours	8.0
Cold startup time	Hours	12.0
Environmental data		
SO_2	Degree of desulphurization %	99.8
NO_x	g per GJ fuel	67.0
CH_4	g per GJ fuel	0.1
N_2O	g per GJ fuel	1.0
Particles	g per GJ fuel	0.3
Financial data (USD)		
Nominal investment	MUSD per MW_{th}—heat output	2.1
– of which equipment	%	1.1

(continued)

Table F.58 (continued)

Technology	Unit	Waste boiler
– of which installation	%	1.0
Fixed O&M	USD/MW_{th}/year heat output	88032
Variable O&M	USD/MWh heat output	6.2
Technology-specific data		
Flue gas condensation		Yes
Combustion air humidification		No
Nominal investment	MUSD/MW fuel input	2.0
– of which equipment	MUSD/MW fuel input	1.2
– of which installation	MUSD/MW fuel input	0.9
Fixed O&M	USD/MW input/year	92176
Variable O&M	USD/MWh input	8.5
– of which electricity costs	USD/MWh	2.0
– of which other O&M costs	USD/MWh	6.5
Nominal investment	USD/tonne/year	757
Fixed O&M	USD/tonne	34
Variable O&M	USD/tonne	19.0

Table F.59 Nominal investment by capacity for a waste boiler

Technology	Unit	Waste boiler								
Heat capacity	MWh	20	25	30	35	40	45	50	55	60
Nominal investment	MUSD/MWh	3.27	2.79	2.46	2.21	2.01	1.85	1.72	1.61	1.51
– of which equipment	MUSD/MWh	1.73	1.48	1.30	1.17	1.06	0.98	0.91	0.85	0.80
– of which installation	MUSD/MWh	1.54	1.32	1.16	1.04	0.95	0.87	0.81	0.76	0.71

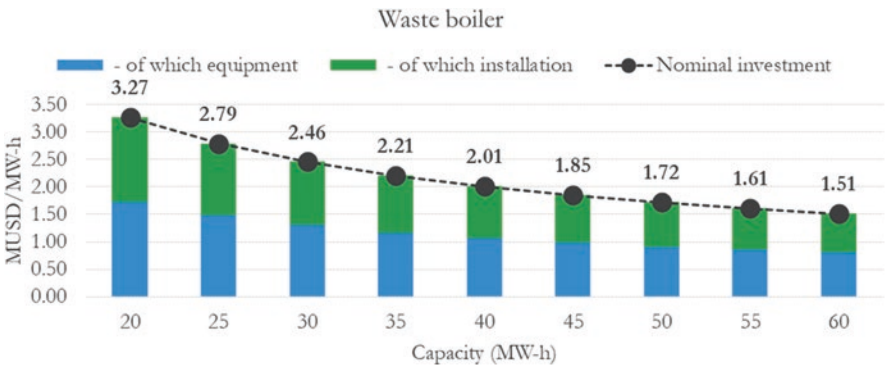


Fig. F.42 Nominal investment by capacity for a waste boiler

Coal Boiler

In some parts of the world, coal boilers are still used for home heating. Table F.60 lists the technical and economic assumptions for a coal boiler. Table F.61 lists (and Fig. F.43 shows) the nominal investment by capacity for a coal boiler.

Table F.60 Technical and economic assumptions for a coal boiler

Technology	Unit	Coal boiler
Energy/technical data		
Heat generation capacity for one unit	MW	5.0
Total efficiency, net, nominal load	%	90.0
Total efficiency, net, annual average	%	90.0
Electricity consumption for pumps, etc.	% of heat gen	0.1
Forced outage	%	1.0
Planned outage	Weeks per year	0.4
Technical lifetime	Years	20.0
Construction time	Years	0.5
Space requirement	1000 m^2 per MW	0.0
Plant dynamic capabilities		
Primary regulation	% per 30 s	–
Secondary regulation	% per minute	–
Minimum load	% of full load	15.0
Warm startup time	Hours	0.1
Cold startup time	Hours	0.4
Environmental data		
SO_2	g per GJ fuel	5.0
NO_x	g per GJ fuel	35.0
CH_4	g per GJ fuel	1.5
N_2O	g per GJ fuel	0.8
Financial data (USD)		
Nominal investment	MUSD per MW	0.07
– of which equipment	%	0.04
– of which installation	%	0.03
Fixed O&M	USD/MW/year	2397
Variable O&M	USD/MWh	1.8
– of which electricity costs	USD/MWh	–
– of which other O&M costs	USD/MWh	–

Table F.61 Nominal investment by capacity for a coal boiler

Technology	Unit	Coal boiler								
Heat capacity	MWh	2	3	4	5	6	7	8	9	10
Nominal investment	MUSD/MWh	0.14	0.10	0.08	0.07	0.06	0.06	0.05	0.05	0.04
– of which equipment	MUSD/MWh	0.09	0.06	0.05	0.04	0.04	0.04	0.03	0.03	0.03
– of which installation	MUSD/MWh	0.05	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.02

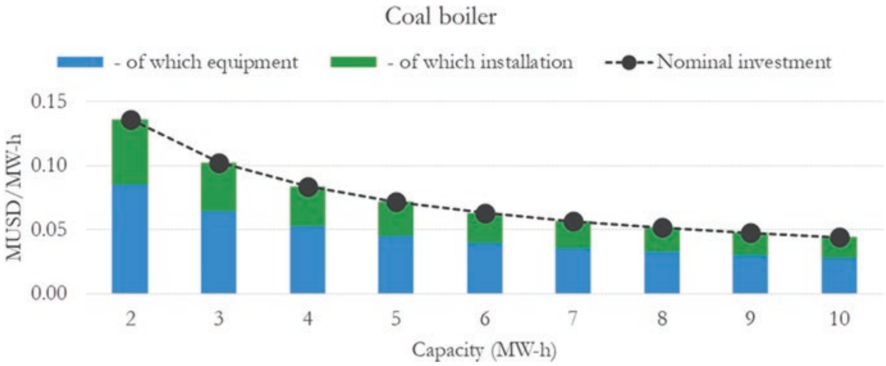


Fig. F.43 Nominal investment by capacity for a coal boiler

Oil Boiler

Oil boilers can be used for peak load heat production. Table F.62 lists the technical and economic assumptions for an oil boiler. Table F.63 lists (and Fig. F.44 shows) the nominal investment by capacity for an oil boiler.

Heat Pumps and Chillers

The electric heat pump is a key technology in the low-carbon energy system, as it can integrate three of the energy carriers, electricity, DH and DC.

Moreover, in the general concept, the heat pump can also operate as a heat-only heat pump, which wastes the cooling (e.g., ground source heat pumps), or as a cooling-only heat pump, which wastes the heat (e.g., chiller).

As the technologies for these three types of heat pumps are similar, we include them all in this category to compare their features, e.g., additional cost of generating cold from a ground source heat pump or additional cost of generating heat from an upgraded chiller.

Also, for comparison, we include absorption heat pumps in this category, both for cooling only and for combined heating and cooling.

As the operational cost of generating heat and cold using heat pumps as well as the value of the generated heat and cold depend on the market prices for power, heat and cold, the cost effectiveness of heat pumps shall be considered based on the energy system analysis.

F.2.1.1 Electric Heat Pump

Heat pumps use the same technology as refrigerators, by moving heat from a low-temperature level to a higher-temperature level. Heat pumps draw heat from a heat source (input heat) and convert the heat to a higher temperature (output heat) through a closed process, either compression-type heat pumps (using electricity) or absorption heat pumps (using heat, e.g., steam, hot water, or oil).

An important point regarding heat pumps is their ability to “produce” both heating and cooling. Hence, the “product” of a heat pump can be both heating and cooling—at the same time.

Table F.62 Technical and economic assumptions for an oil boiler

Technology	Unit	Electric boiler
Energy/technical data		
Heat generation capacity for one unit	MW	5.0
Total efficiency, net, nominal load	%	90.0
Total efficiency, net, annual average	%	90.0
Electricity consumption for pumps, etc.	% of heat gen	0.1
Forced outage	%	1.0
Planned outage	Weeks per year	0.4
Technical lifetime	Years	20.0
Construction time	Years	0.5
Space requirement	1000 m^2 per MJ/s	0.0
Plant dynamic capabilities		
Primary regulation	% per 30 s	–
Secondary regulation	% per minute	–
Minimum load	% of full load	15.0
Warm startup time	Hours	0.1
Cold startup time	Hours	0.4
Environmental data		
SO_2	Degree of desulphurization %	1.8
NO_x	g per GJ fuel	90.0
CH_4	g per GJ fuel	0.0
N_2O	g per GJ fuel	0.0
Financial data (USD)		
Nominal investment	MUSD per MW	0.07
– of which equipment	%	0.04
– of which installation	%	0.03
Fixed O&M	USD/MW/year	2184
Variable O&M	USD/MWh	1.23
– of which electricity costs	USD/MWh	–
– of which other O&M costs	USD/MWh	–

Table F.63 Nominal investment by capacity for an oil boiler

Technology	Unit	Oil boiler								
Heat capacity	MWh	2	3	4	5	6	7	8	9	10
Nominal investment	MUSD/MWh	0.14	0.10	0.08	0.07	0.06	0.06	0.05	0.05	0.04
– of which equipment	MUSD/MWh	0.09	0.06	0.05	0.04	0.04	0.04	0.03	0.03	0.03
– of which installation	MUSD/MWh	0.05	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.02

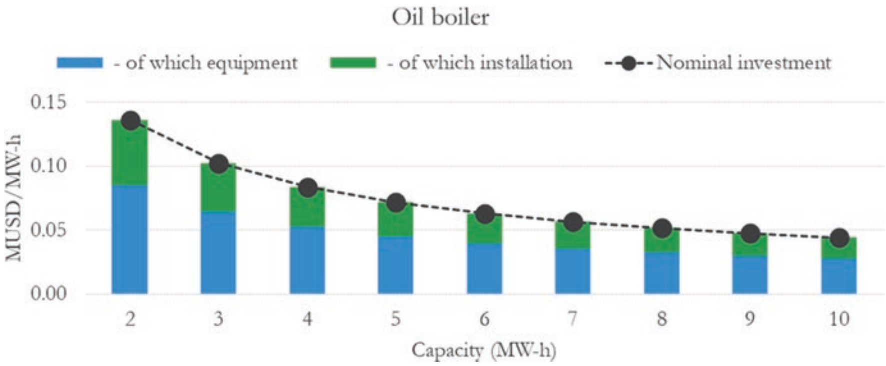


Fig. F.44 Nominal investment by capacity for an oil boiler

When applied with the primary purpose of cooling, the cooling demand defines the capacity. When installed for cooling, the heat pump will typically be the only cooling source, whereas when installed for heating, it will in many cases be in combination with other sources that can provide the heat energy (e.g., at a district heating plant). However, the primary purpose of the heat pumps in the technology catalogue is heating. In this section, the unit MW is referring to the heat output (also MJ/s) unless otherwise noted.

Heat pumps are used for industrial processes, individual space heating, and district heat production.

For compression heat pumps, the practical heat output is usually three to five times (the COP) the drive energy. This factor depends on the efficiency of the specific heat pump, the temperature of the heat source, and the heat sink and the temperature difference between heat source and heat sink.

Table F.64 lists the technical and economic assumptions for electrical compression heat pumps for district heating. Table F.65 lists (and Fig. F.45 shows) the nominal investment of electrical compression heat pumps—district heating.

Absorption Heat Pump

In absorption heat pumps (Fig. F.46), high-temperature heat is used to regenerate a refrigerant that can evaporate at a low-temperature level and hereby use low-grade energy. Energy from both drive heat and the low-temperature heat source is delivered at a temperature in between.

In theory, 1 kJ of heat can regenerate around 1 kJ of refrigerant meaning that an absorption heat pump has a theoretical maximum COP of around 2. Due to losses in the system, the practical COP is around 1.7. For absorption heat pumps, the COP is not affected by temperature levels. Certain temperature differences are required to have the process going, but as long as these are met, the COP will be around 1.7 and will not be affected by further temperature increase of the drive energy.

Table F.64 Technical and economic assumptions for electrical compression heat pumps for district heating

Technology	Unit	Electrical compression heat pumps—district heating
Energy/technical data		
Heat generation capacity for one unit	MW_{heat}	4
Total efficiency, net, name plate	%	N/A
Total eff., net, annual average, ambient heat source, no dev. in supply temp.	%	360
Total eff., net, annual average, ambient heat source, reduced supply temp.	%	400
Total eff., net, annual average, waste heat 20° C, reduced supply temp.	%	500
Total eff., net, annual average, waste heat 40° C, reduced supply temp.	%	900
Electricity consumption for pumps, etc.	% of heat gen	2
Forced outage	%	0
Planned outage	Weeks per year	0.5
Technical lifetime	Years	25
Construction time	Years	0.5
Space requirement	1000 m^2 per MW_{heat}	0.02
Regulation ability		
Primary regulation	% per 30 s	10
Secondary regulation	% per minute	20
Minimum load	% of full load	10
Warm startup time	Hours	0
Cold startup time	Hours	6
Environmental data		
SO_2	g per GJ fuel	0
NO_x	g per GJ fuel	0
CH_4	g per GJ fuel	0
N_2O	g per GJ fuel	0
Particles	g per GJ fuel	0
Financial data (USD)		
Nominal investment	MUSD per MW	0.81
– of which equipment	%	0.37
– of which installation	%	0.44
Fixed O&M	USD/MW/year	2240
Variable O&M	USD/MWh	3.6
– of which electricity costs	USD/MW_{heat}	1.6
– of which other O&M costs	USD/MW_{heat}	2.0

Table F.65 Nominal investment of electrical compression heat pumps—district heating

Technology	Unit	Electrical compression heat pumps—district heating								
Heat capacity	MW_h	2	2.5	3	3.5	4	4.5	5	5.5	6
Nominal investment	$MUSD/MW_h$	1.32	1.13	0.99	0.89	0.81	0.75	0.69	0.65	0.61
– of which equipment	$MUSD/MW_h$	0.60	0.51	0.45	0.40	0.37	0.34	0.32	0.29	0.28
– of which installation	$MUSD/MW_h$	0.72	0.61	0.54	0.49	0.44	0.41	0.38	0.35	0.33

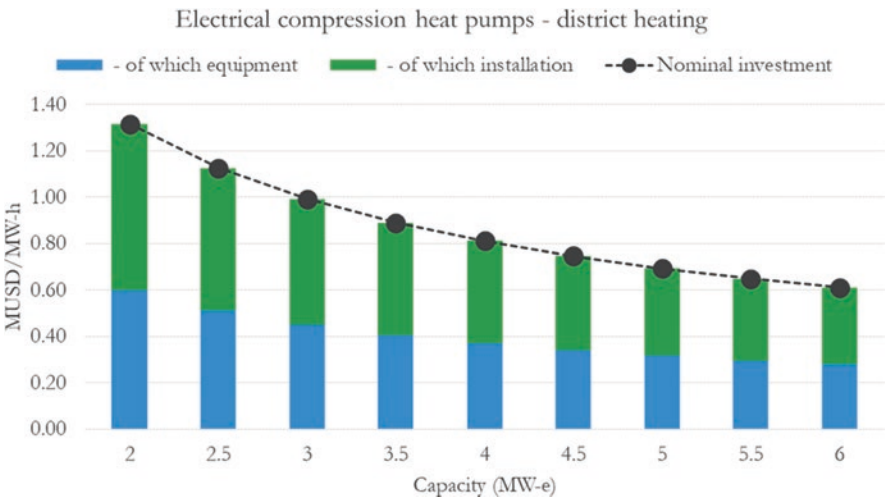


Fig. F.45 Nominal investment of electrical compression heat pumps—district heating

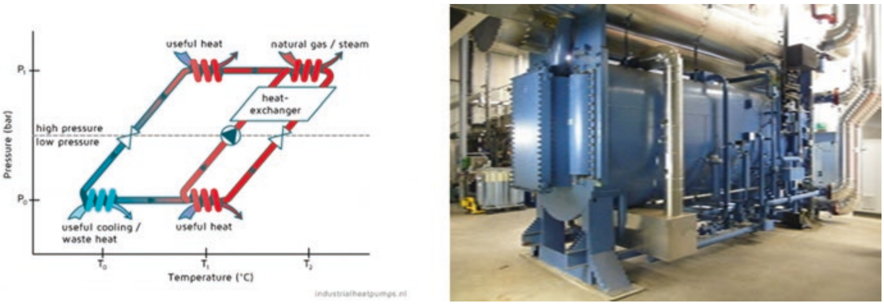


Fig. F.46 Absorption heat pump

Table F.66 lists the technical and economic assumptions for absorption heat pumps for district heating. Table F.67 lists (and Fig. F.47 shows) the nominal investment absorption heat pumps—district heating. Table F.68 lists (and Fig. F.48 shows) the nominal investment absorption heat pumps—single-stage hot water. Table F.69 lists (and Fig. F.49 shows) the nominal investment absorption heat pumps—two-stage hot water. Table F.70 lists absorption chiller performance characteristics and capital and O&M costs (typical values for water/lithium bromide chillers).

Table F.66 Technical and economic assumptions for an absorption heat pumps for district heating

Technology	Unit	Absorption heat pumps—district heating	Absorption heat pump—single-stage hot water	Absorption heat pump—two-stage hot water
Energy/technical data				
Heat generation capacity for one unit (excluding drive energy)	MW_{heat}	12	5.3	15.8
Total efficiency, net, name plate	%	N/A	N/A	N/A
Total eff., net, annual average	%	171	74	142
Electricity consumption for pumps, etc.	%	1	1	1
Forced outage	%	0	0	0
Planned outage	Weeks per year	0	0	0
Technical lifetime	Years	25	25	25
Construction time	Years	0.5	0.5	0.5
Space requirement (MW_h excluding drive energy)	1000 m^2 per MW_{heat}	0.01	0.01	0.01
Plant dynamic capabilities				
Primary regulation	% per 30 s	N/A	N/A	N/A
Secondary regulation	% per minute	N/A	N/A	N/A
Minimum load	% of full load	10	10	10
Warm startup time	Hours	0	0	0
Cold startup time	Hours	0.5	0.5	0.5
Environmental data				
SO_2	g per GJ fuel	0	0	0
NO_x	g per GJ fuel	0	0	0
CH_4	g per GJ fuel	0	0	0
N_2O	g per GJ fuel	0	0	0
Particles	g per GJ fuel	0	0	0
Financial data (USD)				
Nominal investment	MUSD per MW_{heat} (excluding drive energy)	0.69	0.21	0.28
– of which equipment	%	0.32	0.08	0.10
– of which installation	%	0.38	0.14	0.18
Fixed O&M	USD/MW/year	2240	–	–
Variable O&M	USD/MWh	1.1	16.7	25
– of which electricity costs	USD/MW_{heat}	0.78	–	–
– of which other O&M costs	USD/MW_{heat}	0.32	16.7	25

Table F.67 Nominal investment absorption heat pumps—district heating

Technology	Unit	Absorption heat pumps—district heating								
Heat capacity	MW_h	10	11	12	13	14	15	16	17	18
Nominal investment	$MUSD/MW_h$	0.79	0.74	0.69	0.66	0.62	0.59	0.57	0.54	0.52
– of which equipment	$MUSD/MW_h$	0.36	0.34	0.32	0.30	0.28	0.27	0.26	0.25	0.24
– of which installation	$MUSD/MW_h$	0.43	0.40	0.38	0.36	0.34	0.32	0.31	0.30	0.29

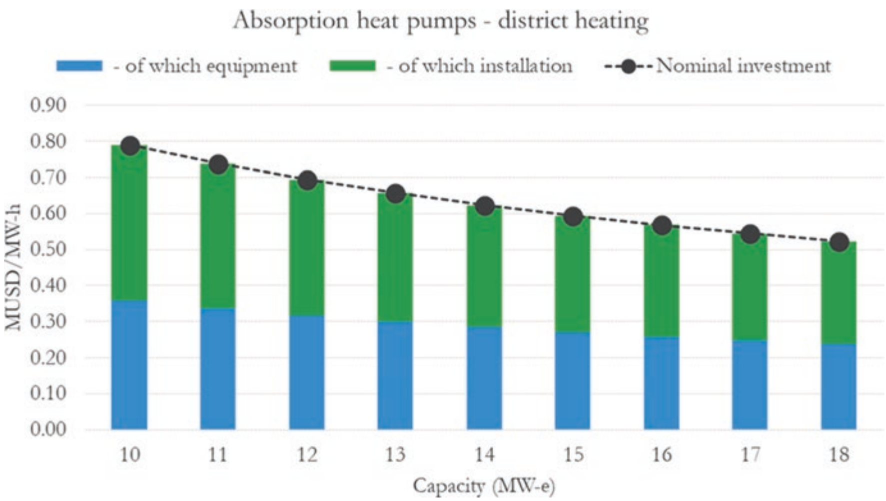


Fig. F.47 Nominal investment absorption heat pumps—district heating

Table F.68 Nominal investment absorption heat pumps—single-stage hot water

Technology	Unit	Absorption heat pumps—single-stage hot water								
Heat capacity	MW_h	10	11	12	13	14	15	16	17	18
Nominal investment	$MUSD/MW_h$	0.14	0.13	0.12	0.11	0.11	0.10	0.10	0.09	0.09
– of which equipment	$MUSD/MW_h$	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.03	0.03
– of which installation	$MUSD/MW_h$	0.09	0.08	0.08	0.07	0.07	0.07	0.06	0.06	0.06

F.2.1.2 Electric Chiller

A chiller is a machine that removes heat from a liquid via a vapor compression or absorption refrigeration cycle (Fig. F.50). (Table F.71 lists the cost of air coolers and electric chiller.) This liquid can then be circulated through a heat exchanger to cool equipment or another process stream (such as air or process water). As a necessary by-product, refrigeration creates waste heat that must be exhausted to ambience or, for greater efficiency, recovered for heating purposes. Chilled water is used to cool and dehumidify air in mid- to large-sized commercial, industrial, and institutional facilities. Water chillers can be water cooled, air-cooled, or evaporatively cooled.

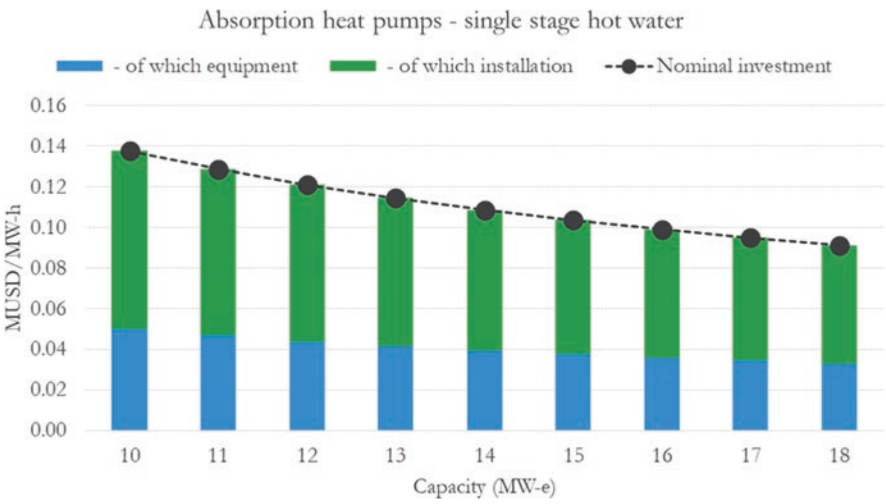


Fig. F.48 Nominal investment absorption heat pumps—single-stage hot water

Table F.69 Nominal investment absorption heat pumps—two-stage hot water

Technology	Unit	Absorption heat pumps—two-stage hot water								
Heat capacity	MW_h	10	11	12	13	14	15	16	17	18
Nominal investment	$MUSD/MW_h$	0.39	0.36	0.34	0.32	0.30	0.29	0.28	0.27	0.26
– of which equipment	$MUSD/MW_h$	0.14	0.13	0.12	0.11	0.11	0.10	0.10	0.09	0.09
– of which installation	$MUSD/MW_h$	0.25	0.23	0.22	0.21	0.20	0.19	0.18	0.17	0.17

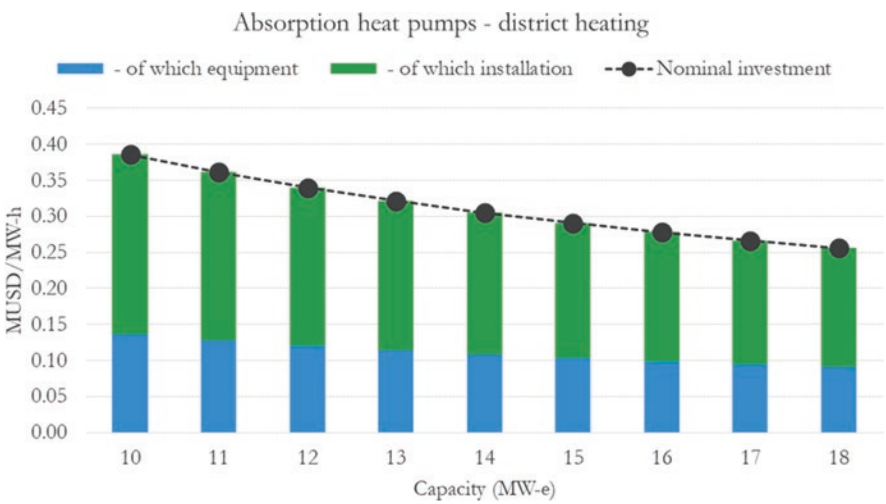


Fig. F.49 Nominal investment absorption heat pumps—two-stage hot water

Table F.70 Absorption chiller performance characteristics and capital and O&M costs (typical values for water/lithium bromide chillers)

Technology system	Unit	Absorption chiller[a] (typical values for water/lithium bromide chillers)						
		1	2	3	4	5	6	7
Performance characteristics								
Design		Single stage			Two stage			
Heat source		Hot water		Steam (low pressure)	Steam (high pressure)		Exhaust fired	
Nominal cooling capacity	tons	50	440	1320	330	1320	330	1000
Thermal energy input								
Hot water inlet temp.	°F	190	208	n/a	n/a	n/a	n/a	n/a
Hot water outlet temp.	°F	181	190	n/a	n/a	n/a	n/a	n/a
Steam pressure	psig	n/a	n/a	14.5	116	116	n/a	n/a
Exhaust gas temperature	°F	n/a	n/a	n/a	n/a	n/a	530	850
Heat required	MMBtu/hr	0.85	7.1	20.1	2.8	11.2	2.9	8.7
Energy output (chilled water)								
Inlet temperature	°F	54						
Outlet temperature	°F	44						
Cooling COP	full load	0.70	0.74	0.79	1.42	1.42	1.35	1.38
Capital and O&M costs								
Equipment cost	$/ton	2010	930	820.0	1190	1000	1330	930
Construction and installation	$/ton	3990	1370	980.0	1810	1200	1970	1070
Installed cost	$/ton	6000	2300	1800.0	3000	2200	3300	2000
O&M costs	¢/ton-hr	0.6	0.2	0.1	0	0	0.3	0.1

Performance characteristics are based on multiple sources, including vendor data and discussions with industry experts. The characteristics are intended to illustrate typical absorption chillers and are not intended to represent performance of specific products. For the hot water and steam examples, the boiler efficiency is not considered in the calculations. Costs are based on multiple sources, including vendor data and discussions with industry experts. The values shown are composite results and are not intended to represent a specific product

Fig. F.50 Electric chiller and air coolers

Table F.71 Cost of air coolers and electric chiller

Reference technology	Unit	Rambøll
Air dry coolers	$MUSD/MW_h$	0.34
Electric chiller	$MUSD/MW_h$	0.45

Water-cooled systems can provide efficiency and environmental impact advantages over air-cooled systems.

Important specifications to consider when searching for industrial chillers include the total life cycle cost, the power source, chiller IP rating, chiller cooling capacity, evaporator capacity, evaporator material, evaporator type, condenser material, condenser capacity, ambient temperature, motor fan type, noise level, internal piping materials, number of compressors, type of compressor, number of fridge circuits, coolant requirements, fluid discharge temperature, and COP (the ratio between the cooling capacity in refrigeration ton (RT) to the energy consumed by the whole chiller in KW). For medium to large chillers, this should range from 3.5 to 7.0, with higher values meaning higher efficiency. Chiller efficiency is often specified in kilowatts per refrigeration ton (kW/RT). Process pump specifications that are important to consider include the process flow, process pressure, pump material, elastomer and mechanical shaft seal material, motor voltage, motor electrical class, motor IP rating, and pump rating. If the cold water temperature is lower than 23 °F (−5 °C), then a special pump needs to be used to be able to pump the high concentrations of ethylene glycol. Other important specifications include the internal water tank size and materials and full-load current. Control panel features that should be considered when selecting between industrial chillers include the local control panel, remote control panel, fault indicators, temperature indicators, and pressure indicators.

Additional features include emergency alarms, hot gas bypass, city water switchover, and casters. Demountable chillers are also an option for deployment in remote areas and where the conditions may be hot and dusty.

The remaining technical and economic assumptions can be taken from the description of the electrical heat pump.

F.2.2 Heat Storage

The biggest challenge in developing net zero communities is not to generate renewable energy but to use it.

The available renewable energy or surplus energy sources, which can contribute to forming net zero communities, are normally not available when needed, and it can even be more expensive to store the energy than to generate it. A good example is that the renewable energy sources wind, solar, and hydro can generate electricity, as the wind blows, the sun shines, and the rain falls, whereas the power grid itself cannot store the electricity.

Therefore, energy storages will play an important role.

To identify the most cost-effective storage, it is necessary to look at the energy generation and actual energy demand to see if generation keeps pace with changes in demand over time. The dynamic fluctuations of the production in seconds, hours (sun), days, weeks (wind), months, and years (dry and wet year) have to be considered. Load management and energy transformation must be considered. If heating or cooling is the final end use, it is, for example, much more cost-effective to transform the electricity to hot or cold water the moment it is generated and use thermal storage instead of electric batteries. If gas or oil is the final end use, it is also much more cost-effective to transform the electricity to hydrogen, gas, and oil and then store the energy in the form of gas or oil.

This section will compare the cost of all relevant energy storages and, in the design of energy systems, will show several conceptual design concepts of integrated systems that can store the fluctuating renewable energy.

F.2.2.1 Hot Water Tanks (Pressureless)

Hot water pressureless tanks (Figs. F.51 and F.52) are the most common energy storage. This is because hot water is the end use for most heating systems and for hot tap water and because water is a very natural and environmentally friendly storage media. The tanks are normally constructed in steel, but it could also be in concrete, fiberglass reinforced plastic. Steel tanks for storage of hot water are a well-established technology, both in small houses and for large DH systems. Typically, a tank used in district heating is insulated with about 2 × 150 mm insulation (mineral wool).

In the last decades, steel tanks have been used as short-term storage in combination with combined heat and power plants to be able to offset production to a more favorable time. For extraction CHP plants (which can generate power only), the storage allows the plant to stop heat generation and generate maximal power only

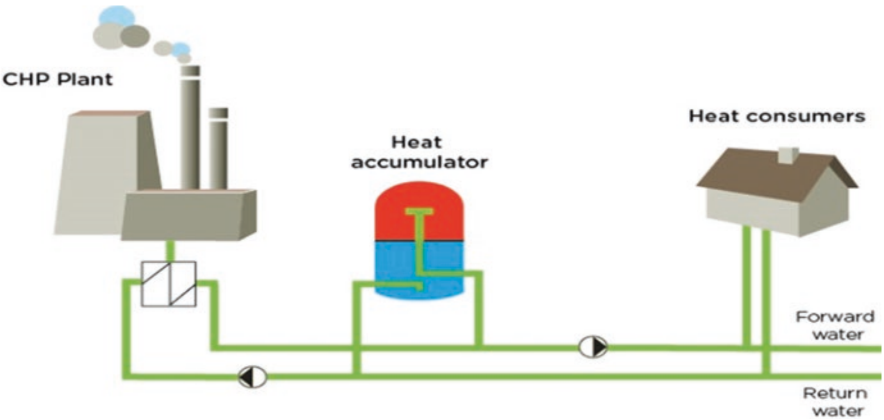


Fig. F.51 The pressureless directly connected tank operates in a simple way. The tank compensates automatically for the difference in flow in the supply pump and the production pump

Fig. F.52 The largest tank is probably the 75,000 m^3 (2,648,600 ft^3) pressureless hot water storage tank in Odense Denmark owned by Fjernvarme Fyn

when electricity is most expensive. For back-pressure CHP plants or engines (fixed ratio between heat and power), it allows the plant to generate electricity and heat when the electricity is most expensive.

In Denmark, a combined heat and power plant typically operates at full capacity during the peak and high load hours of the electricity market, about 75 h a week. Still, the plants often have heat storage capacity to cover the heat load for a full week during the cold season. The largest tanks are above 50,000 m^3 (1766 ft^3).

For a biomass plant, a typical capacity would be 10–12 h full load at peak demand on a cold winter day (service time needed for small repairs) or 72 h on summer load, to allow for weekend stop and/or boiler inspection.

Water is the most cost-effective way of storing low (0–20) to medium (20–100) temperature heat, because it is relatively cheap and convenient. Moreover, water has a very high specific heat capacity as well as a high volumetric heat capacity, compared to other common storage materials. This is important for a compact storage system.

The tank can also level the daily fluctuations of the heat demand and thus also offer peak capacity and improve resilience. Finally, the tank can maintain the pressure in the network and offer storage capacity for makeup water.

The data in Table F.72 may be used to compare tanks and to show the economy of scale factor for tanks, e.g., that a tank at the building level is more expensive than a tank for DH.

F.2.2.2 Hot Water Tanks (Pressurized)

The simple pressureless tank can be augmented to become more advanced (see Figs. F.53 and F.54) to meet the demand in two ways:

1. The temperature can be increased above 200 °F (100 °C).
2. The pressure of tank can be sectioned from the network pressure.

Table F.72 Technical and economic assumptions for a pressureless hot water tank

	Unit									
Efficient volume	m^3	0.5	1	10	100	1000	10000	20000	50000	100000
Diameter, if D/H=1	m	0.8	1.0	2.2	5	10	22	28	38	48
Type of use		Building	Building	Building	DH	DH	DH	DH	DH	DH
Maximal supply temperature	°C	95	95	95	95	95	95	95	95	95
Return temperature	°C	40	40	40	40	40	40	40	40	40
Energy capacity	MWh	0.0	0.1	0.6	6.4	63.8	638	1276	3190	6380
Max load hours design size	h	8	8	8	8	8	8	8	8	8
Normal load/unload capacity	MW	0.0	0.0	0.1	1	8	80	160	399	798
Heat losses standby	MWh/a	14	17	37	80	173	373	470	638	957
Standby losses per volume	MWh/MWh	430.9	271.4	58.5	12.6	2.7	0.6	0.4	0.2	0.2
Heat losses per load cycle	%	0	0	0	0	0	0	0	0	0
Temperature losses per cycle	°C	0	0	0	0	0	0	0	0	0
Investment per energy content	1000 USD/MWh	67	67	67	7	6	5	5	5	5
Investment	1000 USD	2	4	43	44	383	3190	5742	14355	28710
Fixed O&M, pct. of investment	%	1	1	1	1	1	1	1	1	1
Variable O&M	USD/MWh	0	0	0	0	0	0	0	0	0
Lifetime	years	60	60	60	60	60	60	60	60	60

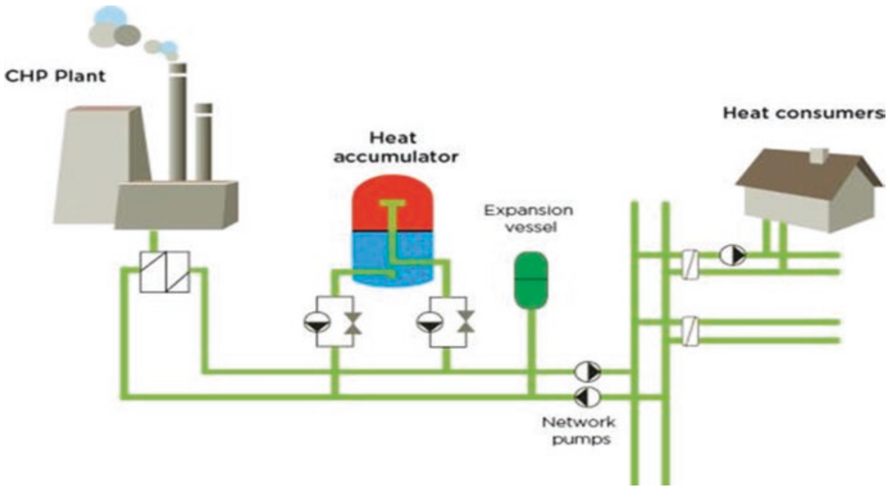


Fig. F.53 This tank is sectioned from the pressure in the network. The operator has to start and stop loading and unloading

Fig. F.54 Thermal storage at Avedøre CHP plant
The heat storage tanks at Avedøre CHP plant in Copenhagen have the following data:
2 x 24,000 m^3
120 °C (245 °F) max. supply temperature
330 MW load/unload capacity
10 Bar pressure difference from tank to network

Table F.73 Technical and economic assumptions for a pressurized hot water tank

Parameter	Unit	Measures			
Efficient volume	m^3	1000	10,000	20,000	50,000
Diameter, if D/H = 1	m	10	22	28	38
Type of use		DH	DH	DH	DH
Maximal supply temperature	°C	120	120	120	120
Return temperature	°C	50	50	50	50
Energy capacity	MWh	81	812	1624	4060
Max load hours design size	h	8	8	8	8
Normal load/unload capacity	MW	10	102	203	508
Heat losses standby	MWh/a	276	594	748	1015
Standby losses per volume	MWh/MWh	3	0.73	0.46	0.25
Heat losses per load cycle	%	0	0	0	0
Temperature losses per cycle	°C	0	0	0	0
Investment per energy content	1000 USD/MWh	7	6	5	5
Investment	1000 USD	546	5275	8289	20,300
Fixed O&M, pct. of investment	%	1	1	1	1
Variable O&M	USD/MWh	0	0	0	0
Lifetime	years	60	60	60	60

Table F.73 lists the technical and economic assumptions for a pressurized hot water tank.

If the DH end users need superheated water, e.g., at 170 °C (338 °F) to generate low-pressure steam for industry or to generate cooling in an absorption chiller, and if production fluctuates (as is likely in a waste incinerator), a pressureless tank can be an option, although a very expensive one, and for this application, the diameter of each tank must be relatively small.

In case the building needs water close to 100 °C (212 °F), it may also be necessary and optimal to operate heat transmission systems at temperatures up to, e.g., 120 °C (248 °F). In this case, the price increase will be more modest, and the tank can be large.

If the tank cannot be used for pressure maintenance due to pressure difference and location, it is possible to separate the pressure in the tank from the pressure in the network. Pumps and turbines/throttle valves on each pipe and a pressure expansion vessel stabilize the pressure while loading and unloading the tank.

An alternative to pressure section valves could be a heat exchanger with the ability to change direction; however, that would cost a temperature loss and be more expensive.

F.2.2.3 Pit Thermal Energy Storage

The hot water storage pit is developed in projects to district heating companies that want to increase the share of solar water heating from around 20% to 50% or more (Fig. F.55). This technology has after the first six full-scale demonstration plants in Denmark been developed to be commercial in Danish market conditions with tax on natural gas without subsidy.

Fig. F.55 Pit thermal energy storage

Table F.74 Technical and economic assumptions for a pit thermal energy storage

Parameter	Unit	Measures				
Efficient volume	m^3	10,000	20,000	50,000	100,000	200,000
Type of use		DH	DH	DH	DH	DH
Maximal supply temperature	°C	85	85	85	85	85
Return temperature	°C	40	40	40	40	40
Energy capacity	MWh	522	1044	2610	5220	10440
Max load hours design size	h	100	100	100	100	100
Normal load/unload capacity	MW	5	10	26	52	104
Heat losses standby	MWh/a	522	626.4	1044	1566	2088
Standby losses per volume	MWh/MWh	1	1	0	0	0
Heat losses per load cycle	%	0	0	0	0	0
Temperature losses per cycle	°C	0	0	0	0	0
Investment per energy content	1000 USD/MWh	1.4	1.3	1.2	1.1	1
Investment	1000 USD	731	1357	3132	5742	10,440
Fixed O&M, pct. of investment	%	0	0	0	0	0
Variable O&M	USD/MWh	0	0	0	0	0
Lifetime	years	25	25	25	25	25

This storage really benefits from economy of scale, as the relative heat losses and the capital costs are reduced for large plants up to a certain size. From around 200,000 m^3 (7,062,934 ft^3), the unit costs are almost constant. The technology is a combination of heat storage tank technology and a protected landfill. The pit itself is like a protected landfill with waterproof welded plastic liner. The diffuser (which can be seen at the picture) is the same as we have in the heat storage tank, and the natural stratification actually takes care of the distribution from one diffuser to the whole area. The floating cover is a new and sensitive component, and several technologies have been tested in full scale at the first plants.

Table F.74 lists the technical and economic assumptions for a pit thermal energy storage.

F.2.3 Renewable Energy

In this category, we include all relevant renewable energy sources except biomass fuels, which are incorporated in the boiler and CHP categories.

As the world is looking for affordable renewable energy, this category is important, and we will compare the cost of generating energy, in the form of electricity, gas, or heat, considering the economy of scale.

F.2.3.1 Solar Heating

Solar water heating is a natural and simple way to use the energy from the sun to provide hot water for heating and hot tap water, and the technology is simple (Fig. F.56).

Due to economies of scale and mass production, it is in particular cost-effective to supply large heat demand with large plants mounted on the ground.

Due to the daily fluctuations, it can be necessary to level the production with a heat storage tank to cover the summer load, and more storage capacity is necessary to cover a larger share of the heat demand. That was the driver for developing the heat storage pit.

The antifreeze liquid in the plant is separated from the district heating and from the heat exchanger storage.

The world record on large-scale solar water heating is almost doubled every year. Three recent world records:

- 20,000 m^2 (215,278 ft^2) Marstal DH in Denmark, the company that tested the concept
- 44,000 m^2 (473,612 ft^2) copper mining industry in Chile, 80% of hot water production to the process
- 70,000 m^2 (753,474 ft^2) Vojens DH, 50% of the annual heat production in combination with a heat storage pit
- 156,000 m^2 (1,679,200 ft^2) Silkeborg DH, 20% of the annual heat production in combination with gas CC and heat pump

Table F.75 lists production from 10,000 m^2 DH solar heating plant, field, and Table F.76 lists economies of scale for solar heating in a warm climate zone with low DH temperature.

The solar panels absorb almost all the solar energy, but the net production is the difference between the absorbed solar energy and the heat losses.

The production is not only depending on the solar radiation. It also depends on the ambient temperature and the temperature of the DH water.

The table on the top shows that there can even be a factor between the productions in a hot climate like in Chile and in a mild climate like Northern Europe.

Fig. F.56 Solar heating

Table F.75 Production from 10,000 m^2 DH solar heating plant, field

Temperatures in panels		Low DH temperature			High DH temperature		
Climate zone	Unit	Mild	Warm	Hot	Mild	Warm	Hot
Annual solar radiation	kWh/m^2 panel	1150	1350	2300	1150	1350	2300
Average outdoor temperature	°C	9	13	16	9	13	16
Supply temperature	°C	60	60	90	90	90	90
Return temperature	°C	40	40	40	70	70	70
Expected production	kWh/m^2 panel	550	850	1500	450	700	1300
Investment in plant 10,000 m^2	USD/m^2 panel	224	224	224	224	224	224
Annual O&M cost 10,000 m^2	USD/m^2 panel	2	2	2	2	2	2
Investment in plant 10,000 m^2	USD/MWh/a	408	263	149	497	320	172
Capital costs, 30 years, 3%	USD/MWh	21	13	8	26	17	9
Annual operation costs	USD/MWh	4	2	1	4	3	2
Average production cost	USD/MWh	25	16	9	30	19	10

Table F.76 Economy of scale for solar heating, warm climate zone, and low DH temperature

Typical heat consumer		Building, rooftop			District heating, field		
Size of consumer	Unit	Small	Medium	Large	Small	Medium	Large
Solar panel area	m^2	5	200	2000	2000	10000	20000
Expected production	kWh/m^2 panel	750	800	850	850	850	850
Total annual investment	USD/m^2 panel	1120	504	448	426	224	213
Annual O&M cost	USD/m^2 panel	10	8	6	4	2	2
Investment in plant	USD/MWh/a	1493	631	528	501	263	251
Capital costs, 30 years, 3%	USD/MWh	76	32	27	26	13	12
Annual operation costs	USD/MWh	13	10	7	6	2	2
Average production cost	USD/MWh	90	41	34	31	16	15

The data in Table F.77 lists the economies of scale that show that solar heat from a small rooftop plant is six times more expensive than solar heat from a large-scale plant. Table F.78 lists (and Fig. F.57 shows) the nominal investment for a solar district heating plant.

In case only part of heat is used from the small plant, due to lack of demand in vacation, etc. the difference can be even larger.

Deep Geothermal

Geothermal energy is energy located in underground water reservoirs of the earth. On average, the temperature of the reservoir increases with around 3 °C per 100 m depth (5.4 °F per 328 ft depth). Recent definitions of geothermal energy include all heat from the ground. Here, only heat produced through deep wells is described including the option to use the wells for heat storage.

Heat from deep reservoirs can be used directly through a heat exchanger. However, both the temperature and the pumping costs increase with the depth. Danish experiences indicate that it is thus more economically attractive to use heat pumps and extract heat from shallower reservoirs, typically at 800–3000 m (2624–9843 ft) depth,

Table F.77 Technical and economic assumptions for a solar district heating plant

Technology	Unit	Solar heating
Energy/technical data		
Typical plant size	m^2 (collector area)	13,000
Collector input	$kWh/m^2/year$	1046
Collector output	$kWh/m^2/year$	473
Total efficiency, net, annual average	%	0
Auxiliary electricity consumption (share of heat gen.)	%	0
Forced outage	%	0
Technical lifetime	Years	30
Construction time	Years	0
Space requirement	1000 m^2 per MWh/year	6
Regulation ability		
Primary regulation	% per 30 s	N/A
Secondary regulation	% per minute	N/A
Minimum load	% of full load	N/A
Warm startup time	Hours	N/A
Cold startup time	Hours	N/A
Environmental data		
SO_2	Degree of desulphurization %	0
NO_x	g per GJ fuel	0
CH_4	g per GJ fuel	0
N_2O	g per GJ fuel	0
Financial data (USD)		
Investment cost of total solar systems excluding diurnal heat storage	$USD/MWh_{output}/year$	456
– of which equipment	$USD/MWh_{output}/year$	376
– of which installation	$USD/MWh_{output}/year$	80
Investment cost of diurnal heat storage	$USD/MWh_{output}/year$	64
Total investment cost of total solar system including diurnal heat storage	$USD/MWh_{output}/year$	507
Fixed O&M	USD/MW/year	0.1
Variable O&M	USD/MWh	0.24
– of which electricity costs	USD/MW_{heat}	0.24
– of which other O&M costs	USD/MW_{heat}	0
Technology-specific data		
Investment cost of total solar systems excluding diurnal heat storage	USD/m^2 (collector area)	209
Fixed O&M	$USD/m^2/year$ (collector area)	0.05

Table F.78 Nominal investment for a solar district heating plant

Technology	Unit	Solar district heating plant					
Solar panel area	m^2	5	200	2000	2000	10,000	20,000
Average production cost	USD/MWh	90	41	34	31	16	15

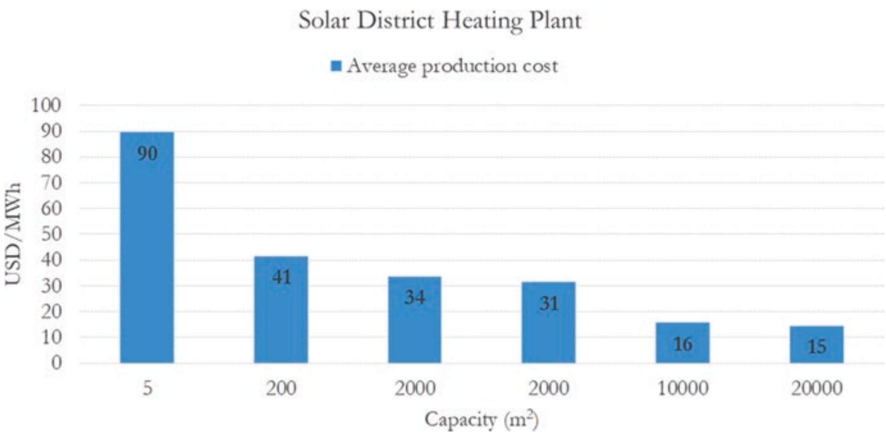


Fig. F.57 Nominal investment for a solar district heating plant

where temperatures are 30–90 °C (86–194 °F). The heat pumps can either be compressor heat pumps driven with electricity or absorption heat pumps driven by heat. The geothermal water has a high salinity—often 10–20%. For comparison, seawater has a typical level of salinity around 3.5%.

Different concepts for extraction of the geothermal heat exist. In the doublet system, warm geothermal water is pumped to the surface from a production well and the heat depleted brine pumped back into the source reservoir via an injection well to maintain the pressure; the bottom-hole spacing is designed to delay premature cooling of the production well.

Several boreholes may also be drilled from one site. This will decrease the cost of heat. Also, one or more of the boreholes may then be used for heat storage, e.g., seasonal, by injection of hot water during the summer and production during winter. However, injection of hot water into the boreholes may cause permeability reductions and change reservoir properties.

Absorption heat pumps driven by district heating biomass boilers can be used to elevate the temperature of the produced heat and increase the heat extraction. Extracting more heat can lower the temperature of the geothermal water to 10–20 °C (50–68 °F) before it is pumped back to the reservoir via the injection well. In some cases, the cooling by heat pumps can help to reduce gas separation (from the water) and avoid precipitation, which may clog the reinjection well.

GDH provides almost all of Reykjavik's district heating demand with an installed capacity of 830 MJ/s serving 180,000 people, 60 million m^3/year of water at an average 75 °C (167 °F) (user inlet) temperature. An important part of the hot water supply is piped from distant wells, and there is no reinjection of the heat depleted water (ca 35 °C [95 °F]) underground.

The Paris Basin GDH system is based on a sedimentary resource and on a doublet system for heat extraction. Here, hot water at an average temperature of 70 °C (159 °F) is pumped from depths of 1500–1800 m (4921–5905 ft). The system consists of 34 geothermal doublets (and as many heating grids), it has been operating since the early 1980s in the Paris area, and the total installed power and generating capacities are 230 MJ/s and 1000 GWh/year, respectively. Table F.79 lists the technical and economic assumptions for a geothermal plant.

F.2.4 District Heating Network

The district heating network is the most important component to consider in the heat planning, as it is an expensive natural monopoly infrastructure that enables the use of many heat sources at various locations to supply heat to customers in each district. That is why one must be careful in the planning only to plan for the network in zones, which has sufficient heat density, and not least ensure that there are incentives for customers to connect the network.

Table F.79 Technical and economic assumptions for a geothermal plant

Technology	Unit	Geothermal heat-only plant with steam-driven absorption heat pump	Geothermal heat-only plant with steam-driven absorption heat pump, Denmark	Geothermal heat-only plant with electric heat pump, Denmark
Energy/technical data				
Temperature of geothermal heat	Degrees °C			
Heat from geothermal source	%	100	100	100
Steam demand, heat pump	%	76	108	17
Heat generation capacity	%	176	208	117
District heat forward temperature, winter	°C	80	80	85
Electricity consumption for pumps, etc.	%	8	5	8
Technical lifetime	Years	25	25	25
Construction time	Years	4–5	4–5	4–5
Financial data (USD)				
Specific investment	MUSD per MJ/s geothermal heat	2	2.2	1.8
O&M excl. electricity consumption	USD/year per MJ/s geothermal heat	52,640	54,880	38,080

The investment in the network related to the sale of heat is a simple key figure and indicator for cost-effectiveness. Therefore, it is a good idea to calculate the indicator "investment in district heating grid per heat sale," in the unit *USD/MWh/a* for each district. In the District Heating Assessment Tool (DHAT) model, a marginal heat cost considering all costs over total heat production is calculated. Once the profitability of a district heating investment project is analyzed based on the difference between customers' alternative heat cost and the cost of generating the heat, we know the critical key figure. Thus, the energy planner can look at all marginal extensions of the network and prove that all key figures for each branch line to individual customers have key figures lower than the critical.

Due to the economies of scale for district heating networks, the key figure will illustrate that it can be a good idea to establish a 500 m (1640 ft) branch line to a large customer, whereas a 15 m (49 ft) branch line to a small customer may not be cost-effective. In this work, the map is essential because it shows how the production plants can be interconnected with all the districts and customers and how the districts can be supplied one after the other and ranked. First priority should be given to districts close to the plants and districts with large heat density. Second priority should be given to districts that can be supplied by pipes via the first priority districts. Third priority is given to districts with a longer distance from the production plants that can be supplied from second priority districts. Finally, small branches of the grid and branch lines can be assessed by the investment key figure. The following information is required:

- Identification of a suitable trench of the distribution network from production to all districts and customers plus large branch lines.
- Estimate of pipe dimensions and length of each pipe for a distribution network and for typical branch lines in each district.
- The network will normally be analyzed by a hydraulic analysis system, but for a simple case, the energy planner can make a rough estimate manually based on a design table and manual measurements of pipe length.
- The planner can draw a logic sequence of the network. For example, connection to District A is necessary for supply of heat to District B. Therefore, the network in District A must be designed to also supply District B.

Moreover, the planner must look for the most cost-effective and realistic design concept, within the local boundaries and constrains. These could be the following:

- The variation of the elevation: The height above sea level of production plant and customers
- The need for maximal supply temperature to most customers on the coldest day
- Analysis of alternative solutions for the few customers, who need larger supply temperature than the majority. For example, customers who need heat at a larger temperature for industrial processes
- The most likely return temperature from customers once their customer installations are upgraded with control valves
- Length of the system and suitable places for booster pump stations

- Capacity constrains in existing district heating pipes
- Possibility to install local peak boilers
- Quality of typical customer heating systems considering direct connection
- The maximal supply temperature of base load production units
- The benefit of heat storages

Based on this information, the energy planner is guided to propose a realistic system design. In the first stage, the options are the following:

1. Steam system in case a majority of industrial customers requires process energy
2. Superheated hot water district heating (temperatures above 110 °C [230 °F] and up to 165 °C [329 °F]) in case industrial customers need low-pressure steam
3. Hot water district heating (temperatures below 110 °C [230 °F]) in case the majority of customers only need heating
4. Low-temperature district heating (temperatures below 95 °C [203 °F] or even lower)

The first two options, which can supply most types of customers, have been the solution in many cities for years, but options 3 and 4 are becoming best practices due to lower costs of pipe installations; lower cost of customer installations; more cost-effective for establishing thermal storages; more cost-effective heat production from combined heat and power, heat pumps, geothermal energy, solar heating, and flue gas condensation; lower heat losses in the district heating grid; and improved reliability.

In the conceptual design of a low-temperature district heating network, the maximal operation temperature must be lower than 95 °C (203 °F) to allow pressureless heat storage tanks or lower than 85 °C to allow heat storage pits and certain renewable heat production sources. Furthermore, the pressure level must be 6 bar for direct connection or 10 bar, 16 bar, or 25 bar for indirect connection at customer installations. GIS-based hydraulic analysis can be used to calculate the accurate length of pipes and to design the necessary dimensions considering heat load of each costumer, diversity of consumption, maximal supply temperature, estimated return temperature, and available pressure difference from the production plants. The network design must consider that the diversity factor is 1.0 at customer branch lines and that this factor is gradually reduced for larger dimensions for a number of customers.

F.2.4.1 Capacities and Losses (Tables F.80, F.81, F.82, F.83, and F.84)

F.2.4.2 Prices (Table F.85 and Fig. F.58)

F.2.4.3 Hydraulic Network Analysis

To determine the dimensions of the pipes in the district heating network (see, e.g., Figs. F.59 and F.60), one must do the following:

- Identify load cases on the heat duration curves (zonal development).
- Determine peak load.

Table F.80 Pre-insulated pipes (1/3)

	Unit	DN15	DN20	DN25	DN32	DN40	DN50	DN65	DN80	DN100
Inner diameter	mm	17	23	29	37	43	55	70	83	107
Velocity at 10 mm/m	m/s	0	0	0	1	1	1	1	1	1
Water flow	m^3/h	0	1	1	2	3	5	11	16	32
Maximal supply temperature	°C	90	90	90	90	90	90	90	90	90
Return temperature	°C	50	50	50	50	50	50	50	50	50
Heat loss capacity	W/m	9	10	10	10	12	12	14	15	15
Heat loss energy per year	MWh/m/a	0	0	0	0	0	0	0	0	0
Capacity	MW	0	0	0	0	0	0	0	1	2
Annual max load hours	h	2000	2000	2000	2000	2000	2000	2000	2000	2000
Annual heat transfer	MWh/a	23	50	93	182	268	499	986	1500	3010
Annual heat losses/km	%/km	77	64	48	32	29	18	11	8	4
Cost per meter	USD/m	419	419	449	470	487	521	568	635	732
Cost per MWh/a per km	USD/MWh/a/km	18,388	8454	4807	2587	1816	1044	577	423	243

Table F.81 Pre-insulated pipes (2/3)

	Unit	DN125	DN150	DN200	DN250	DN300	DN350	DN400	DN450	DN500
Inner diameter	mm	133	160	210	263	313	344	394	444	495
Velocity at 10 mm/m	m/s	1	1	2	2	2	2	2	2	3
Water flow	m^3/h	57	94	190	342	539	694	987	1351	1797
Maximal supply temperature	°C	90	90	90	90	90	90	90	90	90
Return temperature	°C	50	50	50	50	50	50	50	50	50
Heat loss capacity	W/m	16	17	19	35	39	38	39	44	49
Heat loss energy per year	MWh/m/a	0	0	0	0	0	0	0	0	0
Capacity	MW	3	4	9	16	25	32	46	63	83
Annual max load hours	h	2000	2000	2000	2000	2000	2000	2000	2000	2000
Annual heat transfer	MWh/a	5252	8699	17,607	31,765	50,037	64,431	91,565	12,5418	166,805
Annual heat losses/km	%/km	3%	2%	1%	1%	1%	1%	0%	0%	0%
Cost per meter	USD/m	861	995	1244	1623	1953	2274	2472	2472	2797
Cost per MWh/a per km	USD/MWh/a/km	164	114	71	51	39	35	27	20	17

Table F.82 Pre-insulated pipes (3/3)

	Unit	DN600	DN700	DN800	DN900	DN1000
Inner diameter	mm	596	694	795	894	994
Velocity at 10 mm/m	m/s	3	3	3	4	4
Water flow	m^3/h	2911	4326	6187	7917	9779
Maximal supply temperature	°C	90	90	90	90	90
Return temperature	°C	50	50	50	50	50
Heat loss capacity	W/m	44	50	62	68	74
Heat loss energy per year	MWh/m/a	0	0	1	1	1
Capacity	MW	135	201	287	367	454
Annual max load hours	h	2000	2000	2000	2000	2000
Annual heat transfer	MWh/a	270,144	401,460	574,150	734,731	907,481
Annual heat losses/km	%/km	0%	0%	0%	0%	0%
Cost per meter	USD/m	2945	3093	3240	3388	3536
Cost per MWh/a per km	USD/MWh/a/km	11	8	6	5	4

- Determine maximal use of base load.
- Determine summer load.
- Calculate trench in hydraulic model.
- Transfer demand and production capacity to the grid.
- Determine design parameters, pressure levels and zones, and temperature.
- Determine design of network for the base case, including booster pumps.
- Consider optimization, booster pumps, and considerations for future expansion.

F.2.4.4 Pre-insulated Pipes

Development of district heating pipe constructions in brief in five decades:

- 1970: Concrete ducts, expensive, long lifetime, but some failures, first pre-insulated pipes in Løgstør, but poor quality
- 1980: Danish standard for DH pipes in the ground, better quality of pre-insulated pipes of various principles and competition
- 1990: Pre-insulated pipes of good quality almost 100% market share, bonds system, welded muffs, no expansion joints, surveillance system
- 2000: Bent pipes, twin pipes, no-dig methods, etc.
- 2010: Pre-insulated pipes all over the world for DH&C

Standards for district heating pipe systems and pipes freedom to good design, based on function:

- Standards for use of pre-insulated pipes
- Standards for the pipes
- Safety regulations and classification, e.g., pressure and temperature

Table F.83 District heating pipe technical parameters

D_N	D_y	t	D_i	Vel. 10 0/00	Velocity	Flow	Flow	Power	Loss	Loss	Heat	Heat loss
mm	mm	mm	mm	m/s	m/s	l/s	m^3/h	MW	W/m/°C	W/m	MWh/year	MWh/year/m
Dn	Dy	t	Di		Velocity	Flow1	Flow2	Power	Loss1	Loss2	Heat	
DN15	21.3	2.0	17.3	0.29	0.29	0.068	0.245	0.011	0.070	9	23	0.076
DN20	26.9	2.0	22.9	0.36	0.36	0.148	0.534	0.0248	0.080	10	50	0.087
DN25	33.7	2.3	29.1	0.42	0.42	0.279	1.006	0.0467	0.080	10	93	0.087
DN32	42.4	2.6	37.2	0.50	0.50	0.544	1.96	0.0908	0.080	10	182	0.087
DN40	48.3	2.6	43.1	0.55	0.55	0.803	2.89	0.134	0.100	12	268	0.109
DN50	60.3	2.9	54.5	0.64	0.64	1.493	5.38	0.249	0.100	12	499	0.109
DN65	76.1	2.9	70.3	0.76	0.76	2.95	10.62	0.493	0.110	14	986	0.119
DN80	88.9	3.2	82.5	0.84	0.84	4.49	16.2	0.750	0.120	15	1500	0.130
DN100	114.3	3.6	107.1	1.00	1.00	9.01	32.4	1.505	0.120	15	3010	0.130
DN125	139.7	3.6	132.5	1.14	1.14	15.7	56.6	2.63	0.125	16	5,252	0.136
DN150	168.3	4.0	160.3	1.29	1.29	26.0	93.7	4.35	0.140	17	8699	0.152
DN200	219.1	4.5	210.1	1.52	1.52	52.7	189.7	8.80	0.150	19	17,607	0.163
DN250	273.0	5.0	263.0	1.75	1.75	95	342	15.88	0.280	35	31,765	0.304
DN300	323.9	5.6	312.7	1.95	1.95	150	539	25.02	0.318	39	50,037	0.345
DN350	355.6	5.6	344.4	2.07	2.07	193	694	32.22	0.307	38	64,431	0.333
DN400	406.4	6.3	393.8	2.25	2.25	274	987	45.78	0.318	39	91,565	0.345
DN450	457.0	6.3	444.4	2.42	2.42	375	1351	62.71	0.358	44	125,418	0.389
DN500	508.0	6.3	495.4	2.59	2.59	499	1797	83.40	0.399	49	166,805	0.433
DN600	610.0	7.1	595.8	2.90	2.90	809	2911	135.1	0.357	44	270,144	0.388
DN700	711.2	8.8	693.6	3.18	3.18	1202	4326	200.7	0.400	50	401,460	0.434
DN800	812.8	8.8	795.2	3.46	3.46	1719	6187	287	0.500	62	574,150	0.543
DN900	914.4	10.0	894.4	3.50	3.50	2199	7917	367	0.55	68.2	734,731	0.6
DN1000	1016.0	11.0	994.0	3.50	3.50	2716	9779	454	0.6	74.4	907,481	0.7

Table F.84 Design parameters

Design parameters	Unit	Value
Cooling of circulated water	°C	40
Pressure gradient	0/00	10
Max load hours	h/a	2000
Supply temp. average	°C	90
Return temp. average	°C	50
Temperature of soil	°C	8

Prices	Including all construction costs, design supervision, and unexpected costs.
Land	Denmark
System	Pre-insulated steel pipes with welded PEH (*Petroleum Engineering Handbook*) casing including surveillance system
Local conditions	Wide road in suburb areas

- Standards for specific components, boilers, etc.
- Environmental requirements
- Guidelines for infrastructure in the ground in roads—“the guest principle”
- Way of right, same importance as roads for public use
- Declaration in landowners register

Typical design parameters:

- Pressure level: 6, 10, 16, or 25 bar max pres.
- Maximal temperature: <110 °C or <160 °C (<203 °F or <320 °F).
- Return temperature: as low as possible.
- Hydraulic design: optimize based on life cycle cost, use available pressure, but max 3.5 m/s (11 ft/s), typical 10 mm/m (0.12 in./ft) for new networks, as much as possible in old networks.
- Bonded without expansion joints for <110 °C (<203 °F).
- Twin pipes < DN200 if regular flat trench.
- Long trench, “gas pipe” technology.
- No-dig method for crossings.
- Small no-dig tunnels under rail roads.

Figure F.61 shows the installation of pre-insulated pipes.

District Heating Development

1G district heating systems are steam systems with steam pipes in concrete ducts (Fig. F.62). Typically, the costs for establishing and maintaining such a system are much higher than later generations of district heating systems (see Fig. F.63). Most American systems are still operated as steam systems (1st generation).

The 4G district heating systems are operated at lower temperatures. In Denmark, experiences with 4G district heating systems have been limited to a few residential areas. Typically, these systems have much lower heat losses and therefore higher efficiencies.

Table F.85 District heating pipe prices

Country	Denmark	Denmark	Denmark	Denmark	Denmark	Great Britain	Great Britain	Sweden	Sweden	Kazakhstan	United States	United States
Type of road	Large roads	Residential streets	Uncoated	Renovation of concrete edges	Twin	Hard	Soft	Hard	Soft	Hard	Hard	Soft
Reference	Rambøll											
DN	USD/m	USD/m	USD/m	USD/m	USD/m	USD/m	USD/m	USD/m	USD/m	USD/m	USD/m	USD/m
DN20	419	377	312	433	265	1000	770	328	231	118	668	476
DN25	449	389	318	447	271	1005	775	377	293	127	728	527
DN32	470	424	352	487	299	1059	829	426	356	148	759	533
DN40	487	441	357	508	303	1082	851	524	391	172	808	556
DN50	521	470	372	541	316	1157	897	573	447	206	890	535
DN65	568	518	358	595	304	1217	935	629	503	248	991	603
DN80	635	577	403	663	343	1341	1050	678	559	303	1149	710
DN100	732	668	475	769	404	1460	1163	810	636	376	1355	867
DN125	861	789	580	907	493	1564	1280	859	699	444	1400	1025
DN150	995	815	686	937	583	1694	1363	950	762	489	1772	1181
DN200	1120	1031	790	1186	672	1845	1511	1020	811	534	1871	1259
DN250	1244	1147	894	1319	760	1997	1658	1090	859	682	1971	1336
DN300	1623	1502	1050	1728	893	2128	1775	1202	985	917	2583	1570
DN350	1953	1813	1468	2085	1248	2412	2039	1383	1132	1120	3116	2195
DN400	2274	2115	1723	2432	1465	2521	2138	1523	1258	1269	3635	2582
DN450	2472	2304	1884	2649	1601	2631	2236	1663	1383	1417	3960	2816
DN500	2797					2740	2335	1928	1600	1750	4181	2972
DN600	2945					2850	2434	2208	1831	2082	4401	3129
DN700	3093					2959	2533	2321	1928	2198	4622	3286
DN800	3240					3069	2632	2435	2026	2314	4843	3442
DN900	3388					3179	2730	2548	2124	2430	5064	3599
DN1000	3536					3288	2829	2662	2222	2546	5285	3756

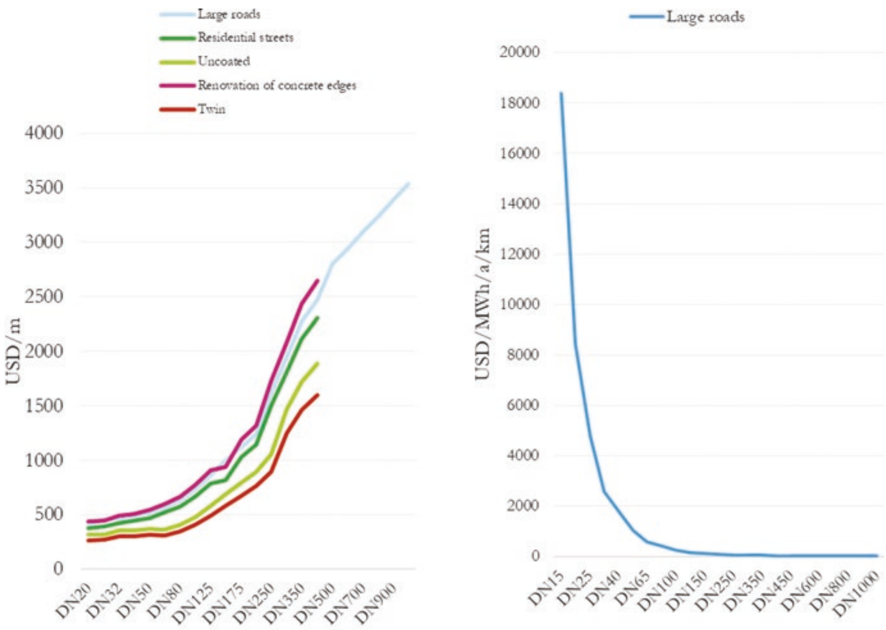


Fig. F.58 District heating pipe prices

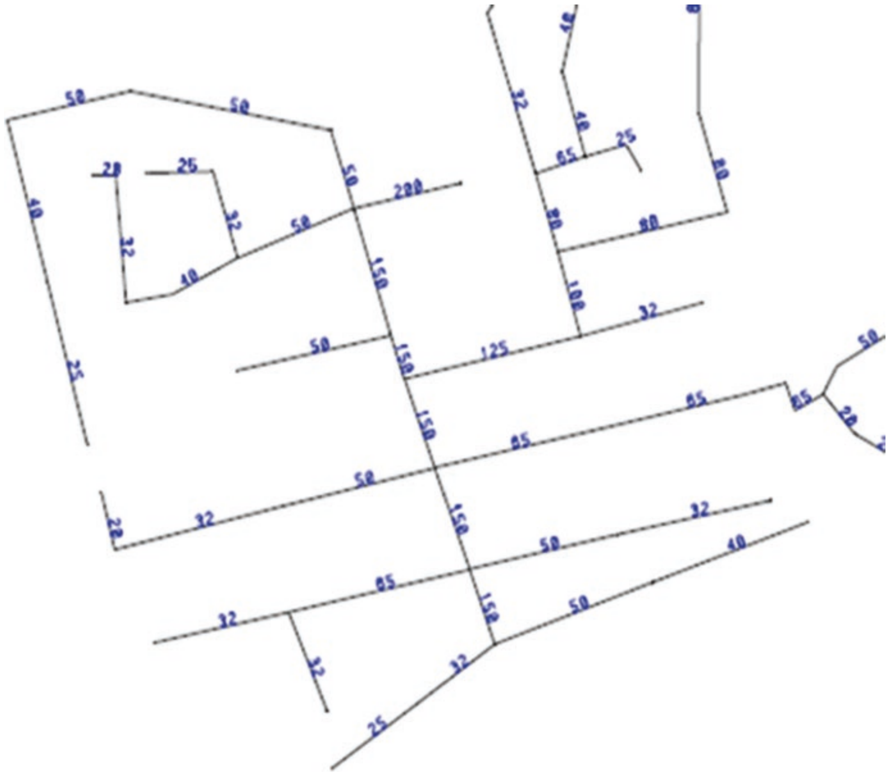


Fig. F.59 Hydraulic network analysis

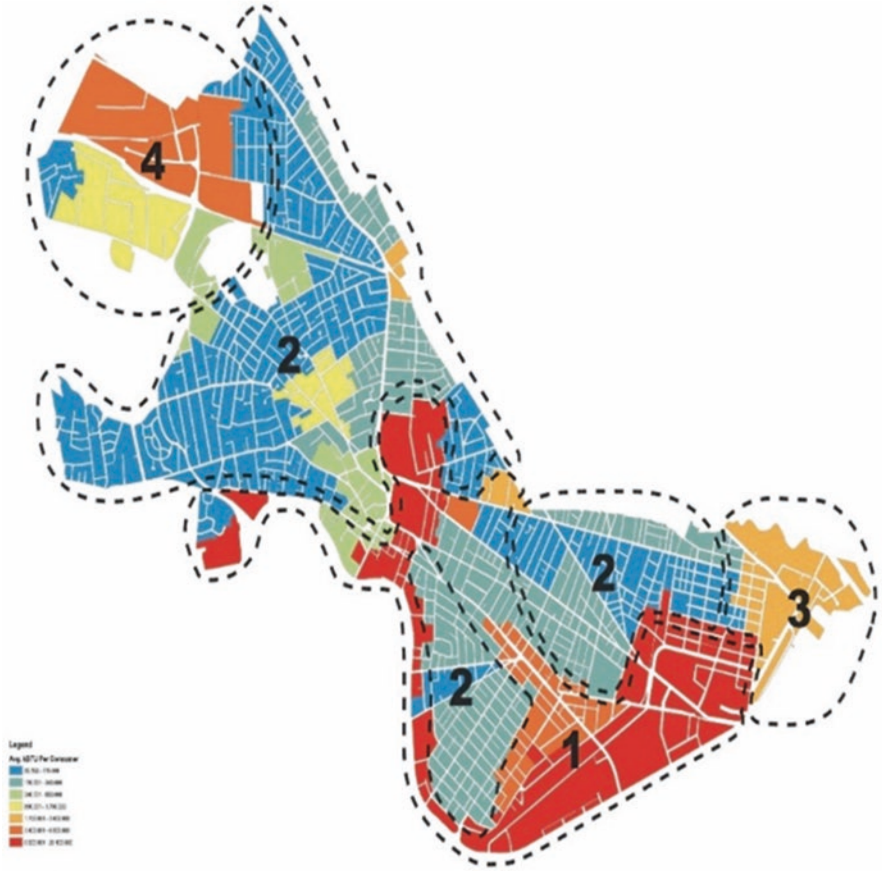


Fig. F.60 District heating network zoning (Cambridge in Boston)

Fig. F.61 Installation of pre-insulated pipes

Fig. F.62 District heating development and concrete duct (utility tunnel)

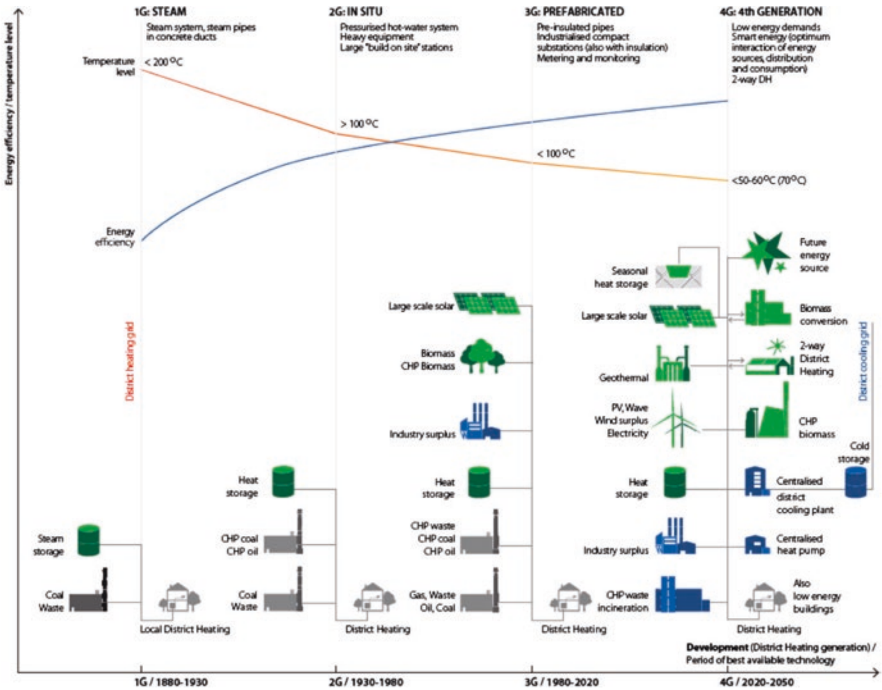


Fig. F.63 District heating development

Synergies between DHC systems are easier to obtain when the temperatures are lowered because the heat pumps cannot operate at very high temperatures (maybe with low efficiency).

It is also easier to convert to 100% renewable energy systems, as heat pumps and electric boilers use electricity production from renewable energy sources like electricity from wind and solar.

Two-Pipe Active Beam System

Technology

Active beams are devices that can provide outdoor air, sensible heating, and sensible cooling to a space. They consist of a primary air plenum, a mixing chamber, a heat exchanger, and several nozzles. The primary air is discharged to the mixing chamber though nozzles. This generates a low static pressure region, which induced air from the room up through the heat exchanger, where the hot or cold water is circulating. The conditioned air is then mixed with primary air, and the mixture is supplied to the space.

Application

Active beams are commonly used in a four-pipe configuration including two supply pipes and two return pipes. Therefore, some zones can receive hot water for heating, while other zones receive chilled water for cooling. The main characteristic of the novel two-pipe active beam system is its ability to provide simultaneous heating and cooling by operating a single hydronic circuit with supply water temperatures of about 22 °C (72 °F), year-round. A room with an indoor air temperature of 20 °C (72 °F) would be heated, while a room at 24 °C (75 °F) would be cooled. Beside the advantages in terms of exploitation of sustainable energy sources, operating such water temperature opens opportunities for transferring heat among different rooms when simultaneous heating and cooling occur in the building.

Scientific studies

The operation of the novel two-pipe active beam system was studied through simulation-based analyses and full-scale experiments. Simulation results showed that the novel two-pipe system is able to reduce the annual primary energy use of buildings by approximately 20% in comparison to conventional four-pipe system.

Full-scale experiments were performed in a newly constructed building in Jönköping, Sweden. Physical parameters such as water flows and temperatures were monitored for a 1-year period in the hydronic circuit, and measurements of room air temperature, air velocity, and humidity were collected in indoor spaces to assess thermal comfort conditions. The monitoring of water flows and temperatures confirmed the ability of the system in operating with a single hydronic circuit to provide simultaneous heating and cooling while reducing annual primary energy use. Measurements and questionnaires regarding thermal comfort showed that the system provides a satisfactory thermal environment in the building.

Reports

A total of nine scientific publications have been produced on the topic of the novel two-pipe active beam system.

Journal Articles

Maccarini, A., G. Hultmark, N. C. Bergsøe, and A. Afshari. 2018. "Free Cooling Potential of a PCM-Based Heat Exchanger Coupled with a Novel HVAC System for Simultaneous Heating and Cooling of Buildings." *Sustainable Cities and Societies*.

Maccarini, A., G. Hultmark, A. Afshari, N. C. Bergsøe, and A. Vorre. 2017. "Transferring Heat among Building Zones through a Room-Temperature Water Loop—Influence of Climate and Occupancy." *Building Simulation* vol. 10, pp 697-710.

Maccarini, A., M. Wetter, G. Hultmark, A. Vorre, A. Afshari, and N. C. Bergsøe. 2017. "Energy Savings Potential of a Two-Pipe System for Simultaneous Heating and Cooling of Office Buildings." *Energy and Buildings*. Vol 134, pp 234-247.

Maccarini, A., G. Hultmark, A. Vorre, A. Afshari, and N. C. Bergsøe. 2015. "Modeling of Active Beam Units with Modelica." *Building Simulation*. Vol 8, pp 543–550.

Articles in Conference Proceedings

Maccarini, A., G. Hultmark, N. C. Bergsøe and A. Afshari. 2018. "Operation of a Novel Two-Pipe System in an Office Building: A Thermal Comfort Study." Presented at the 15th International Conference on Indoor Air Quality and Climate (IndoorAir 2018). Philadelphia, USA, July 22-27.

Maccarini, A., G. Hultmark, A. Afshari, and N. C. Bergsøe. 2017. "Analysis of Control Strategies for a Novel HVAC System Equipped with a Room-Temperature Water Loop." Proceedings of the 15th IBPSA Conference. San Francisco, USA, August 7-9.

Maccarini, A., A. Afshari, G. Hultmark, N. C. Bergsøe, and A. Vorre. 2016. "Development of a New Controller for Simultaneous Heating and Cooling of Office Buildings." Proceedings of the 9th IAQVEC Conference. Seoul, South Korea, October 24-26.

Maccarini, A., A. Afshari, G. Hultmark, N. C. Bergsøe, and A. Vorre. 2016. "Modeling of a Novel Low Exergy System for Office Buildings with Modelica." Proceedings of the 12th REHVA World Congress (CLIMA 2016). Aalborg, Denmark, May 23–26.

Maccarini, A., A. Afshari, N. C. Bergsøe, G. Hultmark, M. Jacobsson, and A. Vorre. 2014. "Innovative Two-Pipe Active Chilled Beam System for Simultaneous Heating and Cooling of Office Buildings." Proceedings of the 13th International Conference on Indoor Air Quality and Climate (IndoorAir 2014). Hong Kong, July 7–12.

F.2.4.5 Steam Pipes (Table F.86)

F.2.5 HVAC

The HVAC installations in the buildings (Fig. F.64) are an important part of the energy system for their:

- Efficient regulation to provide good thermal comfort
- Efficient regulation to avoid waste of heat or cold
- Ability to use low-temperature sources for heating, e.g., supply 70 °C (158 °F) and return 40 °C (104 °F)
- Ability to use high-temperature sources for cooling, e.g., supply 10 °C (50 °F) and return 15 °C (59 °F)
- Ability to deliver hot tap water without any risk of legionella
- Ability to deliver resilient cooling to servers and other vital installations

  Efficient HVAC installations are a precondition for using efficient sources for heating and cooling, both at the building level and via DH and DC.

  HVAC is an important part of residential structures such as single-family homes, apartment buildings, hotels and senior living facilities, medium to large industrial and office buildings such as skyscrapers and hospitals, on ships and submarines, and in marine environments, where safe and healthy building conditions are regulated with respect to temperature and humidity, using fresh air from outdoors.

F.2.5.1 Heat Exchangers (Building Level)

The district heating substation is placed at the end user with the purpose of preparing DHW and delivering heat for the space heating system based on district heating. Each building with a district heating substation is supplied from a branch pipe that connects the building to the overall distribution network.

The substation is equipped with a DHW heater based on either a storage tank or a heat exchanger without storage, e.g., a plate heat exchanger. In some cases, a combination of an external heat exchanger and a storage tank is seen. The space heating is delivered by direct supply of district heating water or by a heat exchanger placed in between the district heating water (primary side) and the space heating water (secondary side). Furthermore, the substation includes all valves, controllers, filters, pumps, etc. that are necessary for the operation.

In large buildings, the substation can be placed centrally, or small substations, the so-called flat stations, can be placed in each apartment.

Table F.87 lists the price of a district heating substation, depending on the nominal transfer capacity. Prices are based on experience from the VEKS Køge district heating project from 2016 and include materials and work, including the preparation of existing boiler rooms for district heating, the district heating substation, new hot water tank, new pumps on the building side, and a new expansion valve as well as installation.

Table F.86 Steam pipes

Steam piping capacity[a]							1000 Lbs./Hr Steam quantity (1000 Ft²) Area [hp] feedwater pump Hp		
Buried pipe			Initial Pressure Δp/100 Ft. Total Δp Saturated Temperature (°F)						
Steam/ condensate	Cost	15 0.4–4 250	30 0.6–8 270	50 0.8–12 300	100 1.2–20 340	125 1.6–26 350	150 2–32 370	250 3–50 400	
24 in./10 in.	$1000/LF	100 (1500) [5]	200 (3000) [20]	300 (4500) [40]	600 (9000) [150]	700 (10,000) [250]	1000 (15,000) [400]	1500 (22,000) [1000]	
20 in./8 in.	$900/LF	70 (1000) [3]	150 (2200) [15]	200 (3000) [30]	400 (6000) [100]	450 (6800) [150]	600 (9000) [250]	950 (14,000) [600]	
18 in./8 in.	$850/LF	50 (750) [2]	100 (1500) [10]	150 (2200) [20]	300 (4500) [75]	350 (5200) [120]	450 (6800) [200]	700 (10,000) [500]	
16 in./6 in.	$700/LF	40 (600) [1]	70 (1000) [5]	100 (1500) [15]	200 (3000) [50]	250 (3800) [100]	350 (5200) [150]	550 (8300) [400]	
14 in./6 in.	$660/LF	25 (380) [1]	50 (750) [4]	80 (1200) [10]	150 (2200) [40]	170 (2500) [75]	250 (3800) [100]	350 (5200) [300]	
12 in./4 in.	$550/LF	20 (300) [1]	40 (600) [3]	60 (900) [10]	120 (1800) [30]	150 (2200) [50]	200 (3000) [75]	300 (4500) [200]	
10 in./4 in.	$500/LF	15 (220) [1]	25 (380) [2]	40 (600) [5]	70 (1000) [20]	80 (1200) [25]	120 (1800) [50]	200 (3000) [150]	
8 in./4 in.	$480/LF	7 (100) [1]	15 (220) [1]	20 (300) [2]	40 (600) [10]	50 (750) [20]	70 (1000) [30]	100 (1500) [75]	
6 in./3 in.	$450/LF	4 (60) [1]	7 (100) [1]	10 (150) [1]	20 (300) [5]	25 (380) [7]	35 (520) [15]	50 (750) [50]	
4 in./1.5 in.	$400/LF	1 (15) [1]	2 (30) [1]	4 (60) [1]	6 (90) [1]	7 (100) [2]	10 (150) [4]	15 (220) [10]	

Building SQFT values are based on 60 Btuh/ft^2 peak average combined load (building heat and domestic hot water). For winter lows below +25 °F: at 0 °F multiply building SQFT by 0.8, at −20 °F multiply building SQFT by 0.6. Steam lines are sized to approximately 10,000 ft/min. Condensate lines are sized to approximately yield pressure drops less than 2′/100′. Prices shown are construction costs for direct buried pipe. For total project cost, add A–E fees, testing, escalations, contingencies, etc. This chart is intended to be used for obtaining an initial estimate of required pipe size and cost. Actual system design must be based on values obtained specifically for the project

Fig. F.64 HVAC facilities

Table F.87 District heating substation price

Nominal capacity	Price	Unit price
kW	USD	USD/kW
30	11,534	384
47	14,848	316
103	16,327	159
177	22,465	127
193	23,364	121
302	28,096	93
607	40,691	67
963	49,261	51

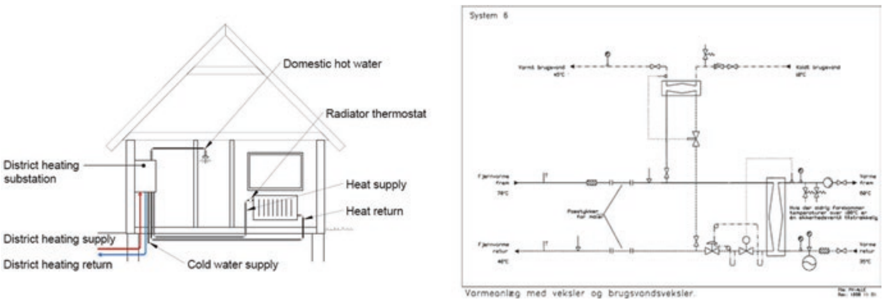


Fig. F.65 District heating substations

Thus, the price estimate is not for new buildings, but we still assume that one needs to prepare a technology room for installation in new buildings. We therefore use the unit prices shown for the district heating substations (Fig. F.65). Figure F.66 shows prices for a fixed temperature set. It is therefore not reflected in the price that a larger surface in the heat exchanger is required at very low district heating temperatures (low ΔT).

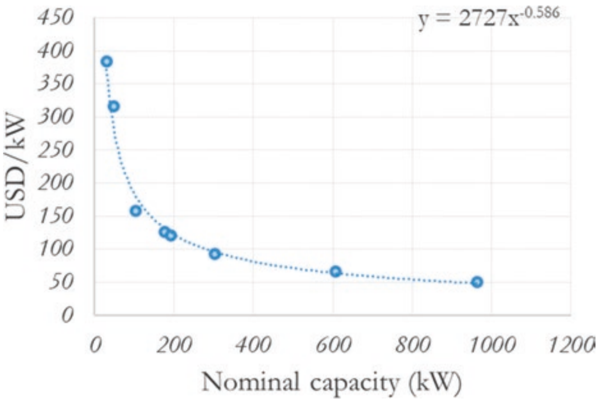


Fig. F.66 District heating substation price

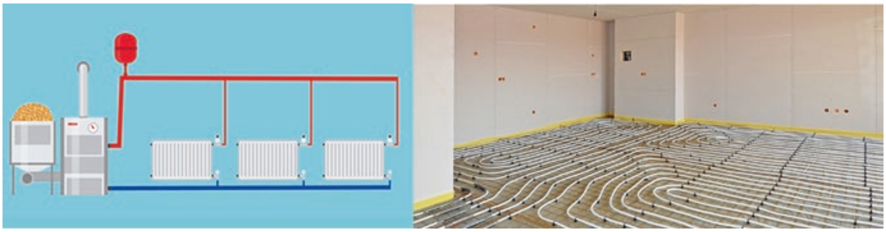


Fig. F.67 Central heating principle and floor heating

Central Heating

Central heating (Fig. F.67) is a heating system where the heat is produced a central place in the building and from there distributed to the rooms to be heated. Most buildings now have central heating, which means that heating systems are more often referred to as energy forms, e.g., oil boiler or electric heating, or by means of supply, e.g., district heating, or by distribution, such as air heating.

Heating by open fire has been known since prehistoric times, but the distribution of heat from a central location has been a problem. The advent of knowledge of steam properties and the emergence of steel and copper pipes gave rise to a new possibility for transport of heat. Steam pressure, even over long distances, can be used to transport the hot steam through a pipeline to radiators in each room in a building. The same type of plant with a pipe grid and radiators also proved to be useful with hot water. However, the use of hot water is not easily paired with a pressurized system; since hot water has a lesser density than cold water, circulation can be maintained by the hot water rising up in the system and the cooled water going downward. This form of construction has contributed to the widespread dissemination of central heating; the same applies for the introduction of circulation pumps, which allows the use of small pipe dimensions with a smooth pipeline to follow.

To a certain extent, central heating is also provided in the form of forced air heating systems, where the addition of fans made it easy to transport the hot air to the rooms. Especially in cases where cooling is required for part of the year, air-conditioning systems have an advantage over installations with hot water systems.

Table F.88 lists (and Fig. F.68 shows) the price of a large hot water tank based on our experience with WPH prices. It requires reasonable detailed knowledge of the hot water consumption in the building to design the container optimally. The price includes investment in a hot water tank, insulation of the cover, pressure thermometer, air discharge, safety valve, and onsite welding. The estimate also includes the cost of pipes in buildings (Table F.89) and radiators and floor heating (Table F.90). Note that, in reality, these cost estimates will vary for each building.

Ventilation System

In many instances, ventilation systems are used to control both indoor air quality and thermal comfort. In such systems, it can be beneficial to increase the ventilation

Table F.88 Hot water tank price

Tank capacity	Price	Unit price
Reference	Rambøll	
liter	USD	USD/liter
650	5536	8.5
800	5625	7.0
800	5625	7.0
1250	7072	5.7
2000	8455	4.2
2200	8903	4.0
2500	9411	3.8

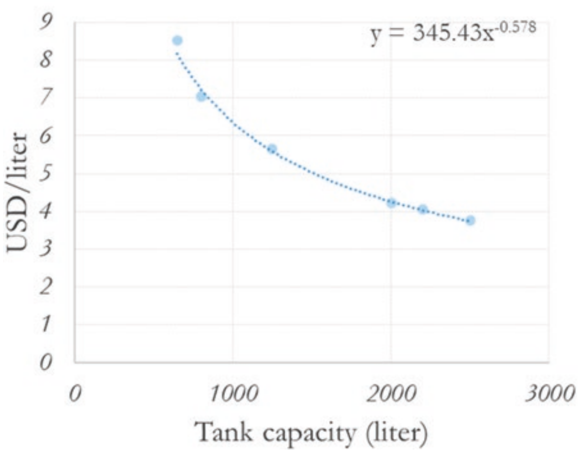


Fig. F.68 Hot water tank price

Table F.89 Pipes in buildings price

Pipe dimension	Price	Unit price
Reference	Rambøll	
DN	EUR/m	USD/m
DN 10	132	148
DN 15	135	151
DN 20	138	155
DN 25	141	158
DN 32	156	175
DN 40	158	177
DN 50	165	185
DN 65	159	178
DN 80	179	200
DN 100	210	236

Table F.90 Radiator and floor heating price

	Radiator	Floor heating
Reference	Rambøll	
	USD/m^2	USD/m^2
Value	747	90
Lifetime	50	50

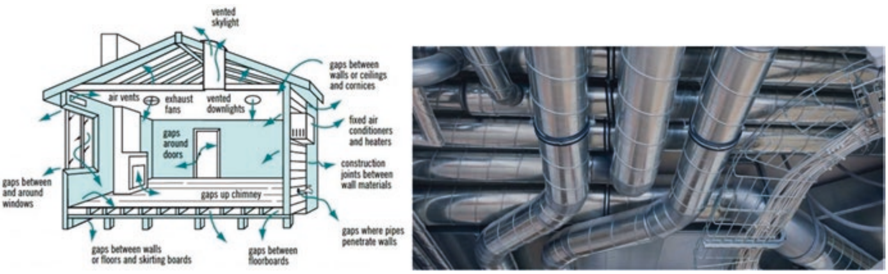


Fig. F.69 Ventilation system

rate beyond the minimum required for indoor air quality. Two examples include air-side economizer strategies and ventilation pre-cooling. In other instances, ventilation for indoor air quality contributes to the need for—and energy use by—mechanical heating and cooling equipment. In hot and humid climates, dehumidification of ventilation air can be a particularly energy-intensive process.

Ventilation should be considered for its relationship to "venting" of appliances and combustion equipment such as water heaters, furnaces, boilers, and wood stoves (Fig. F.69). Most importantly, the design of building ventilation must be careful to avoid the backdraft of combustion products from "naturally vented" appliances into the occupied space. This issue is of greater importance in new buildings with more airtight envelopes. To avoid the hazard, many modern combustion appliances use "direct venting" which draws combustion air directly from outdoors, instead of from the indoor environment.

Natural ventilation can also be achieved through the use of operable windows; this has largely been removed from most current architecture buildings due to the mechanical system continuously operating. The current US strategy for ventilating buildings is to rely solely on mechanical ventilation. In Europe designers have experimented with design solutions that will allow for natural ventilation with minimal mechanical interference. These techniques include building layout, facade construction, and materials used for inside finishes. European designers have also switched back to the use of operable windows to solve indoor air quality issues.

Sources

National Renewable Energy Laboratory (NREL). 2020. *NREL Standard Work Specifications Tool*. Golden, CO: NREL. NREL Standard Work Specifications | Homepage | Standard Work Specifications.

Aldrich and Arena (2013).

USDOE (U.S. Department of Energy). 2002b. *Whole-House Ventilation Systems*. Technology Fact Sheet. DOE/GO-102002-0778. Washington, DC: USDOE. https://www.nrel.gov/docs/fy03osti/26458.pdf

Wikipedia. Undated(h). *Ventilation (Architecture)*. https://en.wikipedia.org/wiki/Ventilation_(architecture).

F.2.5.2 Ventilation with Heat Recovery

Ventilation in buildings with apartments is typically built using mechanical extraction or as natural ventilation without heat recovery (Fig. F.70). Since the existing ventilation is without heat recovery, up to 30% of the building's total energy consumption for space heating is lost.

Ventilation can be provided as vertical exhaust (exhaust ducts) in kitchen and bath or fresh air supply in living rooms and rooms through leaks in the facade or fresh air valves in windows or facades. Insufficient ventilation in the building is often caused by:

1. Too few fresh air valves in the facade.
2. An inadequate exhaustion of natural ventilation.
3. Drainage conditions that have become insufficient in connection with renovation work on the loft, kitchen, and bathrooms or as a result of reduced channel crossing or inappropriate channel entries with many bends.
4. Improper behavior of residents. If a resident closes the air valves to muffle a draft noise or to lower the heat bill, the unfortunate consequence is that it will affect the entire air balance in the other apartments in the building because it creates a negative pressure relative to the surrounding apartments and rooms. A

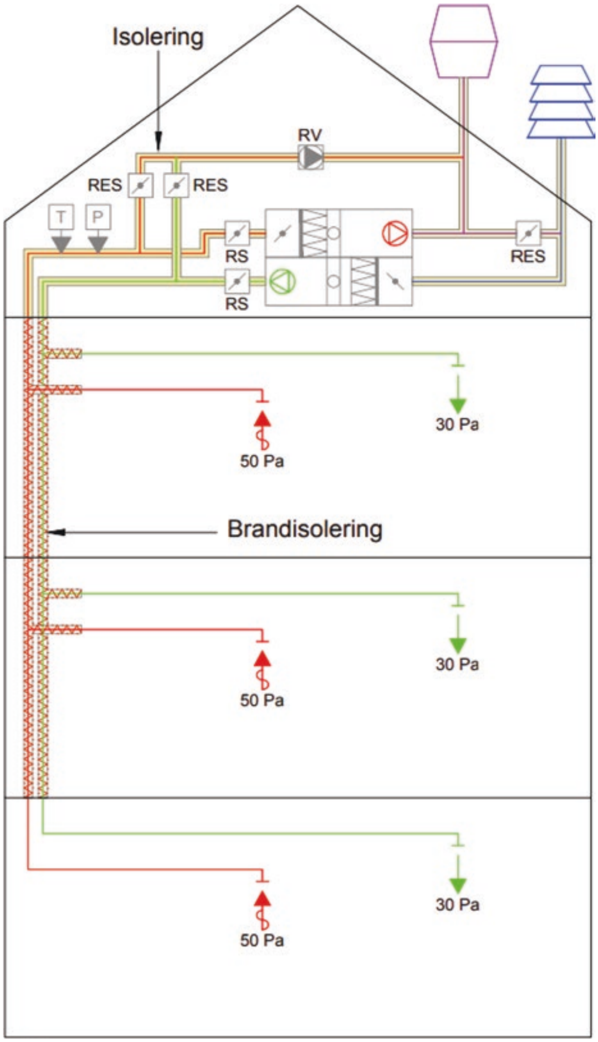


Fig. F.70 Central ventilation with heat recovery

greatly increased negative pressure often produces noise and odor transfer between apartments or from garbage disposal.

Thus, one of two issues is often found:

1. Lack of air shift that compromises indoor air quality and contributes to the risk for the formation of mold due to high air moisture content
2. Adequate or excessive ventilation that partly contributes to poor thermal indoor climate and that is extremely energy consuming

Therefore, always remember to use the option to upgrade the ventilation with heat recovery in the following situations:

- If mold has occurred in the apartment (may often be due to lack of ventilation)
- In connection with energy renovations, for example, facade renovation and window replacement

Source

http://www.danskfjernvarme.dk/-/media/danskfjernvarme/kurser-moder/modematerialer/erfamoeder/2015-maj-erfa-traef-om-energibesparelser/ventilationsguide%2D%2Denergiloesninger.pdf

Hot Tap Water System

Water heating is a heat transfer process that uses an energy source to heat water above its initial temperature. Typical domestic uses of hot water include cooking, cleaning, bathing, and space heating. In industry, hot water and water heated to steam have many uses.

The required temperature of hot water is 60 °C. In Sect. 8.2§3 of the building regulations, it is stated that water treatment plants must be carried out to minimize the risk of growth of legionella bacteria in the hot water. Section 43 of DS 439 makes it clear that a hot water supply system must be arranged so that the temperature can be raised to 60 °C in case of confirmed bacterial growth. There is no requirement for the plant to run constantly at this temperature; in fact, it causes problems with calcification. Today it is common for hot water installations to have a flow temperature of 55 °C (131 °F). In the case of townhouses and apartments with low-temperature district heating units, it will probably be safe to operate at temperatures down to 45 °C (113 °F) if a heat exchanger is installed for the hot water and there is no DHW circulation. European standards (in Germany: DVGW W551) require water content to be less than 3 liters (0.79 gal) in internal pipes and like conveyances to reduce the risk the growth of legionella. (With the "3-liter rule," flow-through units can be used immediately for single-family houses and flats with flat stations [Fig. F.71].) However, this is a task for a later design phase inside the buildings (Fig. F.72).

Fig. F.71 Flat station

Fig. F.72 DHW storage tank

F.2.5.3 Hydronic Balancing

Hydronic balancing of the building heating installation is of major importance to achieve a well-functioning and an energy-efficient operation. In general terms, balancing is about ensuring that the operating conditions of each component in the installation are operating within its design operating conditions, which enables an efficient heating system operation. Hydronic heating installations can be generally grouped as radiator or floor hearing.

Hydronic Heating Systems
Hydronic systems can be further classified in a vertical riser systems and horizontal systems.

Vertical riser systems: Vertical riser systems use multiple pipes running through the floors that supply radiators and hot water taps along the way. Vertical riser systems are generally radiator heating systems.

Horizontal systems: Horizontal systems use one set of a risers for each building staircase that supplies all heat requirements of the connected apartments, both heating and DHW. The heat emitters in horizontal systems can be designed with one type or a mix of radiators and floor heating.

Heating Elements
Over the year, heating demand varies significantly, and the control equipment must be able to provide consistent and accurate control to meet the consumers' comfort requirements, independent of demand. From the standpoint of controls, one should examine the heating system from sink to source, as an efficient operation of the sink is the key to efficient buildings.

Radiators. Radiators should be designed to achieve as much utilization of heat of heat supply media as possible while keeping its supply temperature as low as possible. Current design temperature recommendation for energy-efficient heating system with radiators is 70/30/20 °C, which means 70 °C (158 °F) supply water temperature and 30 °C (86 °F) return water temperature at 20 °C (68 °F) indoor temperature at design conditions.

Thermostatic radiator valves (TRV) are used to adapt the heat supply (flow) to the actual demand. An efficient TRV consists of a preset radiator valve, which is used to limit the maximum flow through the valve, and a thermostatic head, which reacts to the indoor air temperature and adapts the flow to the desired room temperature. The radiator valves are designed for operation at maximum 60 kPa differential pressure across the valve; to avoid flow noises, the pressure drop across the valve should be below 30–35 kPa. The differential pressure available depends on the location of the radiator in respect to the pump; the closer to the pump, the higher the differential pressure. To ensure good operation of the TRV, the differential pressure should be controlled and kept within the desired range. The solutions are to have pressure-independent radiator valves or differential pressure controllers on each riser, which are addressed below.

Floor heating. Unlike radiators, floor heating loops are designed for low supply temperatures, typically in the range of 40–45 °C (104–113 °F), and return temperature of 25–30 °C (77–86 °F) at design condition.

Floor heating controls include a mixing shunt, floor heating manifold, and a room-temperature controller. The mixing shunt adapts the supply temperature to a desired level, and the floor heating manifold adapts the flow to each floor heating loop based on the inputs from the room-temperature controller. As with radiator valves, it is important to operate the floor heating controls within the designed differential pressure range.

Riser Balancing

Riser balancing is to ensure equal operating conditions between risers in the building. This is important as there will be inevitable pressure difference from the pump to the last heat user. Pressure balancing is important from two perspectives:

1. To ensure good distribution of the heat supply through the building. If this is not considered, there is a risk that the first risers "steal" large share of the supply due to wrong setting or malfunction of a TRV, leading to large flow passing through the radiator.
2. To ensure good operating conditions of the TRV at all demand conditions and avoidance of flow noises.

Domestic Hot Water (DHW) Systems

Generally, the DHW system in a multistory building will follow the concept of the heating installation.

Vertical riser systems. In a vertical riser system, DHW is prepared centrally and distributed to taps with vertical risers. To ensure a high degree of safety, hygienic requirements, and comfort at all tapping points, a thermal balancing system is needed. As with the space heating supply, each DHW riser needs to be balanced to ensure good distribution within the building. In addition to flow balancing, the DHW distribution systems need to be maintained at sufficiently high temperatures to prevent bacterial growth at the same time as heat losses are minimized. Utilization of thermal balancing valves will ensure balanced installation, stable DHW temperatures, energy-efficient operation, and, if in combination with electronic controller, a periodic thermal disinfection of the system.

Horizontal DHW system within each flat offers the opportunity to apply a small decentralized and instantaneous DHW preparation unit at the entrance to the flat. This option is especially interesting as it avoids storing of DHW water, which generally is in a temperature range that favors bacterial growth, and large inefficient DHW circulation systems. To ensure high comfort levels, it is important to ensure that the hot water is delivered quickly and at a stable temperature level to the user. This can be achieved with a sophisticated control equipment that immediately detects a hot water draw off using a proportional flow controller and thermostatic controller to achieve and maintain the desired DHW temperature. To avoid temperature fluctuations due to changes in supply conditions, a differential pressure control should be integrated in the DHW controller.

Energy Meters

To achieve energy-efficient operation of a heating installation, it is essential to include energy meters. The purpose of the energy meters is twofold, first to allocate the cost of heat generation to the actual users and secondly to maintain energy awareness of the users. The heat metering options depend on the applied system type. In a vertical riser system, the heat usage is estimated using heat cost allocators at each radiator and volumetric meters at each tap. In a horizontal system, there are two variants, instantaneous DHW unit and a decentralized DHW supply. If there is a DHW unit, the total heat supply to the flat can be measured in one place; if there is a central DHW supply, the space heating demand is measured with a heat meter, and the DHW consumption is measured with a volumetric meter, both at the entrance to the flat.

In addition, there should be a building-level heat meter and a main heat meter to measure the total heat consumption of the building. The deviation between the individual heat meters and the main heat meter, which essentially reflects the heat loss in the building distribution system, should be distributed fairly between the consumers.

F.2.6 Control

The category includes technologies, which do not fit directly into the previous categories. Therefore, for a start any interesting technology can be described here and may be later transferred to another category.

F.2.6.1 Heat Exchanger Stations

Heat exchangers have several advantages; they section pressure levels, lower the maximum temperature, secure against large amounts of water by leakage, ensure good water quality in the large systems, reduce the risk of pressure protection, and more. In the district heating system in Copenhagen, the heat exchangers typically form a natural boundary between the companies and operating organizations. These requirements have led to conditions in some places where, in certain periods, there have been three to four heat exchangers between a final consumer and the producer.

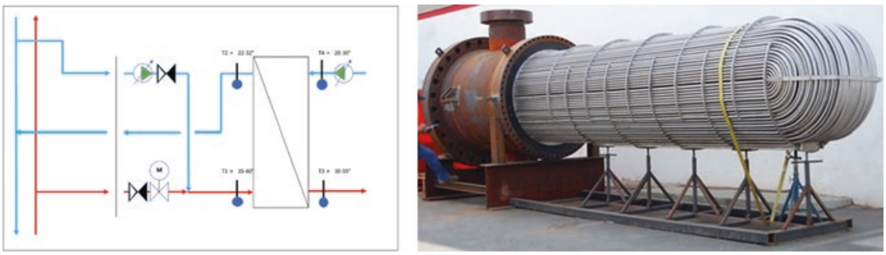


Fig. F.73 Heat exchanger station and bundle-type heat exchanger

Figure F.73 shows a heat exchanger facing a building with indirect district heating supply. (A direct supply would use no heat exchanger.) The shunt pump tries to hold T1, while the control valve first starts when the shunt pump is at maximum and the temperature is not high enough. Temperatures are given for illustration only; temperatures can be adjusted to other flow temperatures in another system.

- T3: Secondary supply depends on outdoor temperature; maximum of 55 °C (131 °F).
- T1: Primary supply will probably be T3 + 5 °C (+ 9 °F) (loss over heat exchanger).

The pump regulates T1 so that the T1's setpoint is kept.

For example, the control valve regulates that T1> T3 + 2 °C (+ 3.6 °F).

Return temperatures, T4 and T2, depend on the flow temperatures and cooling in the buildings.

F.2.6.2 Pressure Sectioning

With direct supply, one can avoid the loss in the heat exchangers. Instead, one can regulate with pressure section and a safety valves system (Fig. F.74).

In future district heating systems where low temperatures are important, certain heat exchangers can be avoided. It is technically possible to supply 70,000 end users from a single system like in Odense if one accepts direct supply and install leakage protection, where it is necessary. In Greater Copenhagen, where the system is more technical and organizationally complex than in Odense, one could argue that there must only be heat exchangers between transmission and distribution and between distribution and final consumption.

We have estimated the prices based on the pipe size that enters the building (Table F.91). All values are based on our experience.

Fig. F.74 Dantaet pressure section (leakage protection)

Table F.91 Price of leakage protection

Pipe size	Price (full leakage protection)	Price (full leakage protection)[a]
Reference	Rambøll	Rambøll
#	EUR	USD
DN 40	4064	4552
DN 50	4790	5365
DN 65	5956	6670
DN 80	6575	7364
DN 100	7596	8507

[a]All included (Dantaet prices)

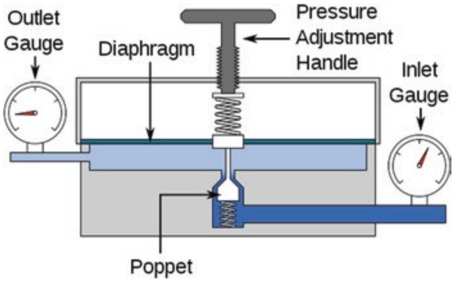


Fig. F.75 One-stage pressure regulator

F.2.6.3 Pressure Regulator

A pressure regulator is a control valve that reduces the input pressure of a fluid to a desired value at its output. Regulators are used for gases and liquids; they can be an integral device with an output pressure setting, a restrictor, and a sensor all in one body, or they may consist of a separate pressure sensor, controller, and flow valve.

Often, water enters water-using appliances at fluctuating pressures, especially in remote locations and industrial settings. This pressure often needs to be kept within a range to avoid damage to appliances or accidents involving burst pipes/conduits. A single-stage regulator (Fig. F.75) (in contrast with a two-stage regulator [Fig. F.76]) is sufficient in accuracy due to the high error tolerance of most such appliances and may also be used in applications where the water supply reservoir is significantly higher in elevation to the end of the line, e.g., underground mine water supply.

Sources

Kostival, A., C. Rivkin, W. Buttner, and R. Burgess. 2013. *Pressure Relief Devices for High-Pressure Gaseous Storage Systems: Applicability to Hydrogen Technology*. NREL/TP-5400-60175. Golden, CO: National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy14osti/60175.pdf

WikiPedia. Undated(j). *Pressure Regulator*. https://en.wikipedia.org/wiki/Pressure_regulator

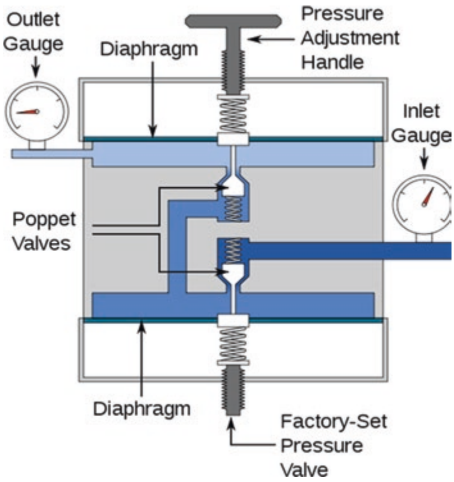


Fig. F.76 Two-stage pressure regulator

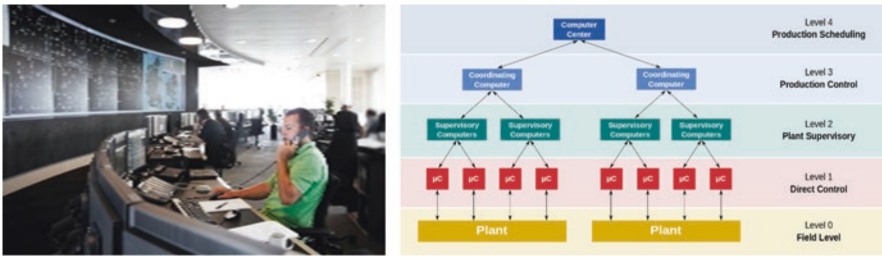


Fig. F.77 Control center Energinet.dk and SCADA structure

F.2.6.4 SCADA Systems

SCADA is a control system architecture that uses computers, networked data communications, and graphical user interfaces for high-level process supervisory management but uses other peripheral devices such as PLC and discrete proportional integral derivative (PID) controllers to interface with the process plant or machinery. The operator interfaces that enable monitoring and the issuing of process commands, such as controller setpoint changes, are handled through the SCADA computer system. However, the real-time control logic or controller calculations are performed by networked modules that connect to the field sensors and actuators.

The SCADA concept was developed as a universal means of remote access to a variety of local control modules, which could be from different manufacturers allowing access through standard automation protocol (Fig. F.77). In practice, large SCADA systems have grown to become very similar to distributed control systems in function, except that they use multiple means of interfacing with the plant. They can control large-scale processes that can include multiple sites and work over large distances as well as small distance. It is one of the most commonly used types of industrial control systems; however there are concerns about SCADA systems being vulnerable to cyberwarfare/cyberterrorism attacks.

Sources

USDOE (U.S. Department of Energy). 2002a. *21 Steps To Improve Cyber Security of SCADA Networks*. Washington, DC: USDOA https://www.oe.netl.doe.gov//docs/prepare/21stepsbooklet.pdf

Wikipedia. Undated(d). *SCADA*. https://en.wikipedia.org/wiki/SCADA

F.2.7 Resiliency

Heating is not as critical as electricity, as normally insulated buildings with a reasonable thermal capacity can be without a heat source for many hours, even days before there is a risk of damage. However, many buildings lack insulation, have pipes outside the building envelope, and have little thermal capacity. In cold climates and in the arctic, this is a challenge that must be taken seriously.

One may argue that it always will be possible to keep apartments warm with gas for cooking and with an electric heater; however this may overload the gas grid, the maximal capacity to the building, and (even worse) to the whole power system. Where buildings are served by individual building-level boilers, each building owner must take his own precautions but is heavily dependent on supply of fuel to the boiler.

District heating has the advantage that professional staff can take care of the overall security of supply by fuel flexibility and can take special precautions to react to unforeseen incidents. However, if this is not done carefully, such special precautions can be too expensive, or the system can be even more vulnerable than one that depends on individual heating such that the city district or even the whole city system can break down. Therefore, the security of supply and need for resilience must be considered in district heating systems. The following sections discuss some of actions to be taken.

F.2.7.1 From Steam to Hot Water

The most important projects for improving resilience and fuel flexibility, and for easing the transition to a low-carbon system, are conversion from steam district heating to hot water district heating and in particular hot water systems with temperatures below 100–110 °C (212–230 °F). The advantages of hot water compared to steam can be seen in the following examples.

Flooding of Steam and Hot Water Mains
It is difficult to take all precautions against flooding, as the source of water is impossible to predict. It can, for example, be seawater from a tsunami, an extremely heavy rain fall, a burst of a water main, or a break in the district heating system. In cases where the ducts and underground construction that hosts the steam pipes are flooded, the system can be restored, but it may take days or a week, as the steam condensates due to heat losses and the water must be removed. In Copenhagen, the old steam

system in the city center was knocked out for a week due to an extremely heavy rainfall that flooded many streets for first time ever; this incident probably sped up the completion of conversion to hot water district heating, which will be completed in 2022. The modern pre-insulated district heating pipes for hot water even up to 160 °C (140 °F) are resistant against flooding. Only underground pumping stations can be flooded in case of a pump failure or in case of water penetrating the underground construction. The entrance to the underground chamber will of course be above the street level to avoid penetrating rainwater; however there are incidents in which a break in a water main and flooding of the street have caused some damage.

Leaks and How to Repair Them in Steam and Hot Water

Pipe leaks can occur, for example, when they become damaged by construction of other infrastructure projects, for example, if a contractor or individual operating a digger is not properly skilled or if a no-dig drilling operation for other pipes or cables falls out of control. Such incidents often happen even when reasonable precautions have been taken.

The problem with steam pipes is even a small hole in the pipe can result in a dangerous explosion due to the huge potential energy stored in the pressured steam in the whole system (see Fig. F.77). Accordingly, it will take several days or a week to repair and restore the supply (Fig. F.78).

Small holes in the hot water pipes due to corrosion or damage of the protection will not normally develop into a severe accident. The leak detection system will discover the leak of the pipe or the damage of the insulation before the corrosion starts, and it will be possible to identify the location precisely and repair the pipe

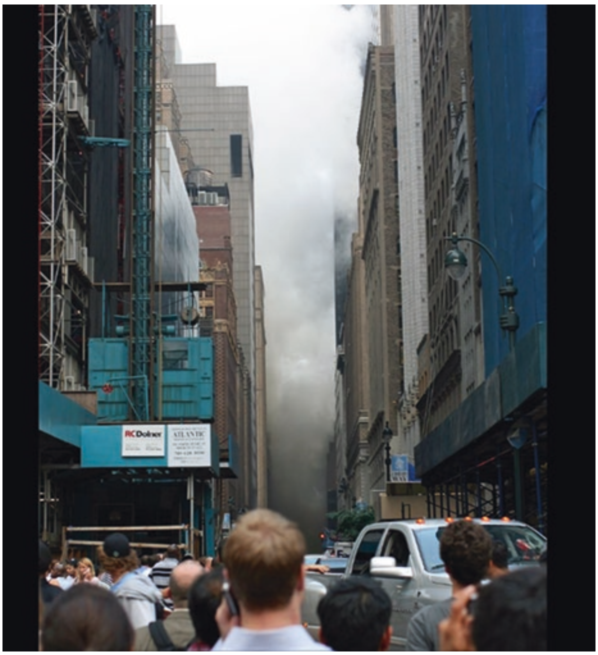


Fig. F.78 Steam pipe explosion, New York City, July 18, 2007 (Wikipedia n.d.[i])

with a temporary repair within 24 h or even faster. However, repairs to systems with temperatures above 100 °C (212 °F) may take a bit longer time.

In such situations, the leak detection system is an important installation; it reveals small leaks, which cause corrosion, which can result in a sudden large leak, which may be a risk for persons walking above the pipes. Therefore, it is important to repair the muffs and leak detection cables in case they are worn out. Some district heating companies have installed new leak detection cables in 30-year-old pre-insulated pipes.

F.2.7.2 Heat Production Capacity and Backup Boilers

The ability of supplying the necessary capacity on the coldest day, even in case of a realistic break down in a part of the system, is an important "political issue," as it is a compromise of resilience against cost.

The district heating company should have clearly defined criteria for the security of supply in a generalized form. This criterion is more political than technical. The question is: how much to pay for the security of heat supply considering that almost all heat consumers can accept a disruption of heat supply in around 24 h, in case of a very infrequent breakdown, which can be impossible to foresee? Reasonable criteria for production capacity can be the following:

- All disruption of heat supply must be re-established within 24 h to normal consumers.
- Vital consumers (hospitals, industries, and others who need 100% reliable heat in the process with not more than 1-h disruption or less) must have warm backup in terms of a warm spare boiler or a heat storage tank with a minimum of hot water at any time.
- Where it is not possible to re-establish the heat supply within 24 h, e.g., a breakdown of a pipe crossing a railroad, at least 60% of the maximal heat demand, roughly the demand on an average winter day, must be available to the district in which the heat is disrupted.
- For districts smaller than 5 GWh, the grid can be prepared, as a mobile peak boiler plant (around 292.8 Btu [1 MWh]) can deliver spare capacity.
- For districts larger than 17,061 MMBtu (5 GWh), there must be an alternative heat supply source to deliver at least 60% of the maximal capacity located in the district in case the largest production plant or pipeline to this district is out of operation.

The chosen reserve margin affects the amount of spare peak capacity installed in the system. If the system has one large production unit as base load, the last criterion could be critical for defining the total need for production capacity. To accommodate a potential breakdown of a section of the network, districts should establish and maintain spare capacity, which must be located at decentralized locations. To ensure adequate supply to vital consumers, a certain amount of this spare capacity should be located near these vital consumers. To summarize, the following capacities would suffice for a district of mainly 10,000 one-family houses or apartments, with horizontal distribution:

Total capacity of all customer installations without hot water tanks	300 MW.
Total capacity for the main distribution lines	60 MW.
Total annual heat sale	100,000 MWh.
Total annual heat production (9% heat losses of production)	110,000 MWh.
Total peak load capacity demand to the network (3000 h)	37 MW.
Total need for cost-effective base load production to meet demand	22 MW.
Total additional peak load capacity to supplement base load	37−22 MW.
Total peak and spare capacity, in case of breakdown on largest unit	0.6 × 37 = 22 MW.
In case base load plant is the largest unit, we need additional	22−15 = 7 MW.

Thus, the total installed capacity has to be 22 MW base load plus 15 MW peak load and 7 MW spare capacity—a total of 44 MW.

In cases where a large part of the heat demand is separated from the base load plant by a critical pipe section, for example, an underground crossing of a railroad that cannot be repaired within 24 h, a sufficient part of the spare capacity must be located on the isolated side of the section and meet the above criteria.

An estimate of the capacity demand for additional production capacity for a new district must consider that different types of consumers have different load profiles. The load fluctuation during the year of each individual customer is not of interest for analyzing the integrated solution. Typically, customers have a variety of load profiles, and it is only of importance for the analysis to know the total load profile for the supply of energy to the network to supply all customers with heating, hot tap water, and thermal losses in the network. Normally, it will be possible to collect data from existing district energy systems in the region as regards daily load fluctuations and annual load fluctuations per hour.

In cases where all customers use the same thermostat settings for heat consumption, where they reduce heat consumption at night, and where they engage a quick start from zero to maximum at 6 am., the task is not trying to meet this demand but to advise the customers to use their heating system efficiently. The benefits of turning down thermostats at night are often overestimated when one considers the resulting lack of thermal comfort and the less efficient use of the heating system, which must work harder to achieve the larger return temperature. If measurements indicate that the thermostat reduction at night and quick return to daytime operating temperatures in the morning cause problems, the planning should include:

- Guidelines on how to use heating systems efficiently to improve comfort and to calculate the actual saved energy.
- A discount for low return temperature or a penalty for large return temperature to encourage customers to use the heating system uniformly and efficiently.
- A requirement that the return temperature must not exceed a certain level (50 °C [122 °F]) and, if necessary, a valve that closes when the return temperature is higher than the designated maximum.

- To use a capacity payment in the tariff measured (USD/kW) for installed capacity. This is as an alternative to a tariff component in USD/m^2.

For large systems, it is important to consider the risk of unforeseen incidents in the planning and the design of the system; consideration of these risks will become part of the basis for the political decision that will determine the criteria to use, how to define the largest production capacity, and the level of spare capacity. In cases where a large base load plant has two production units, one must consider whether to configure spare capacity for only one of these units or for the whole plant. A recent incident illustrates the importance of this design issue. In this case, the base load plant had two units that were independent of each other. To be on the safe side, a policy decision had been made to design the system to meet 100% peak demand even when one of these two units was offline. In an unforeseen incident, a fire in the shaft that housed cables that connected both units to the control center knocked out both units for almost a winter month. The design criteria allowed the utility to supply all consumers, but it was expensive peak production.

In the Greater Copenhagen district heating system, two transmission companies, CTR and Vestforbrænding, had agreed 25 years ago on how to share a new peak and spare capacity boiler plant. From 1975 to 1995, Vestforbrænding had supplied a large hospital with heat in a DN500 heat transmission line with temperatures up to 160 °C (320 °F). The hospital accepted this secure supply due to the high quality of the heat transmission line, which was constructed of steel in concrete duct with ventilation and efficient draining. However, due to the age of the construction and the risk of unforeseen incidents, the parties agreed that spare capacity was needed to supply the main line on the other side of the connection to the hospital. CTR needed more peak capacity due to the large extension of the heat market as well as base load capacity from Vestforbrænding, which had surplus base load from a new waste incinerator. Therefore, the two companies agreed on how to establish an interconnection pipe and a boiler plant with two priorities. In normal operation, the plant should deliver peak capacity to CTR, but if there were a breakdown of capacity from Vestforbrænding to the hospital, the first priority should be given to deliver enough capacity to supply the hospital.

F.2.7.3 Heat Storage Facilities

One of the many advantages of hot water (compared to steam) district heating is that it is possible to establish heat storage facilities in a hot water district heating that can store energy corresponding to several hours of heat demand for the whole system.

The facilities can be installed at low cost in a way that increases system resiliency and improves the optimal production of heat considering the parameters of the production plants and fluctuating electricity prices.

For CHP plants, the typical design criteria are that the plant should be able to store 8–10 h of maximal heat capacity of the CHP plant (see Fig. F.79). Designing

Fig. F.79 Viborg gas CHP with thermal storage and the thermal storage at Avedøreværket, Denmark

the plant for resilience and including spare capacity could accommodate even larger capacities. However, the following conditions should be considered:

- Install more heat storage capacity to level the daily load fluctuations in case the demand peaks cause problems for optimizing the heat production.
- Consider that a heat storage tank can level the load fluctuations on the coldest day and thereby contribute to the installed peak capacity.
- Consider that the heat storage tank could be located next to a critical consumer so the storage could supply sufficient heat to cover the critical demand until local cold spare capacity is in operation.

F.2.7.4 Fuel Flexibility

One of the advantages of the district heating network, in particular the hot water network, is that it can use different fuels and other sources of heat. The infrastructure of the district system has a lifetime of at least 60 years, whereas many building level heat generation systems have a lifetime of 20 years. Typically, new technologies can be introduced as base load suppliers even before the existing units are worn out; the old plants can then remain to provide spare or peak capacity.

The production plants will form a mix of cheap base load, more expensive medium load, and expensive peak load. Therefore, most district heating systems have access to several heat sources and can shift from source to source, hour by hour depending on the availability of fuel, the availability of the plant, and the price of the energy source.

Moreover, in district heating networks, it is possible to invest in new alternative heat sources in less than a year in response to fuel shortages or a sudden price increases. This contrasts with networks without district heating, where the buildings are supplied by individual heat sources, such as oil boilers and gas boilers and where a fuel shift may take 5–10 years or more.

Therefore, district heating is an important technology to strengthen the resilience at the overall campus and national levels. Moreover, district heating infrastructure reduces the dependency on specific fuels or energy sources.

A historical example is the reaction to the OPEC oil embargo in 1973. Holland and Denmark, which before 1973 were very dependent on imported oil, were affected more than other countries and suffered from lack of oil, for political reasons. The energy systems in these countries were not designed to be resilient to a political oil embargo. When the embargo occurred, it was a resilience wake-up call. Holland responded by exploring its own natural gas and by supplying most buildings with gas boilers. Denmark took several major steps to cost-effectively reduce the society's dependency on imported oil (e.g., prohibiting driving on Sundays [see Fig. F.80]). Since 1976, a solid majority of the Danish Parliament has opposed the past dependence on certain foreign regimes and has established an energy policy to support energy independence. Some of the main actions were to explore sources of Danish oil and natural gas and at the same time expand the district heating based on waste and surplus heat from coal-fueled power generation (CHP) supplemented by individual gas boilers to small houses. Today Denmark has almost eliminated oil for heating, and its district heating networks will in a few years have replaced most fossil fuels with biomass, surplus fluctuating wind energy, and other low-carbon heat sources.

Another example of resilience at the European level is its dependency on gas and the related dispute about the gas pipelines North Stream 1 and 2 from Russia to Europe. Some politicians argue that these two pipelines will contribute to Europe becoming dependent on Russia for natural gas energy supplies. In reality, the

Fig. F.80 No cars on Sundays. (Source: Danmarkshistorien) conflict is not caused by the pipelines but by the lack of an energy policy that reduces this high-level dependence. Europe may well benefit from access to inexpensive gas made available through these pipelines until it can shift to renewable energy sources. The problem of some European countries becoming heavily dependent on imported natural gas results from a combination of poor energy policy and the extensive use of building-level gas boilers and small gas engines when there are huge resources of more climate friendly waste heat from industries, waste incineration, and large power plants, which could be used in district heating networks.

F.2.7.5 District Heating Network

A district heating network can be designed to maintain a secure energy supply to meet the needs of all consumers in case of unforeseen breakdown.

The traditional tree structure supplied by one production plant (see Fig. F.81) has no backup in case of unanticipated disruption of any of the distribution pipes. However, a meshed structure, which also is supplied by only one production plant,

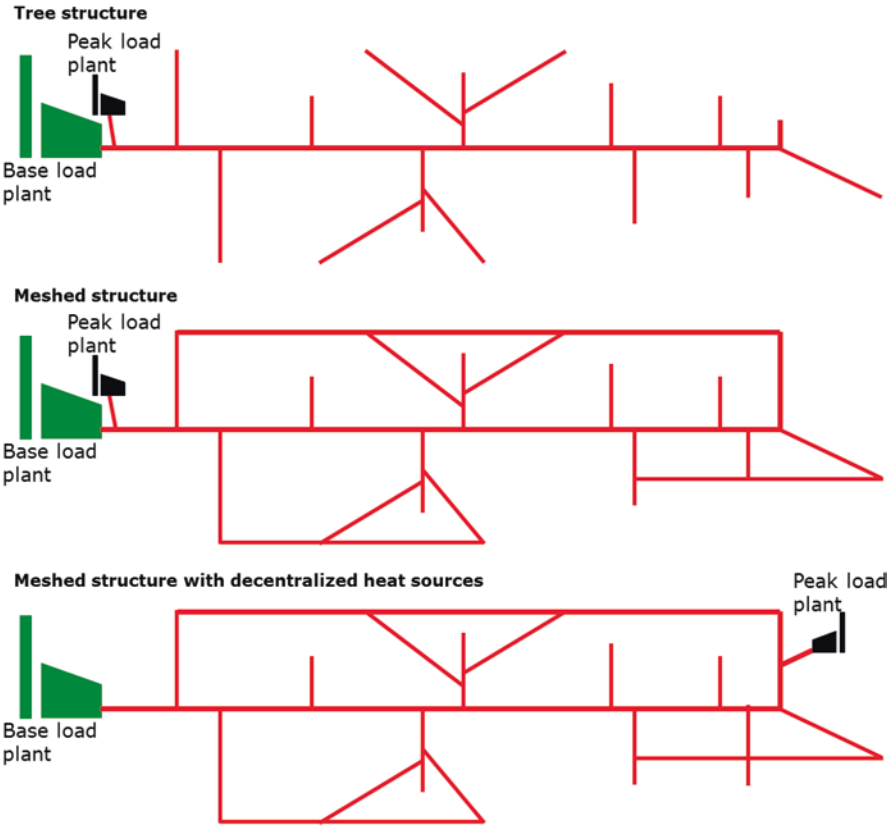


Fig. F.81 District heating network configuration can offer flexibility and spare capacity up to a certain heat load for consumers connected to the ring line. To ensure maximal security for critical consumers, it is necessary to establish stop valves on the main line on both sides of the point of connection. Finally, a meshed structure with two production plants to the grid allows for the maximal flexibility, in particular if both production plants have active pressure maintenance systems, and can thereby operate in island mode. Figure F.81 shows the simplest case in which there is a base load plant at one end and peak and spare capacity at the other end of the network.

Vestforbrænding, Denmark, provides a good example on this configuration. A new network extension had to be supplied from one DN400 main pipe crossing a railroad with an underground pipe constructed with the no-dig method. With this configuration, it would take several weeks to restore a damaged pipe under a railroad. Since there was a need for new peak capacity, a 24-MW gas-fueled boiler plant, equipped with active pressure maintenance, was installed at the other end of the network. Then an unforeseen incident happened in which no-dig horizontal drilling for installation of cables damaged the main pipe, which had to be taken out of operation for several days.

District Cooling System

District cooling is the process of producing cooling energy in a centralized plant and distributing it to several buildings in a district. District cooling systems produce chilled water, steam, or hot water in a central plant and transfer that energy to building air-conditioning, water heating, and space heating. This improves the buildings' energy efficiency while meeting comfort and cooling and heating needs.

District energy cooling is a proven energy solution that has been deployed in a growing number of cities around the world. It encompasses a number of technologies that seek to develop synergies between production and supply of heat, cooling, DHW, and electricity.

Source

UNEP (United Nations Environment Programme). 2015. *District Energy in Cities: Unlocking the Potential in Energy Efficiency and Renewable Energy*. Nairobi, Kenya: UNEP. http://wedocs.unep.org/bitstream/handle/20.500.11822/9317/-District_energy_in_cities_unlocking_the_potential_of_energy_efficiency_and_renewable_ene.pdf?sequence=2&isAllowed=y

F.2.8 Cold Storage

A cold water storage tank can be located next to the energy center. Usually, the size of the cold water storage tank is designed to even out daily fluctuations in the electricity price. So when the electricity price (and distribution tariffs) is low, the chiller or combined heating and cooling heat pumps can produce extra cooling that can be stored in the tank. In high-price periods, the tank can be discharged to reduce (or eliminate) the production of cooling. The following technologies (see Fig. F.82) are relevant:

- A steel tank (similar to the district heating technology)
- A concrete chamber (similar to the water supply technology)
- ATES (also called ground source cooling) (Table F.92)
- A large pit storage filled with cold water instead of hot water

The financial costs for a cold water storage tank and a cold water storage pit are the same as for the hot water equivalent.

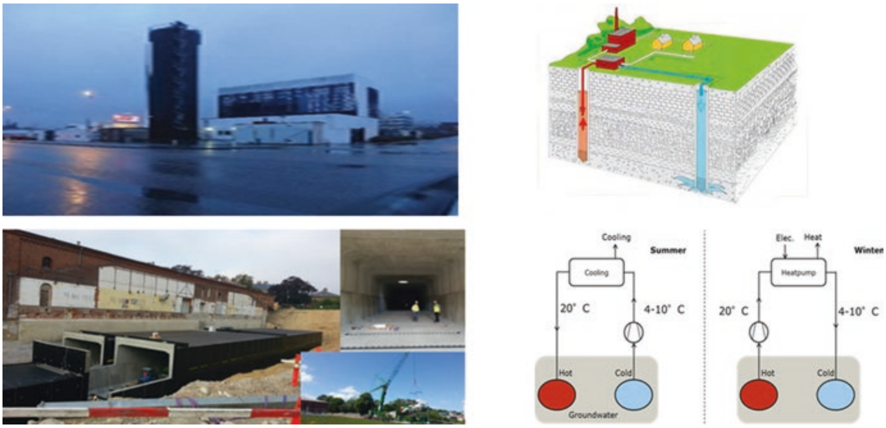


Fig. F.82 Steel tank, concrete chamber, and ATES

Table F.92 Technical and economic assumptions for ATES

Technology	ATES Unit	2020
Energy/technical data		
Heat generation capacity for one unit	MW-c	1–10
COP ATES cooling		40
Financial data (USD)		
Nominal investment	MUSD/drill hole pair	0.6
Fixed O&M	USD/MW-c/year	0.0
Variable O&M	USD/MWh-c	0.0

A cold water pit storage can be used in a factory with a large cooling demand and large differences between day and night charges of the electricity.

F.2.9 District Cooling Network

The district cooling (DC) network is a vital part of the energy infrastructure for developing low-carbon resilient solutions in all campuses' and cities' warm and mild climate, as it is the key to use and store cost-effective and efficient low-carbon sources for cooling. The main focus will be on traditional cold water pipe systems, e.g., 6 °C (320 °F) supply and 15 °C (59 °F) return, which could be established either as a DHW system in pre-insulated pipes or as a freshwater system in PEH pipes, which can distribute water including oxygen. These pipes can also be used to distribute cold deep lake water directly without the use of a heat exchanger.

The secrets of district cooling:

- The design capacity of buildings can be adjusted (avoid overcapacity in buildings).
- Reduce maximum capacity due to diversity, factor 0.8.
- Use tank thermal energy storage for cold water to reduce the peak by factor 0.7.
- Reduce capital expenditure (CAPEX) by taking advantage of economies of scale for chillers, factor 0.5–0.9.
- Optimize electrical consumption using storage tank—which operates during off-peak hours when most efficient plants are supplying electricity to the electrical grid.
- Ensure the optimal location of cooling plant as part of the urban planning.
- Use surplus heat from cooling for district heating.
- Use ATES for heat and cold.
- Combine the use of heat pumps for cooling and heating (co-gen).
- Use absorption chillers to use surplus heat if any.
- Use absorption chillers to reduce electric capacity demand.
- Offer a total solution for thermal comfort to the building owner.
- Save expensive space in buildings, in basements, and on roof tops.
- Use ventilation coils and floor tubes for heating or cooling.
- Take advantage of synergies between district heating and district cooling.

F.2.9.1 Capacities and Losses (Tables F.93, F.94, F.95, F.96, F.97, F.98, and F.99)

Table F.93 Pre-insulated pipes (1/3)

	Unit	DN15	DN20	DN25	DN32	DN40	DN50	DN65	DN80	DN100
Inner diameter	mm	17	23	29	37	43	55	70	83	107
Velocity at 10 mm/m	m/s	0	0	0	1	1	1	1	1	1
Water flow	m^3/h	0	1	1	2	3	5	11	16	32
Maximal supply temperature	°C	15	15	15	15	15	15	15	15	15
Return temperature	°C	6	6	6	6	6	6	6	6	6
Heat loss capacity	W/m	0	0	0	0	1	1	1	1	1
Heat loss energy per year	MWh/m/a	0	0	0	0	0	0	0	0	0
Capacity	MW	0	0	0	0	0	0	0	0	0
Annual max load hours	h	2000	2000	2000	2000	2000	2000	2000	2000	2000
Annual heat transfer	MWh/a	5	11	21	41	60	112	222	338	677
Annual heat losses/km	%/km	37%	24%	14%	8%	7%	4%	2%	2%	1%
Cost per meter	USD/m	419	419	449	470	487	521	568	635	732
Cost per MWh/a per km	USD/MWh/a/km	81,725	37,573	21,364	11,498	8073	4640	2563	1880	1081

Table F.94 Pre-insulated pipes (2/3)

	Unit	DN125	DN150	DN200	DN250	DN300	DN350	DN400	DN450	DN500
Inner diameter	mm	133	160	210	263	313	344	394	444	495
Velocity at 10 mm/m	m/s	1	1	2	2	2	2	2	2	3
Water flow	m^3/h	57	94	190	342	539	694	987	1351	1797
Maximal supply temperature	°C	15	15	15	15	15	15	15	15	15
Return temperature	°C	6	6	6	6	6	6	6	6	6
Heat loss capacity	W/m	1	1	1	1	2	2	2	2	2
Heat loss energy per year	MWh/m/a	0	0	0	0	0	0	0	0	0
Capacity	MW	1	1	2	4	6	7	10	14	19
Annual max load hours	h	2000	2000	2000	2000	2000	2000	2000	2000	2000
Annual heat transfer	MWh/a	1182	1957	3962	7147	11258	14497	20602	28219	37531
Annual heat losses/km	%/km	0%	0%	0%	0%	0%	0%	0%	0%	0%
Cost per meter	USD/m	861	995	1244	1623	1953	2274	2472	2472	2797
Cost per MWh/a per km	USD/MWh/a/km	729	509	314	227	173	157	120	88	75

Table F.95 Pre-insulated pipes (3/3)

	Unit	DN600	DN700	DN800	DN900	DN1000
Inner diameter	mm	596	694	795	894	994
Velocity at 10 mm/m	m/s	3	3	3	4	4
Water flow	m^3/h	2911	4326	6187	7917	9779
Maximal supply temperature	°C	15	15	15	15	15
Return temperature	°C	6	6	6	6	6
Heat loss capacity	W/m	2	2	3	3	3
Heat loss energy per year	MWh/m/a	0	0	0	0	0
Capacity	MW	30	45	65	83	102
Annual max load hours	h	2000	2000	2000	2000	2000
Annual heat transfer	MWh/a	60,782	90,328	129,184	165,314	204,183
Annual heat losses/km	%/km	0%	0%	0%	0%	0%
Cost per meter	USD/m	861	995	1244	1623	1953
Cost per MWh/a per km	USD/MWh/a/km	14	11	10	10	10

Table F.96 District heating pipe technical parameters

D_N	D_y	t	D_i	Vel. 10 0/00	Velocity	Flow	Flow	Power	Loss	Loss	Heat	Heat loss
mm	mm	mm	mm	m/s	m/s	l/s	m^3/h	MW	W/m/°C	W/m	MWh/year	MWh/year/m
Dn	Dy	t	Di		Velocity	Flow1	Flow2	Power	Loss1	Loss2	Heat	
DN15	21.3	2.0	17.3	0.29	0.29	0.068	0.245	0.003	0.070	0	5	0.003
DN20	26.9	2.0	22.9	0.36	0.36	0.148	0.534	0.0056	0.080	0	11	0.004
DN25	33.7	2.3	29.1	0.42	0.42	0.279	1.006	0.0105	0.080	0	21	0.004
DN32	42.4	2.6	37.2	0.50	0.50	0.544	1.96	0.0204	0.080	0	41	0.004
DN40	48.3	2.6	43.1	0.55	0.55	0.803	2.89	0.030	0.100	1	60	0.004
DN50	60.3	2.9	54.5	0.64	0.64	1.493	5.38	0.056	0.100	1	112	0.004
DN65	76.1	2.9	70.3	0.76	0.76	2.95	10.62	0.111	0.110	1	222	0.005
DN80	88.9	3.2	82.5	0.84	0.84	4.49	16.2	0.169	0.120	1	338	0.005
DN100	114.3	3.6	107.1	1.00	1.00	9.01	32.4	0.339	0.120	1	677	0.005
DN125	139.7	3.6	132.5	1.14	1.14	15.7	56.6	0.59	0.125	1	1182	0.005
DN150	168.3	4.0	160.3	1.29	1.29	26.0	93.7	0.98	0.140	1	1957	0.006
DN200	219.1	4.5	210.1	1.52	1.52	52.7	189.7	1.98	0.150	1	3962	0.007
DN250	273.0	5.0	263.0	1.75	1.75	95	342	3.57	0.280	1	7147	0.012
DN300	323.9	5.6	312.7	1.95	1.95	150	539	5.63	0.318	2	11,258	0.014
DN350	355.6	5.6	344.4	2.07	2.07	193	694	7.25	0.307	2	14,497	0.013
DN400	406.4	6.3	393.8	2.25	2.25	274	987	10.30	0.318	2	20,602	0.014
DN450	457.0	6.3	444.4	2.42	2.42	375	1351	14.11	0.358	2	28,219	0.016
DN500	508.0	6.3	495.4	2.59	2.59	499	1797	18.77	0.399	2	37,531	0.017
DN600	610.0	7.1	595.8	2.90	2.90	809	2911	30.4	0.357	2	60,782	0.016
DN700	711.2	8.8	693.6	3.18	3.18	1202	4326	45.2	0.400	2	90,328	0.018
DN800	812.8	8.8	795.2	3.46	3.46	1719	6187	65	0.500	3	129,184	0.022
DN900	914.4	10.0	894.4	3.50	3.50	2199	7917	83	0.55	2.75	165,314	0.0
DN1000	1016.0	11.0	994.0	3.50	3.50	2716	9779	102	0.6	3	204,183	0.0

Table F.97 Design parameters

Design parameters	Unit	Value
Cooling of circulated water	°C	9
Pressure gradient	0/00	10
Max load hours	h/a	2000
Supply temp. average	°C	15
Return temp. average	°C	6
Temperature of soil	°C	8

Prices	Including all construction costs, design supervision, and unexpected costs
Land	Denmark
System	Pre-insulated steel pipes with welded PEH casing including surveillance system
Local conditions	Wide road in suburb areas

Table F.98 Chilled water piping capacity

Chilled water piping capacity[a]						Pipe size vs. tons—Bldg. sq. ft per. tons. Capacity (1000 ft^2) area		
Direct-buried pipe		Water side temperature rise. Δt. Gpm/Ton						
Pipe diameter (IN)	GPM VEL FT/100 FT HP COST	10 °F 2.4	12 °F 2.06	14 °F 1.7	16 °F 1.5	18 °F 1.33	20 °F 1.20	24 °F 1.0
	60,000 GPM 10.6 FPS 0.8′/100′ 400 HP $2500/LF	25,000 (7500)	30,000 (9000)	35,000 (10,500)	40,000 (12,000)	45,000 (13,500)	50,000 (15,000)	60,000 (18,000)
	40,000 GPM 9.2 FPS 0.8′/100′ 200 HP $2200/LF	16,000 (4800)	20,000 (6000)	24,000 (7200)	27,000 (8000)	30,000 (9000)	34,000 (10,000)	40,000 (12,000)
	30,000 GPM 9.4 FPS 1.0′/100′ 200 HP $2000/LF	12,500 (3800)	15,000 (4500)	17,500 (5300)	20,000 (6000)	22,500 (6800)	25,000 (7500)	30,000 (9000)
	20,000 GPM 9.1 FPS 1.1′/100′ 150 HP $1500/LF	8000 (2400)	10,000 (3000)	12,000 (3600)	13,000 (4000)	15,000 (4500)	17,000 (5000)	20,000 (6000)
	12,000 GPM 8.5 FPS 1.3′/100′ 120 HP $1300/LF	5000 (1500)	6000 (1800)	7000 (2100)	8000 (2400)	9000 (2700)	10,000 (3000)	12,000 (3600)
	7000 GPM 9.5 FPS 2.0′/100′ 100 HP $1000/LF	3000 (900)	3500 (1050)	4000 (1200)	4600 (1400)	5200 (1600)	6000 (1800)	7000 (2100)

(continued)

Table F.98 (continued)

Chilled water piping capacity[a]						Pipe size vs. tons—Bldg. sq. ft per. tons. Capacity (1000 ft^2) area		
Direct-buried pipe		Water side temperature rise. Δt. Gpm/Ton						
	5000 GPM 9.0 FPS 2.8′/100′ 100 HP $800/LF	2000 (600)	2500 (750)	3000 (900)	3500 (1050)	3800 (1100)	4000 (1200)	5000 (1500)
	4000 GPM 9.5 FPS 3.0′/100′ 100 HP $700/LF	1700 (500)	2000 (600)	2400 (720)	2700 (800)	3000 (900)	3400 (1000)	4000 (1200)
	3000 GPM 8.7 FPS 3.8′/100′ 75 HP $650/LF	1250 (380)	1500 (450)	1800 (540)	2000 (600)	2300 (680)	2500 (750)	3000 (900)
	2000 GPM 8.0 FPS 3.1′/100′ 40 HP $500/LF	800 (240)	1000 (300)	1200 (360)	1300 (400)	1500 (450)	1700 (500)	2000 (600)
	1200 GPM 7.7 FPS 4.0′/100′ 35 HP $400/LF	500 (150)	600 (180)	700 (200)	800 (240)	900 (270)	1000 (300)	1200 (360)
	600 GPM 6.7 FPS 4.0′/100′ 20 HP $300/LF	250 (75)	300 (90)	350 (100)	400 (120)	450 (140)	500 (150)	600 (180)
	200 GPM 5.0 FPS 4.0′/100′ 5 HP $200/LF	80 (24)	100 (30)	120 (36)	130 (40)	150 (45)	170 (50)	200 (60)

[a]GPMs were selected to maintain water velocities (V) below 10 fps and pressure drop (f) below 1′/100′ for large size pipes. The GPM values for smaller size pipes were selected to maintain water velocities below 7 fps and pressure drop below 4′/100′. The velocities and friction drop values are according to Cameron, (C = 100). HP values to pump the water through 1000′ supply and 1000′ return are calculated using HP = GPM × TDH. TDH = 2000 × f 3940 × 75 100. 1000’s of gross sq. ft. of building are figured at 300 GSF/ton, i.e., (10,500) indicates that approximately 10,500,000 GSF can be air-conditioned with 35,000 tons. For heavy research areas, use 220 GSF/ton. This chart is intended to be used for obtaining an initial estimate of required pipe size and cost. Actual system design must be based on values obtained specifically for the project. Total installed cost per linear ft. of buried supply and return pipes (two pipes). Price includes trenching, insulation, fittings, backfill, and moderate amounts of surfacing repairs. For total project cost, add A-E fees, testing, escalations, contingencies, etc.

Table F.99 Chilled water central plant cost

Element	Capacity	Cost	Average cost
1. Water chillers with starters			
a. Centrifugal	300–600 tons	$320/ton	
	600–1400 tons		$290/ton
	1500–3000 tons	$280/ton	
b. Absorption—1 stage	90–1600 tons	$400/ton	
b. Absorption—2 stage	350–1000 tons	$800/ton	
c. Screw	70–130 tons	$500/ton	
	150–450 tons	$400/ton	
d. Screw—air-cooled	70–400 tons	$550/ton	
e. Setting rigging installation		$50–$150 tons	$130/ton
f. Add 4160 volt motor		$15/ton	
g. Add.035 in. tubes		$10/ton	
h. Add gas engine driver		$300/ton	
2. Pumps		$50–$120/ton	$80/ton
3. Cooling tower			
a. Normal		$50–$140/ton	
b. Permanent		$100–$240/ton	$200/ton
4. Piping		$120–$250/ton	$200/ton
5. Controls		$40–$100/ton	$80/ton
6. Electrical		$80–$300/ton	$180/ton
7. Building		@ 1.5 ft^2/ton at $160/$ft^2$	$240/ton
Total			$1400/ton
Total without building and with permanent cooling tower			$1160/ton
Total without building and with normal cooling tower			$1100/ton
Note			
Chilled water distribution, large campus		$200–$1000/ton	$500/ton
Plate/frame heat exchanger		Unit only $40–$120/ton	$80/ton
Complete installation with piping and simple auto control		$100–$160/ton	$140/ton

F.2.9.2 PEX Pipes

PEX pipes (Fig. F.83) can be used for low-temperature district heating and district cooling. The investment costs for PEX pipes are typically lower at small dimensions than for similarly sized steel pipes. On the other hand, the heat loss is slightly higher for plastic pipes than steel pipes. Thus, plastic pipes are preferable only at low temperatures. We have listed pros and cons for plastic pipes, mostly related to low-temperature district heating but which may also relate to district cooling.

Fig. F.83 PEX pipes for low-temperature district heating and district cooling

The advantages of lower temperatures are:

- Cheaper plastic pipes can be used (see Table F.100 and Fig. F.84).
- Heat loss is lower when the temperature is lower.

The downside is, however:

- The pipe dimensions will increase due to lower ΔT, thus increasing heat loss.

The heat loss for plastic pipes of the same dimension is greater than that of steel pipes.

F.2.10 Resiliency

District cooling systems are generally as important as district heating, sometimes even more important since it is easier to protect yourself against cold than against heat. In modern office buildings, shopping malls, etc., active cooling is necessary even in mild climates. Moreover, some industrial processes and data centers need active cooling.

All the aspects related to heating can also be applied for cooling:

F.2.10.1 Production Capacity and Backup Chillers

The district cooling can be supplied by many different sources, all depending on the local conditions, e.g.:

- Electric chiller
- Electric heat pump for combined heating and cooling
- Cold groundwater
- Cold drain water
- Cold deep lake water

Table F.100 Prices of Alupex and Thermaflex pipes

Pipes	EUR/m	USD/m
Alupex16 Twin	145	162
Alupex20 Twin	175	196
Alupex26 Twin	190	213
Thermaflex 16 Twin	110	123
Thermaflex 20 Twin	130	146
Thermaflex 25 Twin	153	172
Thermaflex 32 Twin	231	259
Thermaflex 40 Twin	255	286
Thermaflex 50 Twin	320	358
Thermaflex 63 Twin	293	329
Thermaflex 75	367	411
Thermaflex 90	418	468
Thermaflex 110	568	636

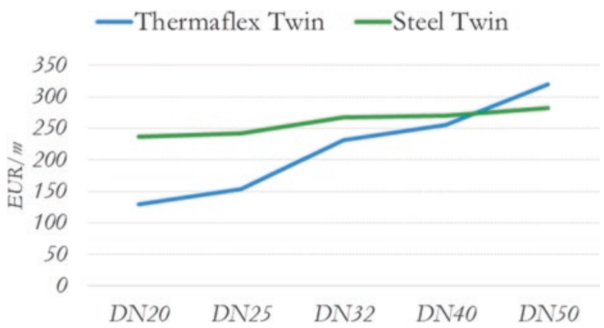


Fig. F.84 Cost comparison between Thermaflex Twin and Steel Twin

- Cold seawater
- Absorption heat pump driven by waste heat, e.g., from a waste incinerator and an available fuel
- Gas-driven chillers

By combining energy sources, the system can become even more resilient and cost-effective.

- District cooling grids will in general have base load chillers with access to efficient cooling, e.g., in an ATES system in combined production with heat and a less efficient peak capacity.
- Chillers can offer peak capacity to the cooling grid and at the same time guarantee security of supply to critical consumers if they are located very close to the critical cooling demand. An example is the new Facebook data center in Odense, Denmark. The district heating company Fjernvarme Fyn has established a large

heat pump facility to generate heat to the district heating system and cooling to a district cooling network, which supplies the new data center and (in principle) other consumers as well. Because the data center has 100% backup, the project could also consider using surplus heat from the data center—a win-win solution.

F.2.10.2 Chilled Water Storage Facilities

Similar to hot water storage facilities, the chilled water storage facilities like the one in Taarnby, Denmark (Fig. F.85), can offer supply security and more optimal operation of the heat pumps to offset fluctuating electricity prices and the value of the heat.

Chilled Water Networks
Chilled water networks can be established using the same pre-insulated pipe technology that is used in district heating. They can also be established with water pipe technology without leak protection. Although this will make it difficult to detect leaks, leaking water is not as harmful as leaking steam or hot water.

F.2.10.3 Brown and Blackouts in Warm Countries

Active cooling is becoming more and more important due to urbanization, industrialization, and global warming. The Intergovernmental Panel on Climate Change (IPCC) estimates that cooling demand will increase dramatically in the next 100 years due to this development.

Fig. F.85 Chilled water tank in Taarnby, Denmark

In some warm industrialized countries where there is no urban planning of the energy infrastructure, uncontrolled electricity demand from chillers overloads the power system, and systematic load shedding is necessary. The solution is not to develop more power capacity but to incorporate smart energy systems that include district cooling, chilled water storage, and large efficient production facilities, some with combined heating and cooling, some with access to ambient cold like Toronto deep lake water cooling, and some with the use of natural gas as the energy source for cooling as it was done in Tokyo.

F.3 Natural Gas System

The role of the gas networks in the low-carbon districts will be to distribute and store natural gas for backup capacity for heat and power and to distribute renewable gas, e.g., biogas or gas generated from low-cost electricity. The energy consumption related to operation of a gas network is generally low. The network is supplied with natural gas at a sufficiently high pressure, so no further compression is required in the main distribution lines or in the distribution system. Therefore, the electric power consumption related to operation of the main distribution lines and the distribution system is as low as 0.005% of the transported energy. Reduction of the pressure in the system necessitates preheating, since the gas is cooled by the expansion. The heat is provided by burning an amount of gas corresponding to around 0.1% of expanded gas. However, as there are different pressure levels in different parts of a system, preheating is not always required.

The gas system has several advantages. It can be supplied with gases from various sources, including green gases, such as upgraded biogas and gases from power-to-gas processes, as long as the gas meets the natural gas specifications. It also provides a large storage capacity. The Danish system contains 2–3 months of gas consumption. These properties may allow integration of large amounts of renewable energy in the energy system. Furthermore, the gas system can provide very high-power capacity compared to most other energy carriers, which is required by some parts of the industry. The energy loss is very low compared to other energy distribution and transport systems. The main disadvantage is that today the cost of producing green gases of natural gas quality from, e.g., renewable power production is relatively high. Therefore, the only green gas in the Danish gas system is upgraded biogas.

Natural gas networks have a minimal environmental impact during the construction phase. The environmental impacts during operation mainly consist of greenhouse gas emissions due to preheating at MR stations and minor losses of mainly methane during distribution of the gas. There are no general data available on methane loss from the Danish gas system. If data from a European survey are applicable for the Danish system, the losses will correspond to 0.1% of the amount of gas transported in gas networks. However, the Danish system is generally newer than European gas networks and may experience fewer losses.

F.3.1 Biogas Plant

Biogas plants (Fig. F.86) produce a methane-rich gas on the basis of biodegradable organic material. The feedstock is transported to the plant by road or pumped in pipelines. At the plant, it undergoes an anaerobic process that generates biogas. Table F.101 lists the technical and economic assumptions for a biogas plant (basic configuration).

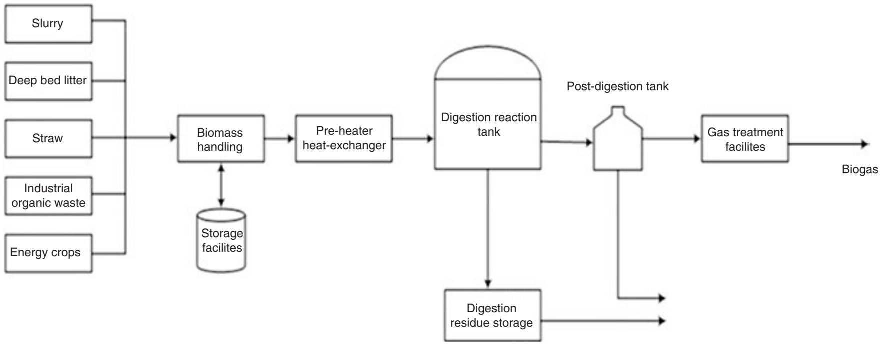


Fig. F.86 Biogas plant

Table F.101 Technical and economic assumptions for a biogas plant (basic configuration)

Technology	Unit	Biogas plant (basic configuration)
Energy/technical data		
Typical capacity	Tons/year input	
Typical total plant size	MW output	9
Inputs		
Biomass	Tons/year	365.000
Aux. electricity	% of output energy	4
Aux. electricity	kWh/ton input	8
Aux. process heat	% of output energy	9
Aux. process heat	kWh/ton input	19
Outputs		
Biogas	%	100
Biogas	GJ/ton input	1
Biogas production	MJ/S heating value	
Forced outage	%	0
Planned outage	Days per year	10
Technical lifetime	Years	20
Construction time	Years	1
Financial data (USD)		

(continued)

Table F.101 (continued)

Technology	Unit	Biogas plant (basic configuration)
Specific investment	MUSD/MW output	1.92
– of which equipment	MUSD/MW output	–
– of which installation	MUSD/MW output	–
Total O&M	USD/MW/year	218,081
Total O&M	USD/(ton input/year)	5.19
– of which O&M, excl. el. and heat	USD/(ton input/year)	4.11
– of which electricity	USD/(ton input/year)	0.62
– of which heat	USD/(ton input/year)	0.46
Technology-specific data		
Methane emission	Nm^3 CH4/ton input/year	0

The technology data sheet covers larger plants and does not include biogas from wastewater treatment plants and landfill sites. The residual biological material can be recycled as a fertilizer in agriculture and may be separated into solids and fluids. The biogas can be used directly in a natural gas engine for local CHP generation or in a local gas boiler, or it can be upgraded to bio-SNG (synthetic natural gas). Upgrading biogas to bio-SNG is treated in a separate chapter of the technology catalogue. The biomass is received, is stored in pre-storage tanks, and is later processed in digestion reactor tanks. The digesters are normally heated to either 35–40 °C (95–104 °F) (mesophilic digestion) or 50–55 °C (122–131 °F) (thermophilic digestion). After being processed in the main reactor, the material is stored in post-processing tanks where further gas is produced and collected. Some plants use continuous digestion in fully stirred digesters. This implies removing a quantity of digested biomass from the digesters and replacing it with a corresponding quantity of fresh biomass, typically several times a day. Finally, the gas is treated to reduce water and sulfur contents to the desired concentrations.

F.3.2 Gas Storage

F.3.2.1 Subsurface Gas Storage

Large volumes of gas may be stored in underground reservoirs or as liquefied gas (e.g., LNG—liquefied natural gas) in tanks. There are three types of underground storage:

Depleted gas reservoirs are the most prominent and common form of underground storage. They are the reservoir formations of natural gas fields that have produced all their economically recoverable gas. The depleted reservoir formation is readily capable of holding injected natural gas. Using such a facility is economically attractive because it allows the reuse, with suitable modification, of the extraction and distribution infrastructure remaining from the productive life of the gas field, which reduces the startup costs. Depleted reservoirs are also attractive because their geological and physical characteristics have already been studied by geologists and petroleum engineers and are usually well known. Consequently, depleted reservoirs are generally the cheapest and easiest to develop, operate, and maintain of the three types of underground storage. However, offshore depleted gas fields are generally quite expensive.

Aquifer reservoirs are underground, porous, permeable rock formations that act as natural water reservoirs. In some cases, they can be used for natural gas storage. Usually these facilities are operated on a single annual cycle as with depleted reservoirs. The geological and physical characteristics of aquifer formation are not known ahead of time, and a significant investment will be required to investigate these and to evaluate the aquifer's suitability for natural gas storage.

Salt caverns allow no gas to escape from storage. The walls of a salt cavern are strong and impervious to gas over the lifespan of the storage facility. Once a suitable salt feature is discovered and found to be suitable for the development of a gas storage facility, a cavern is created within the salt feature. This is done by the process of cavern leaching. Freshwater is pumped down a borehole into the salt. Some of the salt is dissolved leaving a void, and the water, now saline, is pumped back to the surface. The process continues until the cavern reaches the desired size. Once created, a salt cavern offers an underground natural gas storage vessel with very high deliverability. Cushion gas requirements are low, typically about 33% of total gas capacity.

Table F.102 lists the technical and economic assumptions for a gas cavern.

Table F.102 Technical and economic assumptions for a gas cavern

Plant for cavern leaching	
Heat generation capacity for one unit	Mill. USD
COP ATES cooling	11
Establishment of one cavern, (approx. 100 million Nm³ approx. 1.1 TWh)	
Construction and equipment	25
Cushion gas for one cavern (40% of total)	16
Total cost, 100 million Nm³ active volume	40
Process equipment; injection 200,000 Nm³/hour (approx. 2200 MW), withdrawal 600,000 Nm³/hour (approx. 6600 MW)	
Construction work	3.1
Compressors, incl. auxiliaries	34
Pull out train	15
Withdrawal equipment	5
Connections, transformer, regulation, and instruments	15
Total investment cost	71
A new greenfield store, equivalent to Lille Torup in Denmark, would require one leaching plant, five caverns, and one process plant	
Total investment	284
Operation and maintenance, salt cavern, 400–500 million m³ working gas	
Electricity	1.0
Gas consumption to reheat extracted gas	0.1
Total, incl. administration	7.3

F.3.3 Natural Gas Network

Natural gas transmission systems are used to transport gas between countries and regions. While natural gas production has increased in the North Sea, most of the natural gas being used in Europe is imported via pipelines from Russia, Central Asia, the Middle East, and even Africa. Additionally, there are 16 LNG regasification facilities located in Western Europe and more than 50 that are under consideration or construction. Imported natural gas is transported throughout the continent by a vast pipeline network.

A natural gas market/system typically consists of:

- A **wholesale market** consisting of the transmission of gas from producers to the distribution network.
- A **gas transmission system** operated and owned by a TSO. The TSO is responsible for volume balancing in the natural gas system and for the management of gas supply in case of emergencies.
- A **gas distribution system** where distribution companies are responsible for balancing and operating distribution systems in each geographical distribution area.
- A **storage system** typically owned and operated by the TSO. The storage is collected in a company operated on commercial terms. The company sell products that allow the storage customer to store, inject, and extract gas. The storage is in competition with other gas storage and providers of other flexibility services.

Table F.103 lists the technical and economic assumptions for natural gas distribution lines.

Table F.103 Technical and economic assumptions for natural gas distribution lines

Technology	Unit	Energy transport, natural gas main distribution line
Energy/technical data		
Energy losses, lines 1–20 MW	%	0.1
Energy losses, lines 20–100 MW	%	0
Energy losses, lines above 100 MW	%	0
Energy losses, stations [Type 1]	%	–
Energy losses, stations [Type 2]	%	0
Auxiliary electricity consumption	% energy transmitted	0
Technical lifetime	Years	50
Typical load profile	-	0
Construction time	Years	1
Financial data		
Investment costs		
Investment costs; single line, 0–50 MW	USD/MW/m	12.1
Investment costs; single line, 50–100 MW	USD/MW/m	4.7
Investment costs; single line, 100–250 MW	USD/MW/m	2.5

(continued)

Table F.103 (continued)

Technology	Unit	Energy transport, natural gas main distribution line
Investment costs; single line, 250–500 MW	USD/MW/m	1.3
Investment costs; single line, 500–1000 MW	USD/MW/m	0.8
Investment costs; single line, above 1000 MW	USD/MW/m	–
Reinforcement costs	USD/MW/m	–
Investment costs; [type 1] station	USD/MW	–
Investment costs; [type 2] station	USD/MW	30,240
Investments, percentage installation	%	22,680
Investments, percentage materials	%	7560
Fixed O&M	USD/MW/km/year	0
Variable O&M	USD/MWh/km	0

F.3.3.1 Natural Gas Distribution

In Denmark, three distribution companies own and operate all distribution networks. On the other hand, there are 16 gas suppliers. Natural gas customers can freely choose between these companies for the supply of natural gas. The retail market consists of distributing gas from the transmission network to consumers and retailing of gas to the final consumer. The natural gas system must be a central energy carrier in the future renewable energy system, in which hydrogen and biogas must also be integrated. Table F.104 lists the technical and economic assumptions for natural gas distribution lines in rural areas, and Table F.105 lists natural gas piping capacity.

F.3.3.2 Biogas Networks

Biogas is produced by anaerobic digestion of biodegradable material. It consists mainly of 50–80% methane and 20–50% CO_2. In addition, biogas contains low concentrations of undesirable substances, e.g., impurities, such as H_2S, siloxanes, ammonia, oxygen, and volatile organic carbons (VOCs). To be injected into the natural gas network or to be used in gas vehicles, the upgraded biogas quality must meet the same requirements as natural gas. In Denmark, these requirements are described in the gas regulations, Section C.12. The methane limit is not directly specified in C12 but can be deduced from the lower Wobbe limit, which is 50.8 MJ/Nm^3. This equals a minimum methane content of 97.3% assuming the rest is CO_2. H_2S is limited to 5 mg/Nm^3. To avoid the risk of condensation, the water dew point (DP) up to 70 bar must be below –8 °C (18 °F). A large number of technologies are

Table F.104 Technical and economic assumptions for natural gas distribution lines in rural areas

Technology	Unit	Energy transport, natural gas distribution, new distribution in existing rural areas	Energy transport, natural gas distribution, new distribution in existing suburban areas	Energy transport, natural gas distribution, new distribution in existing city areas	Energy transport, natural gas distribution, new developed residential areas
Energy/technical data					
Energy losses, lines	%	0.26	0.26	–	0.26
Energy losses, stations	%	–	–	–	–
Auxiliary electricity consumption	% energy delivered	0	0	0	0
Technical lifetime	Years	50	50	50	50
Typical load profile	–		–		–
– Residential		0	0	0.2	0
– Commercial		N/A	N/A	N/A	N/A
Construction time	Years	0	0	0	0
Financial data					
Distribution network costs, rural	USD/MWh/year	157	168	11	302
Investment costs; service line, 0–20 kW	USD/unit	1792	1792	–	1792
Investment costs; service line, 20–50 kW	USD/unit	–	–	–	–
Investment costs; service line, 50–100 kW	USD/unit	–	–	–	–
Investment costs; service line, above 100 kW	USD/unit	–	–	16,800	–
Investment costs; single line, 0–50 kW	USD/m	56	60	72	52
Investment costs; single line, 50–250 kW	USD/m	56	60	72	52
Investment costs; single line, 100–250 kW	USD/m	56	60	72	52
Investment costs; single line, 250 kW–1 MW	USD/m	56	60	72	52
Investment costs; single line, 1 MW–5 MW	USD/m	60	67	81	56
Investment costs; single line, 5 MW–25 MW	USD/m	77	97	116	71

(continued)

Table F.104 (continued)

Technology	Unit	Energy transport, natural gas distribution, new distribution in existing rural areas	Energy transport, natural gas distribution, new distribution in existing suburban areas	Energy transport, natural gas distribution, new distribution in existing city areas	Energy transport, natural gas distribution, new developed residential areas
Investment costs; single line, 25 MW–100 MW	USD/m	–	–	–	–
Reinforcement costs	USD/MW	–	–	–	–
Type 1 station	USD/MW	–	–	–	–
Type 2 station	USD/MW	–	–	–	–
Investments, percentage installation	USD/MW	1	1	1	1
Investments, percentage materials	USD/MW	0	0	0	0
Fixed O&M	USD/MW/year	840	347	22	1030
Variable O&M	USD/MWh	0	0	0	0

Table F.105 Natural gas piping capacity

Natural gas piping capacity[a]				1000 cu. ft./hr. cu. ft gas (1000 ft^2) area	
Buried pipe		Inlet pressure Δp/100 Ft			
Diameter (in.)	Cost ($/lf)	5 psig inlet with 1 psig drop	10 psig inlet with 1½ psig drop	30 psig inlet with 5 psig drop	60 psig inlet with 10 psig drop
6	$80/LF	100 (1000)	140 (1500)	350 (3700)	650 (7000)
4	$50/LF	35 (380)	50 (520)	120 (1300)	220 (2300)
3	$40/LF	15 (160)	25 (260)	60 (640)	100 (1000)
2½	$36/LF	10 (100)	13 (150)	35 (380)	35 (700)
2	$32/LF	6 (60)	8 (85)	20 (200)	40 (400)
1½	$30/LF	3 (30)	4 (40)	10 (100)	20 (200)
1	$28/LF	1 (10)	1 (10)	4 (40)	7 (75)

[a]Building SQFT values are based on 75 Btuh/ft2 peak average combined load (building heat and domestic hot water) and 80% combustion efficiency. For winter lows below +15 °F: at 0 °F multiply building SQFT by 0.8, and at −20 °F multiply building SQFT by 0.6; numbers shown are calculated for a nominal 400 ft run of pipe; prices shown are construction costs for direct buried pipe, including trench excavation, backfill, and pavement repair. For total project cost, add A-E fees, testing, contingencies, etc.; the energy delivered to the system may be estimated at 1040 Btu/CF. Therefore, a capacity of 20,000 CF corresponds to (20,000 CF)*(1040 Btu/CF), or 20,800,000 Btu; the cost to provide a boiler or other heating equipment to a stand-alone (no steam) building is approximately $2–$4 per square foot; this chart is intended to be used for obtaining an initial estimate of required pipe size and cost. Actual system design must be based on values obtained specifically for the project

available for upgrading, but four technologies stand out as the clearly most common technologies:

- Water scrubber
- Chemical scrubber (amine scrubber)
- Membrane scrubber
- PSA (pressure swing adsorption) scrubber

Possible injection points are:

- Nearby 4 bar distribution network.
- Nearby 19–40 bar distribution network.
- Gas compression is needed before injection.
- Nearby 80 bar gas transmission network. Gas compression is needed before injection.

The selection of injection point(s) depends on:

- Biogas plant capacity.
- Local 4 bar gas distribution network base load consumption.
- Distance to nearby 4 bar gas distribution network
- Distance to nearby 19–40 bar gas distribution network
- Local 4 bar gas distribution network base load consumption
- Distance to nearby 80 bar gas transmission network
- Cost of compression

If the local gas consumption shows large variations during the day, a local intermediate storage facility can be used to increase the local consumption of biogas/upgraded biogas. Selection of entry point(s) will be based on an economic optimization.

F.3.3.3 Hydrogen Networks

It has become ever clearer that the resource of natural gas is an energy source that will be less important in the future due to limitations in natural reserves. To prepare for the future, the gas industry is looking at alternative gaseous fuels; one such fuel gas is hydrogen. Large undiscovered reserves of natural gas can contribute to about 50% of the world energy mix for a longer time, but hydrogen gas is expected to become more and more available from converted wind energy via electrolysis. This gas can be fed to the natural gas network, and the whole gas network, including underground storage facilities, can act as a big buffer (power-to-gas). Alternatively, existing gas networks are gradually converted to pure hydrogen transport systems. During preparation for a future use of hydrogen, it became evident that very little information exists regarding the compatibility between long-term exposure and transportation of hydrogen in polyethylene gas distribution pipelines. A program was, therefore, set to study the transportation in a small-scale pilot grid at the field test facilities of Danish Gas Technology Centre situated at the Scion-DTU research center in Hørsholm, Denmark.

The results showed that 4 years (PE80) and 10 years (PE100) of continuous hydrogen exposure and subsequent laboratory tests based on international standards indicate no influence on PE80 or PE100 natural gas pipes' durability.

Hydrogen is, like electricity, an energy carrier, which is only as clean as the energy source from which it is produced. Electrolysis can be used to enhance the value and thereby possibly the capacity of surplus energy produced from fluctuating renewable energy sources such as wind. In the operation of the electrolyser, there are no environmental concerns.

Figure F.87 shows the new power-to-gas facility in Hobro, Denmark.

Fig. F.87 Power-to-gas facility in Hobro. (Source: https://www.dgc.dk/sites/default/files/filer/publikationer/C1703_IGRC2017_iskov.pdf)

Resiliency

The natural gas system is very important for many households heated by natural gas boilers and industry using natural gas for process steam and power plants producing electricity and heat.

The natural gas system is mainly used for distribution of gas from production centers to the costumer. The system is centralized, but biogas producers and future hydrogen production will make the system more decentralized. An important part of a resilient natural gas system is a well-functioning market. The natural gas market consists of the following:

- **The retail market** consists of distribution of gas from the transmission system to the consumers and retail trade with gas to the end consumer.
- **The gas transmission system** is owned and operated by a TSO, who is responsible for volume balancing in the natural gas system and for the management of gas supply in case of emergencies.
- **The gas distribution systems** are owned by the distribution companies, which are responsible for balancing the distribution network and operate the distribution systems.

- **The gas storages** can be owned and operated by the TSO. The storages are operated on commercial terms. The storage facilities sell a product that allows the storage customer to store, inject, and extract gas. Thus, the storages are in competition with other storages and providers of other flexibility services.

The wholesale market consists of the transmission of gas from producers to the distribution network and the wholesale market of gas. The following players are involved:

- **Shippers** are commercial actors who engage in the wholesale transport of gas in the transmission system. The shippers purchase transport rights in the transmission system to deliver the gas to one or more gas suppliers in the distribution systems. The shipper is responsible for balancing what is delivered into the transmission system and what is being sent in transit out of the transmission system.
- **Gas suppliers** supply consumers with gas and bill them for gas received.
- **The storage customer** owns that part of the gas that the shipper has transferred to them to store in the gas storage. The storage customer can sell the gas from the storage to a shipping company or another storage customer.

A different approach from looking solely at the natural gas markets is to focus on energy system integration. From the standpoint of the electrical system, is it especially interesting to use natural gas system to store renewable energy because the natural gas system does not need to maintain a constant balance between demand and supply. It is possible to use the gas cavern storage, line packing, and transfer of gas to other areas. The most promising technology to enable this ability is P2G, where electricity is used to produce SNG. Hydrogen (H_2) is produced from electrolysis, carbon dioxide (CO_2) is stripped from a source (say a biomass carbon capture and storage [CCS] plant), and by a methanation process, SNG (CH_4) is produced. Producing electricity back from natural gas can be done using gas-fired power plants or a fuel cell technology.

Supply in natural gas systems is typically highly secure because the operators have several opportunities to act on planned outages and emergencies. They can, for example, fill the large caverns with natural gas, and they can use line pack for shorter periods. A natural gas system will only reach a state of emergency if there is a failure of technical equipment, breakdown of pipes, absence of gas in storage, or a lack of production. Anything other than these conditions can usually be handled by the market using the right instruments.

Many of the aspects related to design of a district heating network can also be applied to a natural gas network. This especially relates to the design of a meshed structure of the natural gas networks to allow for a pipe breakdown in one place and still be able to supply the consumers via another pipe route, even when production is decentralized. The greatest danger when operating a natural gas system is explosions, so safety is very important (see Fig. F.88).

Fig. F.88 Natural gas pipe explosion

Miscellaneous
This category includes all non-energy technologies not included in the other categories but which are important for improving the resilience.

F.3.4 Flood Control

Flood control methods are used to reduce or prevent the detrimental effects of flood waters. Flood relief methods are used to reduce the effects of flood waters or high-water levels.

Floods are caused by many factors or a combination of any of these generally prolonged heavy rainfall (locally concentrated or throughout a catchment area), highly accelerated snowmelt, severe winds over water, unusual high tides, tsunamis, or failure of dams, levees, retention ponds, or other structures that retained the water. Flooding can be exacerbated by increased amounts of impervious surface or by other natural hazards such as wildfires, which reduce the supply of vegetation that can absorb rainfall. Periodic floods occur on many rivers, forming a surrounding region known as the flood plain.

During times of rain, some of the water is retained in ponds or soil, some is absorbed by grass and vegetation, some evaporates, and the rest travels over the land as surface runoff. Floods occur when ponds, lakes, riverbeds, soil, and vegetation cannot absorb all the water. Water then runs off the land in quantities that cannot be carried within stream channels or retained in natural ponds, lakes, and man-made reservoirs. About 30% of all precipitation becomes runoff, and that amount might be increased by water from melting snow. River flooding is often caused by heavy rain, sometimes increased by melting snow. A flood that rises rapidly, with little or no warning, is called a flash flood. Flash floods usually result from intense rainfall over a relatively small area or if the area was already saturated from previous precipitation.

According to National Academy of Sciences, floods can be controlled by using structural approaches such as

1. Dams

Dams are barriers that stop the flow of water before they reach areas at the risk of flooding. During heavy rains, dams hold upstream floodwaters. These floodwaters are gradually released to minimize the likelihood of damage to communities in the downstream. Dams can also be dangerous during unexpectedly high precipitation periods. When water capacity exceeds the dam storage, there is a risk of uncontrolled water flow to the downstream areas. This situation occurred in Missouri river during 2011 spring floods. In such circumstances when dams fail, it results in damage to the communities below the dams,

2. Floodwalls and levees

Permanent floodwalls and levees are structured built to provide flood protection for buildings.

Floodwalls are built using reinforced concrete or masonry and provide a barrier against flooding. Floodwalls also protect buildings against hydrostatic and hydrodynamic loads and also divert flood-borne debris and ice away from the buildings. Floodwalls are built at a distance to the building to avoid any structural modifications to the building. Depending on the need, floodwalls can protect the low side or all around the building.

Levees are made of compacted soil and used to protect large areas such as agricultural facilities. Building a levee generally requires a large amount of land and is largely dependent on the topography of the soil. These are not common flood management techniques because of the high cost and land requirement.

3. Floodways, spillways, and channels

Floodways, spillways, and channels are constructed to carry floodwaters around an area where the capacity of a river to pass a large volume of floodwaters past a critical location is limited. Depending on the circumstances, flood channels can also be modified to increase flood-carrying capacity. A good example for this structure is the 2011 Mississippi river flooding, when USACE opened floodways near New Madrid Missouri to take the pressure off upstream and downstream levees in Kentucky, Illinois, and other areas around Missouri.

4. Armored levees, seepage berms, and cutoff walls

Depending on the construction, material, and design of a levee, water may be allowed to flow through or under the levee. This can create a potential for the levee to collapse. Therefore, additional support such as armoring makes it less susceptible to erosion and collapse. Armoring can be done using a variety of materials such as concrete or metal. Sometimes vegetation can also be used as armor for the levee.

Seepage berms and cutoff walls are used to stop the flow of water through or below the levee. Adding berms can add sufficient weight to counteract the upward seepage forces, thereby preventing seepage through the structure.

F.3.5 Nonstructural Methods for Flood Damage Mitigation

F.3.5.1 Dry and Wet Floodproofing

Dry floodproofing refers to methods to seal structures to prevent floodwaters from entering. Wet floodproofing refers to the process of making a structure resistant to flood damage by allowing the water to enter and flow through the structure. FEMA defines floodproofing as a combination of adjustments and/or additions of features to buildings that eliminate or reduce the potential for flood damage (see Fig. F.89).

Examples of such adjustments and additions include anchoring of the building to resist flotation, collapse, and lateral movement; installation of watertight closures for doors and windows; reinforcement of walls to withstand floodwater pressures and impact forces generated by floating debris; use of membranes and other sealants to reduce seepage of floodwater through walls and wall penetrations; installation of pumps to control interior water levels; installation of check valves to prevent the entrance of floodwater or sewage flows through utilities; and the location of electrical, mechanical, utility, and other valuable damageable equipment and contents above the expected flood level

Fig. F.89 Masonry floodwall in Fargo, MD (left); armored levee in Japan (right)

Sources

ready.gov 2020. *Floods*. Webpage. https://www.ready.gov/floods

FEMA (Federal Emergency Management Agency). 2013a. "Other Flood Protection Measures." Chapter 4 in *Floodproofing Non-Residential Buildings*. FEMA P-936. Washington, DC: FEMA. https://www.fema.gov/sites/default/files/2020-07/fema_p-936_floodproofing_non-residential_buiildings_110618pdf.pdf

FEMA. 2013b. "Dry Floodproofing Methods." Chapter 3 in *Floodproofing Non-Residential Buildings*. FEMA P-936. Washington, DC: FEMA. https://www.fema.gov/sites/default/files/2020-07/fema_p-936_floodproofing_non-residential_buiildings_110618pdf.pdf

NRC (National Research Council). 2013. *Levees and the National Flood Insurance Program: Improving Policies and Practices*. Washington, DC: National Academy of Sciences, Engineering and Medicine. https://www.nap.edu/read/18309/chapter/8#100

Wikipedia. Undated(b). *Flood Control*. https://en.wikipedia.org/wiki/Flood_control

F.3.6 Tunnels

A tunnel is an underground passageway, dug through the surrounding soil/earth/rock and enclosed except for entrance and exit, commonly at each end. A pipeline is not a tunnel, though some recent tunnels have used immersed tube construction techniques rather than traditional tunnel boring methods.

A tunnel may be built to accommodate foot, vehicular, or rail traffic or to function as a canal. The central portions of a rapid transit network are usually located in the tunnel. Some tunnels are built to accommodate aqueducts to supply water for consumption or for hydroelectric stations or sewers. Utility tunnels are used for routing steam, chilled water, electrical power, or telecommunication cables and for connecting buildings for convenient passage of people and equipment. Secret tunnels are built for military purposes or by civilians for smuggling of weapons, contraband, or people. Special tunnels, such as wildlife crossings, are built to allow wildlife to cross human-made barriers safely. Tunnels can be connected together in tunnel networks.

Tunnel floods cause billions of dollars of damage. When a tunnel floods, the damage is swift, and dangers are deadly. There are several technologies that can prevent or limit flooding in the transportation tunnels. For example, Department of Homeland Security (DHS) Science and Technology Directorate (S&T) developed a tunnel plug made of high strength Vectran fabric so the tunnel will inflate with air and then fill with water to fulfill specific transit system needs (see Fig. F.90).

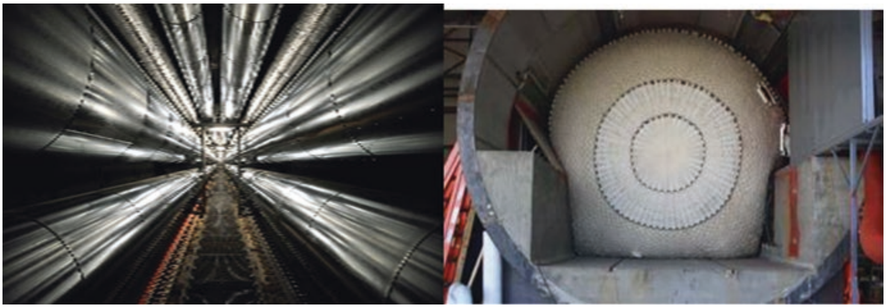


Fig. F.90 (left) Utility tunnel for district heating pipes between Rigshospitalet and Amagerværket in Copenhagen, (right) tunnel plug developed by DHS S&T

Sources

DHS (U.S. Department of Homeland Security). 2017. *Resilient Tunnel Project*. Washington, DC: D DHS S&T Directorate. https://www.dhs.gov/sites/default/files/publications/Resilient%20Tunnel%20Project-508_0.pdf

PNNL (Pacific Northwest National Laboratory). 2017. *Inflatable Plug for Subway Tunnels Demonstrated*. Richland, WA: PNNL. https://www.pnnl.gov/news/release.aspx?id=4415

Wikipedia. Undated(f). *Tunnel*. https://en.wikipedia.org/wiki/Tunnel

F.3.7 Digitalization

SCADA systems, geographic information systems (GIS), network analysis, and other simulation tools, which have been best practice in the energy supply sector for more than 40 years, are very important for the optimal supply of efficient, reliable, and resilient energy. The exchange of information among all stakeholders, not least in GIS, prevents unforeseen damage of infrastructure.

Nevertheless, case studies show several examples in which vital construction has been damaged by no-dig drilling and by contractors who do not follow the rules. In theory, information systems could prevent unforeseen breakdown, but experience does not always confirm this. Therefore, in particular GIS and regulation of underground constructions should have priority.

However, digital equipment can also be abused by hackers. This threat can reduce system resilience. Therefore, vital SCADA systems should not have direct access to the Internet. While it is important to have access to complete data, too much data could have the opposite effect; excess data can obstruct access to more vital data and increase the risk of abuse.

F.3.8 Space for Underground Infrastructure

Even more important than GIS is the need for authorities to issue regulations on how to use the urban area for infrastructure, involving (at least) the four energy carriers, electricity, gas, district heating, and district cooling, in conjunction with all other services, which can involve dangerous excavation (Fig. F.91).

As a best practice, the city makes the space in public roads available for the city infrastructure and issues guidelines and regulations on where to establish the various service lines, e.g., ranked in accordance with the costs, for example:

- Main sewage: middle of the road
- District heating gas and water: one side of the road
- Power: between road and pedestrian path
- Telecommunication: side of the pedestrian path

Regulations should, for example, specify space requirements for the various service lines and construction principles. The Danish Standard 475:2012 specifies, for example, the minimum distance between underground power cables from 1 kV to 30 kV and other services (Table F.106).

Fig. F.91 Dangerous excavation, source: Danish Safety Technology Authority

Table F.106 Minimum distance between underground power cables from 1 kV to 30 kV and other services (Danish Standard 475:2012)

Distance to line:	Parallel	Crossing
Wastewater in concrete or plastic	0.3	0.1
Water in cast iron or plastic	0.5	0.1
Gas 1–4 Mpa	0.3	0.3
District heating hot water > DN400	1.0	0.3
District heating hot water > DN400	1.0	0.2

Appendix G. Renewable Energy Analysis: Geospatial Analysis and Maps (United States)

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G.1 Executive Summary

NREL maintains several geospatial data sets (geographic information system [GIS] data) related to renewable energy project feasibility including solar and wind resources; utility rate data; and natural gas costs. This information is combined with technology characteristics (initial cost and operation and maintenance costs) to calculate a levelized cost of energy (LCOE) at each location in a geospatial analysis. At each location, simple estimates of LCOE were calculated for the following technology configurations:

- Photovoltaics (PV) + 0-hour battery
- PV+4-hour battery
- PV+12-hour battery
- CSP+ 0-hour thermal energy storage (TES)
- CSP+ 4-hour TES
- CSP+ 12-hour TES
- Wind+0 hour battery
- Wind+4 hour battery
- Wind+12 hour battery
- Reciprocating engine CHP
- Recip. CHP w/seasonal storage
- Combustion turbine (CT) CHP
- CT CHP w/seasonal storage
- Solar water heating (SWH) with diurnal storage
- SWH with seasonal storage

Maps of geospatial distribution of LCOE are presented for comparison to maps of prevailing conventional utility rates. These maps illustrate the geospatial dependence of the cost-effective applicability of the technology.

G.2 Background

This section addressing renewable energy resource maps was developed by the National Renewable Energy Laboratory (NREL).

The method used to calculate LCOE in this geospatial analysis is informed by the method described in Nguyen et al. (2014).

G.3 Renewable Energy Resources

The NREL GIS database contains solar resource data on a 10 km (6.2 mile) grid and wind data on a 200 m (656 ft) grid. NREL has already processed the underlying hourly resource data to produce a dataset of capacity factor for each location-based delivered AC. The reference for the resource information is National Renewable Energy Laboratory (NREL n.d.). The solar resource information provided by NREL is satellite image data processed according to Perez et al. (2002), and the wind energy resource information provided by NREL is from AWS Truepower (purchased dataset).

G.4 Per Unit Analysis

The analysis is conducted on a "per kW" basis, where the kW of capacity is measured at the point of delivery. The size of a system that includes both PV and batteries would be defined based on kW delivery to the grid, whether power came instantaneously from the PV or on demand from the battery. So, in the following per unit derivation:

$$\mathrm{P}_{\mathrm{rated}} = 1\,\mathrm{kW}$$

G.5 Annual Energy Delivery

Annual energy delivery per kW of installed capacity of the systems is based on the resource information as reported in the "capacity factor."

CF=capacity factor inclusive of balance of system (BOS) losses (AC capacity factor) from www.nrel.gov/gis (NREL n.d.).

$$\text{Annual energy delivery} = \left(P_{\mathrm{rated}}\right)^{*} \mathrm{CF}^{*} \left(8760\,\mathrm{h} / \mathrm{year}\right)$$

where P_{rated} is the rated electrical power delivery capacity associated with the definition of capacity factor.

G.6 Energy Storage

The efficiency of electrical (battery) or thermal energy (diurnal tank or seasonal pit storage), $\eta_{storage}$, is defined as the energy into charging storage divided into the energy out when discharging storage. In this simple derivation, the loss occurs when charging storage and manifests as an increase in the installed generation capacity required to cover this loss and to maintain a power rating of $P_{rated} = 1$ kW. In general, the columbic efficiency of a battery may be high (in excess of 95%) with some new types promising 99%; and insulation of thermal storage systems is designed typically for 98% efficiency. Here we assume $\eta_{storage} = 0.98$.

The definition of power rating, $P_{rated,}$ is closely linked to the definition of capacity factor, CF, with the product of the two being energy delivery. In the definition here, the daily capacity factor of a renewable energy resource, CF, may be extended by the addition of storage to a higher value CF′:

$$CF' = CF + t / 24 \tag{G.1}$$

where t is defined as the hours that the power level P_{rated} may be maintained beyond that indicated by the resource CF (sun hours/24 in the case of solar). The units of the number 24 are "hours."

The installed capacity to charge the batteries and provide the increased CF′ is

$$P_{install} = P_{rated}{}^{*} (1 + t / \left(CF^{*}\, T\right) / \eta_{storage} \tag{G.2}$$

In the case of both diurnal and seasonal storage, the installed capacity is increased to accommodate both diurnal charging of storage and longer-term accumulation of seasonal storage:

$$P_{install} = P_{rated}{}^{*} \left(1 + t_{diurnal} / 24 + t_{seasonal} / 8760\right) / CF / \eta_{storage} \tag{G.3}$$

where t seasonal is the number of hours the fully charged storage can support P_{rated} (e.g., $t_{seasonal}$=2200 hours). Both $t_{diurnal}$ and $t_{seasonal}$ are considered inputs here and would have to be specified for a particular application. In the case of solar water heating, $t_{seasonal}$ is calculated from a difference between maximum solar radiation in summer and average solar radiation and the number of days in the season:

$$t_{seasonal} = \left(I_{c,max} - I_{c,ave}\right)^{*} \text{days} \tag{G.4}$$

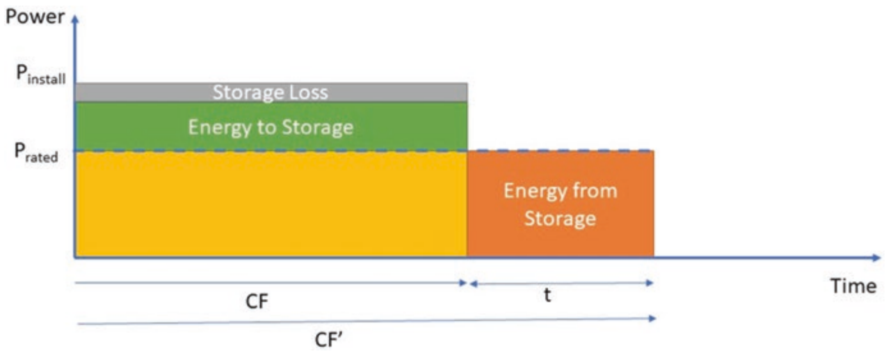

Fig. G.1 Graphical representation of power into storage due to $P_{install}$>P_{rated} and resulting hours of energy storage, t

In this derivation I_c is in units of "sun hours/day" as the original kWh/m^2/day unit divided by the solar radiation associated with P_{rated} which is 1 kW/m^2.

Figure G.1 illustrates how storage is represented in the equations, with the generation capacity $P_{install}$ required to supply the rated power P_{rated} for t hours.

G.7 Initial Cost

Initial cost is calculated as the sum of a fixed project cost and a variable unit cost. The unit cost is reduced by any rebates and then reduced by the federal tax credit.

$$C_{initial} = C_{intial\ fixed} + c_{gen\ unit}{}^{*}\ P_{install} + c_{storge\ unit}{}^{*}\ t^{*}\ P_{rated} \tag{G.5}$$

where

C = initial cost of PV or wind system after rebate and tax credit
$C_{initial\ fixed}$ = fixed project development costs ($)
$C_{gen\ unit}$ = unit cost per kW of installed capacity ($/kW)
$C_{storage\ unit}$ = unit cost per kWh cost of storage technology (battery) ($/kWh)
$C_{storage\ unit\ seasonal}$ = unit cost per kWh cost of seasonal thermal storage (pit storage) ($/kWh)

G.8 Operation and Maintenance Cost

Cost of operation and maintenance, C_{om}, is the cost per unit cost per kW of rated capacity ($/kW/year):

$$C_{OM} = C_{fixed\,O\&M} + P_{installed}{}^{*}\,C_{gen\,O\&M} + c_{storage\,O\&M}{}^{*}\,t^{*}\,P_{rated} + c_{storage\,seasonal\,O\&M}{}^{*}\,t^{*}\,P_{rated} \tag{G.6}$$

where

$C_{fixed\ O\&M}$ = fixed O&M cost independent of size
$C_{gen\ O\&M}$ = unit O&M cost per kW of installed generation capacity ($/kW)
$C_{storage\ O\&M}$ = unit O&M cost per kWh cost of storage technology (battery) ($/kWh)
$C_{storage\ seasonal\ O\&M}$ = unit O&M cost per kWh cost of seasonal thermal storage technology (pit storage) ($/kWh)

G.9 Fuel Use and Conventional Fuel Savings

The general approach includes fuel use, such as the case for combined heat and power fueled by natural gas or biomass fuel. The amount of fuel used per unit of rated electric generating capacity (1 kW) is:

$$F = P_{installed}{}^{*}\left(CF^{*}8760/\eta_{elec}\right)\left[1-\left(1-\eta_{elec}\right)HRF/\eta_{conv}\right] \tag{G.7}$$

where

F = fuel used per year to provide rated electric generation (kWh/year)
η_{elec} = efficiency of electric generator; reciprocating engine $\eta_{elec} = 0.34$, combustion turbine $\eta_{elec} = 0.25$
HRF = fraction of the waste heat from the power generation process which is recovered; reciprocating engine HRF = 0.5, combustion turbine HRF = 0.67, because all the waste heat is manifest in the exhaust stream and easier to recover (USEPA 2017).

To convert this recovered amount of heat into fuel savings, we divide by the efficiency of the conventional heating system, η_{conv}, assumed $\eta_{conv.} = 0.84$ for all options

It is important to point out that here we assume all heat is utilized, either because the CHP system is small compared to the thermal demand load or because storage is sufficient to couple heat generation with heat demand.

The units of this amount of fuel use would be kWh of fuel energy per year, which is an unusual unit for fuels requiring dividing by a conversion factor of 3412 Btu/kWh to convert into the more common $/BTU unit for fuels.

The cost of fuel is fc in in units of $/kWh.

G.10 Present Worth Factor (PWF)

The present value of annual costs or revenues over the analysis period is calculated according to the present worth factors.

$$PWF = (1+i)/(d-i)*(1-((1+i)/(1+d))^N) \tag{G.8}$$

where

I = inflation rate, i = 0.02 in this analysis
D = discount rate, d = 0.03 in this analysis
N = years of analysis period and N = 25 in this analysis.

Annual cash flow (O&M costs) is inflated according to the inflation rate and then discounted to present value according to the discount rate, resulting in the value of the present worth factor. The discount rate and inflation rates are specified by Lavappa and Kneifel (2019).

G.11 Levelized Cost of Energy Calculation

LCOE is the sum of life cycle cost and less savings in conventional fuels in the numerator divided by electrical energy produced in the denominator.

$$LCOE = \{C + (C_{OM} + F^{*} fc)PWF\} / P_{rated} / CF' / (8760) / PWF \tag{G.9}$$

wherein the number 8760 has units of hours/year.

This equation is derived in general to accommodate both electric-only generators such as PV and wind, with and without energy storage, and also combined heat and power with a fuel such as natural gas. In the case of solar PV or wind energy, the fuel cost fc is zero, and for electric-only generators, the HRF is zero. Table G.1 lists the values to be used for each technology option.

G.12 Results

The data in Table G.2 shows an example of the calculation of LCOE for each of the technology configurations using the costs from Table G.1 and a typical capacity factor assumption for each technology. In this example, the LCOE varied from $0.063 for wind to $0.13/kWh for PV and battery combination. This same calculation is repeated for each grid cell of the geospatial analysis.

Table G.1 Values of cost parameters used for the calculation in each grid cell in the geospatial analysis

Case	$C_{unit\ gen}$ ($/kW)	$C_{unit\ storage}$ ($/kWh/year)	$C_{unit\ seasonal\ storage}$ (thermal)	$C_{O\&M\ gen}$ ($/kW/year)	$C_{O\&M\ storage}$ ($/kWh/year)
PV+0-hour battery	$1783.00	$380.00	–	$22.00	$36.32
PV+4-hour battery	$1783.00	$380.00	–	$22.00	$36.32
PV+12-hour battery	$1783.00	$380.00	–	$22.00	$36.32
CSP+ 0-hour TES	$3486.00	$422.22	–	$38.89	$4.71
CSP+ 4-hour TES	$3486.00	$422.22	–	$38.89	$4.71
CSP+ 12-hour TES	$3486.00	$422.22	–	$38.89	$4.71
Wind+0-hour battery	$1624.00	$380.00	–	$41.00	$36.32
Wind+4-hour battery	$1624.00	$380.00	–	$41.00	$36.32
Wind+12-hour battery	$1624.00	$380.00	–	$41.00	$36.32
Recip. CHP	$2200.00	$48.00	$1.50	$83.00	–
Recip. CHP w/ seasonal storage	$2200.00	$48.00	$1.50	$83.00	–
CT CHP	$3400.00	$48.00	$1.50	$54.00	–
CT CHP w/seasonal storage	$3400.00	$48.00	$1.50	$54.00	–
SWH diurnal storage	$1570.00	$48.00	–	$16.67	$0.29
SWH seasonal storage	$1570.00	$48.00	$1.50	$16.67	$0.29

NREL (n.d.), Boslet (2010), and EIA (2019)

This calculation of LCOE is performed for each grid cell of a geospatial analysis. For comparison to these calculated LCOE values, Fig. G.2 shows average rates across the United States for commercial electric power (utility-by-utility) and for natural gas (state-by-state). The LCOE calculation was performed for each map grid cell, and the resulting maps are displayed in Figs. G.3, G.4, G.5, G.6, and G.7.

Photovoltaics use both direct and diffuse solar radiation, so the LCOE is rather uniform across the country, about $0.02/kWh lower in the sunny southwest and about $0.02 higher than average in the cloudier Northeast and Northwest.

Concentrating solar power can focus only the direct solar radiation, so the LCOE is lowest in the desert of south-central California and in the Southwest where skies are clear and humidity is low. The LCOE is much higher in the Northeast and Northwest where solar radiation is less intense and more scattered (diffuse) due to clouds.

Wind power is most cost-effective in the Great Plains states of North and South Dakota, Nebraska, Kansas, Oklahoma, and Texas. In general, the Rocky Mountains and sierras present a barrier to winds, although this high-resolution data shows that winds are concentrated in mountain passes, such as in southern Wyoming and

Table G.2 Example of the calculation of LCOE performed for each grid cell in the geospatial analysis

Case	Prated (kW)	Pinstall (kW)	C initial ($)	C O&M ($/year)	CF' with storage	LCOE ($/kWh)
PV+0 hour battery	1	1.00	$1783.00	$22.00	0.17	$0.069
PV+4-hour battery	1	1.98	$5051.04	$167.28	0.34	$0.134
PV+12-hour battery	1	3.94	$11,587.12	$457.84	0.67	$0.167
CSP+ 0-hour TES	1	1.00	$3486.00	$38.89	0.26	$0.088
CSP+ 4-hour TES	1	1.65	$7438.53	$82.99	0.42	$0.113
CSP+ 12-hour TES	1	2.62	$13,367.31	$149.13	0.67	$0.128
Wind+0-hour battery	1	1.00	$1624.00	$41.00	0.30	$0.044
Wind+4-hour battery	1	1.56	$4046.22	$186.28	0.47	$0.090
Wind+12-hour battery	1	2.67	$8890.67	$476.84	0.80	$0.126
Recip. CHP	1	1.30	$3046.76	$107.70	0.73	$0.104
Recip. CHP w/seasonal storage	1	1.30	$4244.27	$107.70	0.73	$0.115
CT CHP	1	1.30	$4603.90	$70.07	0.73	$0.105
CT CHP w/seasonal storage	1	1.30	$5964.70	$70.07	0.73	$0.118
SWH diurnal storage	1	1.71	$3016.13	$18.67	0.49	$0.036
SWH seasonal storage	1	2.00	$3741.20	$70.87	0.58	$0.048

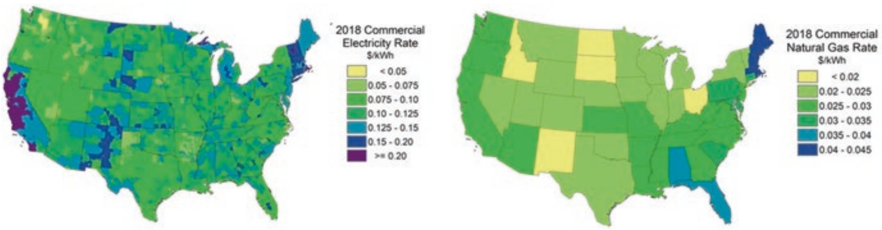

Fig. G.2 For comparison to the calculated LCOE maps, these maps show electric rates (left) varying from less than $0.05/kWh in the Pacific Northwest to $0.20/kWh in California and natural gas rates (right) that vary from <0.02/kWh (thermal) in the Dakotas to $0.045/kWh thermal in the Northeastern United States.

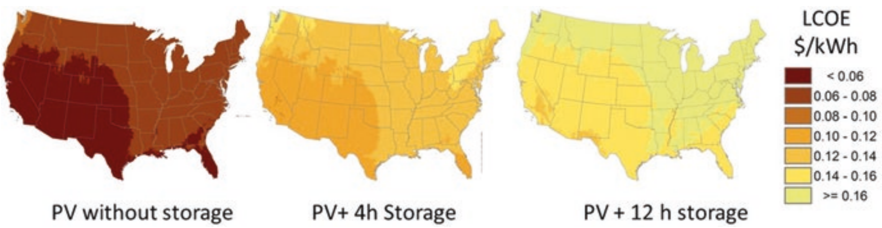

Fig. G.3 LCOE across the Continental United States (CONUS) for photovoltaic systems including 4 hours and 12 hours of battery storage. Costs in sunny areas are on the order of $0.06/kWh without storage and up to $0.16/kWh in less sunny areas with 12 hours of battery storage

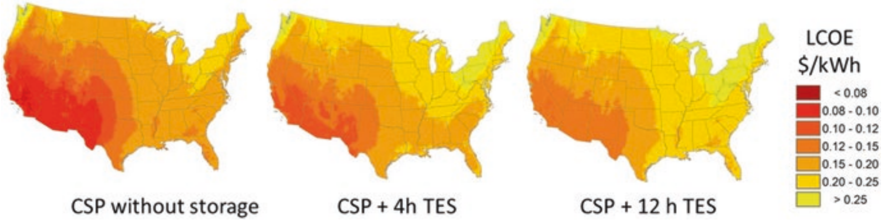

Fig. G.4 LCOE across the CONUS for concentrating solar power systems including 4 hours and 12 hours of TES. Costs in sunny areas are on the order of \$0.08/kWh without storage and up to \$0.25/kWh in less sunny areas with 12 hours of thermal energy storage

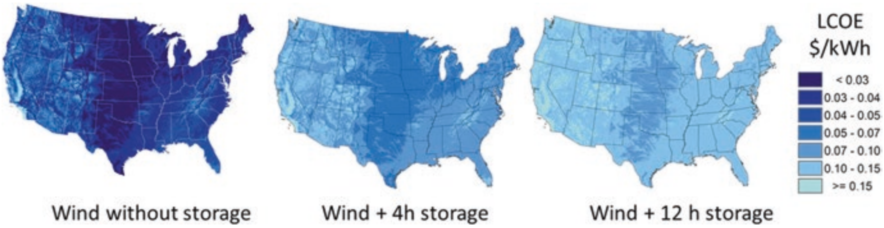

Fig. G.5 LCOE across the CONUS for wind energy systems, including with 4 hours and 12 hours of battery storage. Costs vary from \$0.03/kWh in windy areas (Great Plains states of ND, SD NE, OK, TX) and as high as \$0.15/kWh in less windy areas with 12 h of battery storage

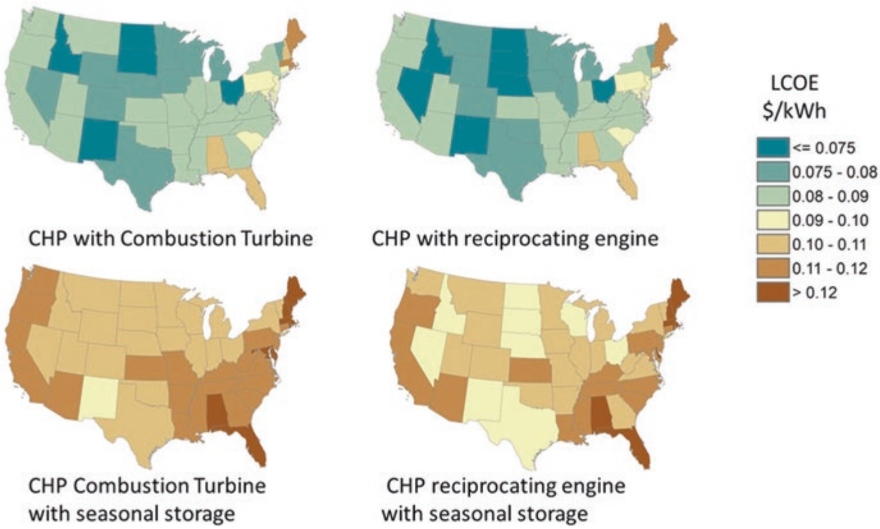

Fig. G.6 LCOE across the CONUS based on 2018 natural gas prices for combustion turbine combined heat and power systems based on combustion turbine and reciprocating engine and with/without seasonal thermal storage. Costs vary from less than \$0.075/kWh in Western states where natural gas is least expensive and over \$0.11/kWh in states with higher gas costs in the Northeast. With seasonal storage, the cost varies from \$0.09/kWh to over \$0.12/kWh

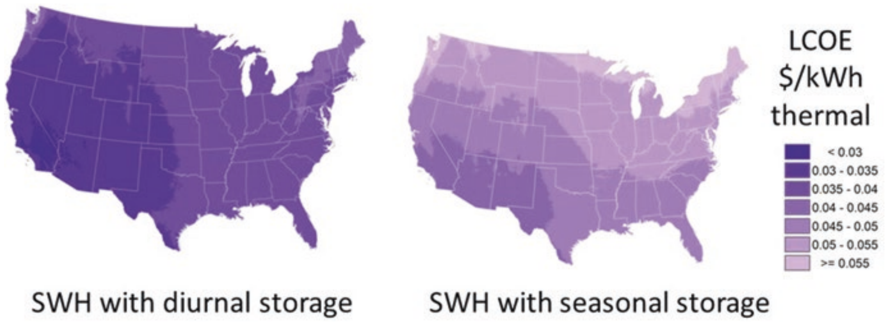

Fig. G.7 LCOE of solar water heating systems varies from less than $0.03/kWh in the best parts of the sunny Southwest to over $0.055 in the Northeast and western Washington state

several spots in California such as Tehachapi Pass and San Gorgonio Pass where wind developments have occurred.

CHP is most cost-effective where electric rates are high and gas rates are low (spark spread), such as the Dakotas and Ohio but also New Mexico.

Solar water heating systems use both direct and diffuse solar radiation, so the LCOE is rather uniform across the country, best in the sunny Southwest, but viable in all parts of the country.

G.13 Conclusions

The maps presented here must be considered highly approximate, but for early planning of projects, they provide a useful guide to how parameters that vary geospatially affect LCOE. Conclusion that can be drawn by inspection of the maps includes:

1. Photovoltaics, which use both the direct and the diffuse components of solar radiation, have a spatially uniform LCOE, although the LCOE is lower in the Southwest where the solar resource is a maximum and highest in the Northeast and in the Northwest (west of the Cascade mountains). The distribution is similar for PV with batteries but is higher due to the initial and operating cost of the batteries and also because of energy losses associated with battery throughput.
2. Concentrating solar power uses only the direct component of solar radiation, so this technology has the lowest LCOE in the Southwest, where dry conditions result in clear skies compared to the rest of the country, and the variation across the country is greater than for photovoltaics.
3. Wind energy system has the lowest LCOE in the center of the continent from Texas, Oklahoma, Kansas, Nebraska, and North and South Dakota. Mountain ranges such as the Rocky Mountains generally present a barrier to winds, but the resolution of this map shows low LCOE where the wind can move though mountain passes such as southern Wyoming.

4. LCOE of combustion turbines and reciprocating engines in combined heat and power applications varies due to the cost of natural gas to fuel the generators. Thus cost is lowest in states with low gas cost in the middle of the continent and higher on the East and West coastal states.

Appendix H. ERIN User's Guide

H.1 Introduction

The purpose of this User's Guide is to give a working introduction to the command-line version of the resilience calculation tool (ERIN[5]) and a user interface for the tool written in Microsoft Excel®.

The purpose of the tool itself is to simulate the energy flows through a district energy system composed of an interacting network of components. The main contributions of this tool that we maintain are unique in aggregate as follows:

- The tool accounts for both reliability (failure and repair) and resilience to various scenarios (design basis threats)
- While also accounting for topology and interaction between an open-ended number of energy networks
- While providing key energy usage, resilience, and reliability metrics for the modeler/planner.

The resilience calculation tool is available as open-source software written in C++ (Nutaro 2011).

Several command-line programs are included with the *E²RIN* distribution including three key executables along with a library written in the *C++* programming language. Documentation of the library itself is beyond the scope of this document. However, the three executables will be given attention in this User's Guide as they are of particular interest to modelers.

The minimal user interface written in Microsoft Excel® uses the command-line simulation tool behind the scenes as well as a *Modelkit/Params*[6] template to make it easier to use. We will cover usage of the Microsoft Excel® interface in addition to the command-line programs.

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[5] E²RIN originally stood for Energy, Economics, and Resilience of Interacting Networks. However, the economics portion has been moved out of the engine itself. The current name at the time of this writing is a working name subject to change in the future.

[6] Modelkit/Params is a separate open-source project available from Big Ladder Software (https://bigladdersoftware.com/projects/modelkit/).

H.2 Simulation Overview

In this section, we describe the simulation process to assess the resilience of a district system network to various scenarios including design basis threats.

District energy systems play a major role in enabling resilient communities. However, resilience is contextual. That is, one must specify what one is resilient to. This is specified in the tool using various "scenarios" which represent normal operation and various design basis threats. Design basis threats are low-probability, high-impact events such as hurricanes, flooding, earthquakes, terrorist attacks, tornados, ice storms, viral pandemics, etc. Considering relevant design basis threats is necessary for enabling resilient public communities.

The tool operates over networks that supply energy to both individual buildings and districts. These networks are comprised of components (loads, generation, distribution/routing, storage, and transmission assets) and connections. These connections form the topology of the network—what is connected to what. Multiple flows of energy can be modeled: notably, both thermal (heating/cooling) and electrical flows and their interactions.

This network of components is subject to various scenarios which represent one or more ideal cases (i.e., "blue sky") as well as design basis threats (also known as "black sky" events). Each scenario has a probability of occurrence and zero or more "damage intensities" associated with it such as wind speed, vibration, water inundation level, etc. Fragility curves are used to relate the scenario's damage intensities with the percentage chance that a given component will fail to work under the duress of the scenario.

Additionally, reliability statistics can be associated with components to model their routine failure and repair times and to take reliability into account in conjunction with various threats. Note, however, that routine reliability statistics are most likely not applicable to an extreme event such as those represented from a design basis threat. Fragility curves are more appropriate for that kind of assessment.

By looking at the performance of the network while considering the possibility of failure due to both typical reliability and failure due to threats, resilience metrics such as maximum downtime, energy availability, and load not served can be calculated. This can, in turn, help planners to see whether a proposed system or change to an existing system will meet their threat-based resilience goals.

The workflow for using the tool is as follows:

- Using a piece of paper, sketch out the network of locations and components and how they are connected.
- Using either the Excel® user interface or a text editor, build an input file that describes:
  - The network of components

    Component physical characteristics
    Component failure modes
    Component fragility
    How components are connected to each other

- The scenarios to evaluate

  The duration of the scenario
  The occurrence distribution
  Damage intensities involved

- Load profiles associated with each load for each scenario

- Simulate the given network over the given scenarios and examine the results.

  The simulation is specified using a discrete event simulator. Events include:

- Changes in a load
- Changes in an uncontrollable source such as PV power generation
- Routine failure of a working component under reliability
- Routine repair of a failed component
- Events due to physical limitations of devices (e.g., depleting the energy in a battery or diesel fuel tank)
- The initiation or ending of a scenario
- Application of fragility curves at a scenario start

For every event that occurs, the simulation resolves and negotiates the conservation of energy throughout the network. This results in resolving the flows through all connections in the network after each event. Loads in particular are tracked to identify energy not served and time that a load's request is not fully supplied and also to calculate the energy availability (energy served × 100%/energy requested). These statistics are calculated *by load* and *by scenario*.

H.3 Concept Overview

This section gives a quick overview of the key concepts used in the tool. Understanding the concepts will help when authoring an input file as well as in interpreting the output results.

H.3.1 Flows

A flow is any movement of a type of energy. Examples include "electricity," "heated water for district heating," and "chilled water for cooling." The flows specified are open-ended and not prescribed by the tool. However, to aid new users, the Excel® user interface does limit the available flows to those typically used in an assessment.

By being imaginative, flows that are traditionally not considered as "energy flows" can be modeled as well. For example, a supply of potable water pumped to a building can be modeled by phrasing it in terms of enthalpy times mass flow rate: $h \times \dot{m}$ (making assumptions for line pressures and temperatures). This allows the contribution of a pump (changing the pressure and thus the flow work across the pump) to easily be considered.

A flow has a direction associated with it. A flow can be zero (i.e., nothing is flowing) but cannot be negative. Negative flows would imply a change in direction which would greatly increase the complexity of the simulation tool. As such, we do not allow negative flows. However, it is possible to simulate bidirectional flow by connecting components from both directions (more on this later).

H.3.2 Components and Ports

A component is meant to represent any of a myriad of equipment used in a district energy system. A component has zero or more inflow ports and zero or more outflow ports. These ports take in zero or more flows, route and/or transform them, and output zero or more flows. A component must have at least one port: inflow or outflow.

The fidelity of modeling is that of a one-line diagram and accounts for energy flows only. A component needs only to be considered if:

- Its function will significantly affect network flows.
- Its failure is statistically significant in the face of either reliability or fragility to a threat.

For example, a relatively efficient stretch of pipe in a district heating system can be ignored from an energy standpoint if its losses are insignificant compared to other equipment. However, if that stretch of pipe is deemed to have a statistically significant possibility of failure during a threat event such as an earthquake, it should be modeled. In this instance, a pass-through component (see below) with a fragility curve (see below) may be a good choice.

H.3.3 Component Types

Because we model components at a high level of abstraction, a few component types are all that is needed to model many real-world components. In this section, we discuss the available component types and their characteristics.

H.3.3.1 Component Type: Load

A load is essentially an exit point out of the network for "useful work." A load typically represents an end-use such as a building or cluster of building's electricity consumption or heating load consumption.

A load specifies its load versus time with a load profile which is specified per scenario.

H.3.3.2 Component Type: Source

A source is an entry point into the simulation for providing energy flow into the network. A source typically represents useful energy into the system such as electrical energy from the utility, natural gas into the district, or diesel fuel transported to a holding tank.

H.3.3.3 Component Type: Uncontrolled Source

Normally, a source responds to a request up to its available max output power (which defaults to being unlimited). In contrast, an uncontrolled source cannot be commanded to a given outflow because the source is uncontrollable. Typical examples of uncontrolled sources are electricity generated from a photovoltaic array, heat generated from concentrating solar troughs, or electricity from a wind farm. Another typical uncontrolled source is heat to be removed from a building as a "cooling load."

An uncontrolled source specifies its supply values versus time with a supply profile that is specified per scenario. Note: functionally, a supply profile and load profile are the same thing.

H.3.3.4 Component Type: Converter

A converter represents any component that takes in one kind of flow and converts it to another type of flow, usually with some loss. Converters have an efficiency associated with them. The current version of the tool only supports a constant efficiency. Typical examples of converter components are boilers, electric generators (e.g., fired by diesel fuel or natural gas), transformers, and line losses.

The loss flow from one component can be chained into another converter component to simulate various loss heat recovery mechanisms and equipment such as CHP equipment.

H.3.3.5 Component Type: Storage

A storage component represents the ability to store flow. The storage unit has both a charge (inflow) port and a discharge (outflow) port. The storage component cannot accept more flow than it has capacity to store. Similarly, a storage component cannot discharge more flow than it has stored. Typical examples of a storage component include battery systems, pumped hydro, diesel fuel storage tanks, coal piles, and thermal energy storage tanks.

The current version of the storage tank does not have an efficiency or leakage component associated with it. However, charge/discharge efficiency can be approximated with converter components and leakage via a small draw load.

H.3.3.6 Component Type: Pass-Through

A pass-through component is a component that physically exists on the system but that only passes flow through itself without disruption. As such, it is does not change the energy flow of the network. Therefore, the main use for a pass-through component is in providing equipment to associate failure modes and fragility curves (discussed below) with. Since failure of the component results in a loss of a flow, it may be important to consider. Typical examples of pass-through components are aboveground and belowground power lines, natural gas pipe runs, district heating pipe runs, etc.

H.3.3.7 Component Type: Muxer

A "muxer" or multiplexer component represents various components for splitting and joining flows. Typical examples include manifolds, routers, electrical bus bars, and the like.

Muxers can have multiple inflow ports and multiple outflow ports. Muxers contain dispatch strategies to choose how requests are routed. There are two dispatch strategies available in the current tool:

- **In-order Dispatch:** All flow is requested to be satisfied from the first inflow port first. If that flow is insufficient, the second inflow port is requested for the remainder until all inflow ports are exhausted. For cases where outflow request is not met, the first outflow port is satisfied first. If flow remains, that flow is routed to the next port until it is satisfied or the flow is spent, and so on to the next port.
- **Distribute Dispatch:** All flow is distributed between all ports. In this strategy, requests are distributed evenly between inflow ports. When flow is insufficient to meet all outflow requests, available flow is distributed evenly to outflow ports.

These strategies are not sophisticated enough to cover advanced energy saving strategies. However, they should be sufficient to mimic basic dispatch strategies for assessing load supply.

H.3.3.8 Component Type: Mover

Note: the mover component is currently only available from the command-line interface. It has not yet been made available for the Excel® user interface.

A mover component is a component that moves energy from its inflow port to its outflow port with the assistance of a support flow. Movers can be used to represent chillers and heat pumps (which move heat) as well as pumps and fans (which move fluids).

H.3.4 Networks and Connections

Component connections via ports form a network. Networks describe the interaction of various flows.

A connection describes:

- A source component and its outflow port
- A sink (i.e., receiving) component and its inflow port
- And the type of flow being delivered

H.3.5 Scenarios

Scenarios represent both typical usage (i.e., blue sky events) and design basis threat events (class 4 hurricanes, earthquakes, landslides, etc.).

A scenario has:

- A duration (how long the scenario will last)
- An occurrence distribution which is a cumulative distribution function that expresses the likelihood of occurrence
- A maximum number of times the scenario can occur during the entire simulation (either *unlimited* or some finite number)
- Various damage intensities associated with the scenario

The damage intensities associated with a scenario are open-ended but are meant to represent numerical quantities that correspond with a fragility curve. Some examples of damage intensities that could be associated with a scenario are "wind speed," "inundation depth," "vibration," etc. Scenarios with no damage intensities are completely fine—these would represent "blue sky" scenarios (typical operation).

H.3.6 Reliability: Failure Modes and Statistical Distributions

Reliability is handled strictly as a statistical matter using failure modes. A failure mode is an associate between a failure cumulative distribution function and the corresponding repair cumulative distribution function. Multiple failure modes can be specified for a single component. For example, a diesel backup generator may have one failure mode associated with its starter battery and another to represent more serious issues with the generator itself.

Every failure mode in the simulation is turned into an "availability schedule." That is, for each failure mode, the dual cumulative distribution functions are alternatively sampled from time 0 to the end of the overall simulation time to derive a schedule of "available" and "failed." When a scenario where reliability is calculated is scheduled to occur, the relevant portion of the availability schedules for components with failure modes are used to "schedule" the component as available and failed to simulate routine reliability events during that scenario's simulation.

H.3.7 Resilience: Intensities (Damage Metrics) and Fragility Curves

Resilience reflects how components react to the intense stresses of a design basis threat event. Each scenario can specify an intensity or damage metric. Any component having a fragility curve that responds to one or more of the scenario intensities is evaluated for failure due to the scenario's intensity.

For example, aboveground power lines may have a fragility to wind speed. If a scenario specifies a wind speed of 150 mph (241 kph), the aboveground power line component will use its fragility curve to look up its chance of failure. For fragility, a component is evaluated for failure at scenario start and either passes (staying up during the scenario) or fails (going down for the entire scenario).

H.4 Input File Format

The simulation engine is a command-line program. Even when it is accessed via the Excel® user interface, a text-based input file is written to describe the network of components and scenarios to simulate.

The input file format is written using the TOML[7] input file language. TOML is a plain text input file format.

The file consists of the following sections that describe the various concepts described above:

- simulation_info: general simulation information.
- loads: load profiles (includes supply profiles for uncontrolled sources).
- components: all components in the network are described here.
- fragility: all fragility curves are described here.
- cdf: cumulative distribution functions.
- failure_mode: failure modes are described here.
- networks: networks are described here.
- scenarios: scenarios are described here.

Valid entries for each of the sections are described in Tables H.1, H.2, H.3, H.4, H.5, H.6, H.9, H.10, H.11, H.12, H.13, H.14, H.15, and H.16.

The types given are one of:

- str: a string of characters in "quotes"
- bool: true or false
- real: a real number (0.0, 1.5, 2e7, etc.)
- real>0: a real number greater than 0.0. 0.0< real >0
- int: an integer
- int>0: an integer > 0
- [*X*]: an array of the given type, *X*
- [[*X*]]: an array of arrays of *X*

[7] TOML is described in detail here: https://toml.io/en/

- time: time unit. One of {“years,” “days,” “hours,” “minutes,” “seconds”}
- cap: capacity unit. One of {“kJ,” “kWh”}
- disp: dispatch strategy. One of {“distribute,” “in_order”}
- frac: real fraction. 0.0≤ frac ≤1.0
- frac>0: real fraction greater than 0.0. 0.0< frac ≤1.0
- rate: the rate unit. Currently, only “kW” is accepted
- $X \to Y$: designates a map data structure (a.k.a., dictionary, hash table, table, etc.). Associates Y with X

In the TOML input file, all constructs except simulation_info have an id. The id is used when one construct references another.

This looks as follows:

```
[loads.load_id_1]
...
[loads.load_id_2]
...
[components.comp_id_1]
...
[components.comp_id_2]
...
[fragility.fragility_id_1]
...
[cdf.cdf_id_1]
...
[failure_mode.fm_id_1]
...
[networks.nw_id_1]
...
[scenarios.scen_id_1]
...
```

An id must follow the rules of TOML “bare keys”[8] with the exception that dashes (-) are not allowed and the key must start with an ASCII letter:

Bare keys may only contain ASCII letters, ASCII digits, underscores,….

Note: Table H.1 specifies various random values. At most, one of these values can be specified

Table H.1 simulation_info specification

Key	Type	Required?	Notes
time_unit	Time	No	The time unit. Default “years”
fixed_random	Frac	No	Sets the random roll to a fixed value
fixed_random_series	[real]	No	Sets random numbers to the given series
random_seed	Real	No	Sets the random number generator’s seed
max_time	Int	No	Maximum simulation time. Default: 1000

[8] See https://toml.io/en/v1.0.0-rc.1#keys

For Table H.2, one must specify either a csv_file *or* time_rate_pairs, time_unit, and rate_unit. Unfortunately, only “kW” is available for rate_unit at the moment although time_unit accepts “years,” “seconds,” or “hours.” Practically speaking, you will almost always use a csv_file unless you just want to test a simple load.

For the csv_file, the header must be “hours,kW” with data filled into the rows below. The “hours” column is the elapsed time in hours. The “kW” column is the flow in kW. The first column header can be set to values beside “hours”; any time unit is valid. However, the rate unit is currently locked in as “kW.”

Table H.3 lists the attributes common to all components. These relate to reliability and resilience: failure modes and fragility curves (Table H.4).

In Table H.5, the loads_by_scenario structure is specified as follows (Table H.6):

```
loads_by_scenario.scenario_id_1 = “load_id_1”
loads_by_scenario.scenario_id_2 = “load_id_2”
```

During simulation, the max_inflow sets the requested charging rate for a storage unit (see Table H.7). By default, a storage unit will always request to charge itself to its maximum capacity. However, it will always honor its discharge request above its

Table H.2 Loads specification

Key	Type	Required?	Notes
csv_file	str	No	Path to comma-separated values (CSV) file with profile
time_rate_pairs	[[real]]	No	Array of (time, rate) pairs
time_unit	time	No	Time unit for time_rate_pairs
rate_unit	rate	No	Rate unit for time_rate_pairs

Table H.3 Components: common attributes

Key	Type	Required?	Notes
failure_modes	[str]	No	Failure mode ids for component
fragilities	[str]	No	Fragility curve ids for component

Table H.4 Components: source component

Key	Type	Required?	Notes
Type	str	Yes	Must be “source”
Outflow	str	Yes	Type of outflow
max_outflow	real	No	Maximum allowable outflow

Table H.5 Components: load component

Key	Type	Required?	Notes
Type	str	Yes	Must be “load”
Inflow	str	Yes	Type of outflow
loads_by_scenario	str → str	Yes	Map of scenario id to load id

charge request. That is, if discharge is requested, it will discharge rather than charge. If charging and discharging at the same time, charge flow will "short circuit" to meet the discharge request first. Any flow left over will charge the store.

In Table H.8, the dispatch_strategy refers to the strategy at the outflow of the muxer. The inflow strategy is always "in_order." That is, the first connected port gets the full request. If that inflow port cannot meet the full flow, we request the remaining flow from the second inflow port, etc. The outflow strategy is set in the model input file using the dispatch_strategy key as shown in Table H.8.

The dispatch_strategy for a muxer only manifests when there is a flow deficiency. That is, normally, all requests at each outflow port are achieved. However, when there is not enough flow, "in_order" dispatch feeds the first outflow port first and then turns its attention to the second and so on until flow runs out. For a "distribute" dispatch_strategy, when flow is lacking, the available flow is distributed evenly.

Let's consider an example. A muxer with four outflow ports gets the following request: [50, 50, 50, 50] (= 200 kW). However, only 100 kW is available to supply these outflow requests. An "in_order" dispatch will provide [50, 50, 0, 0] (= 100 kW) to its four outflow ports. In contrast, a "distribute" dispatch_strategy will provide [25, 25, 25, 25] (= 100 kW) to each outflow port. Consider a nonuniform request of say [50, 10, 90, 50] (= 200 kW) on the same mux; again, however, only

Table H.6 Components: converter component

Key	Type	Required?	Notes
Type	str	Yes	Must be "converter"
Inflow	str	Yes	Type of inflow
outflow	str	Yes	Type of outflow
lossflow	str	No	Type of loss flow. Default: inflow
constant_efficiency	frac>0	Yes	Constant efficiency

Table H.7 Components: storage component

Key	Type	Required?	Notes
Type	str	Yes	Must be "store"
Flow	str	Yes	Type of flow (inflow, outflow, stored)
capacity_unit	cap	No	Capacity unit. Default: "kJ"
capacity	real	Yes	Capacity of the store
max_inflow	real	Yes	Maximum inflow (charge rate)

Table H.8 Components: muxer component

Key	Type	Required?	Notes
Type	str	Yes	Must be "muxer"
Flow	str	Yes	Type of flow (inflow, outflow)
num_inflows	int	Yes	The number of inflow ports
num_outflows	int	Yes	The number of outflow ports
dispatch_strategy	disp	No	Dispatch strategy. Default: "in_order"

100 kW is available. An “in_order” dispatch would provide [50, 10, 40, 0] (= 100 kW). In contrast, a “distribute” dispatch strategy would provide [30, 10, 30, 30] (= 100 kW) to each outflow port (Tables H.9 and H.10).

Similar to the load component, the uncontrolled source’s supply_by_scenario specifies supply profiles by scenario. These look like the following:

```
supply_by_scenario.scenario_id_1 = "load_id_1"
supply_by_scenario.scenario_id_2 = "load_id_2"
```

Note that the uncontrolled source supply profiles are also drawn from the same section of the input file specified as loads.

In Table H.11, the cop field ties together the three flows inflow0, inflow1, and outflow using the following relations:

$$cop = \frac{inflow_0}{inflow_1} \tag{H.1}$$

$$inflow_0 = cop \times inflow_1 \tag{H.2}$$

$$inflow_1 = inflow_0 \times \frac{1}{cop} \tag{H.3}$$

$$outflow = (1 + cop) \times inflow_1 = \left(1 + \frac{1}{cop}\right) \times inflow_0 = inflow_0 + inflow_1 \tag{H.4}$$

Table H.9 Components: pass-through component

Key	Type	Required?	Notes
Type	str	Yes	Must be “pass_through”
Flow	str	Yes	Type of flow (inflow, outflow)

Table H.10 Components: uncontrolled source component

Key	Type	Required?	Notes
Type	str	Yes	Must be “uncontrolled_source”
outflow	str	Yes	Type of outflow
supply_by_scenario	str → str	Yes	Scenario id to load profile id

Table H.11 Components: mover component

Key	Type	Required?	Notes
Type	str	Yes	Must be “mover”
inflow0	str	Yes	The inflow being “moved”
inflow1	str	Yes	The “support” inflow that enables “moving” to occur
outflow	str	Yes	The outflow
COP	real>0	Yes	The coefficient of performance

Fragility curves are specified using the attributes listed in Table H.12. Figure H.1 shows a graphical representation of the data specification.

A fragility curve maps a scenario's intensity (i.e., damage metric) to a probability of failure. We must specify which damage metric is of interest and also the curve relationship. Currently, the only available fragility curve type is linear. For the linear curve, we specify the lower_bound, the bound below which we are impervious to destruction. We also specify the upper_bound, the bound above which we face certain destruction.

Table H.13 specifies a cumulative distribution function. At this time, the only distribution type available is "fixed." A fixed distribution is a degenerate distribution that always samples a single point—the value (Tables H.14 and H.15).

Table H.12 Fragility specification

Key	Type	Required?	Notes
vulnerable_to	str	Yes	The scenario intensity (i.e., damage metric) vulnerable to
Type	str	Yes	Must be "linear"
lower_bound	real	Yes	The value below which we are impervious to damage
upper_bound	real	Yes	The value above which we face certain destruction

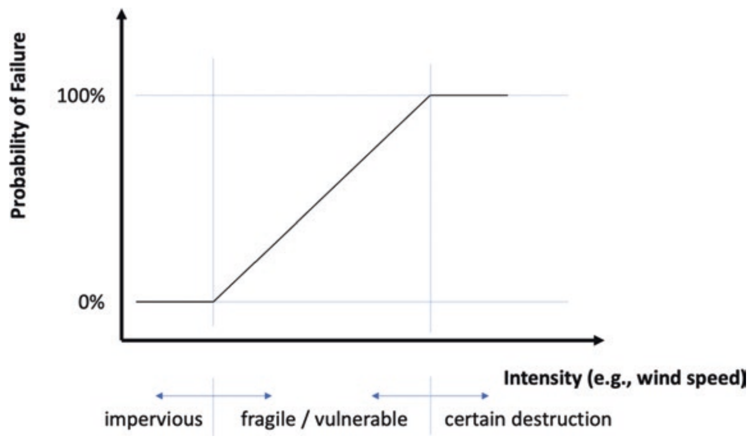

Fig. H.1 Fragility curve

Table H.13 cdf specification

Key	Type	Required?	Notes
Type	str	Yes	Must be "linear"
Value	real	Yes	The value of the fixed CDF
time_unit	time	Yes	The time unit used to specify the fixed value

The networks data definition involves a "mini-language" to specify connections. The language is as follows:

```
connections = [
  [ "src_comp_id:OUT(outflow_port)," "sink_comp_id:IN(inflow_port),"
"flow"],
...
  ]
```

The connections key is an array of 3-tuples. The first element of the 3-tuple is the source component id separated by a ":" and then the word "OUT(.)." You will type the outflow port in place of the ".". Note that numbering starts from 0.

The second element of the 3-tuple is the sink component id, that is, the component that *receives* the flow. The sink component id is written, then a ":," and finally the word "IN(.)." You will type the inflow port id in place of the. "." Numbering of inflow ports starts from 0.

The final element of the 3-tuple is the flow id. You are requested to write the flow id as a check that ports are not being wired incorrectly.

In Table H.16, the occurrence_distribution is currently implemented as a literal table:

Table H.14 failure_mode specification

Key	Type	Required?	Notes
failure_cdf	str	Yes	The failure CDF id
repair_cdf	str	Yes	The repair CDF id

Table H.15 Networks specification

Key	Type	Required?	Notes
connections	[[str]]	Yes	The connections

Table H.16 Scenarios specification

Key	Type	Required?	Notes
time_unit	time	No	Time units for scenario. Default: "hours"
occurrence_distribution	table	Yes	See notes in text
duration	int>0	Yes	The duration of the scenario
max_occurrences	int	Yes	The maximum number of occurrences. -1 means unlimited
calculate_reliability	bool	No	Whether to calculate reliability. Default: false
network	str	Yes	The id of the network to use
intensity	str → real	No	Specify intensity (damage metric) values

```
  occurrence_distribution = { type = "linear," value = 8, time_unit =
"hours" }
```

The possible values for the occurrence_distribution table are given in Table H.13.

H.5 Output Metrics

The metrics used to assess resilience are given an overview in this section. Figure H.2 depicts the metrics graphically. It is important to note that metrics are calculated *by load* and *per scenario*.

As seen in Fig. H.2, there are three basic calculations:

- Energy availability
- Load not served
- Max downtime

Figure H.2 shows four areas of flow integration over time: A, B, C, and D. The sum of A, B, and D is the energy delivered to this load for this scenario. C represents the load not served. The ratio of $\frac{(A+B+D)\times 100\%}{A+B+C+D}$ is the energy availability. The duration of load interruption (from t_0 to t_1) is the max downtime.

The energy availability is calculated as follows:

$$EA = \frac{E_{\text{achieved}} \times 100\%}{E_{\text{requested}}} \tag{H.5}$$

In Eq. H.5, the energy, E, is the integral of the flow, f, over time:

$$E = \int_{t=0}^{t_{\text{end}}} f \cdot dt \tag{H.6}$$

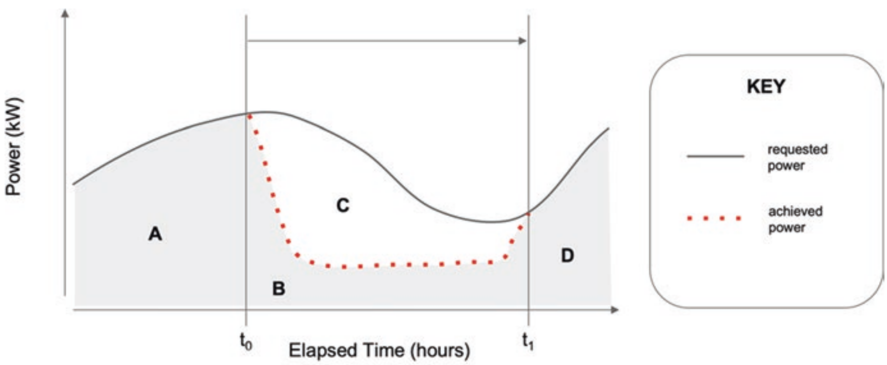

Fig. H.2 Resilience and energy metrics

Max downtime is the duration of load interruption:

$$T_{\text{down}} = \int dt \text{ where } f_{\text{achieved}} < f_{\text{requested}} \tag{H.7}$$

Load not served is then:

$$E_{\text{not served}} = \int_{t=0}^{t_{end}} \left(f_{\text{requested}} - f_{\text{achieved}} \right) \cdot dt \tag{H.8}$$

H.6 Command-Line Tool

Three command-line programs are available for simulation and assistance. They will be given an overview here.

H.6.1 e2rin

Simulates a single scenario and generates results

Usage:

```
e2rin <input_file_path> <output_file_path> <stats_file_path> <scenario_id>
```

- input_file_path: path to TOML input file
- output_file_path: path to CSV output file for time series data
- stats_file_path: path to CSV output file for statistics
- scenario_id: the id of the scenario to run

The output from the call to e2rin will be written into two files: an output file and a statistics file.

The output file has the column headers shown in Table H.17.

The statistics file has the column headers shown in Table H.18.

H.6.2 e2rin_multi

Simulates all scenarios in the input file over the simulation time and generates results.

Usage:

```
e2rin_multi <input_file_path> <output_file_path> <stats_file_path>
```

Table H.17 e2rin output

Column	Description
Time (hours)	The elapsed time since scenario start in hours
*:achieved (kW)	The achieved flow at the event time for each component/port recorded
*:requested (kW)	The requested flow at the event time for each component/port recorded

Table H.18 e2rin statistics

Column	Description
Component id	The id of the component
Type	The type of the component (e.g., load, source, etc.)
Stream	The stream flowing through the given component/port
Energy availability	The energy availability for the given component
Max downtime (hours)	The maximum number of contiguous hours when load not fully met
Load not served (kJ)	The load not served in kJ
X energy used (kJ)	For each flow, report out the energy used in kJ
Total (*X*)	The total energy used by flow by component type
Energy balance	A sum of the energy balance. Should be 0

Table H.19 e2rin_multi output

Column	Description
Scenario id	The id of the scenario simulated
Scenario start time	Start time of scenario in ISO 8601 (ISO 2019) duration format
Elapsed (hours)	The elapsed time since scenario start in hours
*:achieved (kW)	The achieved flow at the event time for each component/port recorded
*:requested (kW)	The requested flow at the event time for each component/port recorded

- input_file_path: path to TOML input file
- output_file_path: path to CSV output file for time series data
- stats_file_path: path to CSV output file for statistics

The output files from e2rin_multi are very similar to those shown in Tables H.17 and H.18. The main difference is that e2rin_multi aggregates across multiple scenario instances and multiple scenario types. The column headers used in the event output file for e2rin_multi are shown in Table H.19.

The statistics file for e2rin_multi has the column headers as shown in Table H.20.

Table H.20 e2rin_multi statistics

Column	Description
Scenario id	Scenario id for the scenario reported out
Number of occurrences	Number of times the scenario occurred during simulation
Total time in scenario (hours)	Total time spent in the scenario during simulation
Component id	The id of the component
Type	The type of the component (e.g., load, source, etc.)
Stream	The stream flowing through the given component/port
Energy availability	The energy availability for the given component
Max downtime (hours)	The maximum number of contiguous hours when load not fully met
Load not served (kJ)	The load not served in kJ
X energy used (kJ)	For each flow, report out the energy used in kJ
Total (*X*)	The total energy used by flow by component type
Energy balance	A sum of the energy balance. Should be 0

H.6.3 e2rin_graph

Generates an input file for use with Graphviz. Graphviz is an external dependency. You do not need Graphviz to generate the Graphviz input file. However, you *do* need Graphviz to process that input file into a.png or.pdf file.

Usage:

```
e2rin_graph <input_file_path><dot_file_path><network_id>
```

- input_file_path: path to TOML input file
- dot_file_path: path to Graphviz DOT file to write
- network_id: id for the network to plot from input_file_path

Upon successful execution, you can render your Graphviz dot file into a *.png (image file) as follows:

- dot -Tpng input.gv -o output.png. The above generates a png (-Tpng) from the input.gv and saves to output.png (-o).

Similarly, you can render your Graphviz dot file into a PDF as follows:

- dot -Tpdf input.gv -o output.pdf. The above generates a png (-Tpdf) from the input.gv and saves to output.pdf (-o).

e2rin_graph is capable of creating sophisticated topological graphs such as the one in Fig. H.3.

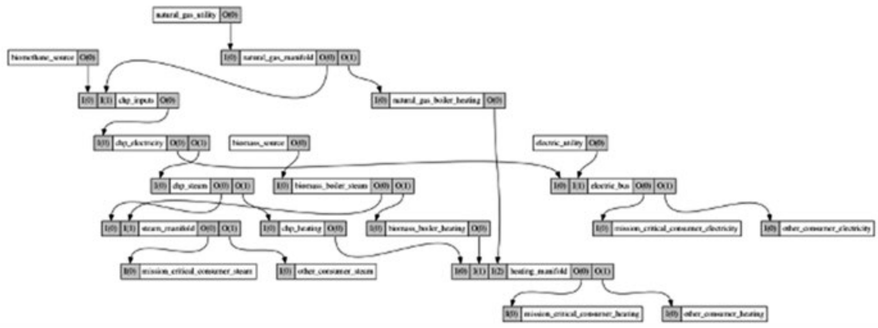

Fig. H.3 Topology example of a network rendered with Graphviz and e2rin_graph

H.7 Microsoft Excel® User Interface

A simple interface using Microsoft Excel® has been created to ease the creation of an input data file for e2rin. This interface runs the simulation on behalf of the user and also pulls the input. Due to limitations in Excel's Visual Basic, the current version of the Microsoft Excel® user interface is limited to the Windows Operating System.

H.7.1 Software Dependency: Modelkit/Params Framework

Modelkit/Params is required to allow the Microsoft Excel® user interface to render an input file template for e2rin_multi. *Modelkit/Params* is a third-party dependency available as open-source software from Big Ladder Software:

https://bigladdersoftware.com/projects/modelkit/.
Please install *Modelkit Catalyst*. Version 0.5 or later is required.
Further detail about *Modelkit* can be found at the above link.

H.7.2 Additional Concept: Location

To make it easier for modelers to specify a network of components, the Excel® user interface introduces an additional concept called a "location." A location is open-ended although the names and ids must follow the same rules for ids as in the input file (see Sect. H.4).

At a given location, any number of components can be specified. The Excel® user interface uses Big Ladder's *Modelkit/Params* to render an input file from a template. That template assumes a given topology for each location as shown in Fig. H.4.

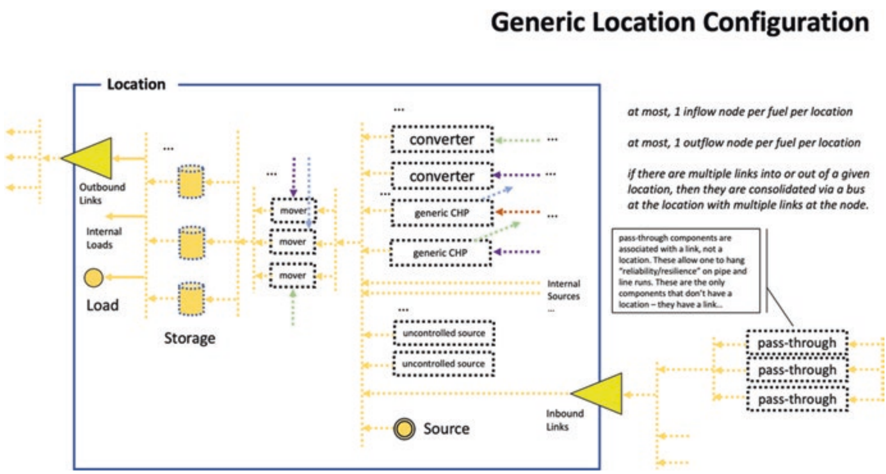

Fig. H.4 Topology at a location

As depicted in Fig. H.4, for any given flow type, the following sets of components are in series:

- All loads: load components, internal loads, and outbound links.
- All storage for the given flow type (multiples are in parallel).
- All mover components: multiples are in parallel.
- All converters and sources: converters (including CHP which is modeled as chained converters), internal sources, uncontrolled sources, inbound links, and normal source components.

H.7.3 Additional Concept: Network Link

The location topology template shown in Fig. H.4 alludes to inbound and outbound links. The links themselves are called "network links." They are similar to normal connections except that they connect locations.

We believe the template in Fig. H.4 to be typical of how components at a location are typically connected, topologically speaking. However, if further variation is needed, it can often be achieved by creating multiple locations and linking them together. For example, if one wanted to model two storage units in *series* (vs. *parallel*), they need only to create a storage in location *A* and another in location *B* and denote that location *B* has a network link from *B* to *A*.

H.7.4 Interface Overview

The Excel® user interface to e2rin_multi is laid out logically to help new users specify a component network to simulate.

The major screens are:

- Instructions (see Fig. H.5)
- Settings (see Fig. H.6)
- Components (see Fig. H.7)
- Network (see Fig. H.8)
- Scenarios (see Fig. H.9).

The "Instructions" sheet gives light instructions on how to use the workbook. The "Settings" tab is where the path to e2rin_multi.exe is set. A modeler can also add additional statistical distributions, failure modes, and fragility curves here. The "Components" tab is where a modeler can add different types of components to a location. The "Network" tab is where network links between locations can be specified. The "Scenarios" tab is where different Scenarios can be added and configured.

H.8 Example Problem

In this final section, we will specify a simple problem using both the input file and the Excel® user interface. The problem will involve a single building with an electrical load, an electric generator onsite, and a utility supply of natural gas. We will simulate two scenarios: a blue sky scenario and a class 4 hurricane scenario.

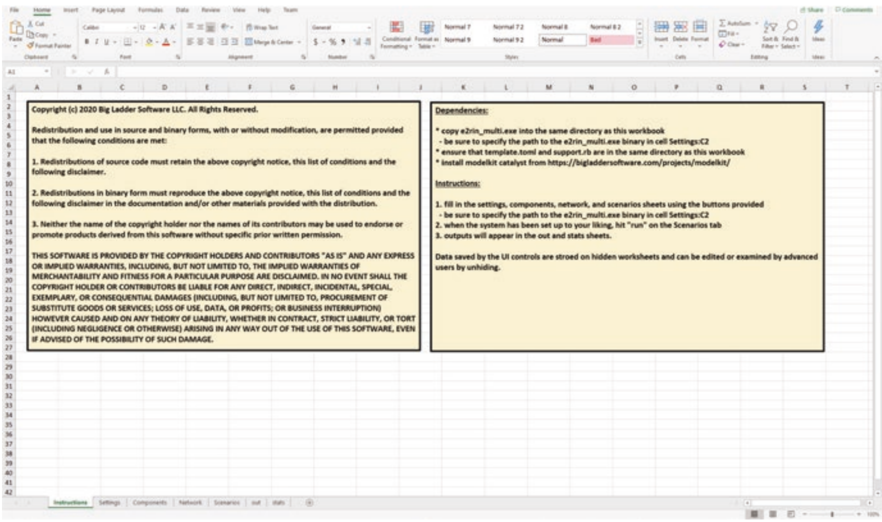

Fig. H.5 Excel® interface: Instructions sheet

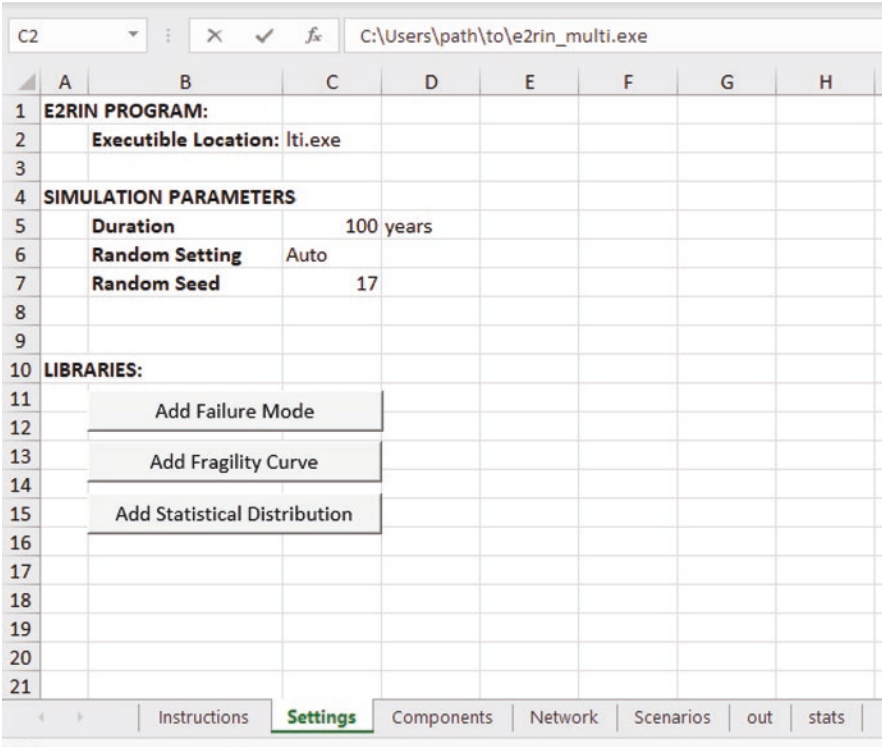

Fig. H.6 Excel® interface: Settings sheet

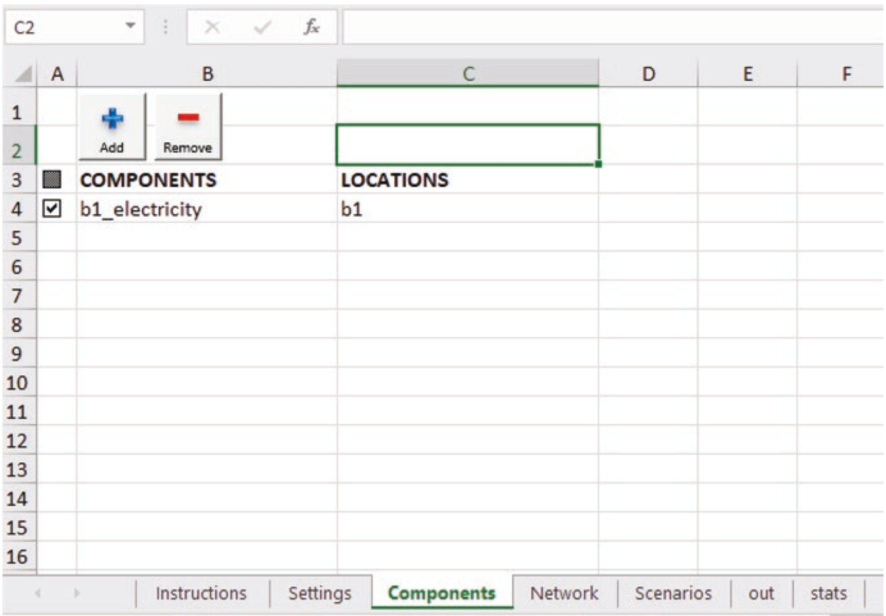

Fig. H.7 Excel® interface: Components sheet

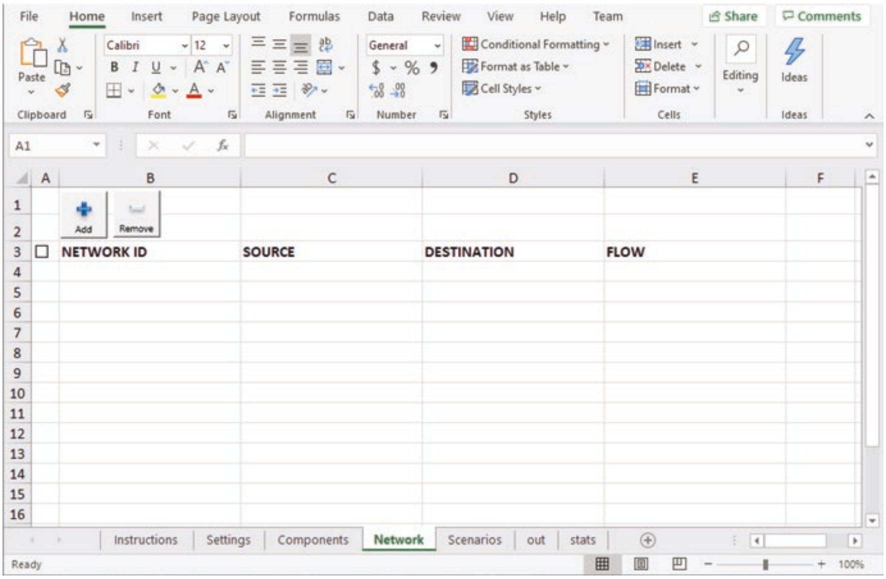

Fig. H.8 Excel® interface: Network sheet

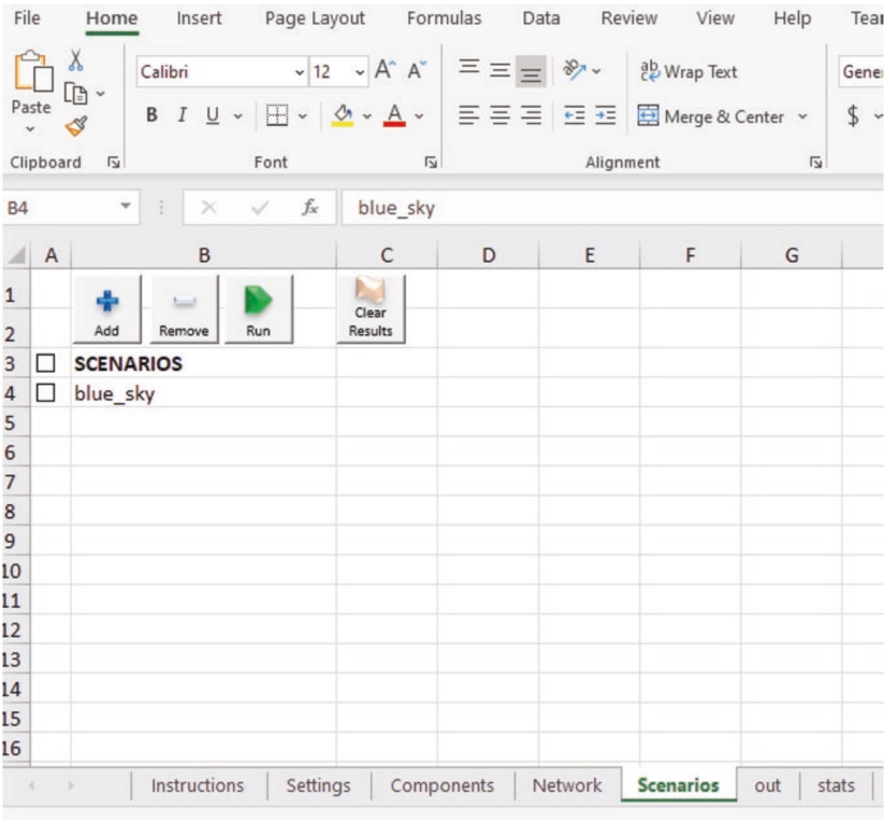

Fig. H.9 Excel® interface: Scenario sheet

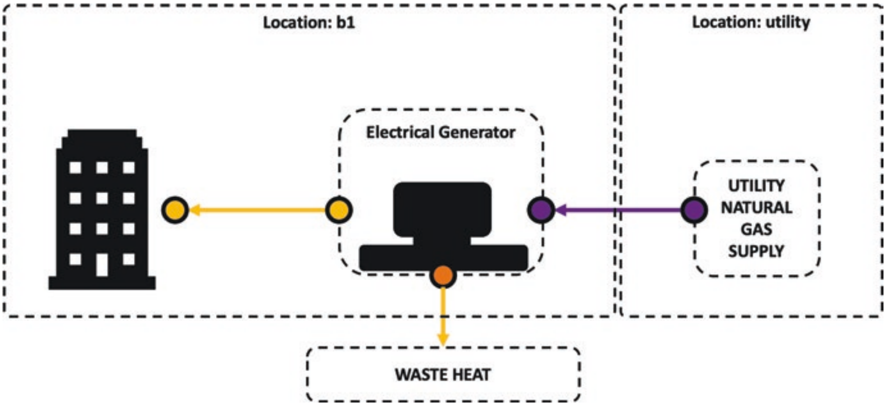

Fig. H.10 Example network

An iconic sketch of the network we will build appears in Fig. H.10.
The steps to create this network and simulate it are as follows:

H.8.1 Text Input File

1. Open a new file input.toml for editing using your favorite text editor. Add the following simulation information:

```
[simulation_info]
rate_unit="kW"
quantity_unit="kJ"
time_unit="years"
max_time=100
```

2. Create a simple load profile by hand. Open the file b1-load-profile.csv in your favorite text editor. Type in the following and save:

```
hours,kW
0,100
8760,0
```

3. Back in input.toml, add the load profile information at the end of the file:

```
[loads.lp1]
csv_file="b1-load-profile.csv"
```

4. Next, still within input.toml, let's add the components:

```
[components.utility_ng_source]
type="source"
outflow="natural_gas"

[components.b1_electricity]
type="load"
inflow="electricity"
loads_by_scenario.blue_sky="lp1"
loads_by_scenario.c4_hurricane="lp1"

[components.b1_electric_generator]
type="converter"
inflow="natural_gas"
outflow="electricity"
lossflow="waste_heat"
constant_efficiency=0.42
fragilities=["flooding,""wind"]
```

In the table above, we have added a natural gas source (utility_ng_source), an electrical load at building 1 (b1_electricity), and an electrical generator at building 1 (b1_electric_generator). The electric generator has an efficiency of 42% and has two fragilities: "flooding" and "wind." Neither of the fragilities have been specified yet, so we'll tackle them next.

5. Within input.toml, specify the fragility curves.

```
[fragility.flooding]
vulnerable_to="inundation_depth_ft"
type="linear"
lower_bound=4.0
upper_bound=8.0

[fragility.wind]
vulnerable_to="wind_speed_mph"
type="linear"
lower_bound=150.0
upper_bound=220.0
```

These fragility curves reflect the specific situation of the equipment versus the threat.

6. Specify the network connections.

```
[networks.nw]
connections=[
[“utility_ng_source:OUT(0),”“b1_electric_generator:IN(0),”“natural_ga
s”],
[“b1_electric_generator:OUT(0),”“b1_electricity:IN(0),”“electricity”]
,
]
```

7. Specify the scenarios.

```
[scenarios.blue_sky]
time_unit=“hours”
occurrence_distribution={type =“linear,”value =0, time_unit=“hours”}
duration=8760
max_occurrences=1
calculate_reliability=true
network=“nw”
[scenarios.c4_hurricane]
time_unit=“days”
occurrence_distribution={type =“linear,”value =30, time_unit=“years”}
duration=14
max_occurrences=-1
calculate_reliability=true
network=“nw”
intensity.wind_speed_mph=155.0
intensity.inundation_depth_ft=6.0
```

The finished file should look like the following:

```
[simulation_info]
rate_unit="kW"
quantity_unit="kJ"
time_unit="years"
max_time=100

[loads.lp1]
csv_file="b1-load-profile.csv"

[components.utility_ng_source]
type="source"
outflow="natural_gas"

[components.b1_electricity]
type="load"
inflow="electricity"
loads_by_scenario.blue_sky="lp1"
loads_by_scenario.c4_hurricane="lp1"

[components.b1_electric_generator]
type="converter"
inflow="natural_gas"
outflow="electricity"
lossflow="waste_heat"
constant_efficiency=0.42
fragilities=["flooding,""wind"]

[fragility.flooding]
vulnerable_to="inundation_depth_ft"
type="linear"
lower_bound=4.0
upper_bound=8.0

[fragility.wind]
vulnerable_to="wind_speed_mph"
type="linear"
lower_bound=150.0
upper_bound=220.0

[networks.nw]
connections=[
["utility_ng_source:OUT(0),""b1_electric_generator:IN(0),""natural_gas"],
["b1_electric_generator:OUT(0),""b1_electricity:IN(0),""electricity"],
]

[scenarios.blue_sky]
time_unit="hours"
occurrence_distribution={type ="fixed,"value =0, time_unit="hours"}
duration=8760
max_occurrences=1
network="nw"

[scenarios.c4_hurricane]

time_unit="days"
occurrence_distribution={type ="fixed,"value =30, time_unit="years"}
duration=14
max_occurrences=-1
network="nw"
intensity.wind_speed_mph=155.0
intensity.inundation_depth_ft=6.0
```

The file can be called as e2rin_multi.exe input.toml out.csv stats.csv. This assumes that e2rin_multi.exe is on your path.

H.8.2 Excel User Interface

Using the Excel® interface, we will create the same problem specified in Fig. H.11.

1. Open the workbook and ensure the path to e2rin_multi.exe is set. See Fig. G.6. Also, ensure you have the four required files in one directory as shown in Fig. H.11.

- e2rin_gui.xlsm
- e2rin_multi.exe
- support.rb
- template.toml.

An easy way to get the path to e2rin_multi.exe is to find it in the file system and, while holding the SHIFT key, right click on the file and select "Copy as Path" as shown in Fig. H.12. The value so copied can be pasted into the cell with the path in the Settings sheet. Be sure to save the workbook once you have set the path.

2. We will start by adding two fragility curves. See Figs. H.13 and H.14.

   We'll call the first fragility curve "wind" and set the "Vulnerable To" field to "wind_speed_mph" with a range from 150 to 220 mph (241 to 354 kph). The second fragility curve we'll call "flooding" and set the "Vulnerable To" field to "inundation_depth_ft" with bounds of 4.0–8.0 ft (13–26 ft).

3. Next we'll begin filling in the components as shown in Figs. H.15, H.16, H.17, H.18, H.19, H.20, H.21, H.22, and H.23.
4. With all the components added, move on to the "Network" sheet. We must add a network link between the "utility" location and the "b1" (building #1) location as shown in Figs. H.24 and H.25.
5. Finally, add the scenarios and intensity values as shown in Figs. H.26, H.27, H.28, H.29, H.30, H.31, H.32, H.33, and H.34.
6. Finally, hit the run button to simulate the network.

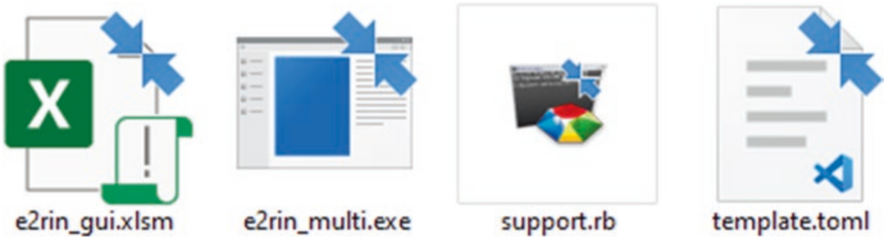

Fig. H.11 Required files to run the Excel® UI

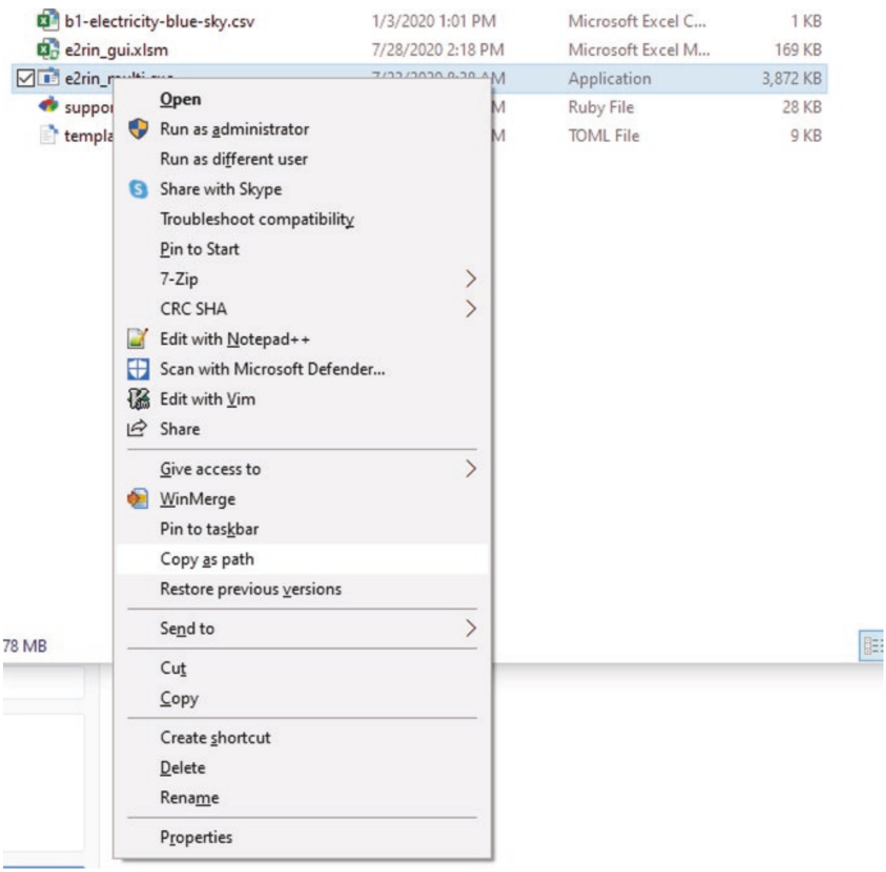

Fig. H.12 Easy way to copy the path to e2rin_multi.exe

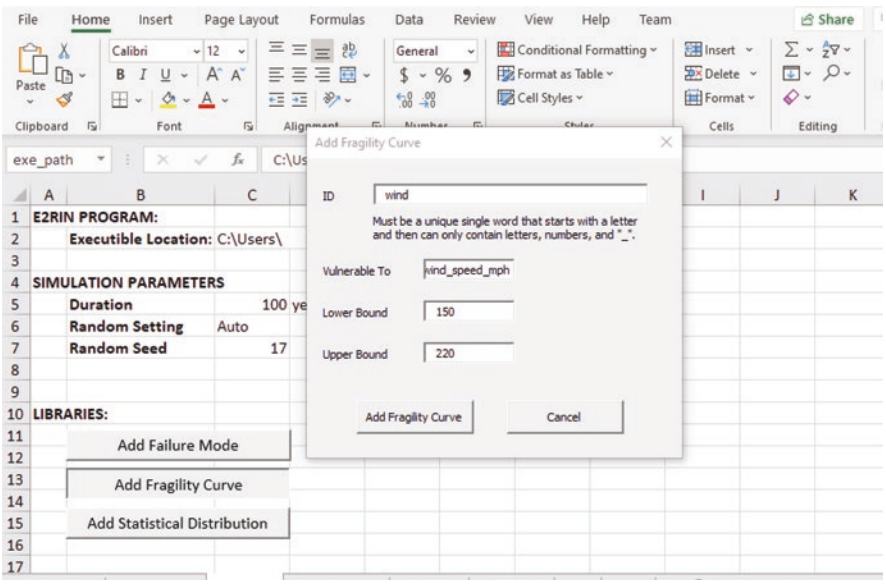

Fig. H.13 Add Fragility Curve #1

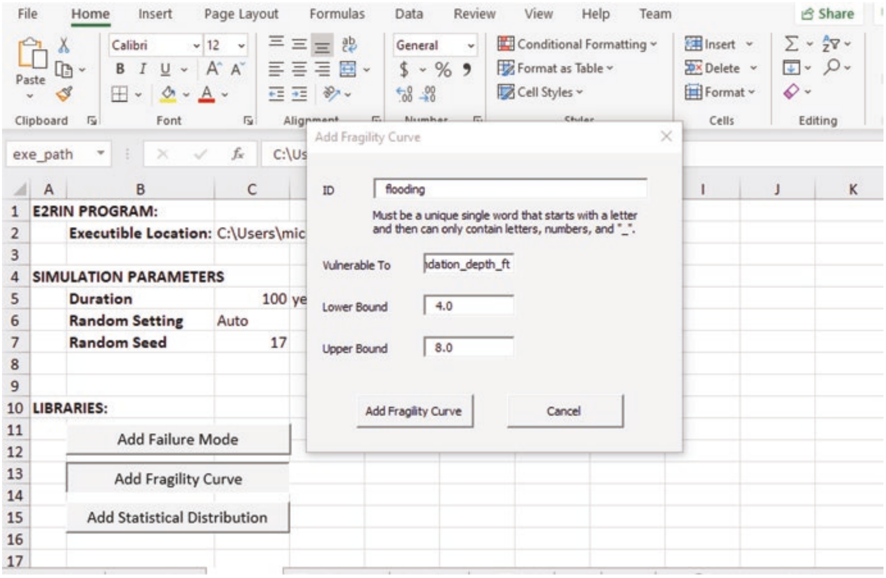

Fig. H.14 Add Fragility Curve #2

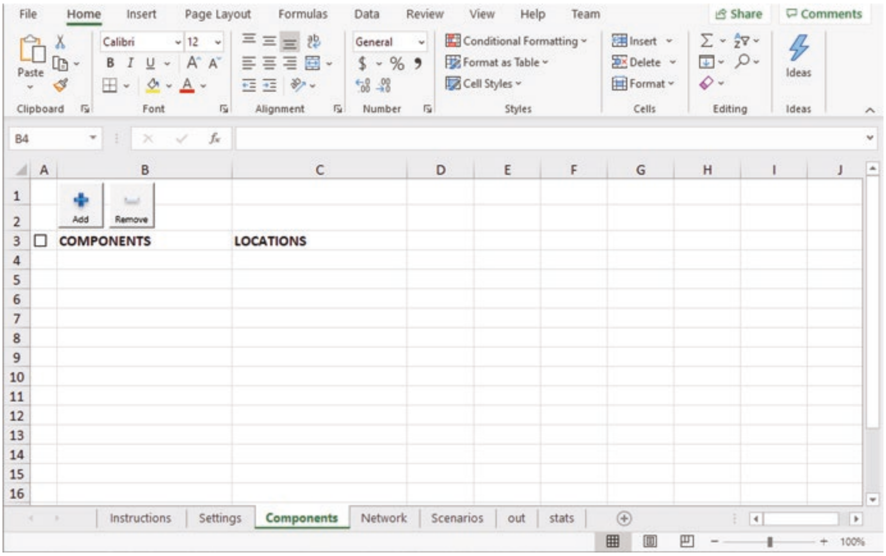

Fig. H.15 Add components

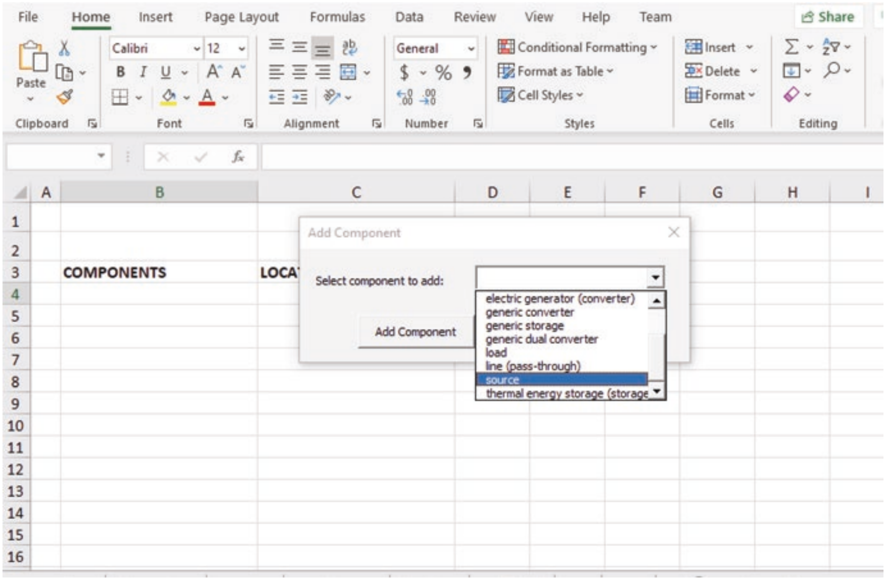

Fig. H.16 Add source components

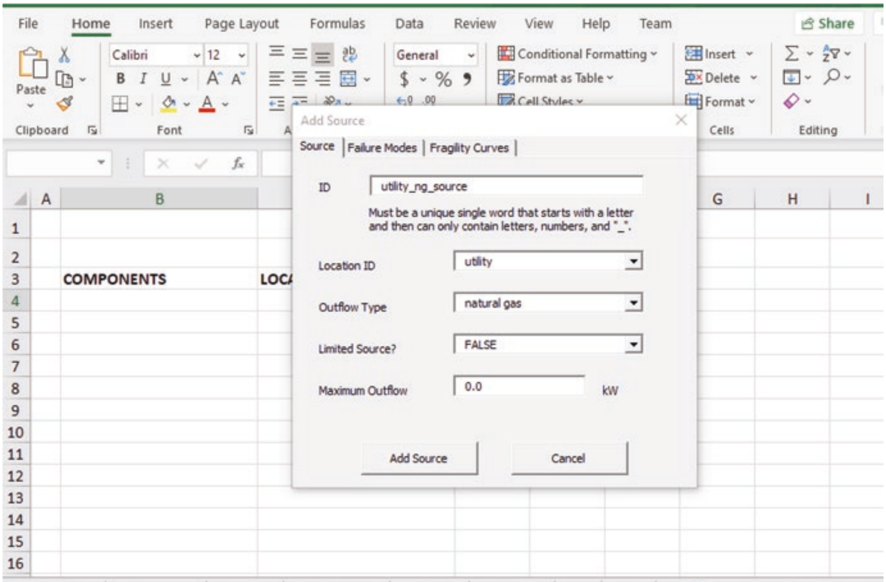

Fig. H.17 Add source component dialogue

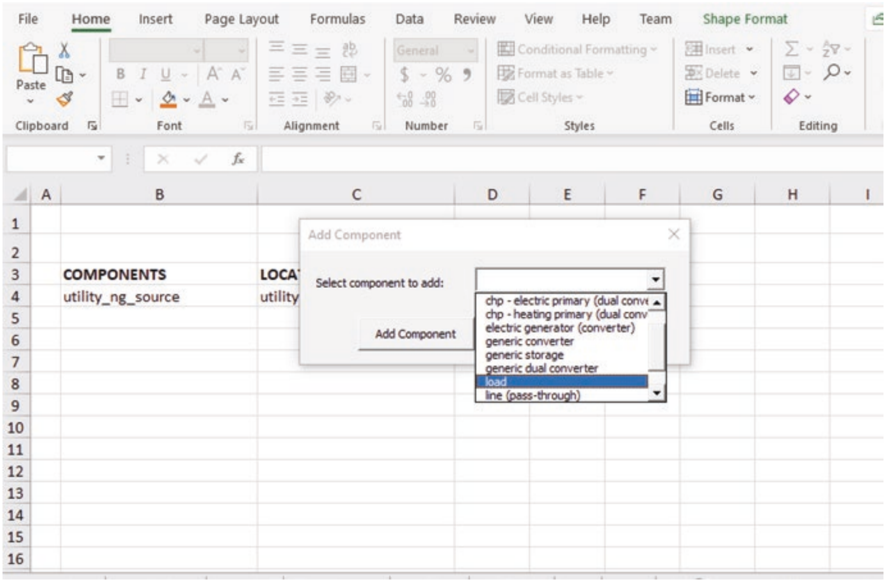

Fig. H.18 Add load component

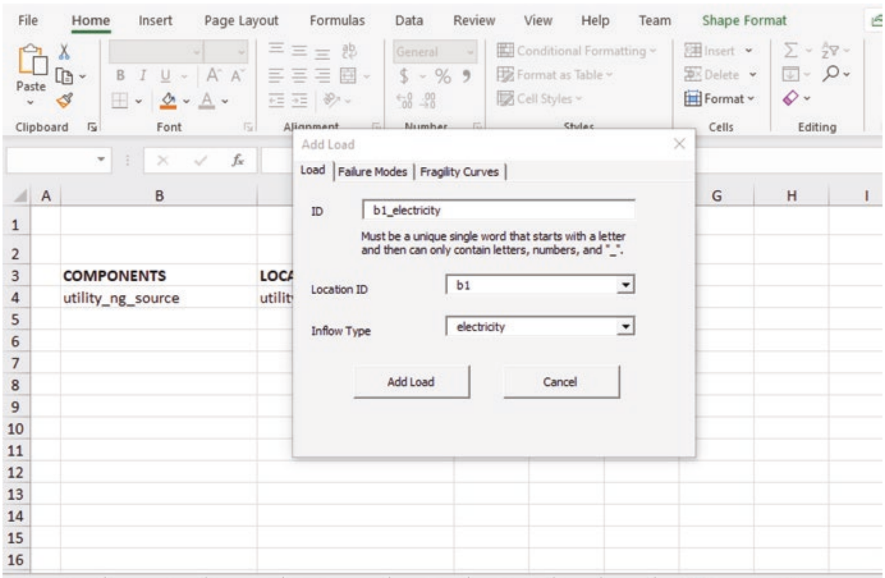

Fig. H.19 Add load component dialogue

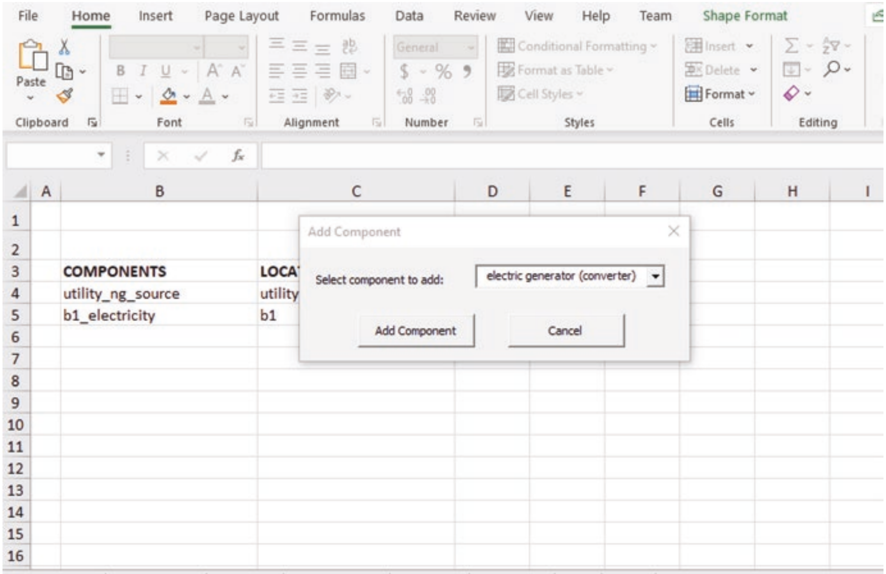

Fig. H.20 Add converter component

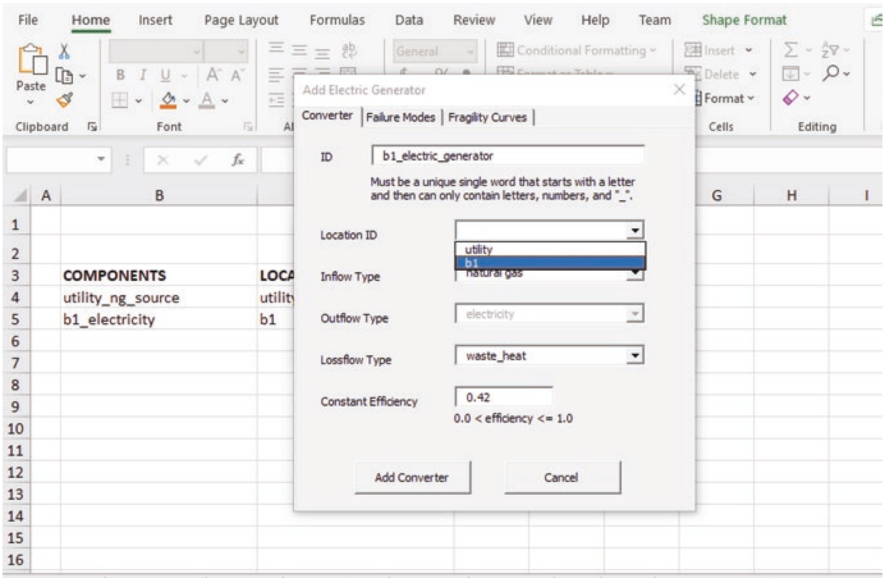

Fig. H.21 Add converter component dialogue

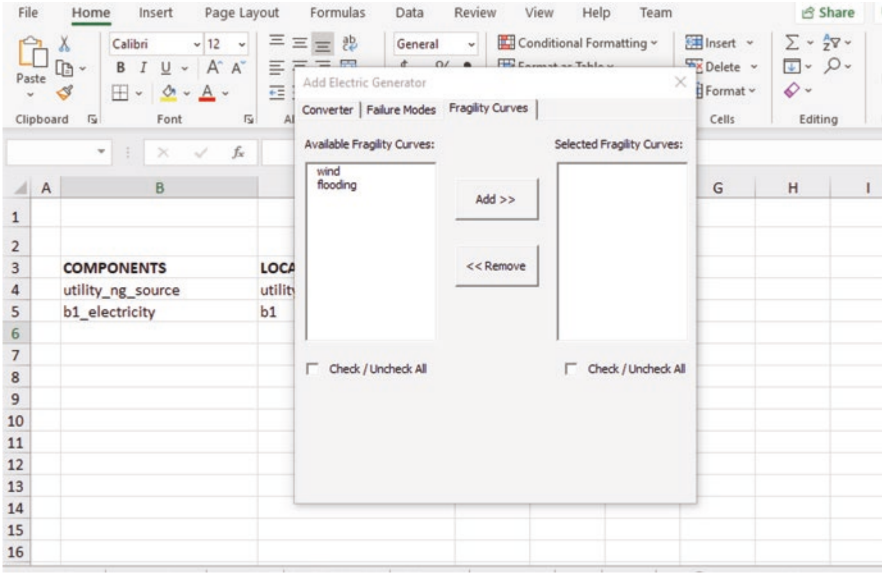

Fig. H.22 Add fragility curves to converter components

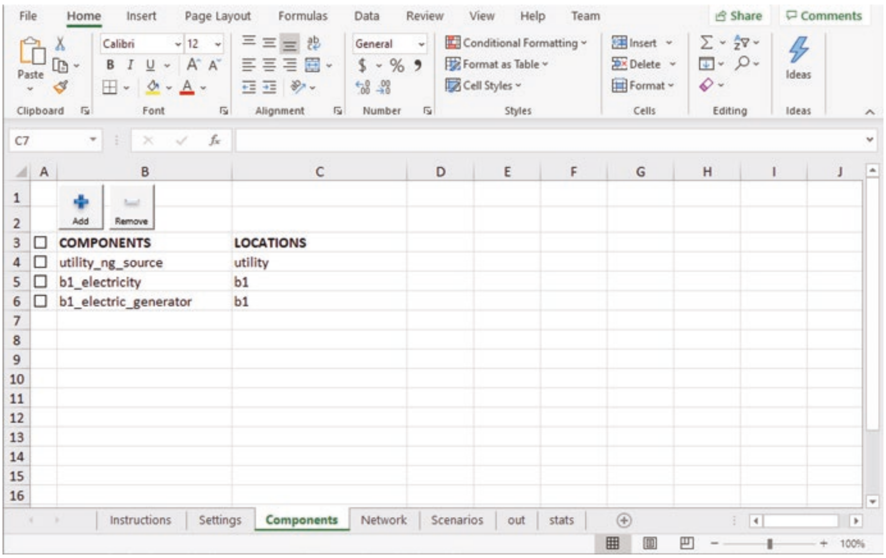

Fig. H.23 All components added

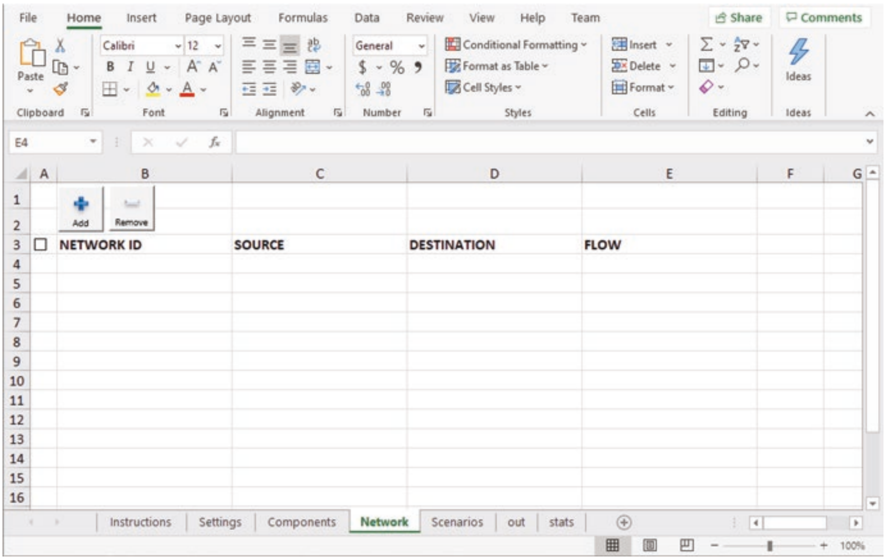

Fig. H.24 The network tab

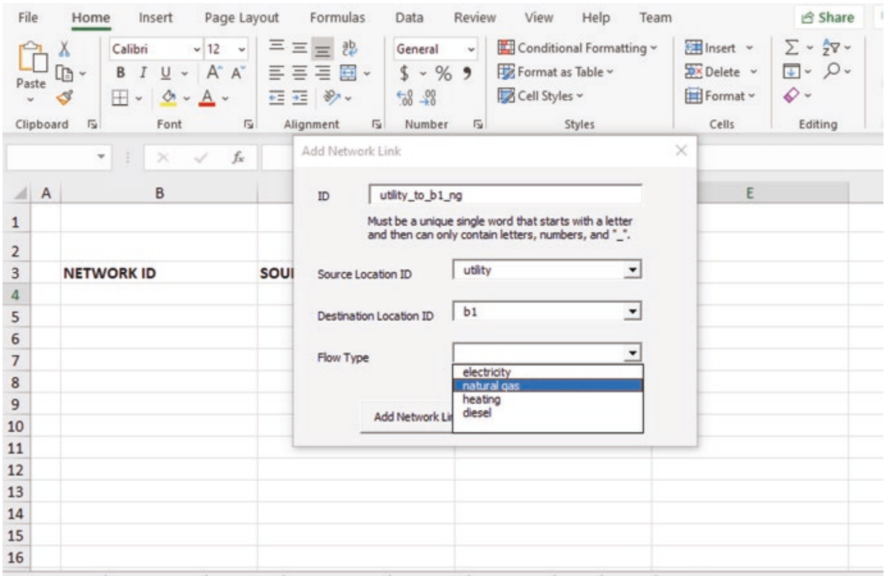

Fig. H.25 Adding a network link from utility to b1

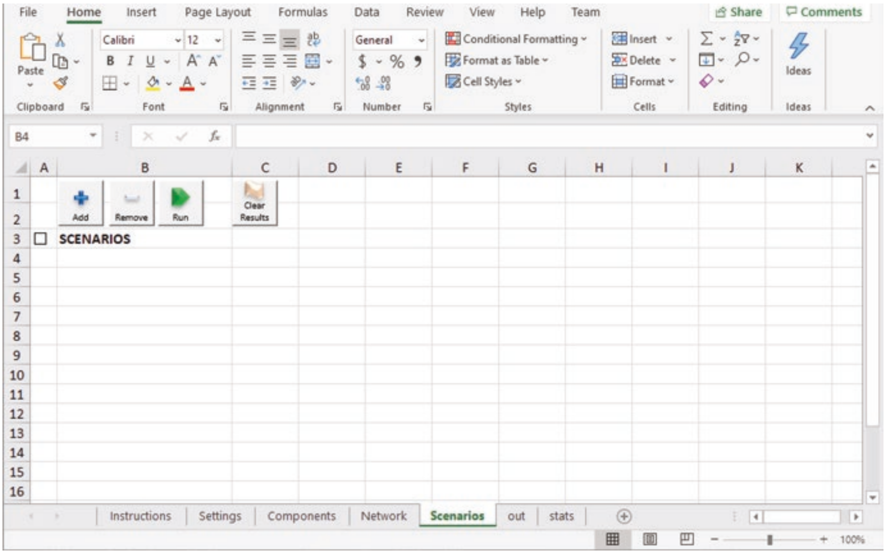

Fig. H.26 The scenario sheet

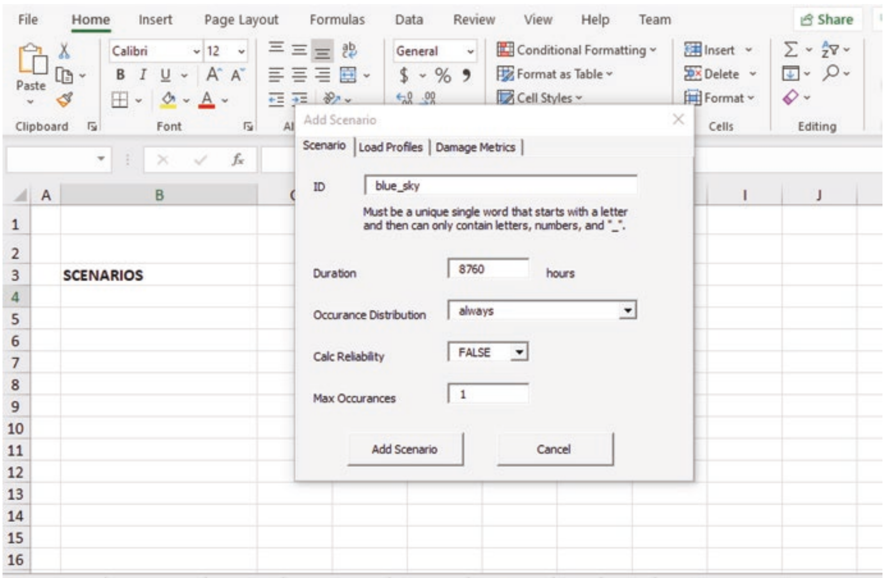

Fig. H.27 Adding the blue sky scenario

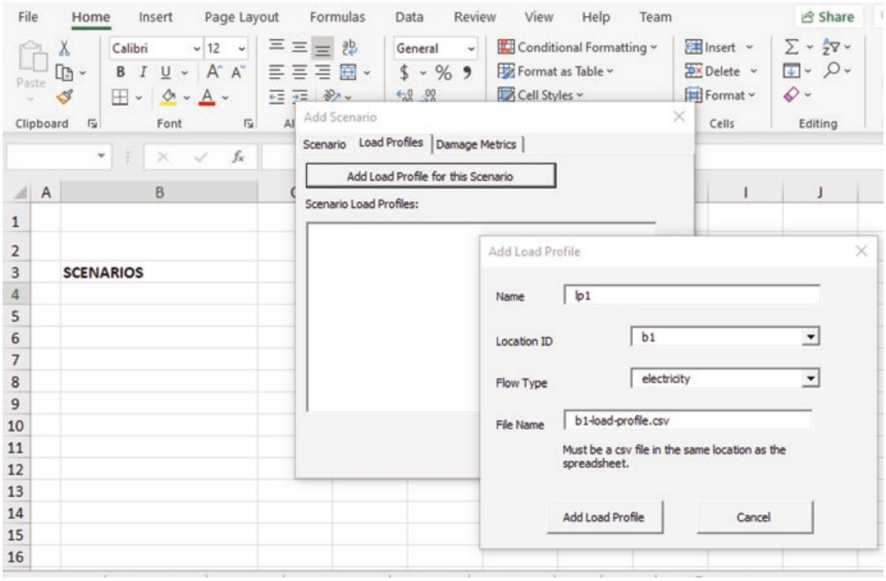

Fig. H.28 Adding the load profile for blue sky conditions

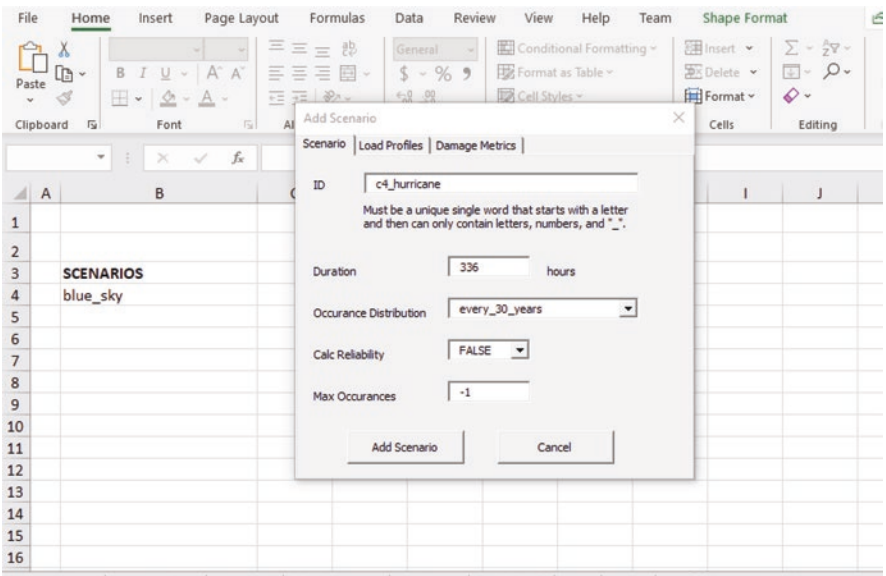

Fig. H.29 Adding the hurricane scenario

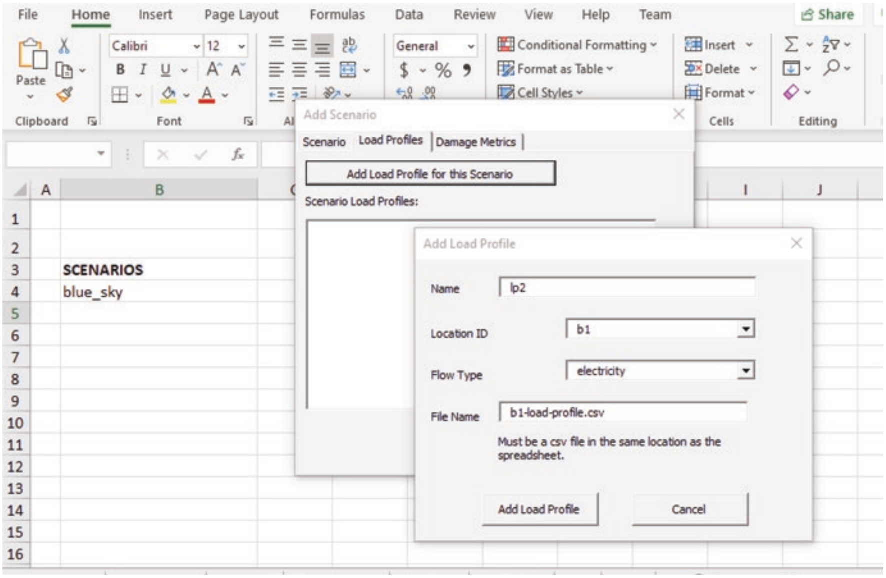

Fig. H.30 Adding the load profile for hurricane

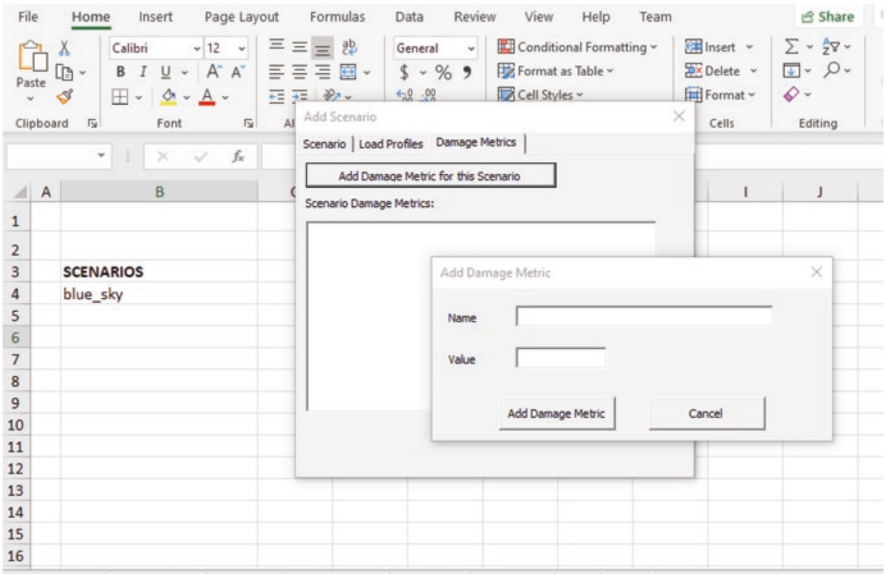

Fig. H.31 The damage metric UI

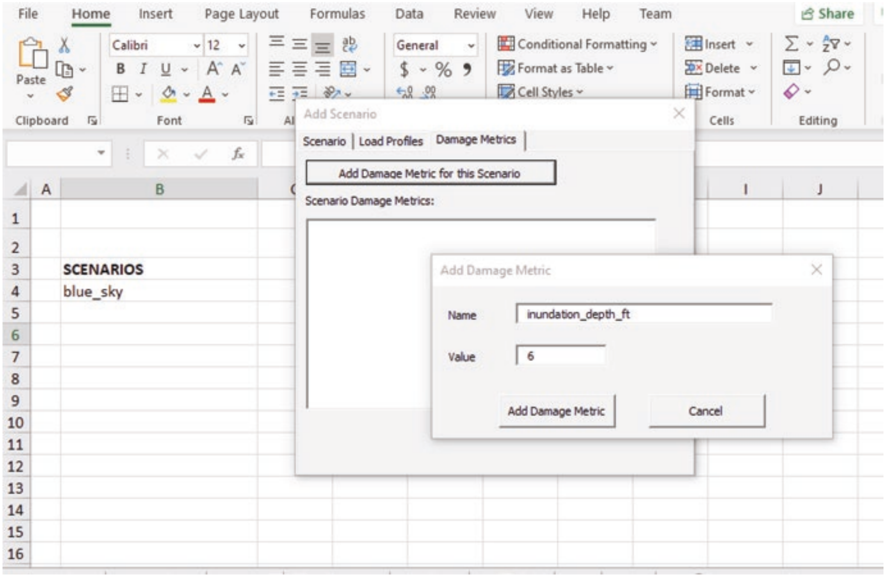

Fig. H.32 Adding inundation depth in feet

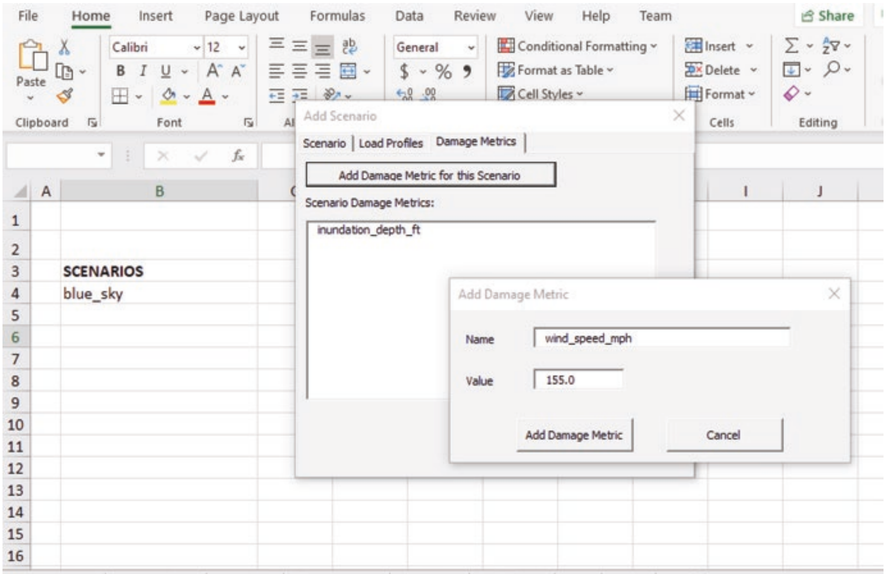

Fig. H.33 Adding wind speed in mph

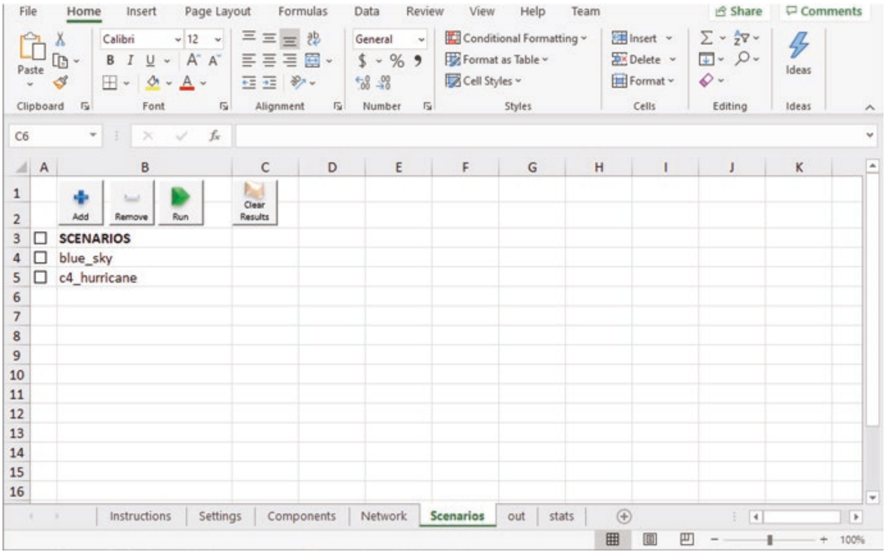

Fig. H.34 GTHE finished scenarios

Appendix I. EMP Implementation Using ESPC

I.1 Exemplary Impacts of an ESPC Project on the LCCA and NPV Calculation for Communities

ESPC contracts must provide an NPV greater than or equal to zero over the life of the contract. According to Equation 10-1:

- **NPV [Δ Energy ($)]—**is the summation of the energy savings of all ECMs within the final SOW for the ESPC.
- **NPV [ΔMaintenance ($)]—**The ESPC typically improves the infrastructure of the building(s) or campus under consideration. Infrastructure improvements involve new equipment that will need to be maintained. Many ESPC contracts require that the ESCO performing the ESPC also provides maintenance of the new equipment. The US Federal Government requires that the ESCO maintains responsibility for the maintenance and repair of equipment that they install even if the agency contractually agrees to perform the maintenance and repair.
  - Typical maintenance items include but not limited to:

    Distributed energy resources (DERs)
    Control systems—especially the cybersecurity maintenance for US Federal Government systems
    Boilers, chillers, and HVAC systems

  - Items that are not usually maintained by the ESCO will generally have an increased warranty period costed in lieu of the ESCO performing maintenance. Items that fall into this category are:

    LED lighting—typical 10-year extended warranty but may be extended to 15 years
    Toilet and sink upgrades
    Deep energy retrofit and weatherization upgrades to tighten buildings
    Similar items that are maintained by third-party contracts

  - With new equipment, O&M cost should decrease. However, capturing these costs and using them as a "savings" value are challenging.
- **NPV [ΔReplacement Cost ($)]—**Over the course of an ESPC contract, the ESCO-maintained equipment will require some parts to be replaced or completely overhauled. This cost is included in the ESPC, and the work is performed by the ESCO (either directly or under subcontract). Typical systems that fall into this category are:
  - DER

    Generators, turbines, fuel cells, solar PV, and BESS need critical systems overhauled periodically. Some components may be replaced as part of the major overhauls.
    These overhauls are usually dictated by operating hours.
    Failure to perform these overhauls will negate any warranty.

  - Critical control systems

    Operating system (OS) upgrades.
    Cybersecurity patches.
    Firmware updates.
    May require hardware updates, but these are more unusual.

  - Other—a general category that may include pumps, HVAC components, etc. Exact replacement/overhaul items will be delineated in the ESPC contract language.

- **NPV [Incentives, rebates, tax ($)]—**Many utilities offer a variety of rebates. The exact amount of any rebate is a function of the utility involved. Care must be taken in applying for rebates, however:

  - Many rebate "pools" are limited during any given calendar year and, once exhausted for that year, are not available until the next calendar year. Best practice is to have the ESCO research the rebates available and apply for and manage them for the customer. ESCOs will only guarantee rebates that can be assured at the time of the contract award. However, rebates are often subject to change without warning or due to factors beyond the control of the ESCO or the owner. Rebates available at the beginning of the investment grade audit (IGA) (defines the final scope of work to be performed) may not be available when the contract is signed.
  - Obtaining rebates for US Federal Government projects can be difficult. All rebates and incentives are typically paid to the US Treasury and not to the contracting entity. ESCOs and their clients should work with the contracting officer to ensure that the rebates help buy down the CAPEX for the project.
  - Tax benefits derived by the ESPC project are often retained by the ESCO, even for government contracts.
  - Classified within incentives and rebates may be the ability to inject one-time payments or a series of cash payments into the NPV calculation.

    One-time payments are typically made at contract acceptance. This can be realized when there is a funded capital project that is included into the ESPC.
    A series of cash payments in to the NPV calculation can also be done. This may represent, for example, a portion of the planned capital budget for several years (see Sect. 10.8 for more details). Most often this is seen in school districts or municipalities that have large capital requirements but insufficient energy savings to pay for them. Utility programs such as demand response can be realized for a few years. This can be a short-term added revenue stream for the ESPC.
    Should a desired ECM prevent the ESPC from being NPV greater than or equal to zero, the client may inject some capital to make the ESPC "cash flow" with the desired ECM. The ECM can be viewed as being procured at a steep discount—e.g., if a resilience ECM costs $10M, but the ESPC cash

flow shows a negative of say \$1M and the \$1M is made as a single, one-time payment, the resilience ECM can be thought of as being obtained at a 90% discount. Creativity in making the NPV greater than or equal to zero is often needed in an ESPC.

- **+ NPV [Benefits from resilience improvement (\$)]—**valuing resilience depends on where resilience is being added:
  - In a manufacturing environment, valuing resilience may be a simple as understanding the value of product lost per hour during a power outage.

    Production lost per hour should be readily available for a manufacturing line.
    Understanding the duration and frequency of utility outages for a given area, when multiplied by the production loss per hour, gives a good approximation of the value of resiliency on a yearly basis. Simply:

$$\Delta\ \mathbf{production} = \mathbf{SAIDI} \times \mathbf{SAIFI} \times \Delta\ \mathbf{production\ /\ hour} \tag{I.1}$$

- The System Average Interruption Duration Index (SAIDI). SAIDI indicates the total duration of electrical interruptions during a predefined period such as a month or a year. It is commonly measured in minutes or hours of interruption. As an example, a SAIDI of 100 means that the average customer on the electric system over a period of a year would experience a total of 100 min of power interruption.
- System Average Interruption Frequency Index (SAIFI). SAIFI indicates how often the average customer experiences a sustained electrical interruption over a predefined period, typically a year. As an example, a SAIFI of 1.00 means that the average customer over a year would experience one single outage.
  - A school or university may measure resilience in terms of hours of classroom time lost and the impact that has on their budgets (tuition, government funding, etc.).
  - Government installations have typically not directly valued resiliency.
  - Improving resilience is like having an insurance policy—it costs money, but you do not really notice it until you need it—and then it is invaluable.

    A supermarket chain had backup generation installed at their stores. When a violent storm hit and knocked out power, they were able to stay open. Not only did they maintain their inventory, but because they were open, they gained market share over their competitors who lost power and could not open.
    Municipalities are expected to still provide services to their citizens during storm events—even when the town is without power. What is the value to people to charge their phones, shower, buy gasoline, etc.? What is that value to elected officials?

A storm event knocked out grid power to a wastewater treatment plant (WWTP), interrupting the process, but not the flow of wastewater (and rainwater). Consequently, the WWTP spilled untreated sewage contaminating the water sources in the area. The WWTP has since added electrical resilience through diesel backup generation.

– Military installations—some installations have very clear needs for resilience:

  Biohazard research
  Munitions storage and preparation
  Communication canters, etc.

– A common metric for valuing resiliency on a military base is the cost of installing emergency generators at critical buildings.

  Many bases have multiple buildings that are deemed critical that have no backup generation.
  Backup generation is funded by the branch of the military, who "owns" a base.
  The CAPEX availability for stand-alone generators is a function of the yearly appropriations process.

Based on the above discussion, what are some of the strategies that can be used to improve the use of ESPC for implementation of EMPs? ESPCs look at the total project when considering a long-term cash flow. Some ECMs (fixing water or steam leaks, energy system commissioning, etc.) offer fairly quick payback—i.e., the total investment required to implement the ECM divided by the cost savings produced by the ECM yields a "small" number or a short payback time. These short-term payback ECMs help to "fund" the longer-term payback ECMs, which may include resilience. Occasionally, some clients will impose a minimum pay back criteria for each ECM—i.e., if the payback time exceeds a certain number, the ECM will be deleted form the project. This tends to limit the value that can be realized from an ESPC and the size of the ESPC contact, essentially eliminating longer payback measures (typically greater than 20 years) such as HVAC, chiller, boiler replacements, as well as resiliency ECMs. It is essential that long- and short-term payback ECMs be considered in a project as a bundle to maximize the value and effectiveness of the ESPC.

Given the above, what are some of the strategies for developing energy savings for resilience ECMs?

Probably all, but in any case, most of the components of a resilience project can be included in an ESPC or UESC. These vehicles are for the purpose of procuring ECMs. The law (42 U.S.C. § 8250(4)) defines ECMs as "measures that are applied to a Federal building that improve energy efficiency and are life-cycle cost effective and that involve energy conservation, cogeneration facilities, renewable energy sources, improvements in O&M efficiencies, or retrofit activities." Here is what that means for resilience projects:

1. "Applied to a Federal building"

   "Applied to" includes measures that deliver energy to a building. For example, a PV array remotely located that energizes a building is considered to be applied to that building.

2. "Improve energy efficiency"

   (a) Onsite generation can be deemed to improve energy efficiency even if the use of electricity in a building or set of buildings stays the same. In such a case the system savings due primarily to avoiding line loss from remote power plants is considered. "In determining whether an ECM qualifies for the energy efficiency definition, calculations may be done on either a 'site-energy' basis or a 'source-energy' basis" (OMB memorandum M-12-21).
   (b) Small energy savings can qualify a measure for this prong of the definition—there is no legal minimum. For example, engineers tell us that even new distribution wires will be more energy efficient than older wires.
   (c) A component of a qualifying ECM need not, by itself, save energy. For example, utility poles save no energy, but if they are necessary to install new wiring, they can be included.

3. "Life cycle cost-effective"

The life cycle cost-effectiveness of ECMs is considered together as a bundle, which means all ECMs are taken as a whole project to determine life cycle cost-effectiveness rather than assessing ECMs individually.

Resiliency measures are not limited to electrical power but may also include thermal energy systems, potable water and wastewater treatment facilities, as well as backup fuel for primary fossil fuel or redundant equipment to maintain sufficient availability. In examples below, we will focus on electrical system resiliency.

Electrical resiliency ECMs usually save energy cost by generating power on site, and either they provide that power to the base or campus or the power generated is sent to the grid. Either way, the base or campus load, as seen by the utility, is lowered in both the energy needed, kWh (kilowatt-hours), and the power required, kW (kilowatts). Most industrial electrical rates have both a kWh and a kW charge; often these charges are based on a time of use, where the rate charged to the customer varies based on the time of day the electricity is used and the time of year. Also, the power charge—kW—will often have a ratchet rate applied. A ratchet rate takes the highest value of kW over the previous 11 months of use and multiplies by a ratchet percentage. If in any given month, the highest value of power used—kW (aka demand charge)—is less than the ratchet rate, the ratchet rate is charged. Resiliency ECMs will produce energy cost savings by changing the load profile (how energy is used during a day) of a base or campus by generating electricity for onsite consumption and save both kWh and kW charges from the utility.

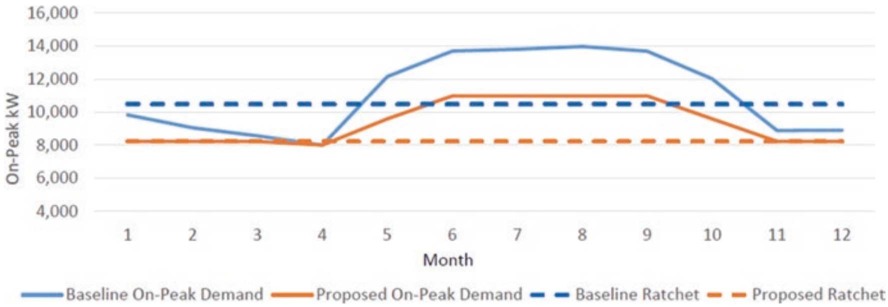

Fig. I.1 Resilient ECMs can use their DERs to lower peak demand and ratchet charges to significantly save energy and provide savings in an ESPC

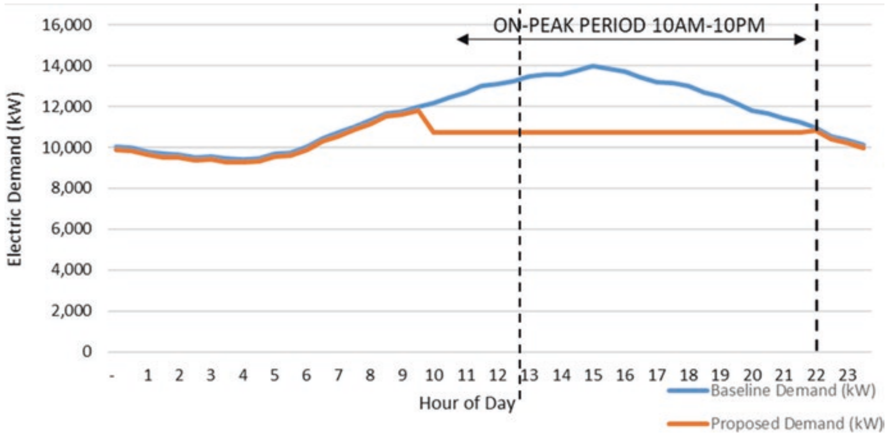

Fig. I.2 During a peak shaving event, the demand, as seen by the utility, is actively managed by the DERs

In Fig. I.1, the blue lines represent the current (baseline) condition for peak demand for each month and the ratchet charge that is applied. The ratchet charge applies 6 months for the year, as the peak demand for those months falls below the ratchet value. When a peak shaving solution is applied, the ratchet charge is sufficiently lowered such that no month's peak demand usage is above the new ratchet value. Also, the peak shaving application lowers the peak demand charge by 2500 kW for this example project. Peak shaving solutions operate the DER periodically rather than continuously like a CHP solution. Peak shaving solutions typically operate the DER 750–2000 hours per year, whereas CHP solutions typically operate throughout most of the year.

Figure I.2 illustrates the operation of a peak shaving ECM over an example 24-hour period. At a predetermined value of demand (kW), the DERs are activated and run for the peak demand charge period for that day. Figure I.2 illustrates a case where peak demand charges are applied from 10AM until 10PM—this will vary by

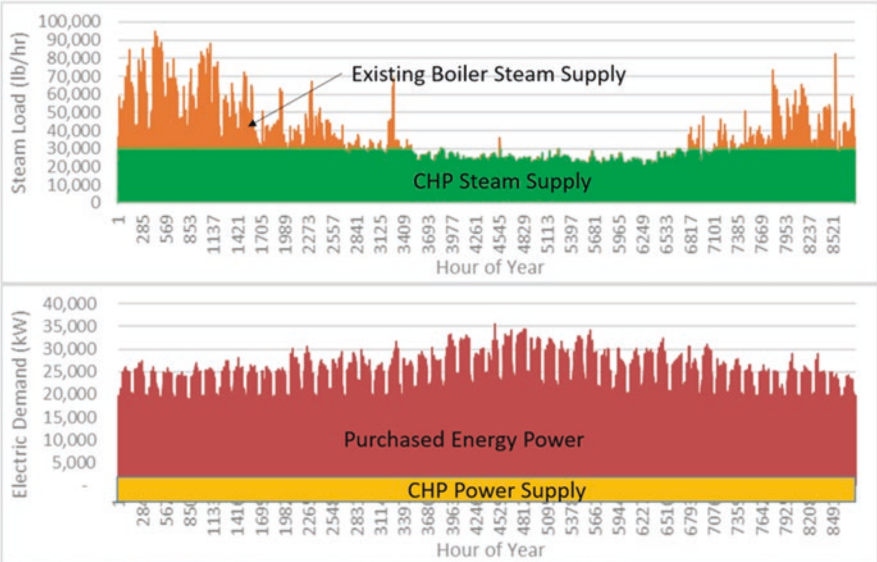

Fig. I.3 CHP resilient solutions generate savings for an ESPC by offsetting heat (steam) and electrical purchases

utility. While the DERs are operating, the total demand from the utility meter will be monitored. If the demand level continues to rise, additional DER assets (if available) will be brought on line to manage the demand from the utility. At the end of the peak demand period, the DERs are shut down.

CHP solutions typically operate over 8000 hours per year, with routine maintenance being the only scheduled "down" time. CHP ECMs provide heat and power to a facility, base, or a campus and offset the cost of the current generation of steam and purchase of power. As can be seen in Fig. I.3, the CHP solutions are sized to a base load value in either heat or power; in the case below, the system was sized to the steam base load. The base load is the minimum value of steam or power used throughout a year. In Fig. I.3, the base load for steam is about 30,000 lb/hr resulting in a power generation of about 2500 kW. The power generation impacts both the energy charges for the facility and the demand charges (and hence any ratchet charge). The key to choosing a CHP is the price of heat, steam in Fig. I.3, and the spark spread. Spark spread is the difference in price for buying electrical power and producing electrical power onsite at the facility, base, or campus. Like all ECMs, the operation, maintenance, repair, and replacement costs must be factored into the total savings for a CHP ECM. CHP solutions generate savings for ESPCs by efficiently generating heat and electricity and capturing those cost savings for the ESPC.

The other revenue stream for resilient-based ECMs is using the DER to access the ancillary markets for the local, serving utility, and the independent system operator. An independent system operator is an organization formed at the recommendation of the Federal Energy Regulatory Commission (FERC). Where an independent system operator is established, it coordinates, controls, and monitors the operation of the electrical power system. An independent system operator may be confined within a single state or may encompass several states. ISOs often offer various programs to customers in their efforts to manage the electrical grid within their area. These programs can be accessed through DERs that are deployed for resilience. Typically, a facility (or the ESCO) will contract with a Curtailment Service Provider who offers services in the independent system operator territory. The CSP essentially acts as a middleman between the facility and the independent system operator and facilitates the program by handling M&V and reporting requirements. If the program requires remote communication or remote dispatch, this communication will likely go to the CSP and then up to the independent system operator. The CSP will typically take a revenue share of 20–30% for providing the services.

Care must be taken when using these programs to develop a savings or revenue stream for an ESPC as many programs change their monetary values each year or every 3 years or may be canceled for a given year(s). When projecting savings out 20–25 years, there is no reliable way to take advantage of these savings. Further, when accessing these programs from a US Federal campus or building, in particular a DoD site, there are issues that may arise over cybersecurity. Specifically, many of these programs have two-way communication requirements attached to them—the independent system operator or local utility sends a signal and wants an acknowledgement that the action requested has been completed. These two-way communications must meet the cybersecurity requirements of the facility or base and most likely will need an authorization to operate (ATO) prior to being in full operation.

The types of programs that exist at each independent system operator or local utility vary in name and monetary value but fall under the same general headings:

- ***Demand Response***: The campus or facility agrees to reduce their electrical demand by specified amount for a duration of time (usually 1–4 hours). Resilient DER capacity can be used to reduce electrical demand/or any other types of strategy such as temporary lighting or HVAC demand limiting. The facility is usually given a day ahead warning that a high-demand event may be called; if an event is called, the facility has approximately an hour to shed the electrical load contracted for. Missing a demand response event or opting out of an event may exclude the facility from participation in the program.
  - Compensation for signing up for this program varies by geographical location but is usually in the range of $20,000–$50,000 per MW per year.
  - The facility is paid for the program even if a demand reduction event is not called for in a given year.
  - The facility will typically be required to test and prove their capability to respond at least once per year.
  - Compensation varies year to year. Contracts typically can be written for 3 years.

  - This program is difficult to predict and guarantee the revenue stream over the life of an ESPC.
  - If resilient DER assets are being used day by day to reduce retail demand or energy charges on the facility's utility bills, this may significantly reduce or eliminate their potential to also generate demand response program revenue.

- ***Demand Curtailment***: Very similar to demand response in that the facility will be called to curtail electrical load for a given time period.
  - The facility is generally not paid for this program.
  - Program compensation comes in the form of guaranteed electrical demand and curtailment load. Curtailment eligible load is charged at a lower kWh and kW rate than non-curtailable load. The difference in tariff rates between curtailed load and non-curtailed load can be hundreds of thousands of dollars per year.
  - Missing a call for curtailment results in financial penalties that the facility must pay to the utility.
  - Missing multiple curtailments will result in the facility being removed from the program.
  - Typically, the number of curtailment events per year and their maximum duration are limited.
  - Generally, this type of utility program, as it is rate based, can be counted on in an ESPC for the full duration of the contract.

- ***Capacity Programs***: This is like a demand response program and is very much like peak shaving in that a call is sent from the independent system operator or utility to take load off the grid by activating facility-based DER.
  - There is no day ahead warning that an event may happen.
  - Generally, the time frame to shed load is 1–15 *min*. Given the quick time frame, remote dispatch by the CSP is typically recommended or required.
  - The facility is compensated more highly for the capacity market than for demand response.
  - Like demand response, capacity programs may or may not exist year to year, and their compensation to the facility will also vary.
  - Capacity revenue streams for an ESPC are difficult to include past the first year because of the uncertainty surrounding the program.

- ***Frequency Regulation***: These programs look to inject or absorb power over very short durations—on the order of seconds or at most a few minutes. The independent system operator or utility will have a direct communication line to the facility's assets to absorb or inject power.
  - These programs are typically entered into with a BESS.
  - The frequency of the calls and the charge/discharge on the BESS usually result in the BESS needing more maintenance than a normal storage BESS where there are only one or two charge/discharge cycles per day.

– Frequency regulation compensation is fairly high, but like demand response and capacity programs, the duration of the program and compensation year to year is variable.
– This program is difficult to include in an ESPC savings stream due to the variability of the compensation and unknown future of the program. Also, the added BESS maintenance requirements will burden the ESPC proforma should the ESCO be responsible for maintenance through the life of the ESPC contract.

- ***Wholesale Market***: Many microgrid controllers have an economic dispatch engine built into the software that would allow the controlled DER assets to be used in the wholesale energy market.

– This market requires fairly fast ramp times for the DERs, i.e., how fast can the DER assets go from a cold start to full power output.
– Wholesale energy prices fluctuate rapidly with each price having a 20–30-minute window to participate at that price point.
– In markets where the independent system operator or utility can experience high stress days (peak summer cooling), this market can be very lucrative with some markets paying up to $9000/MWh.
– Some resilience-as-a-service companies use this market to offset the customers initial CAPEX.
– This is a speculative market and may/may not be attractive to an ESPC (or contracting ESCO) due to the associated risk of the revenue stream.

One complication for using these programs on US Federal campuses or DoD bases is the need for two-way communication between the independent system operator/utility and the DER assets. The curtailment programs and demand response programs have been successfully used on DoD installations because the call for load shed can be made manually to base personnel—there is no direct tie to the DER equipment. Another complication factor for accessing any of these programs as part of a US Federal ESPC is how the revenue flows from the independent system operator/utility programs to the ESPC rather than to the base or US Treasury. A possible way to solve this issue is to have the revenue go to the utility company and the revenue show up as a credit on an electric or gas bill. The ESCO will then count that bill credit as savings under the ESPC.

At the conclusion of the construction period in an ESPC contract, when the systems have been commissioned and accepted by the customer, the ownership of the DER is usually passed to the US government. Even though the ESCO is responsible for the maintenance and repair, the ESCO does not own the hardware. It takes some creativity on the part of the ESCO, the customer, and the contracting officer to ensure that any revenue from these independent system operator/utility programs flows to the ESPC as a revenue stream.

Using these independent system operator/utility-based programs as a revenue stream for the full duration of an ESPC is, at best, difficult. However, they can be used for the first 3 years or so as an injection of savings of that will help the

ESPC cash flow. The ESCO should discuss options with the CSP to create a longer-term revenue structure that extends through 10 years or more and includes a guarantee. Although the guaranteed revenue may be reduced, it would allow for it to be captured in the ESPC proforma. If non-guaranteed, either the ESCO or the Federal customer will be taking the risk associated with fluctuating revenues.

I.2 Sample Cash Flow for an ESPC

ESPC contracts must show an NPV greater than or equal to zero. A typical cash flow is shown and explained in Table I.1.

In Table I1, the basic inputs and calculated values are:

- ECM implementation price—$10,800,000—this is the financed amount or the CAPEX.
- Term—23 years—this is the financing term.
- Interest rate—3.5%—interest rate for the financing term, can be fixed or variable, here it is fixed.
- Discount rate—2.5%—this is the rate used in the NPV calculations and may be different from the financing interest rate. Basically, this is the expected return on investment for the customer for a safe investment like US Treasury notes.
- SIR—total savings over the project divided by the CAPEX value.
- Simple payback—year 1 savings divided into the CAPEX.
- Escalation rate—amount each savings stream[9] or cost[10] is escalated. This is determined by the Energy Escalation Rate Calculator (EERC) tool discussed earlier or approved by the client. The US Federal Government highly recommends the use of the EERC tool. Municipalities, state governments, schools, and universities may not use the EERC tool to define escalation rates. In these cases, escalation rates can be determined based on the history of rate increases of the local, serving utility.

Table I.2 lists the savings revenue in more detail.

- In Table I.2, it is assumed that the award year is 2020 and that there is a 2-year final design and construction period. This means that repayment of the financed amount begins at the end of construction and customer acceptance in 2023.
- Electric savings are escalated at the EERC value for the electric escalation. Savings at the end of the construction period have been escalated from the 2020 values.
- Independent system operator Program A is a place holder of one of the independent system operator/utility ancillary market revenue streams discussed above. The value in year 2020 is $58,000/year. The value has been escalated to 2023 values.

[9] Electrical power.

[10] Natural gas.

Table I.1 Sample cash flow for an ESPC

ECM Implementation Price	$10,800,000	Financed amount									
Term	23	Performance Contract financed term.									
Interest Rate	3.50%										
Discount Rate	2.50%										
Total Interest Paid	$5,102,271										
Total Payments	**$15,902,271**	**Total Saving**		**$16,934,027**	Total Savings > Total Payments for stand-alone viability						
SIR	1.57										
Simple Payback (yrs.)	20.4		ISO Revenue Yrs.	ISO Revenue Yrs.	ISO Revenue Yrs.	ISO Revenue Yrs.					
NPV	$418,979		3	3	3	3					
Escalation Rates (EERC tool)		3.00%	3.00%	3.00%	3.00%	3.00%	3.00%		3.00%	3.00%	
Performance		Electric	ISO Program A	ISO Program B	ISO Program C	Other	OMRR	Total	Gas	OMR&R	Total
					Savings					Costs	

Table I.2 Savings revenue, detailed

Energy Savings over the life of an ESPC								
Performance		Electric	ISO Program A	ISO Program B	ISO Program C	Other	OMRR	Total
Year		Savings	Revenue	Revenue	Revenue	Revenue	Savings	Savings/Revenue
Today	2020	$1,160,000	$58,000					$1,218,000
Award	2021							
Construction	2022							
1	2023	$1,267,563	$63,378	$0	$0	$0	$0	$1,330,941
2	2024	$1,305,590	$65,280	$0	$0	$0	$0	$1,370,870
3	2025	$1,344,758	$67,238	$0	$0	$0	$0	$1,411,996
4	2026	$1,385,101	$0	$0	$0	$0	$0	$1,385,101
5	2027	$1,426,654	$0	$0	$0	$0	$0	$1,426,654
6	2028	$1,469,453	$0	$0	$0	$0	$0	$1,469,453
7	2029	$1,513,537	$0	$0	$0	$0	$0	$1,513,537
8	2030	$1,558,943	$0	$0	$0	$0	$0	$1,558,943
9	2031	$1,605,711	$0	$0	$0	$0	$0	$1,605,711
10	2032	$1,653,883	$0	$0	$0	$0	$0	$1,653,883
11	2033	$1,703,499	$0	$0	$0	$0	$0	$1,703,499
12	2034	$1,754,604	$0	$0	$0	$0	$0	$1,754,604
13	2035	$1,807,242	$0	$0	$0	$0	$0	$1,807,242
14	2036	$1,861,459	$0	$0	$0	$0	$0	$1,861,459
15	2037	$1,917,303	$0	$0	$0	$0	$0	$1,917,303
16	2038	$1,974,822	$0	$0	$0	$0	$0	$1,974,822
17	2039	$2,034,067	$0	$0	$0	$0	$0	$2,034,067
18	2040	$2,095,089	$0	$0	$0	$0	$0	$2,095,089
19	2041	$2,157,942	$0	$0	$0	$0	$0	$2,157,942
20	2042	$2,222,680	$0	$0	$0	$0	$0	$2,222,680

(continued)

Table I.2 (continued)

Energy Savings over the life of an ESPC								
21	2043	$2,289,360	$0	$0	$0	$0	$0	$2,289,360
22	2044	$2,358,041	$0	$0	$0	$0	$0	$2,358,041
23	2045	$2,428,782	$0	$0	$0	$0	$0	$2,428,782
		$41,136,085	**$195,896**	**$0**	**$0**	**$0**	**$0**	**$41,331,981**

Table I.3 Costs in the ESPC model

Energy costs associated with an ESPC				
Performance		Gas	OMR&R	Total
Year		Cost	Price	Cost
Today	2020	$480,000.00	$208,000	$688,000
Award	2021			
Construction	2022			
1	2023	$524,509	$227,287	$751,796
2	2024	$540,244	$234,106	$774,350
3	2025	$556,452	$241,129	$797,581
4	2026	$573,145	$248,363	$821,508
5	2027	$590,339	$255,814	$846,153
6	2028	$608,050	$263,488	$871,538
7	2029	$626,291	$271,393	$897,684
8	2030	$645,080	$279,535	$924,614
9	2031	$664,432	$287,921	$952,353
10	2032	$684,365	$296,558	$980,923
11	2033	$704,896	$305,455	$1,010,351
12	2034	$726,043	$314,619	$1,040,662
13	2035	$747,824	$324,057	$1,071,882
14	2036	$770,259	$333,779	$1,104,038
15	2037	$793,367	$343,792	$1,137,159
16	2038	$817,168	$354,106	$1,171,274
17	2039	$841,683	$364,729	$1,206,412
18	2040	$866,933	$375,671	$1,242,605
19	2041	$892,941	$386,941	$1,279,883
20	2042	$919,730	$398,550	$1,318,279
21	2043	$947,322	$410,506	$1,357,828
22	2044	$975,741	$422,821	$1,398,562
23	2045	$1,005,013	$435,506	$1,440,519
		$17,021,828	**$7,376,126**	**$24,397,954**

The revenue stream is terminated 3 years later. There are place holders for other independent system operator/utility programs, but these were not used in the simple model.

- There are no OMRR (operations, maintenance, repair, and replace) savings associated with this model for the reasons discussed earlier.

Table I.3 lists the costs in the ESPC model

- The value of gas costs to operate the generators is escalated at the EERC tool rate for gas, or 3% in this model.
- OMRR costs are escalated at 3% in this model. These can be modeled on the consumer price index or other acceptable indices that the ESCO and customer can agree upon.

Table I.4 lists the total cash flow for this ESPC

Table I.4 Total cash flow for ESPC

Cash Flow for Fixed and Variable Debt Payment						
Performance	Net	Payment on		Variable payment to show positive cash flow	Net	
Year	Savings	Debt Costant value	Cashflow		Savings Required to not over guarantee	Modified cash flow
Today	$530,000	($691,403)	with no derate		94% derate factor	
Award						
Construction						
1	$579,145	($691,403)	($112,258)	($543,859.17)	$543,859	$35,286
2	$596,520	($691,403)	($94,883)	($560,174.94)	$560,175	$36,345
3	$614,415	($691,403)	($76,988)	($576,980.19)	$576,980	$37,435
4	$563,593	($691,403)	($127,810)	($529,254.13)	$529,254	$34,339
5	$580,500	($691,403)	($110,903)	($545,131.75)	$545,132	$35,369
6	$597,915	($691,403)	($93,488)	($561,485.71)	$561,486	$36,430
7	$615,853	($691,403)	($75,550)	($578,330.28)	$578,330	$37,523
8	$634,329	($691,403)	($57,075)	($595,680.19)	$595,680	$38,648
9	$653,358	($691,403)	($38,045)	($613,550.59)	$613,551	$39,808
10	$672,959	($691,403)	($18,444)	($631,957.11)	$631,957	$41,002
11	$693,148	($691,403)	$1,745	($650,915.82)	$650,916	$42,232
12	$713,942	($691,403)	$22,539	($670,443.30)	$670,443	$43,499
13	$735,361	($691,403)	$43,958	($690,556.60)	$690,557	$44,804
14	$757,421	($691,403)	$66,018	($711,273.29)	$711,273	$46,148
15	$780,144	($691,403)	$88,741	($732,611.49)	$732,611	$47,533
16	$803,548	($691,403)	$112,145	($754,589.84)	$754,590	$48,959
17	$827,655	($691,403)	$136,252	($777,227.53)	$777,228	$50,427

18	$852,485	($691,403)	$161,081	($800,544.36)	$800,544	$51,940
19	$878,059	($691,403)	$186,656	($824,560.69)	$824,561	$53,498
20	$904,401	($691,403)	$212,998	($849,297.51)	$849,298	$55,103
21	$931,533	($691,403)	$240,130	($874,776.44)	$874,776	$56,756
22	$959,479	($691,403)	$268,076	($901,019.73)	$901,020	$58,459
23	$988,263	($691,403)	$296,860	($928,050.32)	$928,050	$60,213
	$16,934,027	**($15,902,271)**	**$1,031,756**	**($15,902,271)**	**$15,902,271**	$1,031,756
	NPV					
	$418,979.26					

- Payment of debt is a yearly payment required on the financed amount and is shown as a constant value over the life of the project. This will be discussed later.
- Net savings is simply the total savings value minus the total cost value over the life of the contract.
- Derated savings are discussed below.
- Cash flow is the net yearly cash flow and is calculated by subtracting the debt payment from the total net savings. Notice that in the first few years, the cash flow is negative, yet the total cash flow is positive over the life of the contact. Notice also that the total cash flow is greater than the total debit payment. This situation is typically called an over-guarantee of savings. Over-guaranteed savings means that the guaranteed risk to the ESCO has increased beyond what is needed to pay back the amount financed for the project.
  - With the negative cash flow in the first few years of paying back the debt, ESCOs and the financier will typically adjust the payment schedule to show positive cash flow each year of the contract.
  - ESCOs will not over-guarantee a project. The column labeled guaranteed savings with 94% derate factor is a modified guaranteed savings that will show the sum of all savings equal to the total debt payment.
  - A derate factor is simply the guaranteed savings divided by the expected savings.
- The variable payment is the modified payment schedule that will show a positive cash flow each year, as shown in the column modified cash flow. This accounts for the variable payment and the derated savings value.
- The modified cash flow sum and the original cash flow sum are the same number. The NPV is calculated from either column and is equal to ~$400,000 (~381,000 Euros). This is greater than zero and meets the requirements of an ESPC showing that the NPV is greater than or equal to zero.
- The variable repayment schedule sums to the same value as the non-variable repayment column.
- The modified cash flow sums to the same value as the original cash flow.

I.3 Major Barriers for EMP Implementation Using ESPC and UESC

I.3.1 Operations and Maintenance

The above list of savings opportunities can support many resilience projects without capturing O&M savings. Resilience related legitimate savings or avoided costs can be significant. Many others savings opportunities could be achieved; however, the inability to capture those avoided costs makes it difficult to include them in the project financing calculationist. For example, many DoD installations have several hundred backup generators—often inefficient, oversized, and expensive to maintain. Installing a microgrid, eliminating all stand-alone generators, or saving some to tie in to the microgrid can produce significant O&M savings.

DoD's current approach to the funding of standalone generators represents another major barrier to the implementation of microgrids. Although our cost analysis shows that microgrids can generate sufficient savings and revenue to make them attractive to Energy Savings Performance Contract (ESPC) and Utility Energy Service Contract (UESC) vendors, the services report that their proposed microgrid projects do not "pencil out" for private vendors. The difference is accounting: whereas our calculation considered all of the costs that standalone generators impose on a hypothetical base (capital, O&M, etc.), DoD's accounting system provides no such recognition; the costs of standalone generators on a base are paid out of multiple budget activities and by dozens of tenants. For third-party financing to "pencil out," DoD needs to recognize the costs that it already pays for energy security (Marqusee et al. 2017).

I.3.2 MILCON

A significant majority of ESPC projects combine appropriations with private financing as the law, 42 U.S.C. § 8287(a)(2)(E), provides:

- Funding Options. In carrying out a contract under this subchapter, a Federal agency may use any combination of:
  - Appropriated funds
  - Private financing under an energy savings performance contract

UESCs may be fully funded or may include any combination of appropriations and financing. DoD has determined that it is prohibited from using MILCON funds in conjunction with an ESPC or UESC. Even ERCIP (Energy Resilience and Conservation Investment Program) funds are off-limits because MILCON is the source of ERCIP funds. Where MILCON or ERCIP funds are available for resilience projects, if it were permitted for those funds be combined with ESPC or UESC, it would result in more comprehensive, coordinated projects that could be done faster and more seamlessly. In addition, more savings could be guaranteed or assured, and those savings could be leveraged for even more investment than the total investment of separate projects—some privately financed and others funded with appropriations.

I.3.3 Utilities Privatization in DoD

In resilience planning, consideration should be given to the status of utilities at a given DoD installation. In particular, where utilities privatization has occurred, there will be a need to coordinate with the utility privatization contractor to ensure that resilience capabilities are at the ready.

According to the Office of the Assistant Secretary of Defense for Sustainment, *maintaining access to reliable, resilient, and cyber-secure energy resources, generation assets, distribution infrastructure, and facility-related controls and data is critical to the execution of DoD missions. Alternative Financing Mechanisms (AFMs) leverage commercial sources of capital to finance near-term enhancements to DoD utility infrastructure. As part of a comprehensive Installation Energy Plan (IEP), AFMs can provide material benefits to DoD Components by providing cost-effective access to capital that might not otherwise have been obtainable through traditional methods. AFMs require DoD Components, however, to also use contractual mechanisms to ensure compliance with energy security, energy resilience, and cybersecurity requirements. Utilities privatization is one of several AFMs that a Military Department may use to finance utility improvements in support of the DoD's energy reliability, energy resilience, and cybersecurity goals. In the privatization process, military installations shift from the role of owner/operators to that of smart utility service customers. Privatized systems continue, however, to function as Defense Critical Infrastructure (DCI) and a DoD Component's decision to pursue utilities privatization must be consistent with prioritized mission assurance requirements, 10 U.S.C. 2688, applicable DoD instructions and guidance, and the affected installation's IEP.*

References

10CFR-433. 2013. *U.S. Code of Federal Regulations Part 433*. https://www.govinfo.gov/app/details/CFR-2013-title10-vol3/CFR-2013-title10-vol3-part433.

10 U.S. Code § 2688. 2003. *Utility systems: Conveyance authority*.

ACGIH (American Conference of Governmental Industrial Hygienists). 2001. *Documentation of the threshold limit values for physical agents*. 7th ed. Cincinnati: ACGIH.

———. 2017. *Heat stress and strain: TLV(R) physical agents*. 7th ed. Cincinnati: ACGIH.

———. 2018. *Cold stress: TLV(R) physical agents*. 7th ed. Cincinnati: ACGIH.

Air Force Civil Engineer Support Agency (AFCESA). 2020. *Installation master planning*, Unified Facilities Criteria (UFC) 2-100-01. Washington, DC: Headquarters, U.S. Army Corps of Engineers (HQUSACE), Naval Facilities Engineering Command (NAVFAC), and AFCESA (Preparing Agency).

Aldrich, Robb, and Lois Arena. 2013. *Evaluation ventilation systems for existing homes*. Washington, DC: U.S. Department of Energy (USDOE) Building Technologies Program. https://www.nrel.gov/docs/fy13osti/56988.pdf

Anderson, Katherine H., Dylan S. Cutler, Daniel R. Olis, Emma M. Elgqvist, Xiangkun Li, Nicholas D. Laws, Nicholas A. DiOrio, and H.A. Walker. 2004. *Energy standard for buildings except low-rise residential buildings*, ASHRAE Std. 90.1-2016. Atlanta: ASHRAE.

———. 2017. *REopt: A platform for energy system integration and optimization*, Technical report NREL/TP-7A40-70022. Golden: National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy17osti/70022.pdf.

Anderson, Kate, Dan Olis, Bill Becker, et al. 2021. *REopt lite web tool user manual*. Golden: National Renewable Energy Laboratory (NREL). https://reopt.nrel.gov/tool/REopt%20Lite%20Web%20Tool%20User%20Manual.pdf.

ASHRAE. 2005. *Design considerations for datacom equipment centers*, ASHRAE datacom series. Atlanta: ASHRAE.

———. 2007. *Energy standard for buildings except low-rise residential buildings*, ASHRAE Std. 90.1-2016. Atlanta: ASHRAE.

———. 2016. *Energy standard for buildings except low-rise residential buildings*, ASHRAE Std. 90.1-2016. Atlanta: ASHRAE. https://www.ashrae.org/technical-resources/bookstore/standard-90-1.

———. 2017. *Thermal environmental conditions for human occupancy*, ASHRAE Standard 55. Atlanta: ASHRAE.

———. 2018. *Energy standard for buildings except low-rise residential buildings*, ASHRAE Std. 90.1-2016. Atlanta: ASHRAE.

A. Zhivov, *Energy Master Planning toward Net Zero Energy Resilient Public Communities Guide*, https://doi.org/10.1007/978-3-030-95833-6

———. 2019a. *HVAC applications. ASHRAE handbook*. Atlanta: ASHRAE. https://www.techstreet.com/ashrae/ashrae_handbook.htmlhttps://www.ashrae.org/about/news/2019/ashrae-releases-new-hvac-applications-handbook.

———. 2019b. *Ventilation and indoor air quality*, ASHRAE standard 62.1-2019. Atlanta: ASHRAE.

———. 2019c. *Energy efficiency in existing buildings*, ANSI/ASHRAE/IES standard 100-2018. Atlanta: ASHRAE. https://www.ashrae.org/technical-resources/bookstore/standard-100.

———. 2020. *Standard for the design of high-performance green buildings*, Standard 189.1-2020. Atlanta: ASHRAE.

Avelar, Victor. 2007. *Guidelines for specifying data center criticality/tier levels*, APC White paper 122. Schneider Electric Data Center Science Center. https://download.schneider-electric.com/files?p_Doc_Ref=SPD_VAVR-6PHPBU_EN.

Axelarris, Lyle, Aaron Cooke, Craig Fredeen, Robbin Garber-Slaght, Emmett Leffel, Lorne Ricketts, William Rose, John P. Zarling, and Alexander Zhivov. 2021. Best practices for HVAC, plumbing and heat supply in Arctic climates. *ASHRAE Transactions* 127 (1).

Ayyrub, B. 2015. Practical resilience metrics for planning, design, and decision making. *ACME Journal of Risk and Uncertainty in Engineering Systems, Part A. Civil Engineering* 1 (3): 04015008.

BMWi (Bundesministerium fur Wirtschaft und Energie [Federal Ministry for Economic Affairs and Energy]). 2018. *Welcome to energieforschung.de, the information portal about funding opportunities and facts about applied energy research*. Web page. http://www.bine.info/publikationen/publikation/solardaecher-doppelt-nutzen/.

Boslet, Mark. 2010. *Is Ivanpah the world's most efficient solar plant?* Annapolis: Green Tech Media (GTM): A Wood Mackenzie Business. https://www.greentechmedia.com/articles/read/is-ivanpah-the-worlds-most-efficient-solar-plant.

BREEAM (Building Research Establishment Environmental Assessment Method). 2020. Web site. https://www.breeam.com/.

Case, M., R. Liesen, A. Zhivov, M. Swanson, B. Barnes, and J. Stinson. 2014a. A computational framework for low-energy community analysis and optimization. *ASHRAE Transactions* 120: 130–144.

Case, Michael, Richard J. Liesen, Alexander Zhivov, Matthew Swanson, Benjamin Barnes, and James Stinson. 2014b. *A computational framework for low energy community analysis and optimization*, NY-14-011, 283. New York: ASHRAE Winter Conference.

Case, M., R. Liesen, M. Swanson, J. Yu, and A. Zhivov. 2015. Integration of master planning and energy planning: From detailed to conceptual analysis. *ASHRAE Transactions* 121 (1): 133–140.

Danish Energy Agency, The. 2019. *Socio-economic analysis methodology and assumptions*. Copenhagen: Danish Ministry of Climate, Energy, and Utilities. https://ens.dk/service/fremskrivninger-analyser-modeler/samfundsoekonomiske-analysemetoder.

———. 2020. *Technology data*. Copenhagen: Danish Ministry of Climate, Energy and Utilities. https://ens.dk/en/our-services/projections-and-models/technology-data.

Danish Heat Supply Act, The. 2000. https://www.energybrokers.co.uk/wp-content/uploads/2015/10/Danish_Heat_Law_2000EN1.pdf. (unofficial translation of 2000 version).

Deru, Michael, Kristin Field, Daniel Studer, Kyle Benne, Brent Griffith, Paul Torcellini, Bing Liu, Mark Halverson, Dave Winiarski, Michael Rosenberg, Mehry Yazdanian, and Drury Crawle. 2011. *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock*, Technical Report NREL/TP-5500-46861. National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy11osti/46861.pdf.

DHS (U.S. Department of Homeland Security). 2017. *Resilient tunnel project*. Washington, DC: DHS Science and Technology Directorate. https://www.dhs.gov/sites/default/files/publications/Resilient%20Tunnel%20Project-508_0.pdf.

———. 2018. *Mission Assurance (MA) Construct*, DoD Instruction (DoDI) 3020.45. Washington, DC: Office of the Under Secretary of Defense for Policy. https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodi/302045p.pdf?ver=2018-08-14-081232-450.

———. 2019. *Emergency Management (EM) Program*, DoD Instruction 6055.17. Washington, DC: DoD.

———. 2020. *DoD Memorandum. Subject: Metrics and standards for energy resilience at military installations*. Washington, DC: DoD, Office of the Undersecretary of Defense, Acquisition and Sustainment.

DoD (U.S. Department of Defense). 2017. *DoD Emergency Management (EM) Program*, DoD Instruction (DODI) 6055.17. Washington, DC: DoD. https://irp.fas.org/doddir/dod/i6055_17.pdf.

Draxl, C., B.M. Hodge, A. Clifton, and J. McCaa. 2015. *Overview and meteorological validation of the wind integration National Dataset Toolkit*, Technical Report NREL/TP-5000-61740. Golden: National Renewable Energy Laboratory. https://www.nrel.gov/gis/wind-resource-maps.html.

EC (European Commission). 2019. *Clean energy for all Europeans package*. Brussels: EC. https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en.

———. 2020. *The renewable energy directive*. https://ec.europa.eu/energy/topics/renewable-energy/renewable-energy-directive_en.

———. 2021. *The energy efficiency directive*. https://ec.europa.eu/energy/topics/energy-efficiency/targets-directive-and-rules/energy-efficiency-directive_en.

Eddy, John, Nadine E. Miner, and Jason Stamp. 2017. Sandia's microgrid design toolkit. *The Electricity Journal* 30 (4): 62–67. https://doi.org/10.1016/j.tej.2017.04.002.

EIA (Energy Information Administration). 2012. *Commercial Buildings Energy Consumption Survey (CBECS)*. Washington, DC: EIA. https://www.eia.gov/consumption/commercial/.

———. 2019. *Cost and performance characteristics of new generating technologies. Annual energy outlook 2019.*

EISA (U.S. Energy Independence and Security Act of 2007). 2007. *Energy Independence and Security Act of 2007*. https://www.govinfo.gov/content/pkg/PLAW-110publ140/pdf/PLAW-110publ140.pdf.

EPAct (Energy Policy Act). 2005. *Energy Policy Act of 2005*. https://www.govinfo.gov/content/pkg/PLAW-109publ58/pdf/PLAW-109publ58.pdf.

EPBD (Energy Performance of Buildings Directive). 2018. *(EU) Directive 2018/844 Amending Directive 2010/31/EU on the Energy Performance of Buildings*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.156.01.0075.01.ENG.

Ericson, Sean, and Dan Olis. 2019. *A comparison of fuel choice for backup generators*, NREL/TP-6A50-72509. Golden: National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy19osti/72509.pdf.

European Environmental Agency, The. 2014. *Costs of air pollution from European industrial facilities*. Copenhagen: European Environmental Agency. https://www.eea.europa.eu/publications/costs-of-air-pollution-2008-2012.

FEMA (Federal Emergency Management Agency). 2013a. Other flood protection measures. Chapter 4. In *Floodproofing non-residential buildings*, FEMA P-936. Washington, DC: FEMA. https://www.fema.gov/sites/default/files/2020-07/fema_p-936_floodproofing_non-residential_buiildings_110618pdf.pdf.

———. 2013b. Dry floodproofing methods. Chapter 3. In *Floodproofing non-residential buildings*, FEMA P-936. Washington, DC: FEMA. https://www.fema.gov/sites/default/files/2020-07/fema_p-936_floodproofing_non-residential_buiildings_110618pdf.pdf.

———. 2014. *Emergency power systems for critical facilities: A best practices approach to improving reliability*, FEMA P-1019. Washington, DC: FEMA. FEMA P-1019 Emergency Power Systems for Critical Facilities: A Best Practices Approach to Improving Reliability | WBDG - Whole Building Design Guide.

———. 2021. *Floods*. Webpage. https://www.ready.gov/floods.

Frankel, Mark, and Cathy Turner. 2008. *Energy performance of LEED® for new construction buildings*. Vancouver: New Buildings Institute. https://newbuildings.org/sites/default/files/Energy_Performance_of_LEED-NC_Buildings-Final_3-4-08b.pdf.

Fraunhofer ISE. 2016. *PVTgen2 – Optimized PVT collectors for combined electricity and heat generation. Web page*. Freiburg: Fraunhofer ISE. https://www.ise.fraunhofer.de/en/research-projects/pvtgen2.html.

GBCI (Green Building Certification Institute). 2020. *RELi: Resilient design for a changing world*. Washington, DC: GBCI. https://gbci.org/reli.

Güssing, Borough of. 2011. *Case study: The European Centre for renewable energy (EEE) in Güssing as an example of how synergies can be realized*. http://www.guessing.co.at/.

Harriman, Lew, Geoff Brundrett, and Reinhold Kittler. 2019. *Humidity control design guide for commercial and institutional buildings*. Atlanta, GA: ASHRAE.

HQDA (Headquarters, Department of the Army). 2007. *Reliability/availability of electrical & mechanical command, control, communications, computer, intelligence, surveillance and reconnaissance (C4ISR) facilities*, Army technical manual (TM) 5-698-1. Washington, DC: HQDA. https://www.wbdg.org/FFC/ARMYCOE/COETM/ARCHIVES/tm_5_698_1_2003.pdf.

———. 2008a. *Emergency employment of army and other resources*, Army regulation (AR) 500–3. Washington, DC: HQDA.

———. 2008b. *U.S. Army continuity of operations (COOP) program policy and planning*, Army regulation 500–3. Washington, DC: HQDA.

———. 2008c. *U.S. Army continuity of operations program policy and planning*, Army regulation (AR) 500-3. Washington, DC: HQDA. (superseded by U.S. Army Continuity of Operations Program. AR 500-3. 2021).

———. 2012. *Command and Control Facilities (C2F) and other army headquarters*, Standard Design. UFC-4-140-03. U.S. Army Corps of Engineers (HQUSACE). USACE. Department of the Army Facilities Standardization Program. https://cryptome.org/dodi/ufc-4-140-03.pdf [THIS UFC MAY ALSO BE OBSOLETE. IT IS ALSO UNAVAILABLE THROUGH ARMY CHANNELS].

———. 2015a. *Energy security and sustainability (ES2) strategy*. Washington, DC: HQDA. https://www.hsdl.org/?view&did=766353.

———. 2015b. *Brigade operations complex, brigade and battalion headquarters*, Standard design. U.S. Army Corps of Engineers (USACE). UFC 4-140-01. Department of the Army Facilities Standardization Program. THIS DOCUMENT IS NO LONGER AVAILABLE, SEEMS TO HAVE BEEN SUPERSEDED BY A NON-UFC DOCUMENT. See: https://rfp-wizard.mrsi.erdc.dren.mil/MRSI/content/cos/sas/bn-bde-hq/Library/Standard%20Designs/BDE-BN_HQ_Std_Dgn_Rev_6.0.pdf.

http://www.danskfjernvarme.dk/-/media/danskfjernvarme/kurser-moder/modematerialer/erfamoeder/2015-maj-erfa-traef-om-energibesparelser/ventilationsguide%2D%2Denergiloesninger.pdf [DEAD LINK].

https://www.seac.cc/wp-content/uploads/2018/01/SEAC_PVTinSHaPeBenchmark_final.pdf [DEAD LINK].

https://www.solarthermalworld.org/sites/gstec/files/news/file/2017-06-01/pvt_switzerland_final.pdf [DEAD LINK].

IEA (International Energy Agency). 2021a. *Application of PVT collectors*, Web page. Bournens: International Energy Agency, Solar Heating & Cooling Programme, Task 60. http://task60.iea-shc.org/.

———. 2021b. *Annex 73. Energy master planning for resilient public communities – Case studies*, ed. Anna Maria Fulterer and Ingo Leusbrock. Paris: International Energy Agency, Energy in Buildings and Communities (IEA-ECB), Annex 73. https://annex73.iea-ebc.org/.

IECC (International Energy Conservation Code). 2012. *IEEE guide for electric power distribution reliability indices*, IEEE 1366. Piscataway: IEEE.

———. 2018. Energy efficiency and carbon reduction. In *Leading the way to energy efficiency*. Washington, DC: IECC. https://www.iccsafe.org/products-and-services/i-codes/2018-i-codes/iecc/.

IEEE (Institute of Electrical and Electronics Engineers). 2007. *IEEE recommended practice for electric systems in health care facilities*, IEEE standard 602™-2007. Piscataway: IEEE.

IMCOM (U.S. Army Installation Management Command). 2010. *Energy and water conservation design requirements for sustainment, restoration and modernization (SRM) projects and MILCON construction*. Washington, DC/Champaign: IMCOM, prepared by the Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL).

ISO (International Organization for Standardization). 2017. *Buildings and constructed assets – Service life planning – Part 5: Life-cycle costing*, ISO 15686-5:2017(en). Geneva: ISO.

———. 2018. *Reciprocating internal combustion engine-driven alternating current generating sets – Part 1: Application, ratings and performance*, ISO 8528-1. Geneva: ISO.

———. 2019. *Date and time*, ISO 8601-1. Geneva: ISO.

Jeffers, Robert F., Amanda M. Wachtel, Alexander M. Zhivov, Calum B. Thompson, Avinash Srivastava, and Patrick W. Daniels. 2020a. Integration of resilience goals into energy master planning framework for communities. *ASHRAE Transactions* 126 (1): 803–823.

Jeffers, Robert, Amanda Wachtel, Alexander Zhivov, Calum Thompson, Avinash Srivastava, and Patrick Daniels. 2020b. *Integration of resilience goals into energy master planning framework for communities*. ASHRAE Winter Conference 2020, ASHRAE.

Jungclaus, Matt, Cara Carmichael, Chris McClurg, Margaret Simmons, Randall Smidt, Kinga Porst Hydras, Sharon Conger, Alexander Zhivov, Fred Winter, John Shonder, and Cyrus Nasseri. 2017. Deep energy retrofits in federal buildings: the value, funding models, and best practices. *ASHRAE Transactions* 123 (1): 55–70.

Kimman, J., R. Rovers, and R. Ravesloot. 2010. *Toward 0-impact buildings and built environments*. Amsterdam: Techne Press. ISBN:978-90-8594-028-9.

Kostival, A., C. Rivkin, W. Buttner, and R. Burgess. 2013. *Pressure relief devices for high-pressure gaseous storage systems: Applicability to hydrogen technology*, NREL/TP-5400-60175. Golden: National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy14osti/60175.pdf.

LaCommare, Kristina, Peter Larsen, and Joseph Eto. 2017. *Evaluating proposed investments in power system reliability and resilience: Preliminary results from interviews with public utility commission staff*, LBNL-1006971. Berkeley: Lawrence Berkeley National Laboratory. https://doi.org/10.2172/1342947.

Lavappa, P.D., and J.D. Kneifel. 2019. *Energy price indices and discount factors for life-cycle cost analysis – 2019, Annual supplement to NIST handbook 135*, NISTIR 85-3273-34. Washington, DC: U.S. Department of Commerce, NIST (National Institute of Standards and Technology [formerly National Bureau of Standards]). https://doi.org/10.6028/NIST.IR.85-3273-34.

Laws, N.D., K. Anderson, N.A. DiOrio, X. Li, and J. McLaren. 2018. Impacts of valuing resilience on cost-optimal PV and storage systems for commercial buildings. *Renewable Energy* 127: 896–909.

Liesen, R., M. Swanson, M. Case, A. Zhivov, A. Latino, and D. Dreyer. 2015. Energy master planning toward net zero energy installation – Portsmouth Naval Shipyard. CH-15-015. *ASHRAE Transactions* 121 (1): 160–175.

Liesen, Richard J., Brianna Morton, Brandy Diggs-McGee, and Alexander M. Zhivov. 2021. Thermal energy system resilience: Thermal Decay Test (TDT) in Cold/Arctic Climates, Part II modeling. *ASHRAE Transactions* 127 (1).

Lohse, R., and A. Zhivov. 2019. *Deep energy retrofit guide for public buildings – Business and financial models*. Basel: Springer.

Loorbach, D. 2007. *Transition management*. Utrecht: International Books.

Marqusee, Jeffrey, Craig Schultz, and Dorothy Robyn Noblis. 2017. *Power begins at home: Assured energy for U.S. military bases*, 24. Reston: Noblis, Inc. https://www.pewtrusts.org/~/media/assets/2017/01/ce_power_begins_at_home_assured_energy_for_us_military_bases.pdf.

McCarthy, Kevin, and Victor Avelar. 2016. *Comparing UPS system design configurations*, White Paper 75. Rev. 4. Schneider Electric. Schneider Electric's Data Center Science Center DCSC@Schneider-Electric.com.

Milbrandt, A. 2005. *A geographic perspective on the current biomass resource availability in the United States*, Technical report NREL/TP-560-39181.

Millar, Madelaine. 2019. *New software helps users build resilient, cost-effective energy architectures*. Lexington: Massachusetts Institute of Technology (MIT) Lincoln Laboratory. https://www.ll.mit.edu/news/new-software-helps-users-build-resilient-cost-effective-energy-architectures.

Ministry of Environment and Energy (Denmark). 2000. *Danish Heat Supply Act*. Copenhagen: Ministry of Environment and Energy. https://www.energybrokers.co.uk/news/resources/danish-heat-supply-act#:~:text=Article%201.,the%20energy%20system%20on%20oil.

Murphy, Caitlin, Eliza Hotchkiss, Kate Anderson, Clayton Barrows, Stuart Cohen, Sourabh Dalvi, Nick Laws, Jeff Maguire, Gord Stephen, and Eric Wilson. 2020. *Adapting existing energy planning, simulation, and operational models for resilience analysis*, NREL/TP-6A20-74241. Golden: NREL. https://www.nrel.gov/docs/fy20osti/74241.pdf.

NAVFAC (Naval Facilities Engineering Command). 2016. *Military medical facilities*. UFC 4-510-01, Unified Facilities Criteria (UFC). Washington, DC: Headquarters, U.S. Army Corps of Engineers (HQUSACE), NAVFAC (Preparing Agency), and U.S. Air Force Civil Engineer Center (AFCEC). UFC 4-510-01 Design: Military Medical Facilities with Change 2 (wbdg.org).

———. 2019. *Engine-driven generator systems for prime and standby power applications*, UFC 3-540-01. Washington, DC: Headquarters, U.S. Army Corps of Engineers (HQUSACE), NAVFAC (Preparing Agency), and U.S. Air Force Civil Engineer Center (AFCEC). https://www.wbdg.org/FFC/DOD/UFC/ufc_3_540_01_2014_c2.pdf.

NERC (North American Electric Reliability Corporation). 2018. *Reliability issues steering committee report on resilience*. Atlanta: NERC. https://www.nerc.com/comm/RISC/Related%20Files%20DL/RISC%20Resilience%20Report_Approved_RISC_Committee_November_8_2018_Board_Accepted.pdf.

NFPA (National Fire Protection Association). 2016. *Standard for emergency and standby power systems*, NFPA 110. Quincy: NFPA.

———. 2018a. *Health care facilities code*, NFPA 99. Quincy: NFPA.

———. 2018b. *Life safety code*, NFPA 101. Quincy: NFPA.

———. 2020. *National electrical code*, NFPA 70. Quincy: NFPA.

Nguyen, Tien, Jacob Spendelow, and Robert Margolis. 2014. *Levelized costs of electricity from CHP and PV*. Washington, DC: U.S. Department of Energy (USDOE). https://www.hydrogen.energy.gov/pdfs/14003_lcoe_from_chp_and_pv.pdf.

NIAC (National Infrastructure Advisory Council). 2009. *Critical infrastructure resilience: Final report and recommendations*. Washington, DC: NIAC. https://www.cisa.gov/sites/default/files/publications/niac-critical-infrastructure-resilience-final-report-09-08-09-508.pdf.

NIOSH (National Institute for Occupational Safety and Health). 2016. *Criteria for a recommended standard: occupational exposure to heat and hot environments*, DHHS (NIOSH) Publication Number 2016-106. Cincinnati: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, NIOSH.

Nouvel, Romain, K-H. Brassel, M. Bruse, Eric Duminil, Volker Coors, Ursula Eicker, and D. Robinson. 2015. *SIMSTADT, a new workflow-driven urban energy simulation platform for Citygml City Models*. Lausanne: CISBAT 2015 International Scientific Conference.

NRC (National Research Council). 2013. *Levees and the National Flood Insurance Program-improving policies and practices*. Washington, DC: The National Academies Press. https://www.nap.edu/read/18309/chapter/8#100.

NREL (National Renewable Energy Laboratory). 2019. *REopt Lite*. Golden: NREL. https://reopt.nrel.gov/tool.

———. 2020. *Geospatial data science*. http://www.nrel.gov/gis.

———. n.d. *2017 annual technology baseline*. https://www.nrel.gov/analysis/data-tech-baseline.html.

Nutaro, James. 2011. *Building software for simulation: Theory and algorithms, with applications in C++*. New York: Wiley.

NYC (City of New York). 2019. *Climate mobilization act*. New York: New York City Council. https://council.nyc.gov/data/green/.

OASD (Office of the Assistant Secretary of Defense). 2016. *Memorandum. Subject: Installation energy plans*. Washington, DC: OSD. https://www.acq.osd.mil/eie/Downloads/IE/Signed%20Installation%20Energy%20Plan.pdf.

Oberg, Bjorn K., Angela Urban, Emmet Leffel, Jonathan Goebel, Matt Perry, Dragos Vas, Dayne Broderson, Richard Liesen, and Alexander Zhivov. 2021. Thermal energy system resilience: Thermal decay test (TDT) in cold/arctic climates, Part I data collection and protocol. *ASHRAE Transactions* 127 (1).

OUSD (Office of the Under Secretary of Defense). 2021. *Memorandum. Subject: Metrics and standards for energy resilience at military installations*. Washington, DC: OUSD. https://www.acq.osd.mil/eie/Downloads/IE/Metrics%20and%20Standards%20for%20Energy%20Resilience%2020%20May%202021.pdf.

Parsons, K., ed. 2003. *Thermal comfort. Human thermal environments*, 196–227. London: Taylor & Francis.

Perez, R., P. Ineichen, K. Moore, M. Kmiecikm, C. Chain, R. George, and F. Vignola. 2002. A new operational satellite-to-irradiance model. *Solar Energy* 73 (5): 307–317.

PNNL (Pacific Northwest National Laboratory). 2017. *Inflatable plug for subway tunnels demonstrated*. Richland: PNNL. https://www.pnnl.gov/news/release.aspx?id=4415.

Preston-Werner, Tom. 2018. *Tom's Obvious, Minimal Language V0.5.0*. https://github.com/toml-lang/toml.

ready.gov. 2020. *Floods*. Web page. https://www.ready.gov/floods.

Roege, P., Z.A. Collier, J. Mancillas, J.A. McDonagh, and I. Linkov. 2014. Metrics for energy resilience. *Energy Policy* 72: 249–256.

Schröder, T., and W. Kuckshinrichs. 2015. Value of lost load: An efficient economic indicator for power supply security? A literature review. *Frontiers in Energy Research* 3: 55. https://www.frontiersin.org/articles/10.3389/fenrg.2015.00055/full.

Seattle.gov. 2018. *Energy compliance through the target performance or total building performance paths*, SDCI Tip #423. Seattle: Seattle Department of Construction & Inspections (SDCI). http://www.seattle.gov/DPD/Publications/CAM/Tip423.pdf.

Sengupta, M., Y. Xie, A. Lopez, A. Habte, G. Maclaurin, and J. Shelby. 2018. The National Solar Radiation Data Base (NSRDB). *Renewable and Sustainable Energy Reviews* 89 (June): 51–60. https://www.nrel.gov/gis/solar-resource-maps.html.

Shafranovich, Yakov. 2005. *Common format and MIME type for comma-separated values (CSV) files. RFC 4180. Internet Requests for Comments*. Reston: The Internet Society. http://www.rfc-editor.org/rfc/rfc4180.txt.

Sharp, Terry. 2015. *Derivation of building energy use intensity targets for ASHRAE standard 100*, ORNL/TM-2014/215. Oak Ridge, TN: Oak Ridge National Laboratory. https://info.ornl.gov/sites/publications/files/Pub49965.pdf.

Sharp, Terry R., Alexander Zhivov, Matthias Haase, and Joergen Rose. 2020. *Energy master planning: Identifying framing constraints that scope your technology options*. ASHRAE Winter Meeting, Atlanta, February 2020.

Singh, Birendra (Rob), Pallavi Roy, Thierry Spiess, Bala Venkatesh. 2015. *Sustainable integrated urban and energy planning, the evolving electrical grid and urban energy transition*. Toronto: Ryerson University, Centre for Urban Energy. https://www.ryerson.ca/content/dam/cue/pdfs/White%20Paper%20-%20Urban%20and%20Energy%20Planning.pdf.

Stamp, Jason E., John P. Eddy, Richard P. Jensen, and Karina Munoz-Ramos. 2015. *Microgrid design analysis using technology management optimization and the performance reli-*

ability model, SAND2016-0429. Albuquerque: Sandia National Laboratories. https://doi.org/10.2172/1235988.

State of Washington. 2019. *Senate Bill 5116*. http://lawfilesext.leg.wa.gov/biennium/2019-20/Pdf/Bills/Senate%20Bills/5116.pdf.

Swanson, Matthew, Benjamin Barnes, Richard J. Liesen, Michael Case, and Alexander Zhivov. 2014. Community-scale energy supply and distribution optimization using mixed-integer linear programming. *ASHRAE Transactions* 120 (January): 145–162.

TIA (Technology Innovation Agency). 2012. *Telecommunications infrastructure standard for data centers*, ANSI/TIA-942-A. Pretoria: TIA.

Turner, W. Pitt, John H. Seader, and Kenneth G. Brill. 2001. *Industry standard tier classifications define site infrastructure performance*. White Paper. https://www.connectixcablingsystems.com/themes/ccs/pdf/Tier_Classification.pdf.

UNEP (United Nations Environment Programme). 2013. *Energy efficiency for buildings*. Paris: UNEP. www.studiocollantin.eu/pdf/UNEP%20Info%20sheet%20-%20EE%20Buildings.pdf.

———. 2015. *District energy in cities: Unlocking the potential in energy efficiency and renewable energy*. Nairobi: UNEP. http://wedocs.unep.org/bitstream/handle/20.500.11822/9317/-District_energy_in_cities_unlocking_the_potential_of_energy_efficiency_and_renewable_ene.pdf?sequence=2&isAllowed=y.

University of Washington. 2017. Utility tunnels and tranches. In *University of Washington facilities services design guide*. Seattle: University of Washington. https://facilities.uw.edu/files/media/fsdg-02-u-utility-tunnels-trenches.pdf.

Urban, A., E. Keysar, K. Judd, A. Srivastava, C. Thompson, M. Case, and A. Zhivov. 2020. Energy master planning for resilient public communities – Best practices from U.S. military installations. OR-20-022. *ASHRAE Transactions* 126 (1).

USARNORTH (U.S. Army North). 2019. *Risk management process*, 210-221-0494. San Antonio: USARNORTH.

USDA (U.S. Department of Agriculture). 2013. *Keeping food safe during an emergency*. Washington, DC: USDA.

———. n.d. *Food safety and inspection service*. Undated. Website. Washington, DC: USDA Food Safety and Inspection Service. https://www.fsis.usda.gov/wps/portal/fsis/topics/food-safety-education/get-answers/food-safety-fact-sheets/emergency-preparedness/keeping-food-safe-during-an-emergency/CT_Index.

USDOE (U.S. Department of Energy). 2002a. *21 steps to improve cyber security of SCADA networks*. Washington, DC: USDOA. https://www.oe.netl.doe.gov//docs/prepare/21stepsbooklet.pdf.

———. 2002b. *Whole-house ventilation systems*, Technology fact sheet. DOE/GO-102002-0778. Washington, DC: USDOE. https://www.nrel.gov/docs/fy03osti/26458.pdf.

———. 2017. Ensuring electricity system reliability, security, and resilience. Ch. 4. In *Transforming the nation's electricity sector: The second installment of the QER*. DOE/EPSA-0008. Washington, DC: USDOE. https://www.energy.gov/sites/prod/files/2017/02/f34/Quadrennial%20Energy%20Review%2D%2DSecond%20Installment%20%28Full%20Report%29.pdf.

———. Undated. *Commercial reference buildings*. Washington, DC: U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/buildings/commercial-reference-buildings.

USEPA (U.S. Environmental Protection Agency). 2017. *Catalog of CHP technologies*. https://www.epa.gov/sites/production/files/2015-07/documents/catalog_of_chp_technologies.pdf

———. 2020. *U.S. Environmental Protection Agency Energy Star Program*. https://www.energystar.gov/.

USGBC (U.S. Green Building Council). 2020. *LEED: Leadership in Energy and Environmental Design*. Web page. http://leed.usgbc.org/leed.html.

van Dronkelaar, Chris, Mark Dowson, E. Burman, Catalina Spataru, and Dejan Mumovic. 2016. A review of the energy performance gap and its underlying causes in non-domestic buildings. *Frontiers in Mechanical Engineering*. https://doi.org/10.3389/fmech.2015.00017.

Viscusi, W. Kip, and Joseph E. Aldy. 2003. The value of a statistical life: A critical review of market estimates throughout the world. *Journal of Risk and Uncertainity* 27 (1): 5–76.

Vugrin, E., A. Castillo, and C. Silva-Monroy. 2017. *Resilience metrics for the electric power system: A performance-based approach*, SAND2017-1493. Albuquerque: Sandia National Laboratories. https://doi.org/10.2172/1367499.

Weiler, Verena, Jonas Stave, and Ursula Eicker. 2019. Renewable energy generation scenarios using 3D urban modeling tools-methodology for heat pump and co-generation systems with case study application. *Energies* 12 (January). https://doi.org/10.3390/en12030403.

White House, The. 2013. *Presidential policy directive 21: Critical infrastructure security and resilience*, PPD-21. Washington, DC: The White House. https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil.

Wikipedia. Undated(a). *Emergency power system*. https://en.wikipedia.org/wiki/Emergency_power_system.

Wikipedia. Undated(b). *Flood control*. https://en.wikipedia.org/wiki/Flood_control.

Wikipedia. Undated(c). *Microgrid*. https://en.wikipedia.org/wiki/Microgrid.

Wikipedia. Undated(d). *SCADA*. https://en.wikipedia.org/wiki/SCADA.

Wikipedia. Undated(e). *Standby generator*. https://en.wikipedia.org/wiki/Standby_generator.

Wikipedia. Undated(f). *Tunnel*. https://en.wikipedia.org/wiki/Tunnel.

Wikipedia. Undated(g). *Uninterruptible power supply*. https://en.wikipedia.org/wiki/Uninterruptible_power_supply.

Wikipedia. Undated(h). *Ventilation (Architecture)*. https://en.wikipedia.org/wiki/Ventilation_(architecture).

Wikipedia. Undated(i). *New York City steam pipe explosion*. https://en.wikipedia.org/wiki/2007_New_York_City_steam_explosion.

Wikipedia. Undated(j). *Pressure regulator*. https://en.wikipedia.org/wiki/Pressure_regulator.

Willis, Henry H., and Kathleen Loa. 2015. *Measuring the resilience of energy distribution systems*. Santa Monica: RAND Corporation. https://www.rand.org/pubs/research_reports/RR883.html.

Winfield, Emily, Robin Rader, Alexander Zhivov, Thomas Adams, Anders Dyrelund, Craig Fredeen, Oddgeir Gudmundsson, and Brent Goering. 2021. Best practices for HVAC, plumbing and heat supply in Arctic climates. *ASHRAE Transactions* 127 (1).

Yamanaka, Keith. 2020. Hawaiian Electric Company Schofield Generating Station. Information Paper IMHW-PW.

Zhivov, Michael. 2020. Enhanced life-cycle cost analysis of sustainable office buildings. *ASHRAE Transactions* 126 (1): 691–712.

Zhivov, Alexander M., Michael Case, Richard Liesen, Jacques Kimman, and Wendy Broers. 2014. Energy master planning towards net zero energy communities/campuses. *ASHRAE Transactions* 119 (1): 325. NY-14-010. New York: ASHRAE winter conference.

Zhivov, A., M. Case, R. Liesen, and M. Swanson. 2015a. *Demonstrate energy component of the installation master plan using net zero installation virtual testbed*, Final Report. ESTCP Project EW-201240. https://apps.dtic.mil/sti/pdfs/AD1024263.pdf.

Zhivov, A., M. Case, R. Liesen, M. Swanson, B. Barnes, A. Woody, S. Richter, A. Latino, C. Björk, L. Fiedler, and P. Simihtis. 2015b. Energy master planning toward net zero energy installation – U.S. Military Academy, West Point. *ASHRAE Transactions* 121 (1): CH-15-014.

Zhivov, Alexander, William Rose, Raymond Patenaude, and William Warren. 2021. Requirements for building thermal conditions under normal and emergency operations in extreme climates. *ASHRAE Transactions* 127 (1).