

ECBCS Annex 49

report

Low Exergy Systems for High-Performance Buildings and Communities

Annex 49 Summary report



"Exergy Assessment Guidebook for the Built Environment"

Edited by Herena Torio and Dietrich Schmidt



International Energy Agency
Energy Conservation in
Buildings and Community
Systems Programme

FRAUNHOFER VERLAG

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Participating countries in ECBCS:

Australia, Austria, Belgium, Canada, P.R. China, Czech Republic, Denmark, Finland, France, Germany, Greece, Italy, Japan, Republic of Korea, the Netherlands, New Zealand, Norway, Poland, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom and the United States of America.

Further information about the ECBCS programme may be obtained from www.ecbcs.org

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PREFACE

International Energy Agency (IEA)

The International Energy Agency was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster co-operation among the twenty-four IEA participating countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems (ECBCS)

The IEA co-ordinates research and development in a number of areas related to energy. The mission of one of those areas, the ECBCS - Energy Conservation for Building and Community Systems Programme, is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research.

The research and development strategies of the ECBCS Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Building Forum Think Tank Workshop, held in March 2007. The R&D strategies represent a collective input of the Executive Committee members to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy conservation technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in three focus areas of R&D activities:

- Dissemination
- Decision-making
- Building products and systems

The Executive Committee (ExCo)

Overall control of the program is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date, the following projects have been initiated by the executive committee on Energy Conservation in Buildings and Community Systems (completed projects are identified 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 Centre
- Annex 6: Energy Systems and Design of Communities (*)
- Annex 7: Local Government Energy Planning (*)
- Annex 8: Inhabitants Behaviour 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 Modelling (*)
- Annex 22: Energy Efficient Communities (*)
- Annex 23: Multi Zone Air Flow Modelling (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 Tool-kit 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: Towards Net Zero Energy Solar Buildings
- Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods
- Annex 54: Analysis of Micro-Generation & Related Energy Technologies in Buildings
- Annex 55: Reliability of Energy Efficient Building Retrofitting (RAP-RETRO)
- Annex 56: Energy and Greenhouse Gas Optimised Building Renovation

- 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 - Energy Efficient Communities

(*) – Completed

IEA ECBCS ANNEX 49

ECBCS Annex 49 was a three year international research project which arose from the discussions held in a Future Building Forum in Padova in April 2005. The project began on November 2006 and ran until November 2009. It involved 22 research institutions, companies and universities from 12 countries, many of which are also members of the International Society of Low Exergy Systems in Buildings (LowExNet). The main objective of this project was to develop concepts for reducing exergy demand in the built environment, thus reducing the CO₂-emissions of the building stock and supporting structures for setting up sustainable and secure energy structures for this sector.

Specific objectives are to:

- to use exergy analysis to develop tools, guidelines, recommendations, best-practice examples and background material for designers and decision makers in the fields of building, energy production and politics
- to promote possible energy/exergy cost-efficient measures for retrofit and new buildings, such as dwellings and commercial/public buildings
- to promote exergy-related performance analysis of buildings, viewed from a community level.

Countries which participated in the IEA ECBCS Annex 49: Austria, Canada, Denmark, Finland, Germany, Italy, Japan, the Netherlands, Poland, Sweden, Switzerland, and the United States of America.

The work within Annex 49 is based on an integral approach which includes not only the analysis and optimisation of the exergy demand in heating and cooling systems, but also all other processes where energy/exergy is used within the building stock. In order to achieve this, the project worked with the underlying basics, i.e. **exergy analysis methodologies**. The work items were aimed at development, assessment and analysis methodologies, and the development of a tool for the design and performance analysis of the regarded systems.

Exergy analysis methodologies	
Exergy supply and renewable resources	Low exergy systems
Community Level	Building Level
Knowledge transfer and dissemination	

Structure of the ECBCS Annex 49

With this basis, the work on **exergy efficient community supply** systems was focused on the development of exergy distribution, generation and storage system concepts, as well as a collection of case studies. For the course of the project, both the generation and supply of and the use of energy/exergy were important issues. Resulting from this, the development of **exergy efficient building technology** depends on the reduction of exergy demand for the heating, cooling and ventilation of buildings. The **knowledge transfer and dissemination** activities of the project are focused on the collection and spreading of information on ongoing and finished work.

This report is the summary version of the final report of ECBCS Annex 49. The full and extended version, the ECBCS Annex 49 Guidebook, is available as a CD-ROM and also freely available on the internet (www.annex49.com).

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www.annex49.com
or www.ecbcs.org/annexes/annex49.htm

The Guidebook of ECBCS Annex 49 is the result of a joint effort of many countries. We would like to gratefully acknowledge all those who have contributed to the project by taking part in the writing process and the numerous discussions. A list of the participants within Annex 49 and their corresponding countries can be found in the Appendix. All participants from all countries involved have contributed to the guidebook. However, the following annex participants have taken over the responsibility of writing the chapters:

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David Solberg	specially chapters 6 and 7

1. INTRODUCTION

Background and Motivation

Environmental problems that have been linked to extended energy use, such as global warming, have raised a growing concern which has emphasised both the importance of all kinds of so-called “energy saving measures”, and the necessity for an increased efficiency in all forms of energy utilisation.

The consumption of primary energy in residential and commercial buildings accounts for more than one third of the total world energy demand. This means that buildings are collectively a major contributor to energy related problems on a global scale. Despite the efforts made to improve energy efficiency in buildings, the issue of gaining an overall assessment, and comparing different energy sources still exists (Schmidt and Shukuya 2003). Current analysis and optimisation methods do not distinguish between different qualities of energy flows during the analysis. In the building codes of several countries, this problem has been solved by the transformation of all energy flows to the primary energy demand. An assessment of energy flows from different sources is first carried out at the end of the analysis by multiplying the energy flows by the so-called primary energy factors. The primary energy factors necessary for the calculation have been derived from statistical material and political discussion and are not based on thermodynamic process analyses. All energy conversion steps from the extraction of energy sources (e.g. fuels) to the final demands are assessed in the primary energy method; however, no information on the quality of the supplied energy and its relation to the required energy demands can be obtained through this assessment.

The quantity of energy is given by the first law of thermodynamics, and is calculated from energy balances for a system. Current energy systems in buildings are designed and improved based on this law. This means that of course the quantity of energy supplied is matched with the quantity of energy required. Highly efficient condensing boilers, with efficiencies of up to 98% are a straightforward result of such an analysis framework.

The quality of energy, is given, in turn, by a combined analysis of the first and second laws of thermodynamics. From these combined analyses, the thermodynamic concept of exergy is derived. Exergy represents the part of an energy flow which can be completely transformed into any other form of energy, thereby depicting the potential of a given energy quantity to perform work or, in other words, its quality.

In every energy system, some part of the exergy supplied to the system in question has to be “consumed” or destroyed to make the system work. In the case of the highly efficient boilers mentioned above when used to supply low temperature heat, the potential to produce work (exergy) of the fuels fed into the boiler is almost completely lost in the combustion process. Due to this loss of energy potential, a large consumption of exergy occurs. Exergy efficiencies for such building systems are lower than 10%.

A combined energy and exergy assessment permits a understanding of the importance of moving away from burning processes for supplying the energy demands in buildings, and paves the way for a new technique of designing energy supply systems in buildings based on the use of renewable and low temperature heat sources.

The exergy approach

Most of the energy used in the building sector is required to maintain constant room temperatures of around 20°C. Since the required temperature levels for the heating and cooling of indoor spaces are low, the quality of the energy demanded for applications in room conditioning are naturally low ($q \approx 7\%$)¹.

Different levels of energy quality are needed for different appliances within a building. If the production of domestic hot water is considered as heating water up to temperatures of about 55°C, the energy quality needed is slightly higher than that of heating a room to 20°C ($q \approx 15\%$). For energy applications such as cooking or heating a sauna, an even higher quality level is needed ($q \approx 28\%$). For the operation of different household electrical appliances and lighting the highest possible quality of energy is needed ($q \approx 100\%$).

Today's energy supply structure is not as sophisticated as today's energy demands. Energy is commonly supplied as electricity or as a fossil energy carrier. Thereby, the energy quality of the supply for all different uses is at a constant value of ($q \approx 100\%$), a value that is unnecessarily high (see Figure 1.1, left). Similarly as in the case of a boiler mentioned above, the typical primary energy efficiency of the heating process in Germany is approximately 70% for heating newly erected dwellings that are equipped with good building service systems. This level of efficiency decreases to approximately 10% when considering exergy.

In turn, an adaptation of the quality levels of supply and demand could be managed by covering, for

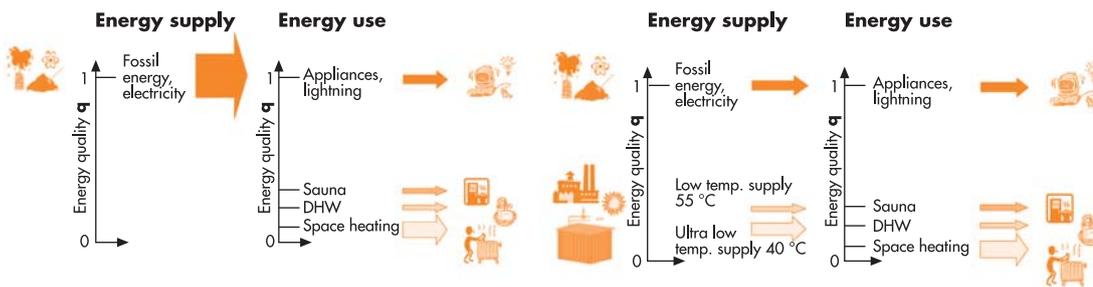


Figure 1.1: Left: Energy supply by means of high quality energy sources for a typical building with several uses at different quality levels. Right: Energy supply with sources at different quality levels for the same building with uses at different quality levels.

example, the heating demand with suitable energy sources, as available waste district heating with a quality level of about 30%. Other appropriate low exergy sources (i.e. low temperature sources) are solar or ground source heat. By using these sources, quality levels of the energy demanded and supplied are adapted to each other as shown in the right diagram of Figure 1.1.

New low temperature heating and high temperature cooling systems are required to make energy use in buildings even more efficient by supplying energy with low quality and creating the possibility of using renewable energy sources. There is a large variety of such emission systems solutions on the market, e.g. water borne floor heating systems, that can be used to supply buildings with the lowest possible supply temperatures ($q \approx 13\%$). Furthermore, it has been found that when low temperature systems are applied to buildings, the thermal indoor comfort is improved at the same cost level as by using conventional, less comfortable building service systems (IEA Annex 37, 2003).

In this report a summary of the methodology and models behind complex dynamic exergy simulations which have been developed within the Annex 49 project is presented. A detailed version of these models and method, with detailed equations and discussions, are presented in the full version of the ECBCS Annex 49 final report.

It should be noted that a simplified steady-state analysis has proven to be adequate for the first estimations on the performance of different building systems. Additionally, several simplified and user-friendly tools that grant building planners, architects, and other decision makers of the built environment access to an exergy-based building approach have been developed within Annex 49 and are also introduced in this report.

Benefits and outcomes: Why exergy?

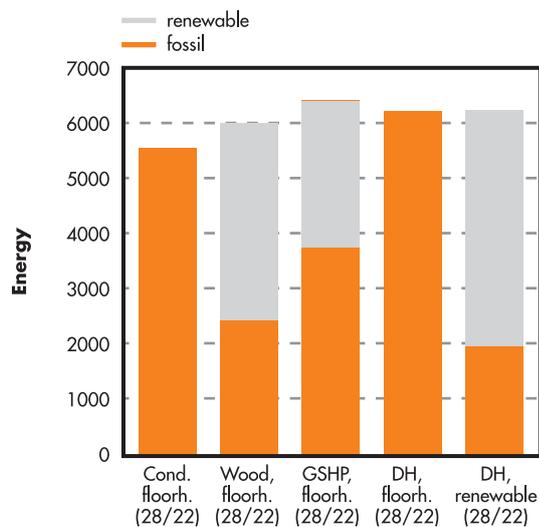
As previously stated, common assessments of energy utilisation in buildings are based solely on quantitative considerations. The exergy analysis approach will take the methods of building energy assessment a step further by considering not only the quantitative aspects of demand and supply, but the qualitative aspects as well.

The following simple example shows how an exergy analysis can help building designers choose more efficient energy supply systems.

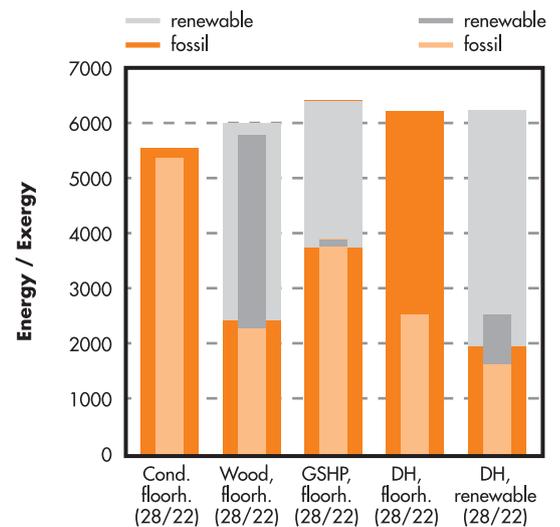
Figure 1.2 shows the results from a simplified exergy analysis on a building case study. Different energy supply systems have been considered to supply the same low-exergy demands for space heating and domestic hot water (DHW) production. Primary energy analyses focus on the maximum possible use of renewable energy sources. Based on the criteria from primary energy analysis the input of fossil energy sources needs to be minimized. Following, the wood pellet boiler would be the best performing solution, allowing minimum use of primary fossil energy.

Exergy analyses aim additionally at minimizing both the fossil and renewable exergy input for a given system. An exergy analysis promotes an efficient energy supply, while highlighting that even renewable energy sources need to be used efficiently. Figure 1.2 depicts the exergy input of a wood-based boiler as being the largest of the four options. This is because wood is a high-quality energy source even though it is renewable and the efficiency of wood boilers is not yet as high as that of conventional liquefied gas condensing boilers. The fact that the exergy input is the largest indicates that such an energy supply does not promote an efficient use of the potential of the energy sources used. As a high-quality energy source, wood could be used instead for supplying high exergy demands such as electricity generation. In this way, wood as a fuel would be used to its fullest potential.

Primary energy demand



Primary energy demand



Where:	
Cond.	Natural gas fired condensing boiler
Wood.	Wood pellet boiler
GSHP	Ground source heat pump
DH	(Waste) District heat
Floorh.	Floor heating system

Figure 1.2: Calculated primary energy demand (fossil and renewable) and the related exergy for different supply options of a building case study. Results correspond to steady state calculations performed with the Annex 49 pre-design tool (see chapter 3).

The use of wood in a combined heat and power (CHP) unit, using the waste heat from the power generation process for low-exergy applications, allows minimum exergy input and minimum fossil energy input.

A deeper understanding of the nature of energy flows and/or conversion processes in buildings would enable building designers and architects to achieve an improved overall design.

Based on the example and considerations above, the main benefits of joining considerations on the quantity and quality of energy supply, i.e. of exergy analysis, can be summarized as:

- Exergy analysis clearly shows the importance of promoting a more efficient use of fossil fuels. Systems such as highly energy efficient boilers would always be avoided following this approach. CHP systems, using better the high potential (i.e. quality) of fossil fuels would be promoted instead.
- The above conclusion is also valid for renewable energy sources with high thermodynamic potential (i.e. high exergy sources), as shown in the example presented (Figure 1.2). Thereby, exergy analysis also promotes an efficient use of limited available renewable sources such as biomass.
- Exergy analysis highlights the importance of using low temperature renewable energy sources available to supply heat demands in buildings.

Low temperature heating and high temperature cooling systems in buildings are exergy efficient emission systems, that allow the integration of renewable sources. The exergy performance of these systems is significantly higher than for conventional air based or high temperature heating and low temperature cooling systems. Thereby, exergy analysis is an appropriate tool for integral building design, allowing to see the benefits of efficient energy use in every conversion step of the supply chain.

Target group

This report is a summary version of the full Annex 49 report. This short version is oriented to building planners, architects and decision makers, and tries to bring them closer to the exergy concept by giving an overview on the main features and benefits from this approach. Therefore, the technical details behind the exergy concept are explained in a simplified and applied manner, focusing more on the outcomes of exergy analysis and its importance for building systems design. In addition, the main features of several building and community case studies highlight the importance and main benefits of this analysis approach.

The full version of the ECBCS Annex 49 report, which is freely available under www.annex49.com, is mainly oriented, in turn, to scientists and researchers working in the field of energy efficient building

systems. The technical background and thermodynamic concepts related to the exergy analysis in building systems are explained thoroughly in a clear and detailed way in the full length report which is intended to present state-of-the-art exergy analyses in buildings. Over the past years, exergy analyses of building systems have become more prevalent in scientific literature; however, exergy analysis in buildings (particularly dynamic exergy analysis) is a controversial issue and is very sensitive to the assumptions made by the user. The full version of the ECBCS Annex 49 report is intended to be a reference for further analyses so that comparability can be guaranteed between the results of exergy analyses of different building and community case studies.

Main objectives and layout of this report

In this context, the main objectives of the ECBCS Annex 49 are to:

- Develop design guidelines regarding exergy metrics for performance and sustainability
- Create open-platform exergy software for building design and performance assessment
- Show best practice examples for new and retrofit buildings and communities
- Document benefits of existing and developed demonstration projects
- Set up a framework for future development of policy measures and pre-normative work including the exergy concept

The topics mentioned above are treated in detail in the following chapters. Chapter 2 gives a brief description on the first unitary methodology for performing dynamic exergy analysis on building systems. Some fundamental concepts and the thermodynamic background of the exergy approach are highlighted. Detailed equations for analysis of several building systems as well as an extended version of the thermodynamic background of exergy analysis can be found in the full version of the Annex 49 report. In chapter 3 the tools developed within the work of Annex 49 are presented. A brief description of the main features, calculation approach and usability of each tool is also given. Chapter 4 highlights and summarizes the main strategies for an exergy oriented design of buildings and community systems. Chapter 5 presents the main parameters developed or used here for characterising exergy performance of any building or community. Based on these parameters, the first discussions and bases for setting pre-normative proposals that include the exergy concept are also included. Chapters 6 and 7 show the main building and community case studies analyzed within the research activities of the ECBCS Annex 49.

¹Quality factors q are explained in chapter 5

2. METHOD AND MODELS FOR EXERGY ANALYSIS

In this chapter a brief overview of the method and mathematical models developed for exergy analysis of building systems within the ECBCS Annex 49 group is introduced. A detailed description of the mathematical models and fundamentals of the exergy analysis method can be found in the full version of this report.

Exergy analysis is a thermodynamic method which has commonly been applied since the 1950s to, for example, complex power generation systems. Yet, energy processes in power plants and buildings are significantly different. In power stations energy processes are operated often far away from environmental conditions. Whereas, thermodynamic variables in the energy processes in buildings are very close to (outdoor) ambient conditions. Thus, for applying the exergy method to the built environment, several adjustments and adaptations are required.

This chapter begins with a brief introduction to the exergy concept and a review of the main thermodynamic fundamentals behind exergy analysis, e.g. the reference environment or sign convention applied are explained in direct relation to energy processes in buildings.

The input-output approach followed for developing the mathematical models for exergy analysis is also briefly introduced. Additionally, main differences between steady-state, dynamic and quasi-steady state assessment methods are presented.

Buildings are erected to be comfortable living spaces and provide adequate shelter to their occupants. Thus, models related to the exergy of human thermal comfort have also been developed and are briefly introduced here.

Like the energy demand of buildings, the exergy demand of buildings is one of the most important variables of exergy analysis in buildings. The exergy demand represents the minimum amount of work that would need to be provided to the building in order to maintain acceptable conditions in the indoor environment. Within ECBCS Annex 49, two different approaches have been developed for determining the exergy demand of buildings: a simplified approach, suitable for analysing the efficiency and performance of building systems, and a detailed approach suitable for analysing the performance of the building design and envelope.

A brief summary of the models developed for dynamic exergy analysis of building systems is to follow.

Finally, a simplified method developed for exergy analysis of community supply systems is introduced. Main results of such method, applied to a case study in Germany, are also introduced.

Applied fundamentals

The aim of this chapter is to provide an overview of the main fundamental concepts for exergy analysis. For a more general introduction to the exergy concept, we refer to the final report from the previous annex on the topic, the Annex 37 guidebook (Ala-Juusela, 2003).

Brief introduction to the exergy concept

Exergy is a measure of the quality of energy. Work is energy with the highest quality, which can be totally converted to any other type of energy. In thermodynamics, exergy can be defined as the maximum theoretical work that can be obtained from a quantity of energy or matter by bringing this energy or matter into equilibrium with a reference environment. The maximum theoretical work will be obtained if the considered energy or matter is converted in a system in which only reversible processes take place, in such a way that equilibrium with the environment is finally achieved.

This definition shows that all systems in a state different from the environmental state contain exergy, or, in other words, have the ability to produce work. The exergy of a system can consist of the following components:

- chemical exergy (due to a difference in chemical composition)
- thermal exergy (due to a difference in temperature)
- mechanical exergy (due to a difference in pressure)

For heating and cooling purposes, thermal exergy is of most importance. Therefore, in this chapter the focus is on thermal exergy. However, as chemical and mechanical exergy can play a role in certain situations such as human thermal comfort, they are also mentioned in some cases.

Heat is the transfer of energy between two systems, resulting from a difference in temperature. This energy is not related to matter. When analysing one system, heat is the transfer of energy across the system boundary, taking place at the temperature of the system boundary. The word "cold" is used to refer to heat at temperatures below the environmental temperature T_0 .

The ratio between the exergy (Ex) and energy of the heat transferred (Q), is defined as the quality factor. In scientific literature, the quality factor is also called

“exergy factor” or “exergetic quality factor” (Dincer and Rosen 2007). The quality factor illustrates the work potential per unit heat and thereby indicates its quality.

Thermal energy is contained by matter. It is the part of its internal energy associated with temperature, including both sensible and latent heat. As described by Shukuya (Shukuya 2009), there can be both a surplus of thermal energy relative to the environment (the system is warmer than the environment) or a lack of thermal energy relative to the environment (the system is colder than the environment). A thermal energy surplus relative to the environment can be called “hot thermal energy” and a thermal energy deficit relative to the environment can be called “cold thermal energy”.

The sign convention used in this report accords with that used in most textbooks on thermodynamics (Bejan, et al. 1996; Moran and Shapiro 2004; Dincer and Rosen 2007):

- $Q > 0$ = Heat transfer to a system;
 $Q < 0$ = heat transfer from a system.
- $W > 0$ = Work done by a system;
 $W < 0$ = work done on a system.

The sign of the heat or work is thus dependent on the defined system, thus showing the importance of defining the system under consideration and its boundaries. The sign convention for exergy accompanying heat is:

- $Ex_Q > 0$ = Exergy transferred to the system;
- $Ex_Q < 0$ = exergy transferred from the system

The reference environment

The thermodynamic reference environment for exergy analysis is considered as the ultimate sink of all energy interactions within the analysed system, and absorbs all generated entropy within the course of the energy conversion processes regarded (Baehr, 2005). The environment needs to be in thermodynamic equilibrium, i.e. no temperature or pressure differences are to exist within different parts of it (thermo-mechanical equilibrium). Chemical equilibrium must also be fulfilled. Furthermore, intensive properties of the environment must not change as a result of energy and mass transfer with the regarded energy system (Baehr, 2005). In addition, the reference environment is regarded as a source for heat and materials to be exchanged with the analyzed system (Dincer, Rosen, 2007), i.e. it must be available and ready to be used by the system under analysis.

The reference environment can also be described as that portion of the surroundings of a system, of which the intensive properties of each phase are

uniform and do not change significantly as a result of the process under consideration (Bejan, et al. 1996). It can thus act as either an unlimited sink or unlimited source.

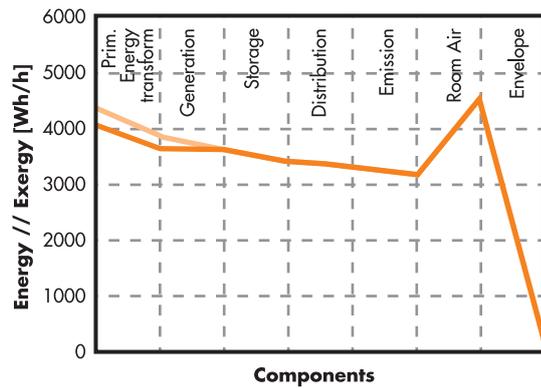
Discussion: Possible choices

Several choices for the reference environment can be found. However, Wepfer and Gaggioli (1980) clearly state that the reference environment for exergy analysis, unlike reference variables for thermodynamic or thermo-chemical tables, cannot be chosen arbitrarily. The reason is that energy analysis is based on a difference between two states and, thus, the chosen reference levels out in the balance. In turn, in exergy analysis the chosen reference does not level out in the balance and values of the absolute temperature chosen as reference, for example, strongly influence results from exergy analysis.

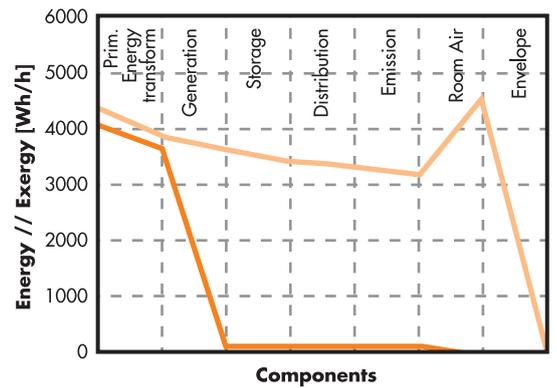
In this section, a discussion on the physical and thermodynamic correctness of different reference environments for exergy analysis is presented. In order to show the influence of choosing one reference environment or another for exergy analysis, steady-state exergy analyses have been carried out on a building case study. Analyses with the four different options for the reference environment introduced below have been performed with the pre-design Annex 49 tool (see chapter 3). Exergy and energy flows obtained with the different reference-environments are shown graphically in Figure 2.1.

a) The universe (nearly zero Kelvin) as reference environment

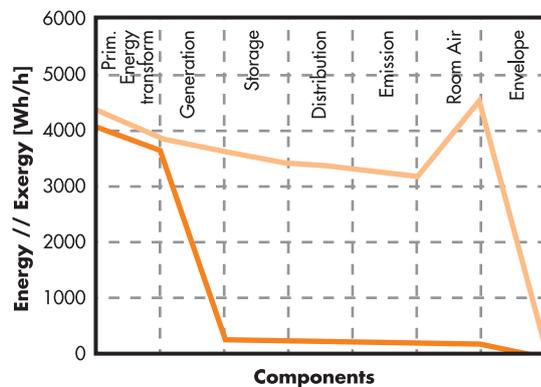
The temperature of the universe is very low, around 3 degrees Kelvin. This allows radiative energy transfer from the earth and, thus, the discarding of entropy produced as a result of energy processes on earth (Shukuya and Komuro, 1996). From a first law of thermodynamics (or energy conservation) perspective, the earth is an open system receiving a net energy flux from the sun in the form of high quality solar radiation, tidal energy from celestial bodies, and geothermal energy from nuclear processes within the crust of the Earth (Sørensen, 2004), with the energy from solar radiation being the greatest input. All incoming energy from the sun is ultimately radiated (or reflected) back into the universe (Rosen, 2002): about one quarter is reflected in the form of light (high quality, short wave radiation) and three quarters are emitted in the form of low-temperature heat (low quality, long wave radiation) (Szargut, 2005; Shukuya and Komuro, 1996). Exergy balances for these processes can be found in Szargut (Szargut, 2003 and 2005). The emission of low temperature heat, occurring since the sky temperature is lower than the mean temperature of the Earth,



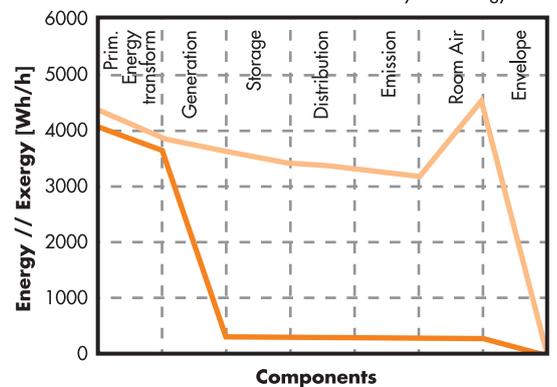
(a) Universe (nearly absolute zero)
 $T_{ref} = 3 \text{ K } (-270^{\circ}\text{C})$



(b) Indoor air temperature
 $T_{ref} = 294 \text{ K } (21^{\circ}\text{C})$



(c) Undisturbed ground temperature
 $T_{ref} = 281 \text{ K } (8^{\circ}\text{C})$



(d) Outdoor air temperature
 $T_{ref} = 273 \text{ K } (0^{\circ}\text{C})$

— System Energy Total
— System Exergy Total

Figure 2.1: Energy and exergy flows for a building case study with the four introduced reference environment options.

allows for the discarding of the entropy produced through the degradation of the incident solar radiation and maintains the so-called “exergy-entropy” process on the global environment (Shukuya and Komuro, 1996). It could be regarded, therefore, as the ultimate sink of energy processes within a building. It is infinite and undergoes no variation in its intensive properties as a result of heat and mass transfer processes within the building.

However, cool radiation from the universe is not always directly available and ready to be used by the built environment (otherwise no cooling energy would be required). This is shown in Figure 2.1 (a). Thermal energy and exergy flows from storage system to the building envelope are equal. Differences in the “generation” and “primary energy transformation” subsystems occur due to quality factors for liquefied natural gas (LNG), regarded as 0.94 (Szargut and Styrylska, 1964)³.

b) Indoor air inside the building

Indoor air within the building has also been proposed as a reference environment for exergy analysis. However, indoor air is neither an infinite sink nor in thermodynamic equilibrium. In addition, its temperature varies as a result of energy processes within the building. Therefore, it does not fulfil the necessa-

ry requirements for being regarded as a thermodynamically correct reference environment.

Results using indoor air as a reference environment are shown in Figure 2.1 (b). As with this approach the exergy demand of the building (input in the “envelope” subsystem) is zero, for it is regarded as the reference environment. In consequence, this approach does not allow for the derivation of efficiencies for the overall energy supply in buildings since the desired output would always be zero.

c) Undisturbed ground

The undisturbed ground can also be proposed as a reference environment for building exergy analysis. It can be regarded as an infinite sink, whose properties remain uninfluenced by interactions with the building. Yet, the main objection for regarding it as a reference environment, similarly as absolute zero, is that it is not always directly available and ready to be used within the built environment⁴.

d) Ambient air surrounding the building

Most energy processes in the building sector occur due to temperature or pressure differences to the surrounding air. Thus, the air surrounding the building can be regarded as the ultimate sink (or source) for the energy processes occurring in the build-

ding. On the other hand, the air volume around the building can be assumed as being large enough (infinite sink) so that no changes in its temperature, pressure or chemical composition occur as a result of the interactions with the building. In addition, outdoor air surrounding the building is naturally available and ready to be used⁵.

Conclusion & recommended reference environment

It is recommended to use the (current) surrounding outdoor air as the reference environment for the exergy analysis of buildings and their energy supply systems since this is the only system that is unlimited (either acting as a sink or a source), unchanged by the processes that are regarded, and always available.

However, outdoor air temperature and pressure do vary with time and space, i.e. external air is not a homogeneous system in thermo-mechanical or chemical equilibrium. As stated in Dincer and Rosen (Dincer and Rosen, 2007), "the natural environment is not in equilibrium and its intensive properties exhibit spatial and temporal variations. Consequently, models for the reference environment are used which try to achieve a compromise between theoretical requirements and the actual behaviour of the reference environment". In order to model the outdoor air surrounding a building as a thermodynamic reference environment, temperature and pressure are assumed to be uniform for the air surrounding the building (thermal and mechanical equilibrium). Concentration of different chemical species in the atmospheric air is also regarded as homogeneous.

Exergy of different thermal heat transfers

Exergy can be calculated for different thermal heat transfer processes, e.g. conductive, convective and radiative. The commonly known expression for calculating the exergy of heat (shown in equation 2.3), related to the so-called Carnot cycle, is suitable for calculating the exergy of conductive and convective heat transfer processes.

The exergy of heat is based on a reversible thermal power cycle (e.g. Carnot cycle) operating between a hot and a cold reservoir, see Figure 2.2. Heat (Q_H) is transferred to the system from the hot reservoir. From the second law of thermodynamics, it is known that not all heat to the system can be converted into work, but a certain amount ($-Q_C$) must be rejected to the cold reservoir.

The work obtained from this cycle can be calculated using equations 2.1 and 2.2, based on the first and second law of thermodynamics respectively. For

these equations Q_C is regarded as negative, according to the sign conventions.

$$W = Ex = Q_H + Q_C \quad (2.1)$$

$$\frac{Q_H}{T_H} = -\frac{Q_C}{T_C} \quad (2.2)$$

The maximum amount of work for a given Q_H and given temperatures can be calculated with (2.3). The factor $(1-T_C/T_H)$ is called the Carnot efficiency.

$$\begin{aligned} Ex &= Q_H + Q_C = Q_H - Q_H \cdot \frac{T_C}{T_H} \\ &= Q_H \cdot \left(1 - \frac{T_C}{T_H}\right) \end{aligned} \quad (2.3)$$

Exergy of radiative heat transfer processes

As stated above, equation 2.3 is only valid for conductive or convective heat transfer processes. In turn, the exergy of radiative heat transfer process needs to be assessed by a different expression, being the quality (i.e. exergy level) of a radiative heat transfer lower than that of a conductive or convective process. In the full and extended version of this report the mathematical expression used for exergy of radiative heat transfer is presented. Besides, differences between both assessments and implications for exergy analysis of building systems are also analysed and explained in detail. It can be generally said that if the goal of exergy analysis is to assess the performance of building systems as a whole (not at a component level) the exergy of radiative heat transfer can be assessed with the Carnot factor. Otherwise, if the main focus is to optimise one single component (e.g. floor heating system); assessing the exergy of radiative heat transfer as such might be relevant.

Exergy of matter

An amount of matter which is not in equilibrium with the environment contains a certain amount of exergy. The exergy of matter consists of a thermal, mechanical, and chemical component, due to a difference in temperature, pressure and chemical composition respectively. Unlike the transfer of energy by heat, the thermal energy of matter can be regarded as a state of this matter. This state can be brought to equilibrium with the environment by heat transfer with the environment.

For latent heat, the heat transfer takes place at constant temperature and therefore equation 2.3 can be

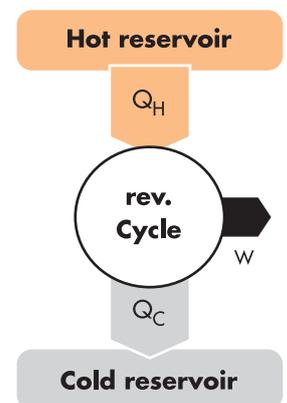


Figure 2.2: Scheme of a reversible thermal power cycle (e.g. Carnot cycle).

used. For sensible energy however, the temperature of the heat transfer changes as the system (or matter) comes closer to equilibrium. Equation 2.4 must be used in this case.

$$Ex = c \cdot m \cdot \left(T_0 - T - T_0 \cdot \ln \frac{T_0}{T} \right) \quad (2.4)$$

Heating and cooling processes: Exergy input or output?

In the above statements and paragraphs, the focus is on the exergy 'available' from heat. However, it depends on the direction of the heat flow and on the temperatures of the system and of the reference environment T_0 , whether heat has the ability to produce work or requires the input of work. In general the following rules are valid:

- Heat transfer which brings a system into equilibrium with the environment (and thus closer to T_0) can theoretically produce work. This means heat transfer that takes place spontaneously could produce work.
- Heat transfer bringing a system further from T_0 requires work. (All non-spontaneous heat transfer requires work).

It can be helpful to picture an imaginary Carnot cycle between the environment and the heat transfer that is considered, in order to visualise if work has to be supplied or work can be obtained.

In the image below, the different options are shown:
 Heating a system (A) of which $T > T_0$
 → energy input → exergy input / required

Cooling a system (A) of which $T > T_0$
 → energy output → exergy output / available

Heating a system (B) of which $T < T_0$
 → energy input → exergy output / available

Cooling a system (B) of which $T < T_0$
 → energy output → exergy input / required

The negative value for the exergy should not be understood as "negative work", but as an indication of the direction of the exergy into the system (= exergy supply).

As it can be seen from Figure 2.3, the exergy accompanying heat transfer is in the same direction of the heat transfer in the case of $T > T_0$, and in the opposite direction of the heat transfer in the case of $T < T_0$. By using equation 2.3 (with the natural Carnot factor), the signs of the heat and exergy values will demonstrate whether they are inputs or outputs to the system.

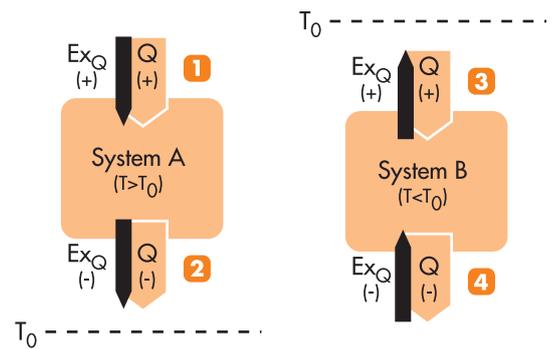


Figure 2.3: Direction of the exergy transfer related to energy transfer and temperatures T and T_0 .

Description of the method for exergy analysis

Input-output approach

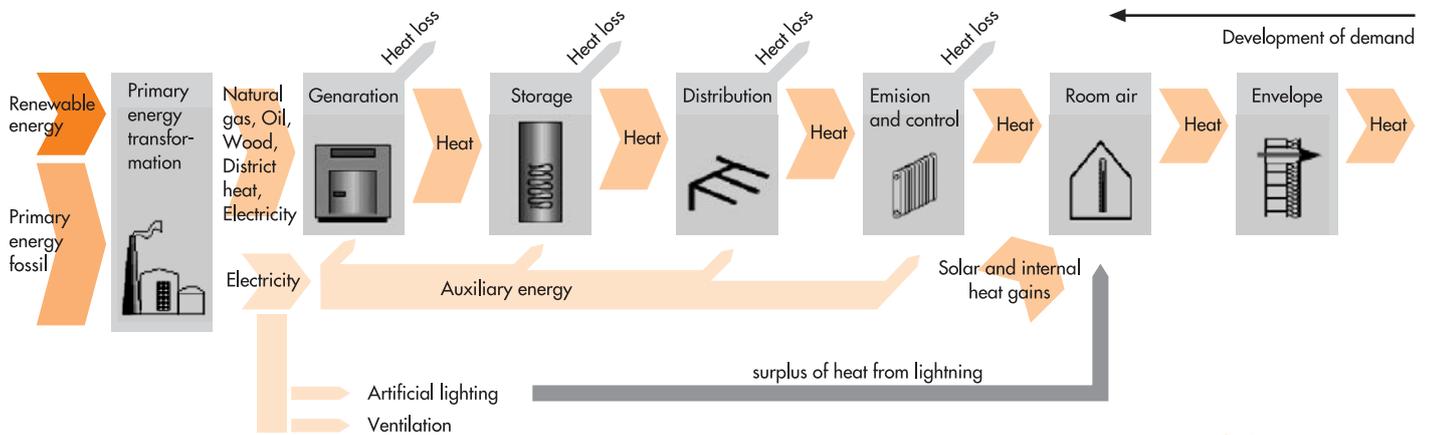
In order to improve the energy and exergy performance of energy supply in buildings, the whole energy supply chain needs to be assessed. This approach can also be found in many energy regulations and standards (DIN 4701-10, 2003; EnEV, 2007; DIN 18599, 2007, CEN EN 13790:2004). For this, the energy supply chain in buildings is divided into several subsystems. Figure 2.4 shows the subsystems of such an energy supply chain, from primary energy conversion to the building envelope, for the particular case of space heating applications. In order to assess the energy performance of the complete energy chain, a simplified input/output approach is usually followed. A similar approach can be used for exergy analysis. This whole exergy chain analysis is implemented in an Excel based pre-design tool developed by Schmidt (2004) within the framework of the IEA ECBCS Annex 37 project. The tool has been improved and enhanced within the framework of Annex 49.

The input-output approach followed with Annex 49 pre-design tool for a steady-state assessment can also be applied for dynamic analysis. Equations for a dynamic analysis based on this input-output schema are shown in detail for each of the subsystems in Figure 2.4 in the full version, the guidebook, this report.

All the conversion steps in the energy supply chain are directly related to each other and their performance often depends on one another. While analysis of single components happens as part of the energy supply chain, an overall optimisation of complete building energy supply systems, as a whole, can also be accomplished. Optimisation of single components is desirable and required, but the influence of optimising one component based on the performance of the following and previous ones should always be taken into consideration (Torío et

al., 2009). With the holistic energy and exergy analysis of the whole supply chain optimisation of single components which might have a negative influence on other steps of the energy supply process is avoided.

For example, the exergy input and exergy losses of a condensing boiler are expected to be rather constant even under varying outdoor reference conditions, since high quality fossil fuels with a constant quality factor of 0.94 is used. In turn, the tempera-



The models for exergy assessment presented here follow the sign convention mentioned above, i.e. exergy inputs are regarded as positive and exergy outputs as negative.

Steady-state, quasi-steady state and dynamic approaches

Steady-state and quasi-steady state estimations of the energy demands and flows in buildings are proposed and used by building regulations in several European countries (EnEV, 2007; EN 13790, 2008). However, exergy is a parameter that refers to both the state of the reference environment and that of the system under analysis. Exergy flows have shown to be very sensitive to variations of the chosen reference environment⁶ when the variables of the system and those of the environment do not differ very much from each other, as in the case of space heating and cooling in the built environment. Thus, an estimation of the error of steady-state exergy assessment as compared to dynamic approaches is mandatory. Results from investigations comparing both methods (Angelotti and Caputo, 2007; Angelotti and Caputo, 2009; Sakulpipatsin, 2008) show that steady-state exergy analysis might be reasonable for an initial estimation of the exergy flows in space heating applications, particularly in colder climates. The error is expected to be higher, the milder the climatic conditions are. Yet, exergy flows in cooling applications can only be assessed by means of dynamic analysis, where variations in outdoor reference conditions are taken into account (Torío et al., 2009).

The impact of variable climatic conditions is also expected to be different in different energy systems.

ture of the heat output from a solar thermal system or a ground source heat pump (GSHP) varies significantly depending on outdoor conditions. Thus, strong variations in the quality factor associated to the exergy flow from the solar thermal and GSHP systems are expected and greater exergy analysis can be presumed. Therefore, if the goal of exergy analysis is to compare different energy systems, dynamic exergy analyses are preferable, so that errors arising from the steady state assessment can be excluded and the differences between energy systems can be solely attributed to improved or optimised performance.

Alternatively, a quasi-steady state assessment can be performed. Quasi-steady state represents a hybrid approach between fully dynamic and fully steady-state calculation methods. Quasi-steady state exergy assessment is performed by using steady-state equations for exergy assessment combined with dynamic energy simulations. The exergy flows are evaluated following a steady-state approach, i.e. storage phenomena are not regarded separately in the exergy balance, over discrete time-steps. This simplified quasi-steady state evaluation method has been compared to a full dynamic approach by means of two building case studies.

Results from analysis comparing both assessment methods show that if the main aim of exergy analysis is to improve, study or optimise a storage system, the dynamic behaviour of the exergy stored and consumed needs to be analysed dynamically. A quasi-steady state approach is not accurate enough to depict the dynamic behaviour of the exergy flows accurately. However, if the aim is to perform exergy

Figure 2.4: Energy supply chain for space heating in buildings, from primary energy transformation to final energy, including all intermediate steps up to the supply of the building demand (Schmidt, 2004).

analysis on a system level, the dynamic behaviour is not that relevant, but total required input and output over a certain period of time might be enough. A quasi-steady state exergy assessment method combined with dynamic energy analysis (including storage phenomena) is suitable in this case.

Exergy and thermal comfort

Low exergy systems for heating and cooling of buildings, similarly as buildings themselves, should not solely be designed to be energy or exergy efficient. Above all, they need to provide adequate comfort conditions in the built environment. Physics with respect to the built environment and its technology must be in harmony with human physiology and psychology. Thus, it is vitally important to have a clear understanding of the exergy balance of the human body in order to understand in which way thermal energy demands in buildings could be provided with minimum losses while guaranteeing comfort conditions.

This section gives an introduction on the exergy processes in the human body. Based on these mathematical models for human body exergy balance, it has been determined that minimum exergy consumption within the human body occurs at thermally neutral conditions.

Figure 2.5 shows the human-body exergy consumption rates for winter and summer conditions: the former is shown as a function of mean radiant temperature and air temperature and the latter as a function of mean radiant temperature and air movement. During the heating period minimum exergy consumption can be achieved at higher mean radiant temperatures and lower air temperatures. The experience of many building engineers and scientists indicates that these conditions of minimum exergy consumption in the human body are coherent with maximum level of thermal comfort. During summer conditions, minimum exergy consumption happens at higher mean radiant temperatures and air velocities. Natural ventilation based concepts for cooling allow to achieve these indoor conditions.

The conditions for minimum exergy consumption might be achieved with low-temperature heating and high temperature cooling systems (i.e. radiant systems) which supply the required energy demands at a temperature very close to the indoor temperature, thus being low-exergy heating and cooling systems. These findings suggest that the development of so-called low-exergy systems for heating and cooling are on the right track also from the perspective of providing good thermal comfort.

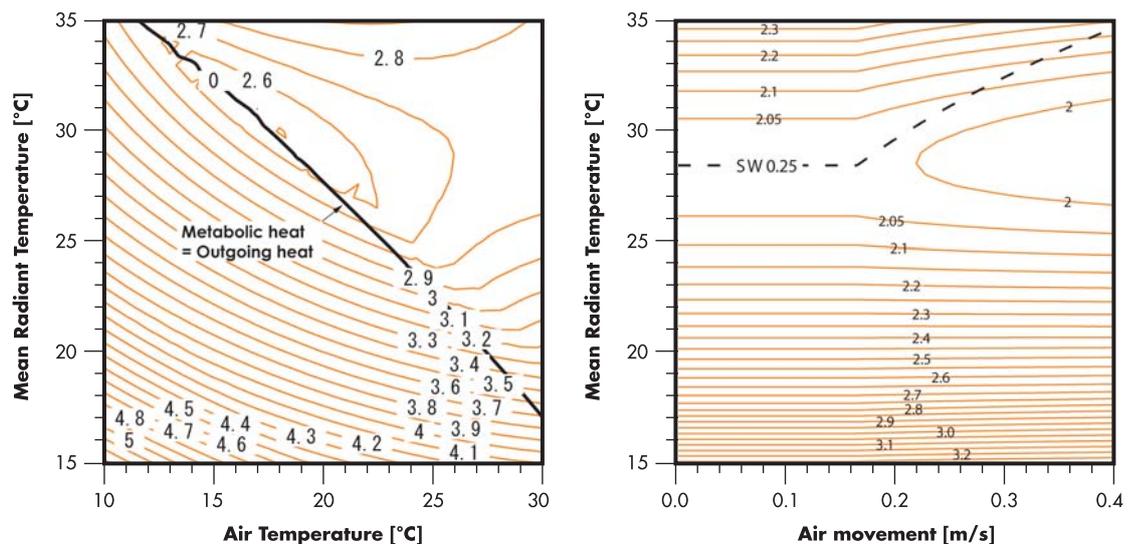


Figure 2.5: (left): Relationships between human body exergy consumption rate, represented by the unit W/m^2 (body surface), and the human body's environmental temperature under a winter condition ($0^{\circ}C$; 40% relative humidity). There is a set of room air temperature (18 to $20^{\circ}C$) and mean radiant temperature (23 to $25^{\circ}C$) which provides the body with the lowest exergy consumption rate; (right): Relationships between human body exergy consumption rate, of which the unit is W/m^2 (body surface), and the combination of mean radiant temperature and air movement under a summer condition ($33^{\circ}C$; 60% relative humidity).

Human body exergy consumption

Animals and human beings live by feeding on organic matters containing a lot of exergy in chemical forms. They move muscles by consuming exergy, not only to obtain their food but also not to be caught as food by other animals. All such activity realised by their body structure and function is made possible by chemical-exergy consumption.

The chemical-exergy consumption brings about quite a large amount of “warm” exergy. In fact, this is the exergy consumed effectively by animals known as homeotherms, including human beings, to keep their body-core temperature almost constant. At this temperature, various bio-chemical reactions are necessary for life to proceed smoothly. This temperature level, as we know by our own (usually unconscious) experience, is generally higher than the environmental temperature.

There are two kinds of animals, from the viewpoint of thermoregulation of their body temperature: homeotherms (endotherms), as described above, and poikilotherms (ectotherms). Homeotherms include animals which maintain their body temperature at an approximately constant level regardless of temperature variations in their environment. Poikilotherms include those animals whose body temperature fluctuates in accordance with temperature variations in their environment.

Both homeotherms and poikilotherms generate a certain amount of entropy in proportion to the exergy consumption inside their bodies in the course of their life and they must excrete the generated entropy into their environmental space by long-wavelength (LW) radiation, convection, conduction, and evaporation.

To stay alive, it is vitally important for the homeotherms to be able to get rid of the generated entrop-

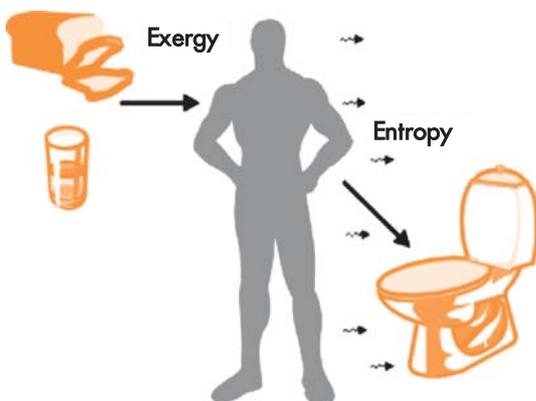


Figure 2.6: Simplified representation of the exergy and entropy processes in the human body

py immediately and smoothly due to their relatively large rate of exergy consumption. We humans are no exception. Energy processes in the human body are complex and involve a great number and variety of heat transfer processes, e.g. through blood circulation, and moisture transfer through sweating and breathing or radiative heat exchange. Exergy analysis of human thermal comfort is in consequence also complex. In the full version of this report and in the Annex 49 report on the exergy of the human body, the equations and their derivation for the processes involved can be found (see appendix B).

Exergy demand of a building

The energy demand of a building can be defined as the amount of energy required to keep the indoor environment within the comfort ranges required by its users. Similarly, the exergy demand is the amount of exergy required to keep the indoor environment within the comfort ranges required by its users. This is equal to the exergy content of the required energy. In order to achieve a more clarifying description, exergy demand is defined as the minimum amount of work needed to provide the required energy.

The minimum amount of work depends on the quality of the energy that is required. This means for the minimum amount of work, the energy should be provided at the lowest quality possible. In practice, however, it happens very often that energy is supplied at a higher quality (= more exergy) than necessary, as is the case when heating is supplied at 90°C to obtain a room temperature of 20°C. While providing more energy than required leads to overheating or under-cooling, providing more exergy than required does not lead to overheating or under-cooling; it only leads to the destruction of exergy, since mixing (in this case of higher and lower temperature energy) involves exergy destruction.

The exergy demand of a building can be calculated according to two different approaches:

- **Simplified approach:** the exergy demand is calculated as if all energy would be provided at the minimum possible temperature level (i.e. room air temperature). The exergy demand is, thus, obtained by multiplying the energy demand of the building with the Carnot factor (i.e. quality factor, equation 2.3) for indoor air temperature.
- **Detailed approach:** in this calculation method the exergy demand is divided into exergy which could be provided by ventilation and exergy provided directly by heat. The exergy of ventilation is assessed as exergy related to matter (equation 2.4), i.e. air, and that of heat is calculated with the Carnot factor (equation 2.3).

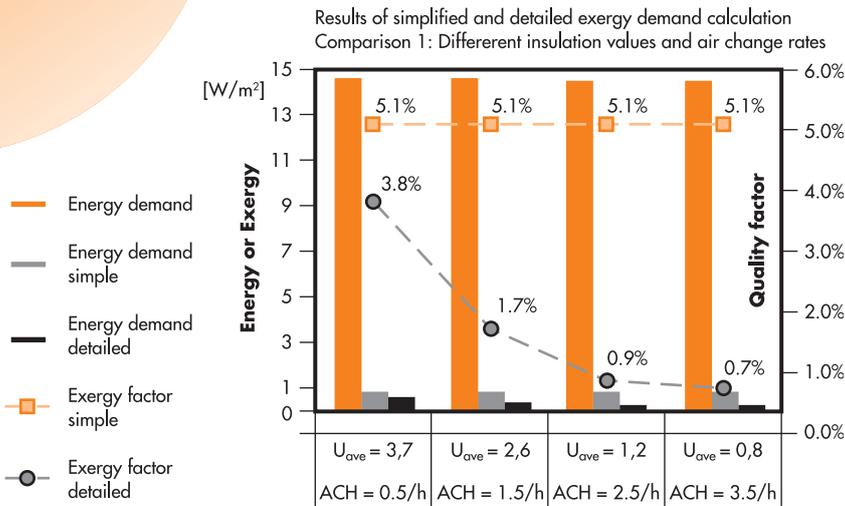


Figure 2.7: Results from the simplified and detailed exergy demand calculation methods for four situations with equal energy demand but different characteristics (insulation value and Air Change Rate)

Neither of the methods includes humidification. The (small) difference between the exergy of convective and radiative heat exchange between surfaces with small temperature differences is also ignored in both cases. A detailed description of both calculation approaches can be found in the full version of this report.

Figure 2.7 shows the differences in both assessment methods for a building case study. Different thermal insulation level and ventilation losses have been considered in order to check the influence of these parameters on the detailed assessment approach.

The detailed exergy demand (which is the sum of the demand related to ventilation air and the demand related to heat) is always smaller than the simplified demand calculation, as a result of the lower quality factors for the exergy of matter as compared to that of heat.

Since the energy demand and the temperatures are constant, the simplified exergy demand is also constant. However, due to the different contribution of ventilation and transmission losses, the detailed demand is different in each case.

The simplified calculation method is easy to use, whereas the detailed method requires much more equations. Therefore it is recommended to use the simplified method when looking at a complete energy supply system of a building (from building to primary energy source) in a preliminary design phase. When zooming in to the building in a detailed way, it is recommended to use the detailed calculation method. The detailed approach should be used especially when trying to optimise heating and ventilation systems at the building level.

Exergy in building systems

Expressions for evaluating the dynamic exergy flows in different building energy systems have been developed. In the full version of this report the equations for several energy systems can be found: condensing boiler, ventilation unit, storage tank, solar collectors, emission systems, distribution pipes, etc. These equations have also been implemented in an add-on calculator allowing quasi-steady and dynamic exergy assessment on TRNSYS. A screenshot of this calculator included in a TRNSYS model is shown in Figure 2.8. The energy flows and temperatures calculated by TRNSYS at every time step are given as inputs to the calculator in order to evaluate the corresponding thermal exergy flows.

Exergy in community systems

Communities are complex energy systems where a wide diversity of energy supply chains are often interconnected. A great number of data with high time resolution would need to be obtained and evaluated for depicting the dynamic behaviour of a community system. A detailed and dynamic assessment of the energy and exergy flows in them would thus be very accurate, but also very time consuming. In this section, some simplifications are introduced which could be used for the exergy analysis method of energy supply systems for community structures.

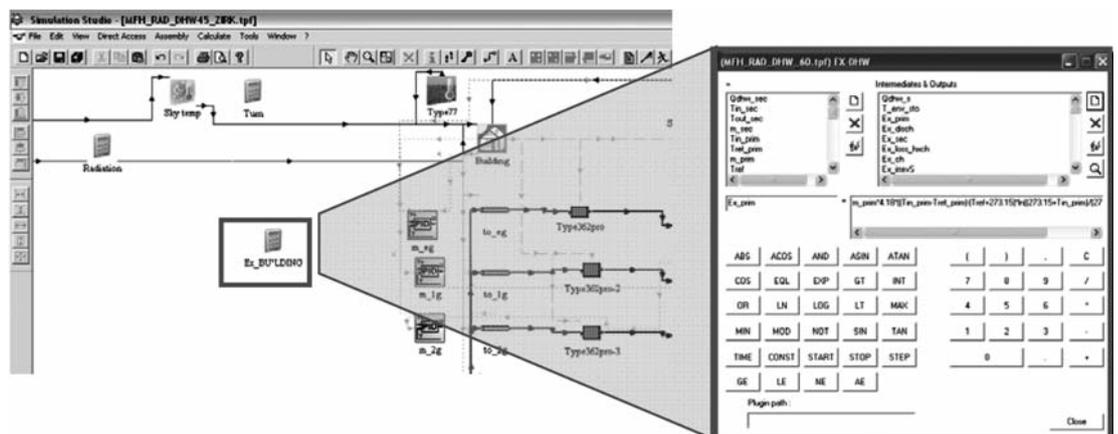


Figure 2.8: Screenshot showing an example of add-on TRNSYS equations for calculating exergy flows.

Dynamic or steady-state assessment

Dynamic exergy analysis of community systems might be required if the purpose is, for example, to optimise the performance of a system or to size the energy systems involved in an appropriate manner. For this aim, the detailed equations presented in the full version of Annex 49 report for the analysis of building systems can be used. A great number of input data with good time resolution are required for this purpose, e.g. results from dynamic energy simulations.

However, if the main aim of the analysis is to obtain an initial idea of the general performance of an energy supply concept for a community, preliminary steady-state assessment might be used.

To assess the accuracy of simplified steady-state analysis, results with such an approach are compared to results from dynamic analysis for the case study of Oberzwehren (Germany), which is also included as a case study in chapter 7.

The case study corresponds to a small neighbourhood whose space heating (SH) and domestic hot water (DHW) demands are supplied with a low-temperature district heating system. District heat corresponds to waste heat and is supplied to the hydraulic distribution network inside the neighbourhood by means of a centralised heat exchanger. The buildings and energy supply systems, i.e. heat exchangers, pumps and thermal losses in the hydraulic network, have been dynamically simulated with TRNSYS using a time step of 3 minutes. Following

the simplified input-output approach mentioned at the beginning of this chapter, the exergy associated to main energy inputs into the system are analysed. These energy inputs are the heat input from the primary side of the district heating heat exchanger, pumping energy in the secondary sides and auxiliary energy to power the back-up electric heater for DHW supply.

Since it is a waste heat district heating system, the exergy associated to the primary side heat transfer from the heat exchanger can be evaluated as a function of its inlet and return temperatures (i.e. as exergy of matter as expressed in equation 2.4). In turn, if it were heat from a heat plant, the quality factor of the fuel used to supply the heat would need to be assessed.

For steady-state exergy analysis, average outdoor air temperature during the heating period is used here as reference temperature. Estimated annual energy demands for SH and DHW are used in combination with design conditions for the supply systems chosen, i.e. design inlet and return temperatures and mass flows for the district heating heat exchanger.

Figure 2.9 (a) shows results for the exergy supply and demand following a dynamic and steady-state assessment. Figure 2.9 (b) shows the exergy efficiencies for both analysis methods.

With the conditions considered here for stationary analysis, steady-state evaluation gives a reasonably

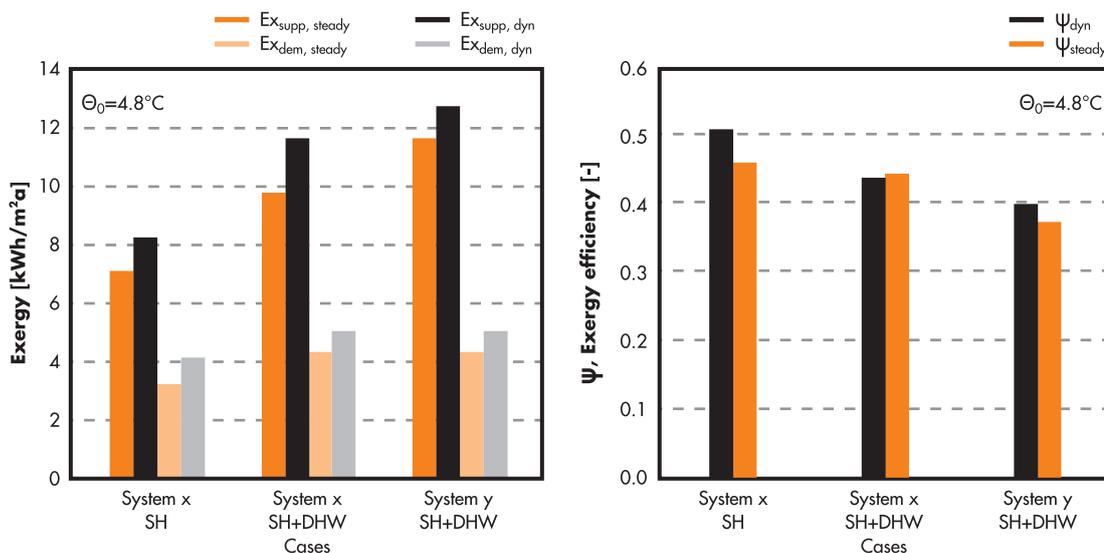


Figure 2.9: (a): Exergy demand and supply following dynamic and steady-state assessment methods for two different hydraulic configurations (system x and system y) as well as only for SH and for combined SH and DHW supply; (b): Seasonal dynamic exergy efficiency and steady-state exergy efficiency calculated assuming design operating conditions and yearly energy demands..

accurate first estimation of the trend of the exergy efficiency of the system. Mismatching between the exergy efficiency for different configurations of the supply systems is lower than 10%. In turn, differences for the exergy demanded and supplied with both assessment approaches (dynamic and steady-state) are higher, amounting to as much as 22%. The trend, however, is similar for both assessment methods.

It can be concluded that steady-state exergy analysis as performed here gives correct insight into the trend of the exergy performance for different systems and can therefore be used for comparing them. Absolute values of the exergy performance obtained with this simplified evaluation method are, however, not accurate.

Simplified input-output approach for communities

As shown above, simplified steady-state analysis is suitable for giving an idea of the exergy behaviour of community supply systems. Energy systems in communities often enclose a great diversity of energy supply systems. A detailed assessment of every energy conversion step in the different supply systems involved would require a great number of data and time consuming analysis. To avoid this, as a first step, communities can be depicted as a set of demands to be provided, with their corresponding quality level (i.e. exergy content associated to them) and an available set of possible energy supply sources. With this simplified approach, the suitability of different supply options can be depicted in a relatively simple manner by assessing the matching level between the demands and the sources used.

In Figure 2.10, some possible energy sources and energy uses present in a community system are classified according to their quality level (i.e. exergy content). Ideally, high quality sources are used only to provide high quality applications, whereas low quality sources should be used for low quality applications.

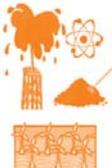
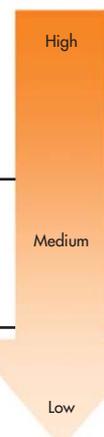
Sources	Quality	Uses
 <p>Oil Coal Uranium (fossil fuels) Wind energy</p>	 <p>High</p> <p>Medium</p> <p>Low</p>	<p>Lighting </p> <p>Electrical appliances </p>
 <p>High temp waste heat, e.g. from industrial processes (200°C)</p>		<p>Cooking </p> <p>Washing machine </p>
 <p>Low temp. waste heat, e.g. from CHP (50-100°C) Ground heat</p>		<p>DHW </p> <p>Space heating </p>

Figure 2.10: Simple classification of energy sources and uses (i.e. demands) in a community according to their quality level.

²Primary energy transformation" and "Generation" subsystems referred to here correspond to the modular method for exergy analysis developed by Schmidt (2004)

³The quality factor of 0.94 is referred to a reference temperature of 25°C. However, the variation of this value due to deviations in the reference environment chosen are expected to be lower than the uncertainty in the calculated value. Consequently, the same value is assumed here for all reference environments chosen.

⁴Directly available in the sense that if a heating load is present, i.e. $T_{\text{indoors}} < 20^{\circ}\text{C}$, having an undisturbed ground temperature greater than 20°C would not directly reduce the heating load unless a suitable energy system (e.g. ground heat exchanger) was installed.

⁵On the contrary as the undisturbed ground temperature, if a heating load is present, i.e. $T_{\text{indoors}} < 20^{\circ}\text{C}$, having an outdoor air temperature greater than 20°C would directly reduce the heating load (by e.g. opening the window).

⁶The reference environment here is assumed to be outdoor air, as concluded in the previous sections.

⁷Quality factors for the solar thermal system are referred to the heat output from the solar collectors. The conversion of solar radiation in low temperature heat is not taken into account.

⁸See the full version of the final report of ECBCS Annex 49 for detailed insight into the results.

3. TOOLS FOR EXERGY ANALYSIS

Tools to facilitate exergy analysis of buildings

In order to promote the use of the exergy concept among building planners and decision makers a variety of software tools have been developed within ECBCS Annex 49. These have different levels of complexity and can be used in various applications. These tools are at the forefront of the use of exergy in the building sector. They provide a unique viewpoint that simple analysis based on energy balances alone might overlook. Many designers may be unaware or incapable of performing an analysis that considers exergy flows through buildings. These tools provide designers with a range of options to produce results pertaining to the exergetic performance of a particular design. These can lead the designer to subsequent optimizations that would otherwise not be applied.

Application of tools

The tools developed have a wide range of applications and are focused on the analysis of different parts of energy supply systems in buildings. Three MS Excel based tools are available: Annex 49 pre-designing tool for exergy analysis of building systems, SEPE performing exergy analysis of system components and Cascadia which can be used for exergy analysis of community systems. The exergy calculations have also been implanted into a Building Information Modeling (BIM) tool, allowing energy and exergy calculations for the three-dimensional computer designs of architects. Beyond system analysis, another MS Excel software tool has been developed to improve comfort analysis, which models the exergy of the human body. Finally a graphical tool has been created, which acts as a decision tree to provide a very simple guide for owners and designers in the selection and integration of low exergy building cooling systems.

Annex 49 pre-design tool

The Annex 49 pre-design tool is a MS Excel-based calculation tool intended to analyze energy supply systems in buildings. It is based on a simplified steady-state approach for energy and exergy analysis. The tool allows to depict the overall performance of energy supply systems in buildings, as well as the exergy performance of single components of such supply systems (i.e. boiler, solar collectors, floor heating systems...).

This tool is based on the German energy saving Standard (EnEV, 2007), which targets the limitation of the energy consumption of buildings. Thereby, the field of application is focusing mainly on buildings with normal and low internal temperatures respectively, as e.g. residential buildings, day-care facilities for children and office buildings.

The objective was to develop a simple and transparent tool which is easy to understand and comprehensible for its users, such as architects and construction engineers. Further assumptions have been made to compose exergy analysis as clearly as possible, and to limit the required input data.

This tool is based on the MS Excel tool developed within IEA ECBCS Annex 37. Main changes introduced in the ECBCS Annex 49 pre-design tool are:

- Two different energy sources, or energy supply systems for DHW and space heating demands can be combined, e.g. solar thermal collectors and heat pumps, boilers, etc.
- Renewable energy flows are accounted for, both in energy and exergy terms, in the generation and primary energy transformation subsystems.
- Renewable and fossil energy and exergy flows are regarded separately, allowing good traceability of different energy sources on the energy supply chain.

Table 3.1: Summary of tools for exergy analysis in the built environment developed during the Annex 49 project.

Tool	Ideal User	Calc Level	Interface	Programming	Availability	Manual	Repository
Annex 49 pre-design tool	Engineer/Architect	System/Building	Excel	BASIC	Public	Yes	Annex 49
Cascadia	Eng./Planner	Community	Excel	BASIC	Public	No	Annex 49
SEPE	Engineer	System/Component	Excel	BASIC	Public	Yes	Annex 49
DPV	Arch./Eng.	Building	GUI	C	Private	Yes (DE)	Keoto
Human Body	Engineer	Occupant	Excel (GUI)	BASIC (FORTRAN)	Public	Yes	Annex 49
Decision Tree	Owner/Planner	System/Building	Graphical	--	Public	Yes	Swiss BfE

All relevant building data as well as heating ventilation and air conditioning (HVAC) systems can be selected directly by the user on the first page. Results are presented graphically and analytically at the end of the first page. Main assumptions are summarised in tables on further pages. The analysis considers all steps of the energy chain – from the primary energy source to the building and the environment (i.e. the ambient climate).

Potential uses of this tool are for studies of, e.g., effects of improving the building envelope compared to improving the building equipment, or system flexibility and the possible integration of renewable energy sources within the building system.

A definition of the building details (e.g. building envelope, air tightness,...) is required from the user. By means of several drop-down menus, different building systems can be chosen to supply the required building demands. The amount of input data required can be limited in this way. In Figure 3.1, a screenshot of the menu for required input data to define the building and the drop-down menus for selecting building services are shown.

In the energy and exergy analyses, all steps of the energy chain – from the primary energy source to the building and the environment (i.e. the ambient climate) are considered and displayed, following the energy chain as shown in Figure 2.4.

The calculated energy and exergy flows are illustrated in two diagrams. Here, a separation occurs for the heating system and the DHW production. Thereby, an energy and exergy analysis for each specific energy demand is possible (see Figure 3.2).

Additionally, several parameters allow a direct and quantitative comparison between the performances of different building systems. The main parameters included for this use are:

- overall energy and exergy efficiencies for the complete energy supply chain
- exergy expenditure figures for the generation and emission systems and exergy expenditure figure for the energy demand (i.e. its quality factor). This parameters provide an idea of the “matching” between the quality levels of the energy demanded and supplied.

(a) Pre-design sheet for an energy optimized building design (Annex 49)

Steady state calculations for heating case

Version 2.0

1. Project data, boundary conditions	
1. Volume (cubic meter)	V = 427.3
2. Net floor area (m²)	A _n = 112.9
3. Indoor air temperature (°C)	t _{in} = 20
4. Outdoor air temperature (°C)	t _{out} = 0 = reference temperature

2. Heat losses						
2.1 Transmission losses (J/h)						
Building part	System	Area A _s (m²)	Thermal transmittance U _s (W/m²K)	U _s · A _s (W/K)	Temperature correction factor F _t	U _s · A _s · F _t (W/K)
64	External wall	108.82	0.80	87.06	1	87.06
65	Window	30.30	1.60	48.48	1	48.48
66	Door	1.50	1.60	2.40	1	2.40
67	Roof	116.80	0.20	23.36	1	23.36
68	Upper story floor	0	0.0	0.0	0.0	0.0
69	Wall and floor to adjacent spaces	0	0.0	0.0	0.0	0.0
70	Flows to ground	0	0.0	0.0	0.0	0.0
71	Areas of unheated outdoor ground	0	0.0	0.0	0.0	0.0
72		A _s · A	360.07			158.30

(b) Drop-down menus for selecting building services

Source 1: Condensing boiler	Primary energy factor fossil F _{pe,ss,1}	1.10
	Primary energy factor renewable F _{pe,ss,1}	0.00
	Quality factor fossil F _{q,ss,1}	0.94
	Quality factor renewable F _{q,ss,1}	0.00
	Max. supply temperature θ _{s,ss,1} [°C]	70.00
	Auxiliary energy P _{aux,ss,1} [W/kWh _{heat}]	1.00
	Auxiliary energy P _{aux,ss,1} [W]	20.00
	specific CO ₂ emissions c _{CO2,ss,1} [g/kWh _{heat}]	247.00
	Thermal efficiency η _{th,ss,1}	
64	Factor environmental energy for Heat pump F _{env,ss,2}	
	Primary energy factor fossil F _{pe,ss,2}	
	Primary energy factor renewable F _{pe,ss,2}	
	Quality factor fossil F _{q,ss,2}	
	Quality factor renewable F _{q,ss,2}	
	Max. supply temperature θ _{s,ss,2} [°C]	
	Auxiliary energy P _{aux,ss,2} [W/kWh _{heat}]	
	Auxiliary energy P _{aux,ss,2} [W]	
	specific CO ₂ emissions c _{CO2,ss,2} [g/kWh _{heat}]	
	Fraction source 1 F _{1,ss}	80%
	Fraction source 2 F _{2,ss}	20%
65	Storage:	
	Heat loss / efficiency η _{h,ss}	1.00
	Auxiliary energy P _{aux,ss} [W/kWh _{heat}]	
	Solar fraction F _{sol,ss}	

Figure 3.1: Fields for input data to define the building envelope in the Annex 49 pre-design tool (a) and drop-down menus for selecting building services (b).

Energy and exergy assessments follow a steady-state approach. Based on the energy flows obtained, and depending on the temperature levels chosen for the building systems, an estimation of the exergy flows is carried out on a steady-state basis. The equations for each of the performed exergy calculations are directly shown in the calculation sheet. Furthermore, all required assumptions, such as energy efficiencies and temperature levels regarded for the operation of the building systems, are introduced in tables displayed in different worksheets and referred to in the calculations. The user can modify the default values for these parameters, allowing him to adjust the parameters to his particular system. In addition, this allows transparency and intends to enhance understanding of the thermodynamic background and calculations within the tool.

In Figure 3.3, all energy and exergy losses are shown separately for each subsystem. Negative values of the energy and exergy losses in a component indicate gains in this component, e.g. solar gains. Since all energy flows are regarded in the balance (i.e. fossil and renewable), the only system where energy and exergy gains are possible is the building envelope. Here, energy gains through the building envelope are taken into account and contribute in compensating for the total transmission and ventilation losses.

Cascadia tool

The MS Excel-based tool “Cascadia” intends to provide insight about the exergy performance of different energy supply systems for communities. The tool aims thereby at introducing the exergy concept to municipal planners and decision makers, so that main conclusions from exergy analysis on a community level can be integrated on the design process. Cascadia is based on the calculation method implemented in the spreadsheet Annex 49 pre-design tool. While the model in the pre-design tool is focused upon individual building components, radiators, heat transfer equipment, etc, the model used in Cascadia represents the building as a simple thermal load and emphasises more in the form of the energy supply and its distribution network.

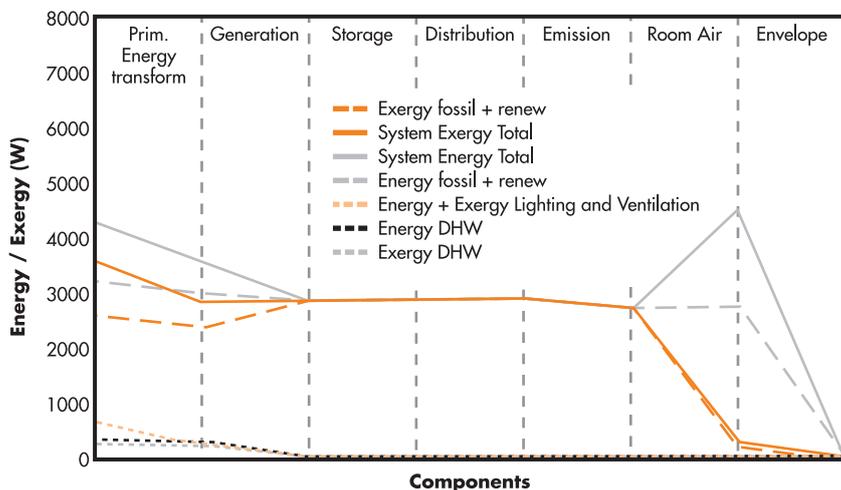


Figure 3.2: Exergy and energy flows in each sub-system of the energy supply chain.

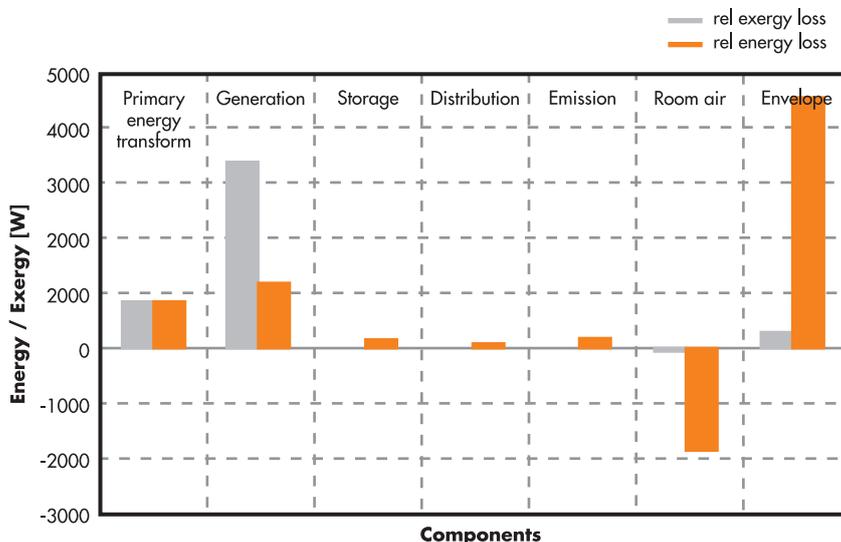


Figure 3.3: Exergy and energy losses in each sub-system of the energy supply chain.

The model of the neighbourhood, shown in Figure 3.4, consists of a centralised energy plant supplying a district heating pipe network. Heating loads are from a typical neighbourhood, including high rise apartment buildings, low-rise or detached residential homes and a retail sector comprised of strip malls or single storey retail buildings. Individual buildings are connected to the district energy system in a parallel configuration with the supply and return lines, whereby the three categories of buildings – high rise, residential and retail, are connected sequentially.

The model includes an allowance for both space heating and internal electrical loads. Building details provided to the model relate to the heat loss and ventilation requirements of the building and the electrical loads (pumps, fans, plug loads, etc.) associated with the building and distribution system.

Different building designs (high rise, residential, and commercial) can be chosen. They are considered only representative for the purposes of this analysis and serve only to provide nominal thermal and electrical loads. Since the quality of the energy demands is independent of the absolute quantity of the loads (i.e. a quality can be assigned to each load independently of their energy value), the load itself affects only the demand for primary energy and not the energy or exergy efficiency. The number of buildings in each category enables the temperature drop in the district energy system to be determined by balancing the water flow rate required.

For the evaluation process the district energy supply temperature has been selected, based upon the capabilities of the supply technology. Five technologies were included within the model:

1. a medium efficiency gas fired boiler
2. a high efficiency, condensing gas fired boiler
3. a reciprocating gas fired engine based co-generation system
4. an electrically driven ground source heat pump
5. flat plate solar thermal collectors

For options 1 to 3, the initial exergy level is related to the combustion temperature of the fuel. Electrical power, where not provided by the neighbourhood system (i.e. in options 1, 2, 4 & 5), is assumed to originate from a utility owned gas fired simple cycle co-generation system.

In the district energy loop, the supply temperature is considered to be 90°C for the first three options and reduced to 54°C for the heat pump and solar panel options. Heat distribution within the buildings can be either forced air or waterborne radiators.

Keeping in mind the concerns relating to urban design and energy use, and, in particular, the desire to reduce the need for fossil fuels as outlined earlier, the model can be used to examine the implications of different energy supply technologies, urban formats and heating techniques in terms of their overall energy and exergy usage.

The results of the analysis are presented in terms of the primary energy requirements, i.e. the fossil based energy required for the creation of all thermal and electrical needs of the system. Since the intent of the tool is to demonstrate the impact of both the technology and the reduced demand for fossil fuel, information is provided on:

- the energy efficiency of the system – heating and electrical generation as a percentage of input primary energy. This illustrates the amount of energy usefully deployed as space heating or as available electricity.
- the exergy efficiency of the heating system – heating and electrical generation exergy as a percentage of available exergy. This illustrates the exergy consumed in space heating and in the generation of available electricity.
- the exergy efficiency of the overall system – the total exergy consumed in the process of space heating and power generation as a percentage of the overall exergy available. This illustrates the exergy lost in the delivery system.
- the fossil fuel efficiency – heating and electrical generation energy as a percentage of fossil fuel energy input. This illustrates the potential for a reduction in fossil fuel.

Results are also displayed graphically in terms of the exergy flow through the district heating network and the temperature level for each use within the supply structure. In Figure 3.5, two examples of such graphs are shown for a supply with a condensing boiler (above) and solar flat plate collectors (below).

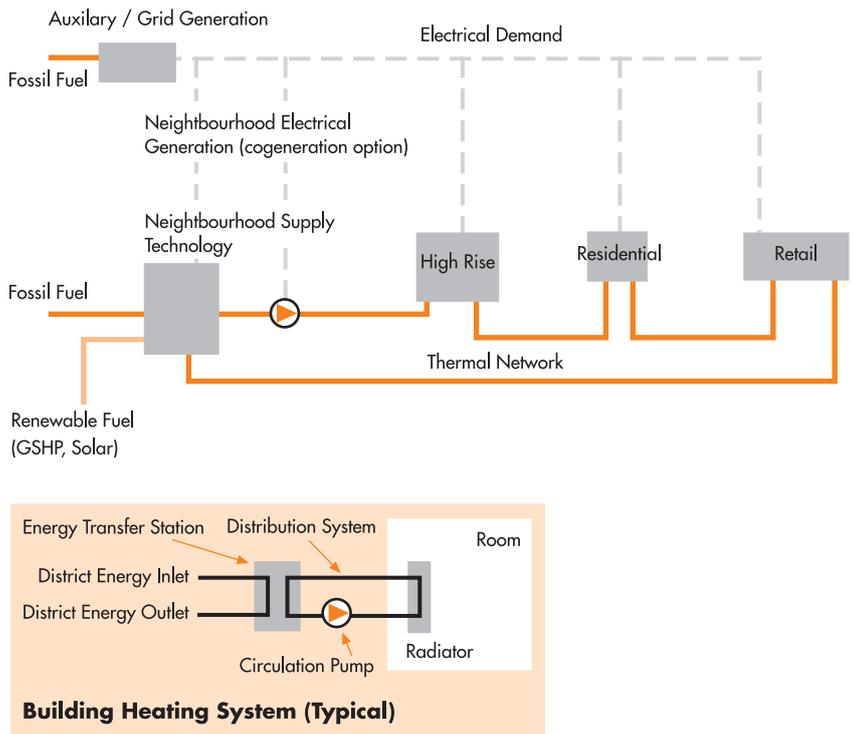


Figure 3.4: Scheme for neighbourhood design implemented in Cascadia.

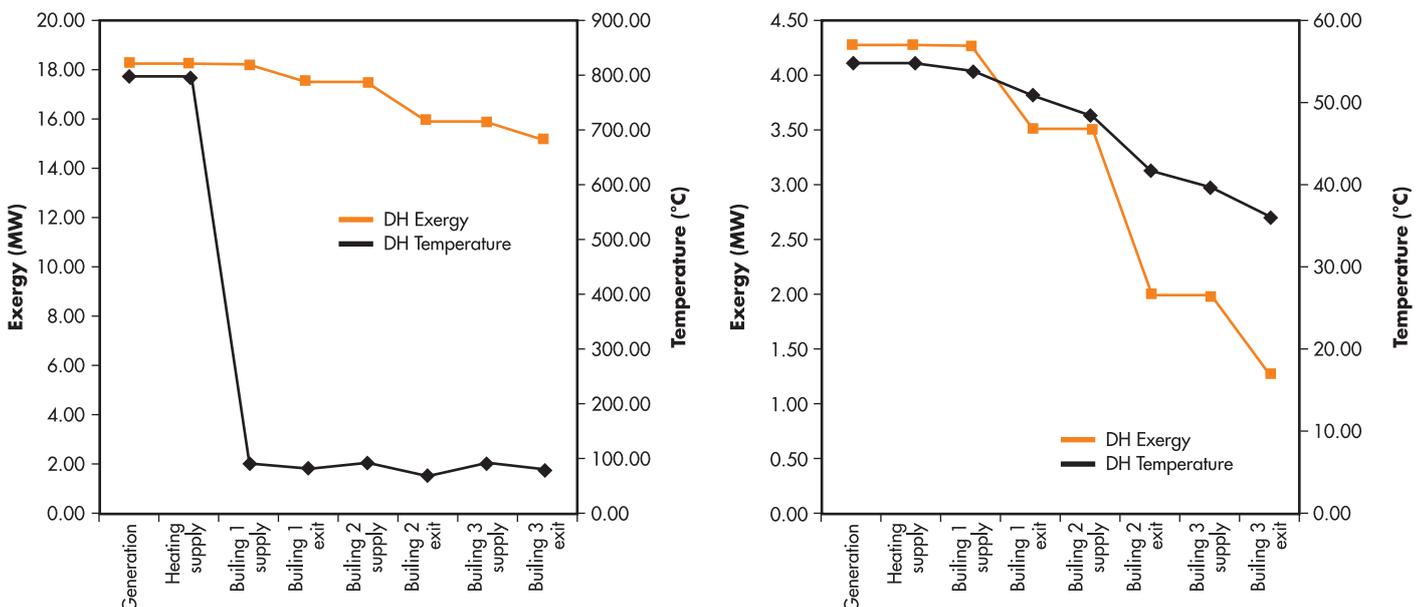


Figure 3.5: Graphs displaying the results of investigated options. Left: district heating network is supplied by means of a condensing boiler. Right: network is supplied with flat plate solar collectors.

SEPE an Excel calculation tool for exergy-based optimisations

SEPE (Software Exergy Performance Assessment) is a MS Excel-based tool, with which it is possible to model and analyze the most common heating and cooling system components. It uses the iterative potential of MS Excel to perform steady state energy and exergy analyses. The fact that the software performs iterative loops and calculates the outputs on a physical basis increases the model reliability. The various components of the heat production chain are modelled here as black boxes, each one with independent internal equations. By copying and pasting these equations and connecting the input and output variables for each component, it is possible to create a whole space heating and cooling system. Since the dependent variables are calculated by the single absolute temperatures, this ensures a quick connecting process and control over the operation itself. Figure 3.6 shows as an example the connection of two system components.



Figure 3.6: Example of a two-systems layout and connections

To perform loops, once the required components have been placed and connected in the MS Excel sheet, the input variables (absolute temperature and pressure) need to be connected to the output ones of the loop. Once the iteration options have been enabled, the program automatically updates the values until convergence.

So far, the following models have been developed and included in the software:

Table 3.2: Available models in SEPE

Generation	Emission	Distribution	Other Models
Boiler	Air handling unit	Air ducts	Room model
Heat pump	Floor cooling/heating	Water pipes	Heat exchanger
Chiller	Radiator	Fans	
Adiabatic saturator (for evaporative cooling)		Pumps	

The ability to perform thorough and meaningful simulations depends on the ability of the user to model the system and adapt the existing components to his own needs. A heat exchanger, for instance, is used to allow heat exchange from the primary to the secondary loop but it is equally effective as a heat recovery system in the air handling unit. In addition, a saturator can be used both for evaporative cooling and as a cooling tower.

Basically, all the systems share the same structure. Each model is divided into three areas: an input area on the right, an output area on the left and the central area. All the defining equations, which define the transfer function (how the values are processed from the input to the output value) of the model, are included in the central area. The user is requested to insert sizing and characteristic parameters to define the model: for example, a heat exchanger is modelled by the type and the mass flow of the energy carriers in the first and the second loop (air or water), and by the exchange surface and the type of heat exchanger itself (i.e. parallel or counter flow).

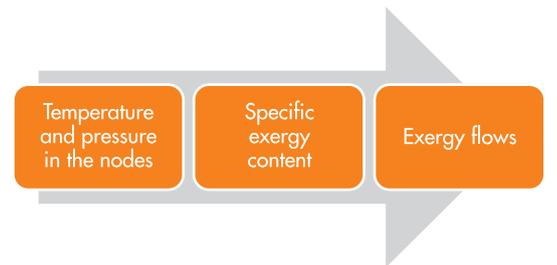


Figure 3.7: Exergy flows calculation steps.

The calculation of the exergy flows is performed by evaluating inlet and outlet pressures and temperatures in the nodes, given the reference temperature. In this way, specific thermal and pressure exergy is calculated in two different ways according to whether the medium is water or air. The calculation of the exergy flows and exergy losses is then made possible by multiplying them for the mass flow passing through the system. This calculation process is shown schematically in Figure 3.7.

The program opens up vast possibilities of analysis and optimisation within the whole chain – exergy losses can be detected from generation to room system, through primary and secondary loops heat exchange, and within distribution and emission systems. This allows for a better understanding of the weaknesses of the different systems.

Design performance viewer (DPV)

The Design Performance Viewer takes a step toward a more simplified and accessible tool for the analysis of building performance. Not only that, but the tool takes the procedures developed by the ECBCS Annex 49 group to include an exergetic performance aspect that has never before been integrated into a Building Information Model (BIM) model. The tool, which is integrated with Autodesk Revit software, allows planners, designers, and architects to obtain an easy-to-understand graphic display of the energetic and exergetic performance of their buildings.

The energy and exergy performance of a building design is shown using the BIM system interface (see Figure 3.8). This allows the various parts of the building design to be compartmentalised within the model itself. Thus, the designer sees the building form along with its function in one model. Still, for most BIM systems the input is not automated and retrieving significant information from the model can be difficult.

The tool can be implemented in all phases of design and, most importantly, allows the user to observe the potential impacts of changes during the earliest and most influential phases of the design process. This facilitates an awareness of energy and exergy performance throughout a project, instead of energy analysis just being an afterthought. It is not easy to design a modern building, and as buildings have become more complex so have the tools used to design them. Nearly all buildings today rely on some form of Computer Aided Design (CAD) tool in their creation.

The need for higher performance buildings has led to the development of energy simulation tools that not only show the construction of a building, but also its operation. Yet, these simulation systems often require complicated inputs, making analysis of various constructions or multiple design possibilities very difficult. The development of object orientated CAD models has facilitated the development of more accessible energy analysis systems. These BIM's include both geometric data as well as other information about various components of the building, such as wall thermal resistance and room orientations. The information stored in the BIM can be used directly to perform calculations for the design, for example shading and lighting, as well as energy calculations. The DPV tool uses an API from a Revit building model to take information and use it to determine the performance factors for a building and display them in a simple graphical interface. A Sankey diagram of the energy flows is also automatically generated (Figure 3.11). There is also a flow chart of the relative exergy destruction as cal-

culated with Annex 49 pre-design tool (also shown in Figure 3.11). The inputs are also defined by means of drop down menus (see Figures 3.9 and 3.10).

The exergy aspect of the tool illuminates the importance of the type of system chosen by the designer, especially with respect to the temperature of operation. The value of low temperature heating and high temperature cooling is demonstrated through the use of the DPV tool. The interest in the DPV tool is growing rapidly and the start-up keoto AG (www.keoto.net) will soon begin consulting in the use of the tool.

At present, the third version of the DPV is under final development. The interface has been completely revamped and dynamic calculations including weather data are now being implemented. Also, exergy calculations are able to be re-evaluated more efficiently to show the direct impact of certain design decisions, not just in the system drop down boxes, but within the parametric model itself. This is where the real preliminary design decisions are made, and if exergy can play a role here it would become even easier to reduce the primary energy demand of buildings.

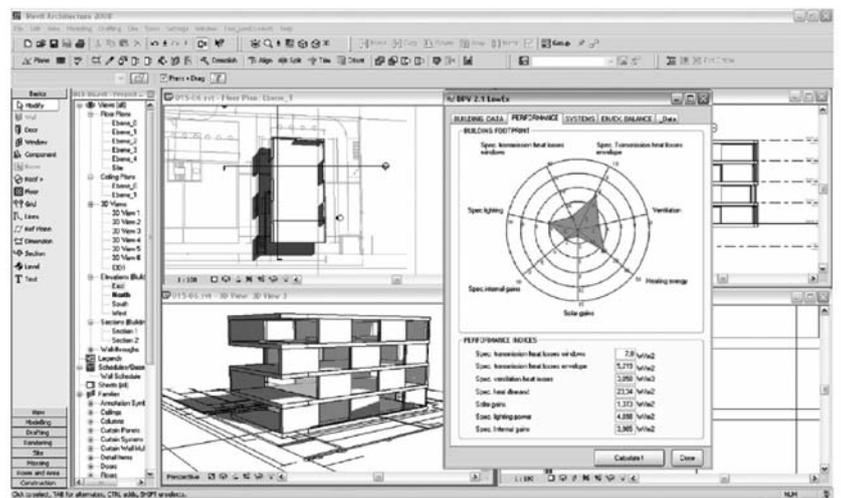


Figure 3.8: Screenshot from DPV tool with spider graph for comparing the performance of different parts of a building design.



Figure 3.9: This tab allows the user to input various system parameters.

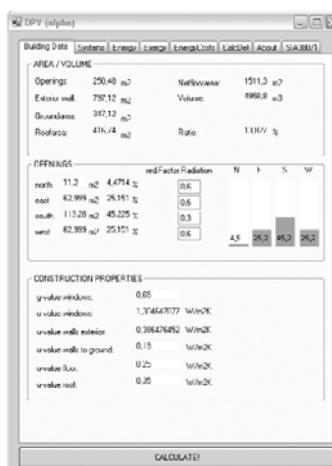


Figure 3.10: This tab shows the building data acquired from the Revit Model.

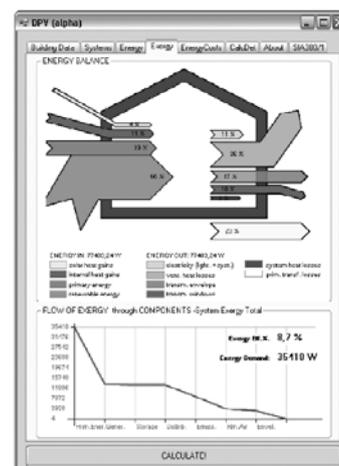


Figure 3.11: This panel contains the energy balance showing the Sankey diagram. Below: the exergy flow through the building systems.

Tool for calculating exergy in thermal comfort

In this section a MS-Excel based calculation tool for estimating the exergy associated with thermal comfort and energy processes within the human body is introduced.

People spend a lot of time in the built environment. As thermal environment has a great influence on quality of life, it is important to investigate the built environment from the viewpoint of human-body exergy balance.

The development of the theory of human-body exergy balance began in the middle of the 1990's by Saito and Shukuya. About 15 years before they started to develop the theory, Prof. Dr. I. Oshida, a Japanese scientist, who was one of the pioneering researchers in the field of solar exergy utilisation, mentioned in his essay (Oshida, 1981) that a relationship between the input exergy and output exergy of human body and thermal sensation must exist but he himself did not create the theory of human-body exergy balance.

The first version of the human-body exergy balance model, initiated by Saito and Shukuya, combines the energy balance and entropy balance equations for the human body, using the, at that time, state-of-the-art knowledge. They calculated human-body exergy balance under a thermally steady-state environmental condition assuming that the environmental temperature equals the ambient air temperature and mean radiant temperature. They found that the exergy consumption rate within the human body is at its least under the conditions when the metabolic heat generation is equal to the outgoing heat. This suggests that the thermally neutral condition is provided

with the lowest exergy consumption rate within the human body (Saito and Shukuya, 2001).

The second version of human-body exergy calculation model was developed by Isawa, Komizo and Shukuya in the early 2000's. They made a few modifications to the human-body exergy balance equation. First of all, the overall sensible thermal exergy transfer was split into radiant exergy and convective exergy. This enables us to calculate radiant exergy flux and convective exergy flux separately. The other modification was to improve the mathematical expression for sweat secretion and its evaporation, thus making the calculation for cases when indoor relative humidity varies from outdoor relative humidity possible. Following these modifications, some theoretical re-examination on the derivation of liquid-water exergy and moist-air exergy has taken place more recently, since 2006, and the model has reached its present version.

The original version of this calculation tool was developed as a FORTRAN code by Saito and Isawa. We converted this FORTRAN code to a Visual-basic version and added a graphic user interface for the spreadsheet application.

Figure 3.12 shows the appearance of the calculation tool when opened with MS Excel. It consists of two parts: the upper is to fill in the input values and the lower to display the results of the calculation. A grey button in between is to execute the calculation. The eight input values for calculating the human-body exergy are: balance, metabolic energy generation rate, clothing insulation level, mean radiant temperature, surrounding air temperature, relative humidity, air velocity, and outdoor air temperature and relative humidity.

The human-body exergy balance equation is derived by combining the energy and entropy balance equations with the environmental temperature for the exergy calculation, which is outdoor air temperature. In this calculation model, the human body is assumed to consist of two subsystems, the core and the shell, because the temperature of the core is stable due to its homoeothermic mechanism, while the temperature of the shell, the peripheral part, varies due to its surrounding thermal conditions.

The tool consists of two sub-programs: one to calculate the temperature of the core, the skin and clothing surface based on a two-node energy balance model (Gagge et al., 1972); the other to calculate incoming and outgoing exergy fluxes together with the exergy consumption rate within the human body. The calculation proceeds as follows:

- 1) Calculate the core temperature, skin temperature, clothing-surface temperature and sweat secretion rate using the first six input values: metabolic energy generation rate, clothing insulation level, mean radiant temperature, surrounding air temperature, relative humidity, and air velocity.
- 2) Calculate incoming and outgoing exergy using the three calculated temperature and sweat-secretion rates given by 1), together with outdoor air temperature and humidity.
- 3) Calculate the exergy-consumption rate, the last unknown variable, substituting all of the incoming and the outgoing exergy fluxes obtained from 2) into the exergy-balance equation.

As you fill in the eight input values and push the button, "Execute Calculation", then you will immediately find the results of the calculation at the lower part of the calculation tool. The quantities displayed on the drawing of the human body in Figure 3.12 are incoming and outgoing exergy fluxes and the exergy consumption rate. The unit of these quantities is Watt per one square meter of human-body surface W/m^2 . The three values appearing on the upper right side of the human-body picture are the calculated corresponding values of PMV*, skin-surface temperature and clothing-surface temperature. PMV* is a thermal comfort index which so far seems to take into rational consideration the effect of sweat evaporation, in particular in hot and humid conditions (Gagge et al., 1986).

In general, the exergy balance equation for a system is expressed as follows:

$$[\text{Exergy input}] - [\text{Exergy consumed}] = [\text{Exergy stored}] + [\text{Exergy output}] \tag{3.1}$$

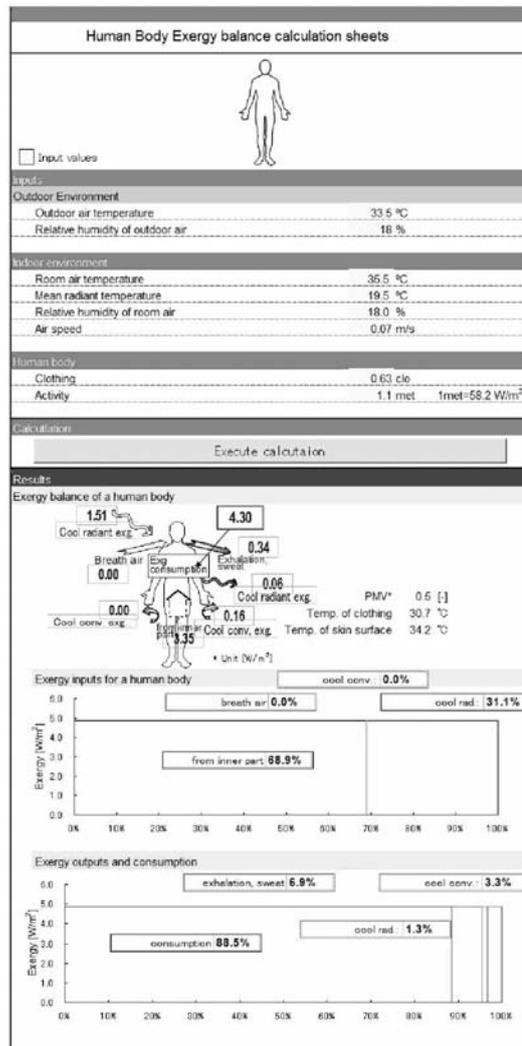


Figure 3.12: Appearance of a spreadsheet tool for the human-body exergy balance calculation.

The twin-bar graph shown at the bottom of Figure 3.12 indicates the whole exergy balance of the human body. The upper bar shows all exergy input rates and the lower bar shows the sum of the rates of exergy consumption, exergy stored and outgoing exergy. That is, the upper bar indicates the first term of the left-hand side of equation (3.1) and the lower bar, the second term of the left-hand side, exergy-consumption rate, and two terms of the right-hand side of equation (3.1). The height of the bars indicates the exergy rate, while the width of the bars indicates the percentage of the exergy rates of each component. The quantities on the bar graph are the percentages of each component.

This tool enables us to find out the thermal exergetic aspect of human body in relation to given indoor and outdoor environmental conditions. This calculation tool can be used by those interested in low-exergy system solutions for concentrating on achieving a variety of thermal environments for human body in low-exergy, high performance buildings.

Decision tool for energy efficient cooling for building retrofit

The decision tree tool is intended to provide an overview on the different possibilities for energy efficient cooling when retrofitting a building. It shall serve as an instrument in the early phase of design in the discussion with HVAC designers.

Only systems available on the market in Switzerland at the time of the study are discussed. An important precondition is that the supply cooling water temperature to the rooms shall not be lower than 18°C, i.e. low exergy cooling emission systems are a prerequisite. The presented emission systems are all able to secure the required indoor climate with the high cooling temperature. Consequently, only generation systems which can produce a supply temperature of 18°C are considered. Due to this precondition mainly low exergy systems, such as natural heat sinks and chiller units with high COP, are considered.

The boundary conditions for the tool are set by the Swiss energy code SIA 382/1 (2007) which is based on EN 13779 (2007). Here the minimum requirements for glazing, shading, available building mass etc. which have to be fulfilled to be allowed to cool a building are defined. The design room temperature is not allowed to be lower than 26.5°C.

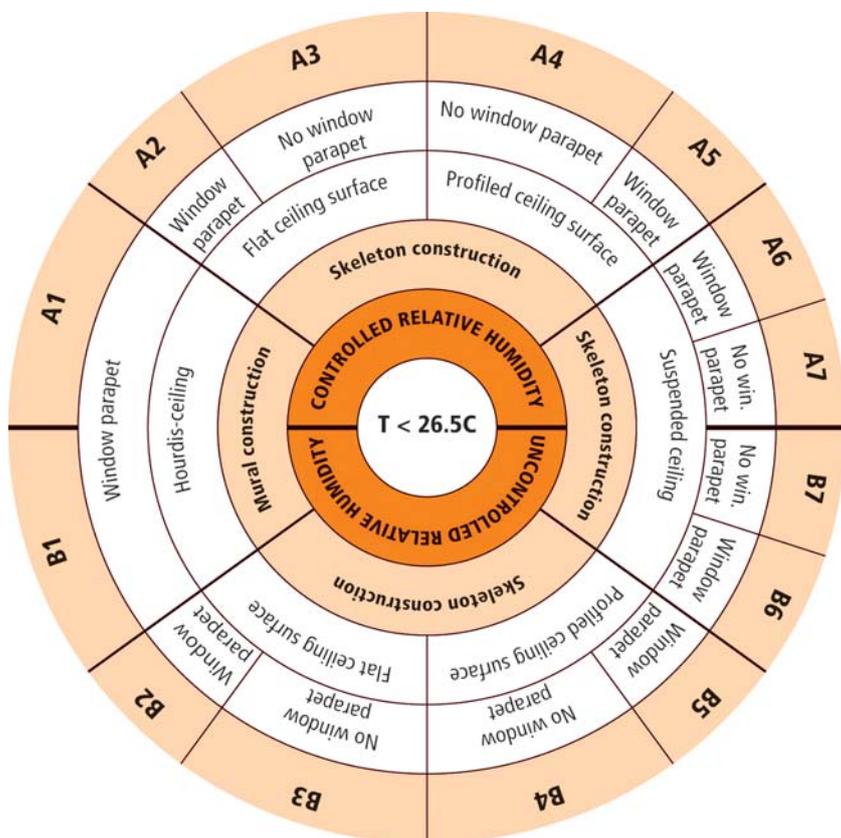


Figure 3.13: Rose for finding appropriate emission systems in the Decision Tree tool.

A standard office environment with a cooling load of 30 W/m² was chosen as reference. The data gathered derives from system producers as well as from empirical values from Basler & Hofmann Consulting Engineers, Zürich.

The decision tool is comprised of two main parts: The choice of emission system and the choice of generation system. To find the appropriate emission system suitable for the existing building, the first step is to analyse the building design post retrofit and the desired range of indoor climate variation. This is done by means of a rose (Figure 3.13, to be read from inside and out):

- Is regulated indoor air humidity desired?
- What is the basic structure of the building?
- Which type of ceiling is intended?
- Are the ceilings constructed flat or with ribs?
- Does the building have window parapets?

By answering these questions, the number of potential systems is reduced. A table (Figure 3.14) shows which systems are available for the respective result-category A1-A7 and B1-B7. A comparison of the different systems is possible by comparing the system descriptions and the provided characteristics: efficiency, investment costs, annual energy costs and required surface area. The efficiency is defined as the emitted cooling energy relative to the electrical energy needed for the water circulation and, if applicable, unit fans.

The choice of generation system depends on the available heat sinks and whether waste heat of high temperature is available. Here a description of the different systems is given as well as characteristics. Of high importance is the efficiency, defined as the cooling energy produced divided by the electrical energy required. It defines a reference point as to how high efficiency should be expected.

The characteristics investment costs, annual energy costs and required surface area are given related to m² cooled floor area, resulting in a number which is easy for buildings owners and architects to recalculate to their specific case.

As every building is different, the calculated characteristics can not be generally applied. Especially the costs vary according to the specific situation, and the overall efficiency also depends among other things on the energy needed for distribution. The tool however shows the relation between the systems at the given boundary conditions.

possible emission system	A (controlled relative humidity)							B (uncontrolled relative humidity)						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
Metal cooling panels	X					X	X	X					X	X
Gypsum cooling ceiling	X					X	X	X					X	X
Gypsum cooling ceiling with capillary tubes		X	X						X	X				
Convective cooling panels	X					X	X	X					X	X
Free hanging cooling panels		X	X	X	X		X		X	X	X	X		
Fan coil	X	X	X	X	X	X	X							
Convection unit below window	X	X	X					X	X			X	X	
Cooling panel which activates the ceiling mass			X	X	X				X	X				

Figure 3.14: Table showing available systems in the Decision Tree tool.

4. LOW EXERGY DESIGN STRATEGIES

To make exergy analysis reach a wider public of building planners and decision makers it is important to clearly state and summarize the central strategies that can be derived from this new approach. A wider use of the method will contribute to a significantly more rational and efficient use of fossil fuels, while promoting the integration of renewable energy sources in the built environment.

As stated in chapter 2, exergy analysis has already proved to be successful in optimising power plants and is making its way into building analysis (see the tools presented in chapter 3). The targets of exergy analysis applied to power plants and buildings are of course different in scope and aims. The optimisation of a power plant aims at increasing the output, i.e. the electricity produced. The reduction of the exergy losses in buildings aims, instead, at decreasing the exergy input to maintain the required outputs, i.e. the comfort conditions.

The core and first principle of the exergy method applied to the design of energy systems is to match the quality levels of the energy supplied and the energy demanded. In this sense, exergy can be

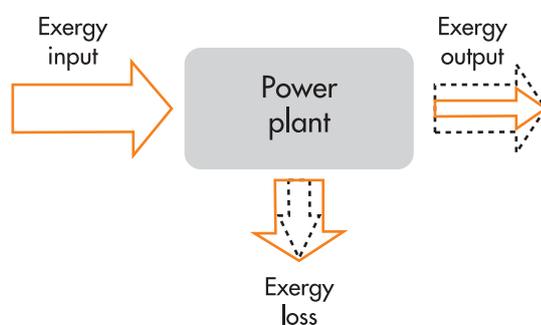


Figure 4.1: Power plant optimization aims at increasing the exergy output.

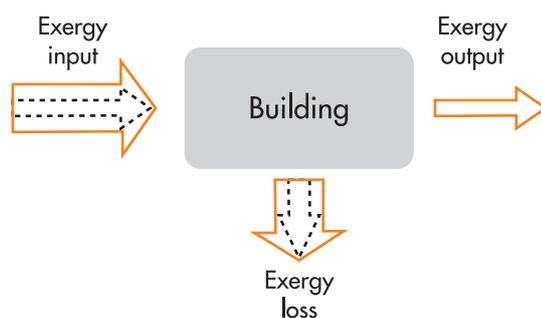


Figure 4.2: Building exergy optimization aims at decreasing the exergy input.

understood as optimisation tool for the use of energy sources.

Applying the exergy method to energy systems in buildings contributes to increase their efficiency using both fossil and renewable energy sources, as it is shown for several building and community case studies in chapters 6 and 7.

An example showing the additional information offered by exergy analysis is the use of biomass or photovoltaic (PV) panels to provide space heating in buildings, as it is shown in the graphs in chapter 1. Although both are renewable energy systems and thus have a low environmental impact and CO₂ emissions allocated, the exergy quality of biomass and that of the electricity output from the PV panels is very high. Exergy analysis helps showing that these renewable energy sources should rather be used for equally high quality applications (e.g. lighting, mobility, etc.) instead of using them for low exergy demand heating purposes.

In this chapter strategies for a general design of energy supply systems in buildings and communities are introduced. Based on these strategies, implementation technologies presented both on a building and community level. Aspects related to control strategies and costs of the systems are also briefly discussed.

General strategies for building systems

Buildings are major energy consumers (energy use for space and domestic hot water heating). Due to the low temperature level of most of these demands, their quality is very low (approximately a quality factor of 7%). The energy approach, in this context, intends to reduce energy demands in buildings by increasing insulation levels or increasing the air tightness of the building envelope, i.e. optimizing the building shell and later also an implementation of renewable energy sources. The exergy approach additionally requires the use of low quality sources for these equally low quality demands, i.e. by matching the quality levels of energy demand and supply (as shown in Figure 1.1).

Condensing boilers are considered highly efficient energy supply systems. Their energy efficiency is close to 100%. However, their exergy efficiency can be as low as 5-10% because they degrade high exergy natural gas to rather low temperature heat. The core conclusion from exergy analysis on this basic level is that, in an exergy efficient energy system combustion processes should not be used for the production of low temperature heat.

Instead, **low quality sources should be used for space heating and cooling applications** in buildings. Examples of available low exergy sources are solar thermal heat, geothermal heat or process waste heat.

Additionally, **low temperature heat flows existing within the built environment**, such as heat in waste water or exhaust ventilation air, could also be used to supply a share of the energy demands via heat recovery systems. The use of these waste heat flows requires the use of innovative heat recovery concepts. Some examples of such systems are shown in chapter 6. These concepts already play a significant role in low energy building concepts. Taking into account exergy balancing, the mostly electrical auxiliary systems become more important. In order to minimize the high-exergy input in terms of electricity required for pumps and fans in these concepts, heat recovery connected to highly efficient energy systems, such as heat pumps is beneficial¹⁰.

However most of the low exergy sources mentioned are not constantly available and almost important, are available in very limited power. **Reducing energy demands in buildings** consequently reduces the required peak power for space heating and cooling applications, making the use of low exergy sources more favorable.

In addition, lower specific power demands for space heating and cooling also allow the use of **surface heating and cooling systems** such as floor heating, chilled ceilings or thermally activated building components. Surface heating and cooling systems operate at lower temperature levels than conventional units (radiators or fan coils), thereby making also the use of low exergy sources more effective. Since these low temperature heating and high temperature cooling systems deliver the required heating or cooling energy at temperature levels closer to that of the energy demand in the building, they can be called **low exergy emission systems**. The use of these low exergy emission systems is a necessary step for a wider and more efficient integration of low exergy sources in building supply systems. In consequence, low exergy emission systems are “more flexible” since they allow the efficient integration of low exergy sources, but could also be supplied with high exergy sources. In turn, systems requiring higher supply and return temperatures such as old radiators with temperature levels of 90/70°C cannot be efficiently coupled with low exergy systems such as ground source heat pumps (GSHP) or solar thermal systems.

Yet, it is important to stress that the use of low-exergy emission systems is only a prerequisite for a low-

exergy building, since low exergy needs with a high exergy supply would not improve the outcome from a standard building solution significantly.

For instance, a low-temperature floor heating system with a gas boiler would not perform much better than a high temperature radiator supplied by the same boiler (Figure 4.3).

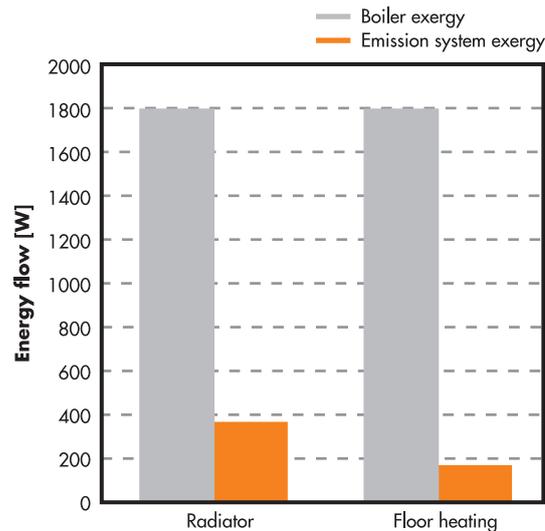


Figure 4.3: Comparison of exergy flow. The lower exergy need in the floor heating system gives no advantage since the boiler requires high exergy input regardless of the emission system.

The main focus to achieve an exergy efficient building supply is to decrease the quality of the source used and to find low exergy sources to be exploited for buildings.

As energy demands for space heating and cooling are reduced, the share of other uses within buildings such as domestic hot water (DHW) demands increases. The exergy quality factor of DHW energy demand is about 13%, being almost twice as high as for space heating applications. Energy systems using low energy sources show lower efficiencies for these demands on higher temperature levels. Strategies aiming at improving the performance of **low exergy systems for DHW supply** are desired and a promising future research topic.

In addition, higher and lower exergy demands within a building can be supplied one after another, following a cascading principle. This means that appliances needing higher exergy levels are served prior to appliances with lower exergy demand, making use of the same energy flow several times. **Cascading of thermal energy flows in buildings** is also a promising field which can be directly derived from

the exergy approach and where future research is also required.

In addition to the concept and design of systems making use of appropriate energy sources for low exergy demands, **control strategies of building systems to minimize exergy losses** in the supply process are necessary. The first step is the application of good building physics to reduce the energy demand of the building. Here a good insulation level, air tightness of the building envelope, the use of daylight and the passive use of solar energy are important factors.

Economic aspects in Low Exergy building design

Cost efficiency is a key issue in all building projects and in turn an important part of the development of low exergy solutions for buildings. Prototype solutions will always be more expensive compared to common market technologies. The potential of a new technology to perform better than a standard system the development of energy prices is a key factor. The cost efficiency of solutions is, in the long run, determined by the quality of the system design. High costs can therefore indicate that maybe better and more economic alternatives to reach the same result have been overlooked.

The development of components for low energy and low exergy buildings has been rather slow in the past. Solutions such as concrete core heating and cooling, waterborne solar collector systems and various heat pump solutions have been commercially successful on their own merits. There are solutions that have been commercially successful due to dual functionality such as floor heating where customers have probably been more often interested in the increased comfort rather than the exergy aspects. Waterborne radiative panels or chilled beams have often been chosen instead of air heating and cooling because of the comfort aspects, the reduction of fan electricity and operational costs being a positive side-effect. Offering a more comfortable system, integrating additional functions and advantages or positive side-effects (e.g. saved construction costs by reduced floor heights because of the integration of thermally activated floor slabs) is a key issue for the success of new systems. In recent years, efforts were made to integrate collector panels into façade or roof structures where the collector elements replace the normal cladding and, thereby, some costs can be saved. These technologies are still mostly in a prototype stage. There is also a known potential of saving energy by better control and a variable operation of the energy system in buildings, especially in commercial buildings. But, the costs of sensors and actuators and the wiring in residential buildings were still far too high to motivate private

investment. With further development of the components and using wireless technology this could change if larger market potentials are identified.

General optimization strategies for communities

At the community level, generally speaking, two directions can be taken to address building related energy issues:

- the first focuses on the single building and aims at energy self-sufficiency (e.g. by designing zero energy buildings ZEBs)
- the other direction, characterized by higher complexity, aims at taking advantage of the variety of demand structures and available energy sources of a whole city by an integral energy supply and adjusted use profile

Very often, main efforts are directed to technological improvements for low-energy, self-sufficient and low-exergy buildings (e.g. by the development of so-called zero energy buildings (ZEBs), but this strategy can not have the same potentials as using synergies in communities instead of individual buildings. Communities are intrinsically characterized by a level of complexity and by a efficiency potential respectively higher than single buildings. At the community scale, however, it is possible to adopt deep-reaching changes in the supply structures, enabling the use of technologies that make a more rational and efficient energy use possible on a wider scale.

The core of the exergy approach for communities is similar to the building approach: the quality levels of the energy demanded and supplied shall match each other (see Figure 1.1). To accomplish this, the use of low exergy sources for supplying low exergy demands in buildings has to be promoted.

However, additionally to the similarities with the building level, communities supply strategies can offer synergies for an exergy optimized supply system design which can not be found in buildings, e.g. several demands with different quality levels are present, several low exergy sources can be linked to each other more efficiently and economically than in a decentralized supply, or a more efficient use of fossil fuels can be promoted more cost effectively and efficiently on the community scale.

The first step for a more exergy optimized community supply is, similar as for buildings, to promote a **wider integration of low-temperature renewable energy sources**, such as solar thermal or ground source heat. Higher solar fractions are generally achieved if solar collector fields are used in combination with heat networks, connecting several supply systems (e.g. collector or borehole fields) with diffe-

rent users. As the solar fraction increases, i.e. the share of low exergy supply increases, the exergy efficiency of the energy supply also rises. Similarly, the use of ground source based systems in combination with heat networks will increase the energy efficiency (i.e. COP) of heat pump units, if demands of higher temperatures, such as DHW supply, can be supplied by solar thermal heat. Solar thermal heat can be used in winter to reduce the required temperature lift from the heat pump units, allowing significant increase of the COP. This way high exergy input in terms of electricity required for operating the heat pumps can be reduced.

On the other hand, a **more exergy efficient use of fossil fuels** needs to be promoted. Decentralized supply with individual boilers should be substituted by electricity driven **CHP units**, maximizing the exergy output obtained from the high-quality fuels used. Distributed or centralised generation with CHP units can reduce the demand of fossil fuels and thus reduce the use of combustion processes for heat production in total, characterized by a high level of exergy losses.

As stated above, **heat networks** can play a significant role in a more exergy efficient energy supply on community level. They allow combining several renewable energy sources with waste heat from an exergy efficient use of fossil fuels. Heat networks also allow **cascading energy flows according to their temperature**, to supply high temperature applications, such as process heat, first followed by medium temperature demands such as DHW and finally low temperature heat can be directly used for space heating. In this way, pumping energy, i.e. high exergy input, into the network can be minimized and the exergy efficiency of the energy supply increases.

Exergy analysis can be a useful tool for improving the design of heat networks. Coming back to the two main strategies mentioned at the beginning of this section, and bearing in mind the main directions for promoting a more exergy efficient supply at the community scale, it can be concluded that designing more “sustainable” buildings could be regarded a necessary but not sufficient condition for reaching energy and exergy efficient communities. Innovative supply structures allowing the application of the strategies mentioned above are required.

From an exergy perspective pumping energy in pipes and ducts shall be minimized. This is also valid for the design of heat networks. For this purpose, the diameter of the pipes in the networks can be increased. Thereby, lower heat losses can be found in the network and lower maximum fluid speeds occur. In turn, as a result of the greater pipe diameter, thermal losses in the network increase. First results on the sizing criteria of small scale district heating systems show that actually a trade off between the increase of (low exergy) thermal losses in the network and the decrease in pumping energy for its operation can be found. While from the perspective of energy analysis lower target fluid velocities for sizing the network, i.e. smaller pipes, seem always advantageous, exergy analysis shows that an optimum between both criteria can be found (see Figure 4.4).

Storage units are also a key component in low exergy supply systems, particularly if based on heat networks to integrate a higher share of fluctuating renewable energy supplies (e.g. thermal solar power) into the system.

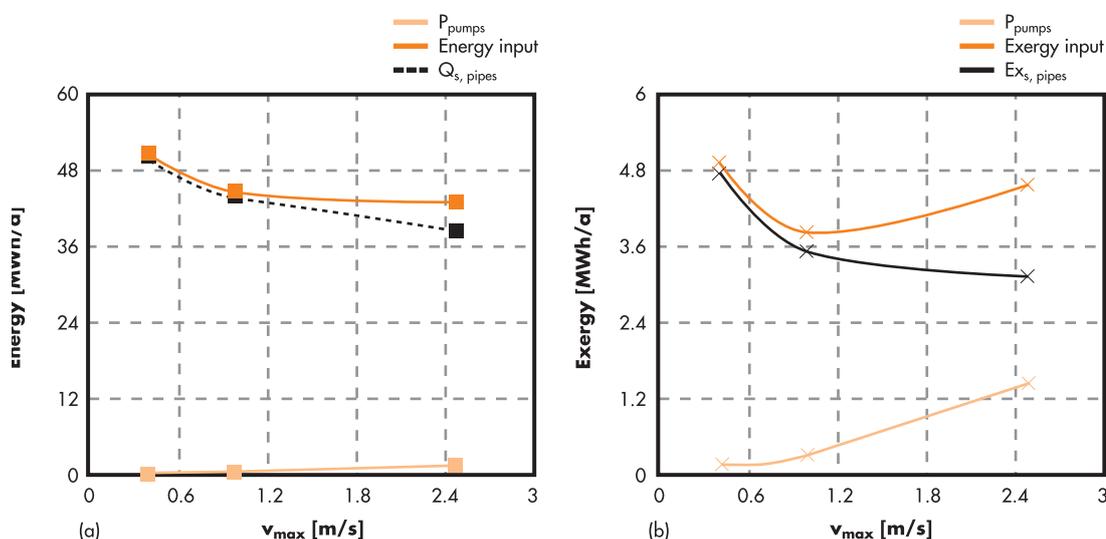


Figure 4.4: Pumping energy required for the operation of the heat network, thermal losses in the pipes and resulting required net energy input to supply both demands in energy (a) and exergy (b) terms (Torío, 2010).

Economic issues in LowEx community design

Due to the different scale and the large number of decision makers involved, different technologies might be cost-efficient at the building and community level.

Considering technical-economic feasibility, solar photovoltaic and solar thermal systems, if properly integrated, can be well applied in the urban context. However, implemented community case studies show that the cost of these technologies as compared to their energy yield is still relatively high as compared to other systems such as district heating systems or heat pumps (Jank, 2009).

For this report the integration of biomass plants has been investigated in terms of economics and is outlined here as an example. The urban scale applica-

bility of biomass is challenging because of plant feature problems, their location in the cities and management difficulties as well as supply and storage issues. On the basis of the actual conditions, biomass plants are more suitable in low-density urban environments and as close to the source as possible. Of course, in all cases with combustion (or pyrolysis or gasification) processes, CHP are recommended for improving both the energy and exergy performance. This is shown in Figures 4.5 and 4.6.

Figures 4.5 and 4.6 combine the exergy efficiency and the capital costs of several investigated systems for the biomass energy use chains. If we are separating the areas (1) thermal plants and CHP and (2) mobility (because the latter shows clearly additional costs for different reasons) we can observe that there is a clear trade-off between exergy output (efficiency) and capital costs (for the selected woody biomass chains this is an almost linear relation, for the selected biogas chains the situation is not that clear). This shows that there are higher investments necessary for a CHP compared to a thermal plant in order to make use of the full exergetic potential of biomass resources.

If we would follow the objective to gain a highest possible exergetic use of biomass resources with a minimum of capital cost, we would have to draw an envelope line in these figures connecting those points situated on the left hand and top side of Figures 4.5 and 4.6. This would lead to the conclusion, that using biomass for transport purposes in any case is not efficient, both from an exergetic and from an investment costs point of view. But, biogas plants feeding biogas into the gas grid and for combined heat and power production are an efficient option.

However, if we are considering that currently there is a high demand for individual transport systems, the lowest exergy losses result from bio-based e-mobility models compared to combustion engines. This would require clearly higher investment costs (which are partly offset, at least for the case of 2nd generation liquid biofuels by lower running costs).

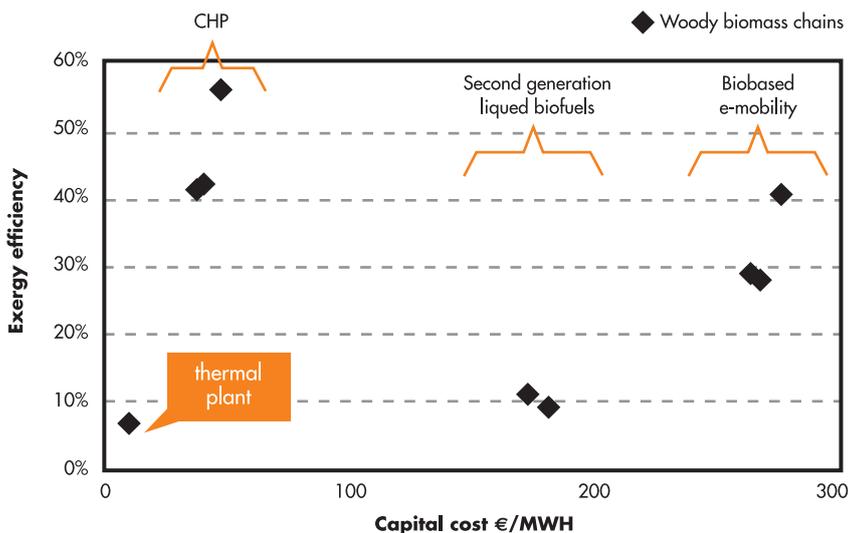


Figure 4.5. Exergy efficiency and capital costs (woody biomass)

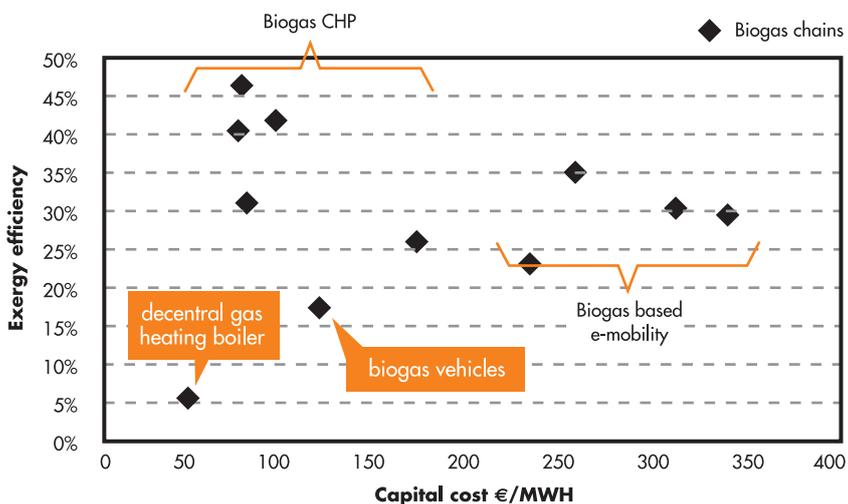


Figure 4.6: Exergy efficiency and capital costs (biogas)

¹⁰In chapter 6 an example of such an innovative system is shown.

5. EXERGY BENCHMARKING PARAMETERS

To bring the method for exergy analysis of building systems to the wider public parameters able to characterize the exergy performance of different systems are required.

A great number of parameters can be found in the literature (Cornelissen, 1997; Dincer and Rosen, 2007; Tsatsaronis, 1993). In this chapter the set of parameters considered as relevant by the ECBCS Annex 49 group are presented. These parameters are used to characterise the performance of the building and community case studies found in chapters 6 and 7. The diagrams used for graphically showing the exergy performance of energy systems in buildings and communities based on the parameters introduced, are also presented. Additionally, a benchmarking proposal for characterising the performance of building systems is introduced.

The main added value of the exergy approach is shown through the parameters and diagrams presented. Including exergy assessment in building energy codes would be an important step towards a more energy efficient built environment and would help bringing the exergy approach to the public and decision makers. Therefore, at the end of this chapter, a proposal on how to include exergy in energy codes is suggested.

Parameters for exergy performance

Quality factors

Quality factors allow depicting the exergy associated to a given energy flow (i.e. energy transfer) or the energy content of a given system. They represent the convertibility of an energy flow into mechanical work, i.e. high valued energy with high exergy content. Thereby, they allow high exergy sources and demands to be characterised and distinguished from low exergy sources and demands. They allow a simple yet thermodynamically correct representation of the matching in the quality levels between energy supplied and demanded, and are used for this purpose in the "arrow diagrams" presented below in this chapter.

Quality factors are defined as the ratio between the exergy and energy of a given energy system. From a thermodynamic point of view, they represent the proportion of work that can be obtained from an energy conversion process which brings an energy system into equilibrium with its environment¹¹ as related to the energy input in the process (i.e. the energy present in the system before the conversion process takes place).

Thermal, chemical, mechanical, potential and kinetic exergy derived from different temperature, composition, pressure, height and velocity between a system and its reference environment might be present. Exergy flows can be derived from quality factors related to all of the above items.

Equation (5.1) shows the general expression of quality factors which can be applied to any energy flow or source.

$$F_{Q,i} = \frac{Ex_i}{En_i} \quad (5.1)$$

However, this report, as well as the method introduced in chapter 2, focuses on thermal exergy. The most popular expression of quality factors for thermal energy transfers are Carnot factors (or Carnot efficiencies). Carnot factors can be applied if an isothermal heat flow happens via a heat engine between two temperature levels. Equation 5.2 shows the expression of Carnot factors for a temperature T of the system and a reference temperature T_0 . Carnot factors are used to calculate the so-called "exergy of heat" (see chapter 2).

$$F_{Q,Carnot} = \frac{T_0}{T} \quad (5.2)$$

If the heat transfer is not isothermal, as it is in the case of, for example, storage processes, Carnot factors cannot be applied. Instead, the quality factor shown in equation 5.3 needs to be used¹². The so-called exergy of matter (see chapter 2) can be obtained using the quality factors defined in equation 5.3.

$$F_{Q,matter} = \left(1 - \frac{T_0}{(T - T_0)} \ln \frac{T}{T_0} \right) \quad (5.3)$$

Exergy efficiency

Exergy efficiencies are a suitable and appropriate base for comparing the performance and optimisation of different heating and cooling systems. As any other efficiency, exergy efficiencies are defined as the ratio between the obtained output and the input required to produce it. Exergy efficiencies help in identifying the magnitude and point of exergy destruction within an energy system (Cornelissen, 1997). Therefore they allow to quantify how close a system is to ideal performance or where the energy and exergy inputs to the system are better used (Torío et al., 2009).

Different definitions of exergy efficiency parameters can be found in the literature. At least two types of exergy efficiencies can be identified and differentiated: “simple” or “universal” and “rational” or “functional” (Cornelissen, 1997; Tsatsaronis, 1993). In (Schmidt and Torío, 2009; Torío et al., 2009) a discussion on the differences and suitability of these two efficiencies can be found.

The mathematical expressions of the simple and rational exergy efficiencies are shown in equations 5.4 and 5.5.

$$\Psi_{simple} = \frac{Ex_{out}}{Ex_{in}} \quad (5.4)$$

$$\Psi_{rat} = \frac{Ex_{des,out}}{Ex_{in}} \quad (5.5)$$

The main difference between both exergy efficiencies is the way the exergy output is considered. The rational efficiency considers the difference between “desired output” and any other kind of outflow from the system. In turn, the simple exergy efficiency considers any kind of output as such, be it desirable or not for the investigated use. In most building systems undesirable outputs are present, e.g. in a waterborne heat or cold emission system in a building, outlet water flows back via return pipes into the heat/cold generation system. In consequence, the simple exergy efficiency works better when all the components of the incoming exergy flow are transformed into some kind of useful output. In turn, the rational efficiency shows how much exergy is getting lost while providing a specific output. Exergy losses regarded in the rational efficiency are due to both irreversible (not ideal) processes present and to unused output exergy flows. Therefore, the rational exergy efficiency is a more accurate definition of the performance of a system and can be better used without leading to false conclusions.

The rational exergy efficiency is the parameter used in the “PER-Exergy efficiency” diagram presented below to characterise the exergy performance of community supply systems.

Depending on whether the exergy efficiency refers to a single component or process of an energy system, or whether it refers to all processes and components constituting the system, so-called “single” and “overall” exergy efficiencies can be defined.

An example of single and overall efficiencies for the room air subsystem and complete energy chain in Figure 2.4 (in chapter 2) is shown in Equations 5.6 and 5.7. Overall efficiencies are derived from an

input/output approach¹³ for the analysis of a given energy system and can be calculated as the product of the single efficiencies of the single processes or components comprising the system (Torío et al., 2009).

$$\Psi_{single,r} = \frac{Ex_{in,env}}{Ex_{in,ra}} \quad (5.6)$$

$$\Psi_{single,r} = \frac{Ex_{out,env}}{Ex_{in,prim}} \quad (5.7)$$

Exergy expenditure figure

To clearly show the relation between the exergy required for supplying a given energy demand, and the energy demand itself, Schmidt, et al. (2007) defined the “exergy expenditure figure”. Exergy expenditure figures can be used to characterise the performance of components in energy supply systems. This figure can be seen as an enhanced version of the quality factors (exergy to energy ratio), where both the energy and exergy losses in a certain energy conversion unit are depicted.

In Equation 5.8, the exergy expenditure figure is defined for a component i of an energy system. It is calculated as the ratio between the exergy input (effort) required to supply a given energy demand and the energy demand itself (use). Auxiliary energy for operating the component is also included as input (i.e. effort) in the parameter.

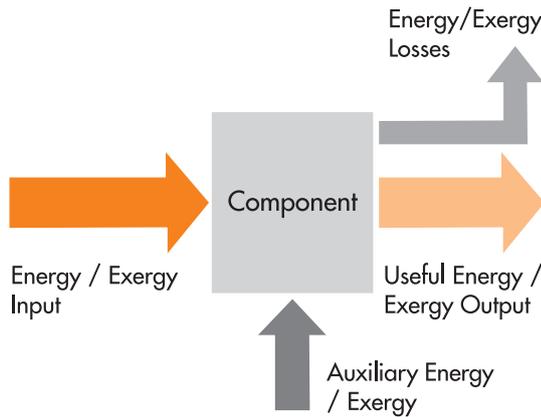
For supplying a given energy demand due to inefficiencies in the supply systems a greater amount of energy needs to be supplied. Ideally, however, the energy supplied should have a similar quality as the demand. Providing smaller amounts of energy with higher quality would not be sufficient. Therefore, in the exergy expenditure figure the “use” of a given component (e.g. heat loads to be supplied by radiators in buildings) are regarded in terms of energy and not in exergy terms.

Comparing the exergy expenditure figure to the quality factor of the demand provided (use) the level of matching between the quality levels of energy supplied and demanded can be obtained.

$$\varepsilon_i = \frac{Effort}{Use} = \frac{Ex_{in,i}}{En_{out,i}} = \frac{F_{q,in,i}}{\eta_i} \quad (5.8)$$

Figure 5.1 shows the energy and exergy flows used for the general definition of the exergy expenditure figure for a component i .

Figure 5.1: Graphical representation of the exergy flows included in the exergy expenditure figure for a general component of an energy system (Schmidt et al., 2007).



Energy and exergy losses happening in the component are implicitly taken into account by the ratio of provided output to required input. Energy losses are taken explicitly into account by means of the energy efficiency in equation 5.8. Exergy losses are taken into account by comparing the exergy expenditure figure of the component with the quality factor of the final demand to be provided. In consequence, if the energy losses in the component are high, i.e. low energy efficiency, the exergy expenditure figure might reach values higher than 1 (see equation 5.8).

For the particular application of space heating and cooling of buildings, the quality factors of the energy demanded are very low. Figure 5.2 shows that for space heating applications assuming an ambient temperature (i.e. reference temperature) of 0°C and an indoor air temperature 21°C the quality factor of energy demand is 7%. Therefore, for space heating of buildings, the closer the exergy expenditure figure for a given system to 7%, the better the system exergy performance is. Consequently, in space heating and cooling applications, energy supply systems with low exergy expenditure figures shall be used.

The definition of the exergy expenditure figure used here is not equivalent to the expenditure figure in the German Standard (DIN 4701-10, 2001), despite similar nomenclature. The main difference is that the exergy expenditure figure as proposed here represents a ratio between an energy output and an exer-

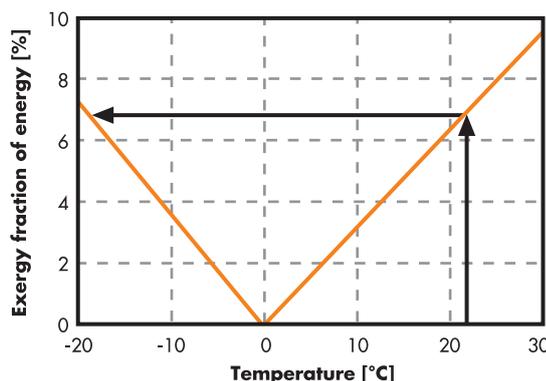


Figure 5.2: For a reference temperature of 0°C, the exergy content of the energy in the room air, assuming an indoor air temperature of 21°C, is 7%.

gy input. In the German Standard the expenditure figure is the inverse of the energy efficiency of a given component, i.e. a ratio between the required input and the provided output.

Again, the exergy expenditure figure regards the quality level of the energy supplied (effort), whereas the output (use) is regarded in energy terms (i.e. quantity). Therefore, as long as a certain energy source with its corresponding quality level is used with the same energy efficiency, the exergy expenditure figure would be the same and the parameter will not vary. By comparing the exergy expenditure figures for different steps or subsystems of the energy supply to the exergy level of the energy demand (e.g. 7%) the suitability of each component for that particular use can be checked. Therefore, it is a better indicator of the good matching between the quality level of the energy used by a given component and the final energy demand, i.e. of the suitability or appropriateness of the energy system for providing a given use. In (Schmidt and Torío, 2009) a case study comparing the exergy expenditure figure and the single exergy efficiency for different components of the energy supply chain is presented. Results showed the suitability of the exergy expenditure figure for providing insight on the appropriateness of using a given component for a certain energy use.

Primary energy ratio, PER

Exergy assessment provides information on the matching between the quality levels of the energy demanded and supplied. It allows a common and scientifically grounded approach for analysing different energy sources, be they renewable or fossil. In turn, exergy does not provide any information on the renewability of a certain energy source. To connect these considerations with exergy analysis, a further parameter is required. For this purpose, the primary energy ratio (PER) is introduced.

PER is calculated as the ratio between the useful energy output, i.e. the energy demand to be supplied, and the fossil energy input required for its supply. The analytical expression of PER is shown in Equation (5.9). High PER values indicate that the proportion of fossil energy in the supply is low, and, thus greater share of renewable energy sources is present in the supply.

$$PER_i = \frac{En_{out,i}}{En_{in,fossil,i}} \tag{5.9}$$

PER's are used in the PER-Exergy efficiency diagram introduced below in this chapter for characterising the performance of community systems.

Benchmarking for components of building systems

The exergy benchmarking proposed here for components of building supply systems is based on the exergy expenditure figure. Here the benchmarking method and its applicability are presented by means of an example where several building systems are analyzed.

The case study consists on a building heating case. Several building systems are considered for supplying the same space heating demand. In particular, different heat generation and emission systems are regarded: condensing boiler (Cond. in Figure 5.3) without and with solar thermal systems, wood pellet boiler (Wood. in Figure 5.3), ground source heat pump (GSHP in Figure 5.3), district heating (DH in Figure 5.3), radiators (radiator in Figure 5.3) with supply and return temperatures of 55/45°C and floor heating systems (floorh in Figure 5.3) with supply and return temperatures of 28/22°C, respectively (see also Figure 1.2).

A component, e.g. a radiator, is designed to supply a specified heating power. An appropriate building system should perform this task with the smallest possible amount of exergy input. Furthermore, the use of high quality (auxiliary) energy, e.g. electrical power, and losses to the environment, should be low.

As described above (see Figure 5.2), the exergy fraction of the energy needed to heat a room is only around 7%. This value can be directly compared to the exergy expenditure figures of the building service systems discussed above (Figure 5.3). They satisfy the heat demand with a more or less well-adapted heat supply. Heat generators that utilise a combustion process use much more exergy than required, and are thus less efficient from an exergy perspective. As for emission systems, for heating the same room, the radiator system uses more exergy than the floor heating system, which is closer to being ideal in terms of exergy use.

Benchmarking for buildings

All parameters presented until now in this chapter represent different ratio between effort invested and use obtained. In consequence, they state the matching level between energy supplied and demanded, but do not give any information on the total energy or exergy demand of a building. For benchmarking the performance of buildings, similarly as it is done currently in terms of energy, a limitation of the exergy of the primary energy demand is suggested.

An ideal line can be drawn based on the real exergetic demand of the regarded zone. The exergy supplied by different building systems should be compared with the exergy of the demand. Ideally

they should be as similar as possible, i.e. for low exergy demands such as space heating or domestic hot water production (DHW) low exergy should be supplied. To promote the use of building systems making use of low quality energy sources, i.e. which require low exergy inputs, the upper limit of the exergy of primary energy input should be limited according to the demand of a good building service equipment solution, similarly as it is done for the limitation of fossil primary energy demands. The limit is set here close to the exergy demand of a condensing boiler, regarded as an available and energy efficient state-of the art technology.

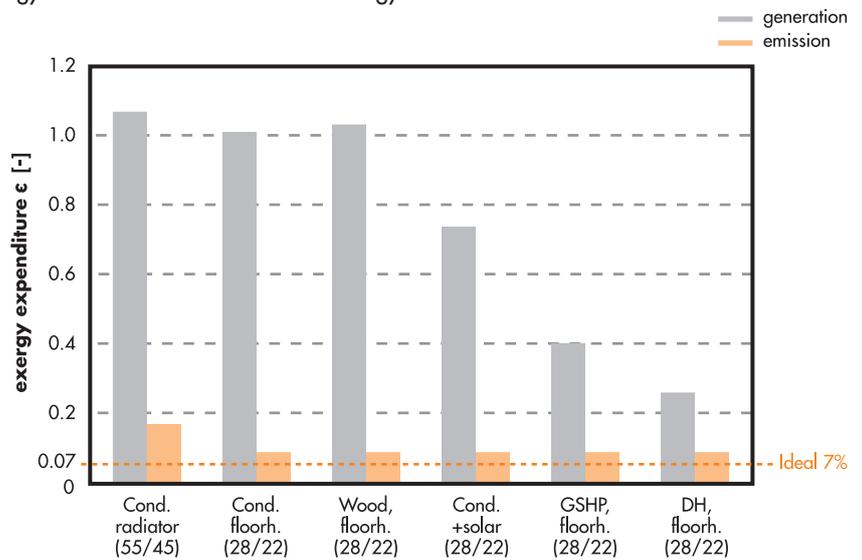


Figure 5.3: Assessment of the components “heat generation” and “emission system” with the exergy expenditure figure for the chosen variants of the building service system.

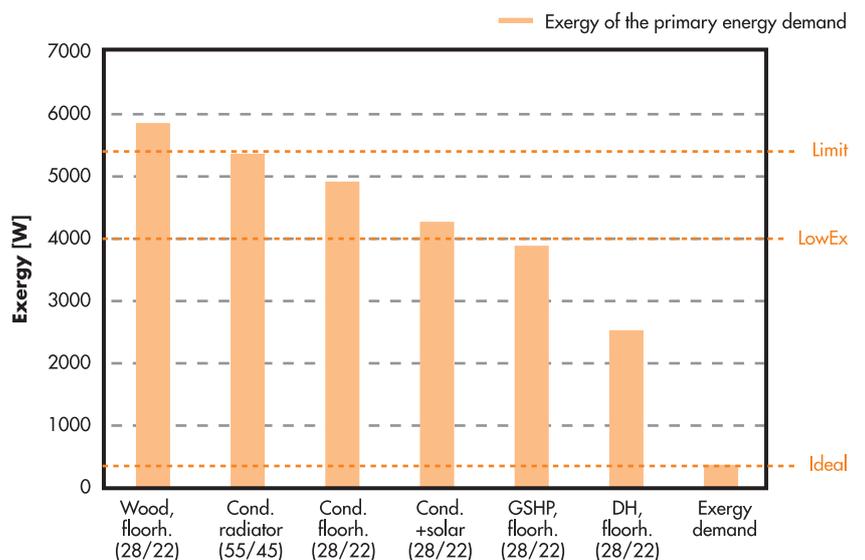


Figure 5.4: Calculated exergy of total primary demand (fossil and renewable) for the chosen variants of the building service equipment (steady state) and a suggested benchmarking classification.

However, it can be clearly seen in Figure 5.4 that a condensing boiler demands higher exergy inputs as needed for satisfying the demand. The exergy input can only be reduced if building systems which do not use combustion process are used to provide low temperature heat.

As the supply matches the needed demand and the exergy destruction in the regarded building is kept to a limit, the building can be regarded as a "LowEx"-building.

Four main design principles can be extracted from the examples shown in Figure 5.4:

1. The limitation of the (fossil) primary energy demand is a useful tool to reduce energy consumption and the related CO₂-emissions from buildings. The exergy approach needs to be combined with the primary energy approach in order to include insight on the renewability of energy sources used. This is already mandatory in a number of European countries (e.g. Germany).
2. Maximal heat transmission losses through the building envelope should also be limited (e.g. as it is done in German regulations by limiting the mean transmission heat loss coefficient) in order to ensure a good building envelope construction. The energy demand should be reduced. Thereby exergy demands would automatically be reduced.
3. To assess and use properly the thermodynamic potential of the utilised energy, the exergy demand of fossil and renewable sources should be limited. This limitation could be done in a similar manner as already known from the procedure of limiting the primary energy demands.

4. The exergetic demand of a zone should be satisfied with a suitable supply system, e.g. the exergy expenditure figure should be oriented to the actual exergetic demand of the zone.

Exergy fingerprint diagram

The "Exergy fingerprint" diagram depicts the energy demanded and supplied against the quality of each energy demand (Jentsch et al., 2009)¹⁵. It allows a quick graphical overview on the matching between the quantity and quality levels of the energy supplied and demanded. The calculation algorithm corresponds to a steady-state approach similar to that implemented on the Annex 49 pre-design tool (see chapter 3). The diagram is shown here for completeness but has not been used to characterise the case studies from ECBCS Annex 49 work.

Figure 5.5 shows an example of two exergy fingerprint diagrams, for two different energy supply scenarios. The grey areas represent exergy losses in the energy supply. The rest of colours represent the different energy demands considered: electricity, lighting, process heat, DHW and space heating, respectively. The length of the coloured areas (its value on the X-axis) represents the share of the respective energy use on the entire demand. Its height (i.e. its value on the Y-axis) represents the quality of the given demand, i.e. its quality factor. By the mere definition of quality factors (see equation (5.1) with the product of the quantity of the energy demand (i.e. value on the X-axis) and its quality (i.e. value on the Y-axis) the exergy associated to the energy demand can be obtained.

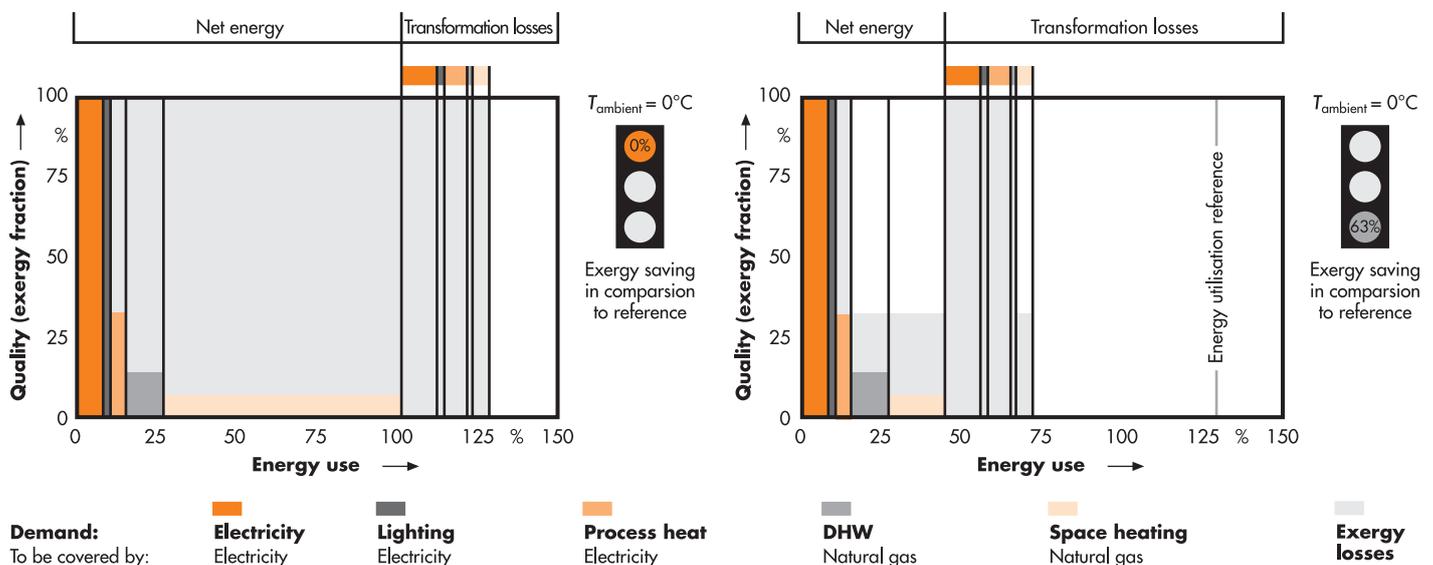


Figure 5.5: (a): Exergy fingerprint diagram for a reference scenario consisting of an average residential building with an energy supply via a gas fired condensing boiler; (b): Exergy fingerprint diagram for an improved scenario consisting of a well insulated building supplied with CHP units and district heating.

Exergy losses, associated to the energy losses present in the energy supply systems used, are shown at the right of the diagram for the different energy demands analyzed.

Figure 5.5(a) shows the diagram for a reference scenario consisting of an average residential building in Germany whose demands are supplied with electricity from the German grid and a gas fired condensing boiler.

By comparing the diagram of different supply options with this reference scenario, improvements can be recognized. An ideal supply system would imply firstly a reduction of the demands, i.e. of the length of the coloured areas (on the X-axis). Furthermore, exergy losses, i.e. grey areas, also need to be reduced. An improved insulation level for the building shell and the use of suitable energy supply systems, such as CHP units and waste district heat, allow achieving these aims as shown in Figure 5.5 (b). The better performance is also shown at a glimpse through the a traffic light complementing the diagram, where the exergy savings in percentage as compared to the reference scenario can be read.

The diagram gives similar information as that delivered by the Annex 49 pre-design tool. However, the performance of the different components in building supply systems cannot be assessed individually with this diagram. The Annex 49 pre-design tool allows to obtain such information on a quick and easy way. Different building energy demands (e.g. DHW, space heating or lighting) are also included in the tool.

Graphical representations for characterising the exergy performance of community supply systems

Graphical representations for characterising the exergy performance of community supply systems enable to visualize the performance of a given case study and make different community energy supply concepts comparable. The characterisation of the exergy performance of different case studies and community concepts is presented here by means of different diagrams included under the section "LowEx Diagrams" in the respective case study (see chapter 7).

Arrow diagrams

The arrow diagram shows the matching between the quality levels of the energy supplied and demanded. The diagram is a qualitative representation of the quality and quantity of energy demands and supply in buildings. Figure 5.6 shows an arrow diagram as an example.

The position of the arrows on the Y-axis (i.e. "Energy quality, q", with a scale from 0 to 1) represents the quality factor of the energy supplied and demanded and thereby depicts the exergy content of the energy flow. The thickness of the arrows represents the amount of energy demanded or supplied. By these means both the quality and quantity of the different regarded energy flows is shown. Thus, similarly as the exergy fingerprint diagram introduced in the previous section, the matching between the quantity and quality levels of the energy supplied and demanded can be seen.

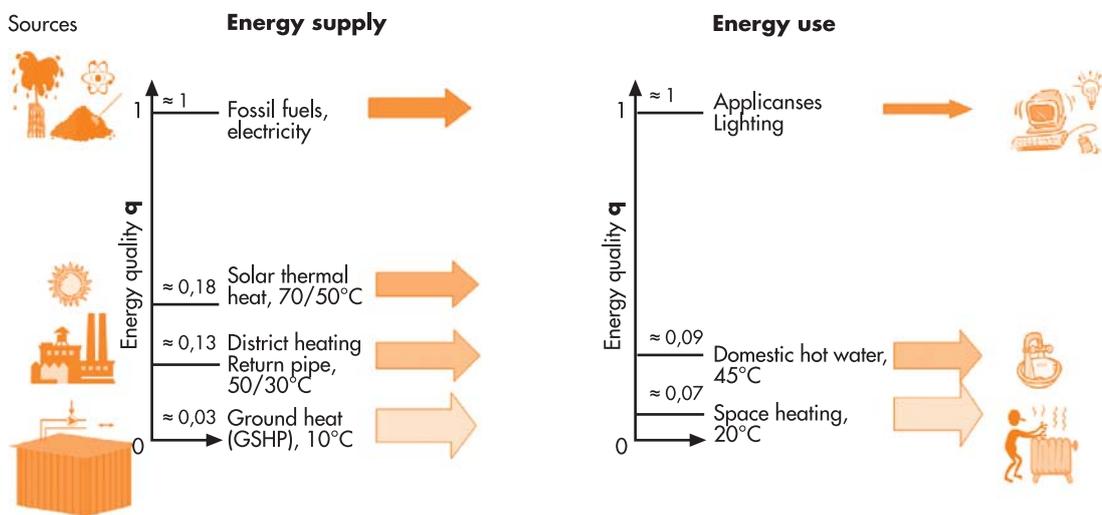


Figure 5.6: Example of an arrow diagram.

PER – Exergy efficiency diagram

The Primary Energy Ratio (PER)-Exergy efficiency diagram characterises the exergy performance and use of renewable energy in the supply of a community project. Exergy efficiency is represented in the Y-axis. PER ratio is represented in the X-axis. Each case study is represented by both factors (white dots in the diagram). Ideally, high values for the exergy efficiency and PER ratio should be obtained. White dots show both parameters for different supply concepts, characterising the performance of the case study. Dots in the upper right corner indicate good exergy performance and high use of renewable energy sources. Supply concepts on the area close to the upper right corner would correspond to “LowEx” community concepts. In turn, dots close to the lower left corner depict case studies with low exergy efficiency and high fossil fuel share on the energy supply.

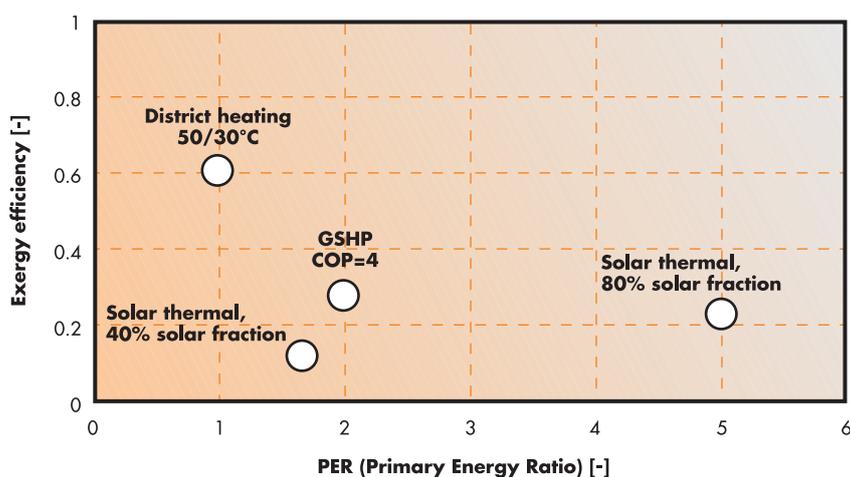


Figure 5.7: Example of an “PER – exergy efficiency” diagram.

Pre-normative proposals

Buildings are major contributors to the final energy demands in many industrialized countries (Eurostat, 2007). Therefore, to reduce CO₂ emissions from the built environment and thereby contribute to a more sustainable development and to international targets trying to avoid or limit climate change, energy directives for buildings have been developed.

Generally all current energy laws are based on energy (i.e. the first law of thermodynamics), not on exergy. In this sections some thoughts and suggestions on including the exergy concept in energy legislation are presented.

There are five important questions to be asked when designing energy legislation:

Which **objectives** are to be obtained by this legislation?

Which **parameters** are the right indicators of the (energy) performance the building in relation to the foreseen objectives?

Which analysis **method** should be used?

Which **‘requirements’** should be set to the building? (e.g. benchmarking against comparable buildings or set a maximum value to the chosen parameters)

Which **administrative instrument** could best be utilized? (i.e. energy tax, ‘force’, subsidies)

The following section gives a brief introduction to current European energy legislation and tries to give some thought and suggestions on including the exergy concept, hereby also addressing the five questions mentioned above.

Current status of energy laws and exergy in energy laws

Reducing energy consumption and eliminating waste are among the main goals of the European Union (EU). There is significant potential for reducing energy demands, thereby limiting consumption of energy sources. The EU has introduced legislation to implement energy efficiency measures in the built environment. According to the Energy Performance Building Directive (EPBD, 2002) the Member States must apply minimum requirements as regards the energy performance of new and existing buildings, ensure the certification of their energy performance and require the regular inspection of boilers and air conditioning systems in buildings (EU, 2010). Regarding the five main questions raised in the previous section, the following answers can be given related to current energy legislation on a European level:

Objectives: the final aim is to promote secure and sustainable energy supply systems for the built environment. Related to sustainability this objective is translated to the aim to reduce primary energy use and CO₂ emissions. This objective should be obtained by reducing energy demands in buildings and enhancing the use of renewable energy sources within the sector.

Parameters: the secondary objectives formulated above already determine primary energy use and CO₂ emission as indicators for the performance of a system.

Method: The analysis method must be determined by the member countries. However, it should be according to some defined standards to allow certain comparability and based on common framework methodology for all member states. It is also mentioned that “the calculation shall also include a numeric indicator of carbon dioxide emissions and primary energy use” (van Dijk, 2008).

Requirements: the Member States are responsible for setting their own minimum thresholds and benchmarks.

Administrative instrument: compulsory energy performance certificates should be made available when buildings are constructed, sold or rented.

Including exergy in energy legislation

As it can be concluded from the previous paragraph there are no exergy requirements (using exergy as a methodology or as an indicator) in current energy legislation.

Some literature about including exergy in energy legislation (Van Gool 1997; Dincer 2002; Favrat et al. 2008) can be found. These works mainly focus on the importance of including exergy in energy legislation. Favrat, et al. (2008) describe a practical approach determining fixed exergy efficiencies for various energy conversion processes. In this work it is also mentioned that the Canton of Geneva requires that documents from city developers include an exergy performance evaluation of their project.

In this paragraph the main motivation and contribution gained by including exergy in energy legislation is presented. The same structure used in the previous sections is followed:

Objectives: the main motivation for including exergy in building energy regulations is that this concept can contribute to design and operate more efficient energy supply systems in the sector since exergy depicts the real thermodynamic efficiency (and thereby the improving potential) of energy systems. This could contribute to the main objective of the energy legislations available of achieving more sustainable energy supply systems. In addition, exergy allows analyzing all kinds of energy sources on a common and scientifically grounded basis (be they renewable or fossil). It can be argued that in the future, when all energy supply is based on renewable energy, it will also be important to use renewable energies in an efficient way, since they are limited in time or space, and the conversion of energies will never be free of materials. Therefore it can be argued that a secondary objective can be to reduce exergy destruction by designing more intelligent systems, even if these are based on renewable energies.

Parameters: exergy is in the first place related to the thermodynamic performance of a system. An exergy analysis can, therefore, determine how much potential has been lost and thus how well the performance of an energy supply system really is, compared to the ideal performance. In this way exergy has an added value to energy:

- Exergy efficiency is always <100% (different from

COP), thus a real improvement potential can be determined, while energy analysis is only able to compare systems;

- Exergy analysis shows quality losses that are not shown with energy analysis, being thereby a true measure for the thermodynamic efficiency and performance of a given system or process;
- Exergy assessment is not limited to the consumption of "primary energy" as in energy from fossil fuels (as the primary energy approach is), but it also includes the analysis of the potential of renewable energy sources used. Therefore it is also a tool to design intelligent systems using renewable energies.

Method: using exergy analysis as a method to determine the exergy losses and the improvement potential is the most obvious application of the exergy concept, which is already used by many designers of energy systems. An exergy analysis can support meeting the objective to reduce the consumption of primary energy sources by making available more efficient building systems. Furthermore, by matching the quality, i.e. exergy, level of the energy supplied and demanded suitable energy sources and energy systems can be identified for providing different uses with different quality levels within the built environment (e.g. space heating and lighting). At this moment no standard tool at the level of most national energy analysis tools is available. A first idea of the exergy performance can be obtained with the Annex 49 pre-design tool (see chapter 3). Alternatively the calculation methods as explained in chapter 2 can be applied. The development of a generally applicable tool as are the current energy tools will require additional work.

Requirements: since exergy analysis is relatively new in the built environment it is difficult to set minimum standards at this moment. By now, a common scientifically grounded methodology has been developed and agreed upon by the ECBCS Annex 49 group (see chapter 2). The next step would be to apply the methodology to several case studies and define benchmarks based on the results. For a first idea the paragraph on benchmarking (chapter 5) can be considered. In addition, requiring an exergy analysis as is done by the Canton of Geneva (Favrat et al. 2008) can be a good first step, since this will give insight in the losses and motivate designers to come up with more intelligent systems. It is also a way of introducing the concept to many professionals working in the built environment.

Administrative instruments: once the benchmarks are set, administrative instruments to make sure that they are met can be defined. However, as stated above, further research needs to be conducted to reach this stage. Thus, the discussion of possible administrative instruments is not further treated in this work

Exergy as sustainability indicator

Sustainable development can be defined as a development that “meets the needs of the present without compromising the ability of future generations to meet their own needs” (Bruntland, 1987). Several authors have linked the exergy concept with insights on sustainable energy supply and sustainable development (Cornelissen, 1997; Rosen and Dincer, 2007; Wall, G. and M. Gong, 2001). This link is based on the fact that exergy is a thermodynamic concept that clearly identifies the improvement potential of an energy system, thus opening up the possibility of increasing its efficiency (Rosen et al., 2008). For this aim, all energy flows involved, fossil and renewable, must be analyzed. This allows showing the thermodynamic efficiency of using different energy sources, independently of their renewable or fossil character, and allows a common basis for the comparison of different energy sources and uses (Schmidt et al., 2007). Since energy sources, and particularly fossil fuels, are limitedly available, increasing the efficiency of their utilization leads to increase the time span in which they can be utilized and reduce negative environmental impacts derived from its use, thus increasing sustainability of energy systems.

However, it must be clearly stated that systems based on renewable energy sources are more “sustainable” than fossil fuel based ones, even if the exergy efficiency of the first might be lower than that of an equivalent fossil-based alternative. The exergy concept does not distinguish between renewable and non-renewable energy sources. This distinction, crucial for finding options towards a more “sustainable” energy supply, must always be regarded additionally to the exergy analysis.

Therefore, within research group of ECBCS Annex 49 consensus was agreed upon that exergy can NOT be understood as an indicator able to depict sustainability on its own. Exergy performance and sustainability are not equivalent concepts, and exergy analysis can only be seen as a further indicator to complement existing analysis methods in order to develop more “sustainable” energy systems.

Main conclusions

Several parameters usable to depict the matching of the quality levels between the energy supplied and demanded have been introduced. Through their application to case studies it has been shown that exergy analysis adds information to conventional energy analysis: the supply of high quality exergy in buildings for space heating and DHW supply purposes needs to be minimized. This implies avoiding combustion processes in building supply systems

and substituting them by low temperature systems and sources. In consequence, the core of the benchmarking proposal is to minimize the exergy of primary energy supply. With the parameters and benchmarking proposal presented in this chapter, this information is made directly and clearly available to building planners on a scientifically grounded basis.

Additionally, exergy analysis provides a commonly and scientifically grounded base for comparing energy systems using different energy sources, renewable and fossil, giving a true measure of the efficiency of their performance. In this sense, exergy analysis contributes to promote the efficient use of renewable energies. Since they are limited in time or space, and the conversion of energies implies also material use and process, reductions in the exergy destruction contributes to design more intelligent and efficient energy systems, even if these are based on renewable energies. However, it is important to remark that, despite the great added value of exergy, it cannot depict the sustainability of an energy system.

Including exergy analysis in energy legislation might be useful for two reasons: it supports meeting the objective to reduce primary energy consumption, and it supports the design of intelligent energy supply systems based on renewable energy, which will also become important in the future. The practical implication as to standardised methods and minimum requirements must be further developed. However, the methodology presented in chapter 2 of this work and results from case studies presented in chapters 6 and 7 can be a very valuable contribution for this purpose.

¹¹So-called "reference environment", see chapter 2.

¹²The quality factor in Equation 5.3 corresponds to a thermal heat transfer, where the temperature of the system changes from T to T_0 reversibly, i.e. via several heat engines working respectively at temperatures infinitesimally smaller than T (i.e. $T-dT$; $T-2dT$; etc.) up until T_0 .

¹³A description of this input/output approach can be found in chapter 2.

¹⁴For cooling systems the quality factor of the demand to be provided is even lower due to the closer temperature level to outdoor air.

¹⁵This diagram has been kindly supplied by the research group from the Fraunhofer UMSICHT Institute, Germany, Jentsch, A. et al. (2009).

¹⁶By some authors (Wall and Gong, 2001) exergy is also used as an environmental indicator, meaning it is also a measure for sustainability in a broader sense than just 'reducing energy consumption'. However, this vision is not supported by the ECBCS Annex 49 group, as it is clearly stated further below in this chapter.

6. APPLICATION OF THE EXERGY APPROACH TO BUILDING SYSTEMS

Introduction

In the present chapter, some building case studies are shown where the general exergy-based design strategies for buildings presented in chapter 4 are applied. Emphasis is put on the reduction of energy use by means of innovative approaches for cold and heat storage as well as energy recovery. Six case studies of innovative concepts or technologies are presented here. Three of them are related to air-conditioning systems, in order to reduce both the energy required for cooling and for the air circulation to ensure proper indoor air quality. The need for cooling, in fact, is becoming increasingly high in buildings: since there are less alternatives for producing cold than for heat generation – cold is commonly produced with air heat pumps or compression chillers with relatively poor efficiency – the possibility of using natural ventilation or evaporative cooling would be beneficial, where ever possible and with suitable ambient conditions.

Similarly to the seasonal storage systems, ground heat helps improving the performance of the building system by using a renewable and freely available source: its exploitation is particularly interesting with heat pumps, raising their COP to a value that makes the use of a high exergy source like electricity convenient. The use of hybrid technologies, coupling the use of renewable and non-renewable energy is in fact one of the most promising trade-off between availability and exergy efficiencies.

Waste heat utilisation can be considered another type technology particularly efficient from an exergy point of view: its use in the cogeneration approach is now widespread but it has to cope with problems like the matching of heat and electricity demand in the power plant, the need of an extensive planning and energy loss due to the heat distribution. An innovative approach that would partially solve these issues is the local heat recovery in the building, as it will be shown in the before last case study.

Two cases are about seasonal storage systems both for cooling and for heating (see the fourth and fifth building case studies). They are mandatory for an effective exploitation of renewable sources but they are also useful to lower the peaks in the supply system and to make it work preferentially in the best possible conditions. By letting the demand and the supply not being directly matched, they pave the way for a flexible energy use management.

A further case is about a waste water system to recover heat from buildings waste waters similarly to the

heat recovery systems in the Air Handling Units (AHU): a rational energy use, in fact, would comprise the recovery of all valuable types of energy.

The following is the list of the cases presented in this report:

1. Innovative Concepts for Exergy Efficient Air-conditioning Systems and Appliances in Buildings
2. Temperature and Humidity Independent Control (THIC) air-conditioning system
3. Adjustment of the ventilation rates based on the variation in time of the actual needs
4. Seasonal heat storage by Ground Source Heat Pumps (GSHP) system
5. Shallow ground heat storage with surface insulation
6. Exergy recovery from waste water in small scale integrated systems
7. Innovative configuration for cooling purposes: series design for chillers

Innovative building case studies

Innovative concepts for exergy efficient air-conditioning systems and appliances in buildings¹⁷

By using outdoor dry air as the driving force, the indirect evaporative chiller is aimed at providing a novel air-conditioning concept for public buildings in dry regions. In this manner, it takes advantage of the use of “wet” exergy contained in liquid water (which is very large) in order to produce cool exergy and subsequently cool the air or water as a cool carrier.

It produces cold water with a temperature between ~ 15 and 18°C, lower than outdoor wet bulb and infinitely close to the dew-point temperature of the inlet air. As the heat carrier of the chiller is water rat-

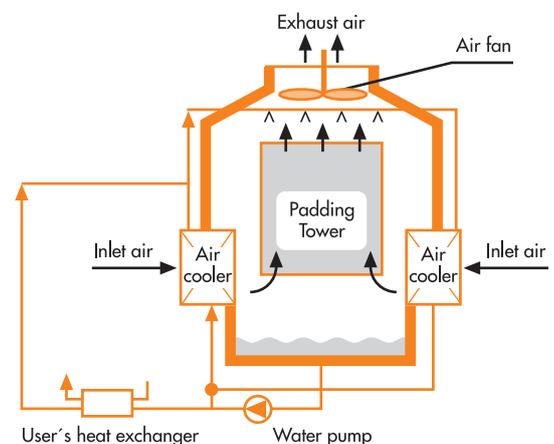


Figure 6.1: Principle of the chiller

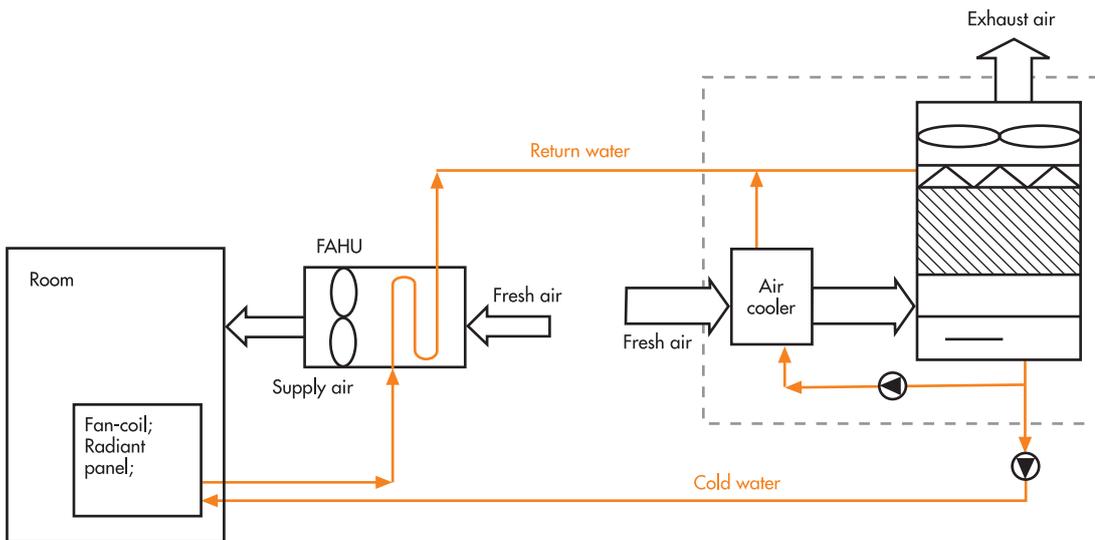


Figure 6.2: Structure of the air-conditioning system using the indirect evaporative chiller

her than air, the energy consumption for transmission is greatly reduced. An air conditioning system is also designed using the indirect evaporative chiller, as Figure 6.2 shows, which can use outdoor dry air sufficiently by matching the temperature level of the cold water and the heat sources.

Relevance as low-exergy technology

Exergy use in cooling has two big benefits: the exergy needed for heat conversion and the exergy for heat distribution and emission. In regards to heat conversion, cold water is produced at 16-18 °C, or high temperature and low-exergy cooling. In addition, it is produced using dry air as the driving force instead of electricity, as used in common chillers. The use of water strongly contributes to lowering exergy losses, with respect to airborne systems, due to better heat vector behaviour.

Temperature and humidity independent control (THIC) air-conditioning system¹⁸

Temperature and humidity control are the two main tasks of air-conditioning systems. In most centralised air-conditioning systems in China, the air is cooled at the temperature below the indoor dew point temperature, dehumidified by condensation, and then supplied to the occupied spaces to remove both the sensible and latent load. The required chilled water temperature should be lower than the air dry bulb temperature or air dew point in order to remove the sensible load (control temperature, covers 50%-70%) or the latent load (control humidity, covers 30%-50%), respectively. However, the same 7°C water is used to remove both sensible and latent load and, as a result, available energy is wasted.

The proposed THIC (Temperature and Humidity Independent Control) system is composed of two separated systems, a temperature control system and a humidity control system, as shown in Figure 6.3. The temperature of chilled water in the temperature control system is raised from 7°C in the conventional system to about 18°C, which also allows for the utilisation of some natural cooling sources. Even if the chilled water is still produced by a mechanical chiller, the COP (Coefficient of Performance) increases greatly.

In the southeast of China, where many large buildings are located, the outdoor air is humid: the main task of air-conditioning systems is to dehumidify the air. In this case, the liquid desiccant dehumidification method is recommended. In the northwest of China, the outdoor air is dry and the main task of air-conditioning systems is to decrease its temperature. Direct or indirect evaporative cooling is recommended.

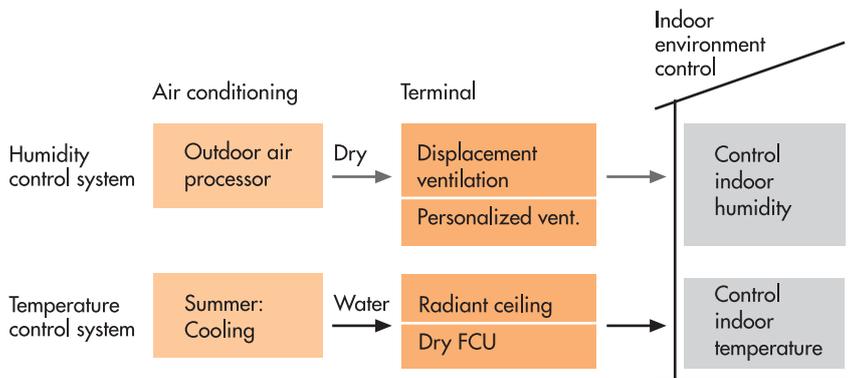


Figure 6.3: Device scheme

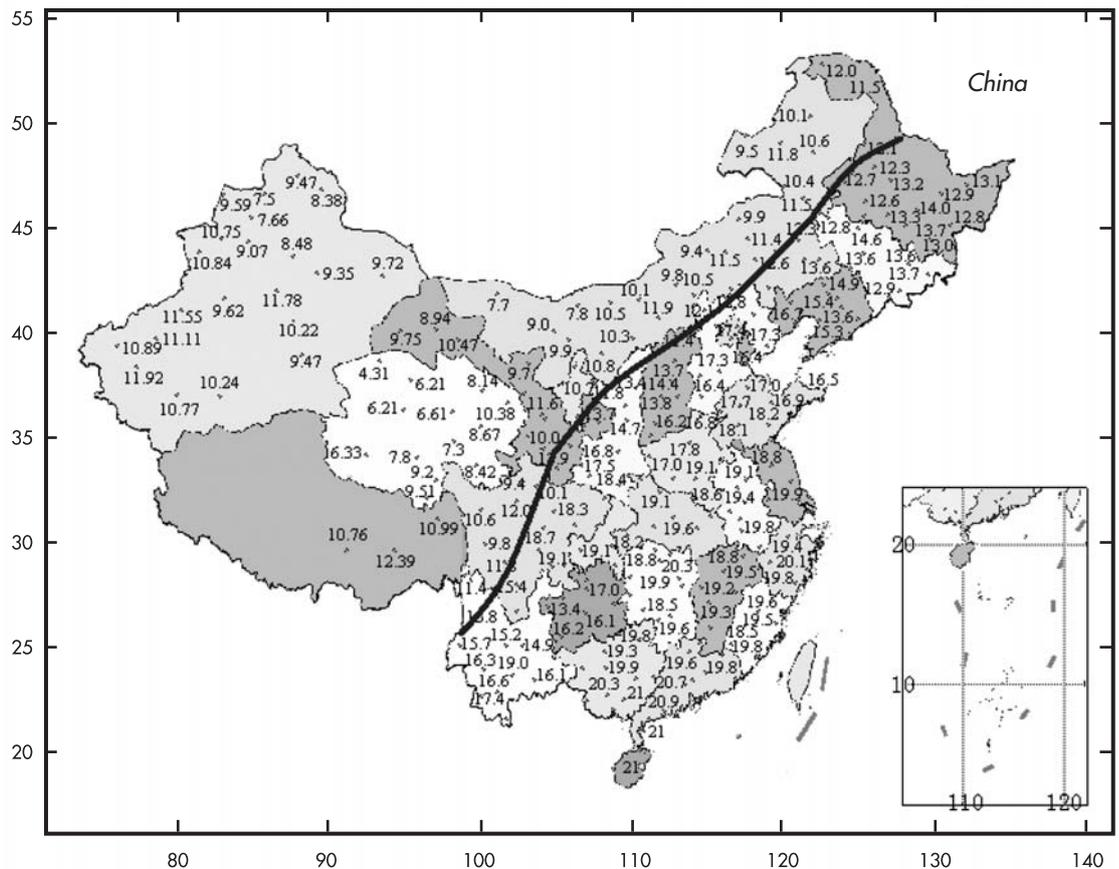


Figure 6.4: Average humidity ratio of the most humid month in China. Southeast of the line: outdoor air is humid. Northwest of the line: outdoor air is dry enough.

Relevance as low-exergy technology

This system allows the control of both humidity and temperature by splitting the management of them into two independent systems. Due to the increased temperature for cooling from 7° to 18 °C, much better performances in terms of exergy can be obtained. Referred to an outside reference environment at 25°C, the exergy content is respectively 6.4% and 2.4% of the produced and delivered heat. Similarly, a chiller ideally working in the same environment would perform almost three times more effectively. Consequently, relevant amounts of exergy can be saved, while still assuring good comfort conditions in the cooled areas.

Adjustment of the ventilation rates based on the variation in time of the actual needs

Ventilation plays a role of key significance in the overall building performance in terms of energy consumption, indoor air quality and thermal comfort. Ventilation can be ensured by natural means or by a mechanical system. The major challenges for the development of purely natural ventilation techniques are the uncertainty about practicing real control on airflows and the unreliability related to the stochastic nature of its driving forces - wind and temperature gradients. Mechanical ventilation may result in an

unnecessary use of energy. Hybrid technology represents the attempt of combining the benefits of both ventilation strategies in a unique system by promoting interactions between occupants, indoor climate and outdoor conditions. Hybrid technology urges a technological development of system components (supply inlets, exhaust grilles and control algorithms) in order to always make airflow rates consistent with actual ventilation needs (e.g. amount of fresh air). The energy required by air conditioning and distribution also has, of course, to be minimised.

Relevance as low-exergy technology

Energy use for air circulation in air unit systems is a relevant part of the overall energy balance. To overcome the pressure drops in air ducts, which implies slight exergy destruction, electricity-driven fans are needed as their exergetic efficiency is very low. This approach limits the electricity consumption for air circulation by making use of the natural pressure differences in the environment that would be otherwise supplied. Furthermore, active systems, such as chillers, can be switched off to maintain IAQ comfort requirements. As a result, in intermediate seasons, it is possible to cut off the electricity consumption, that is exergy, and make use of available environmental sources.

Seasonal heat storage with ground source heat pump system¹⁹

Ground source heat pump (GSHP) systems with vertical ground source heat exchangers can be an effective solution to heat and cool buildings with low-exergy consumption. In the case of small buildings the tubes are normally installed satisfactorily far from each other and utilise the geothermal energy of the constant temperature of far-away soil volumes. In this way the seasonal energy storage is not available. However, in the case of larger buildings where several boreholes have to be installed, a more effective conception can be used. In this case the tubes can be installed in a cylindrical branch. If the number of boreholes increases, the proportion among the cylindrical boundary surface and the heat storage soil volume becomes smaller. As a result, the heat storage soil volumes are in contact with a relatively smaller surface with the far-away soil volumes. Consequently the effectiveness of the seasonal heat storage becomes higher (see Figure 6.5). In order to decrease the exergy loss of the stored energy (the temperature drop can be decreased), the heat exchangers are distributed into more groups and used in a suitable sequence during the heating and cooling periods (Simón, 2008).

Relevance as low-exergy technology

The main precondition to the exploitation of many renewable sources is the possibility to store energy, due to their inconsistent availability. The exploitation of renewable sources is considered as a low exergy approach. Even though solar radiation has a theoretically great exergy potential, the exergy destruction of the solar radiation would take place anyway, regardless of human exploitation, and its use replaces high-exergy fossil fuels.

Seasonal heat storage has a two-fold positive effect on exergy consumption in buildings: it allows the massive exploitation of solar energy in an efficient way – thus collecting freely available exergy – and it improves the performance of active, electricity-driven systems, such as heat pumps.

Shallow ground heat storage with surface insulation

Coupling solar panels and a heat pump with a pipe system merged into the ground under the building, either warm or cool exergy can be stored and then released to the building itself (see Figure 6.6). By covering large ground surface areas with insulation of sufficient thermal resistance the heat loss from the storage will be closer to the solution for a semi-infinite solid heated on the surface. Such storage will be favourable compared to a single borehole, especially when heat is supplied and extracted by the heat

carrier in an annual cycle. The aim is to combine such an annual storage with solar collector and a low-exergy heating system in order to minimize the use of high quality energy for heating and/or cooling. The energy carrier can be as an example air in ducts or in a gravel bed or a fluid in pipes with high conductivity flanges.

Relevance as low-exergy technology

This technology opens up the possibility of providing heating and cooling with low exergy supply. The reduced heat loss to the ground is also a way to minimize exergy losses in the system. However, special care will probably be needed to control the moisture from the ground.

Exergy recovery from wastewater in small scale integrated systems

In order to create a truly low exergy building, the sources of unnecessary exergy consumption must be eliminated. These include the exergy consumed by warm air being released to the external environ-

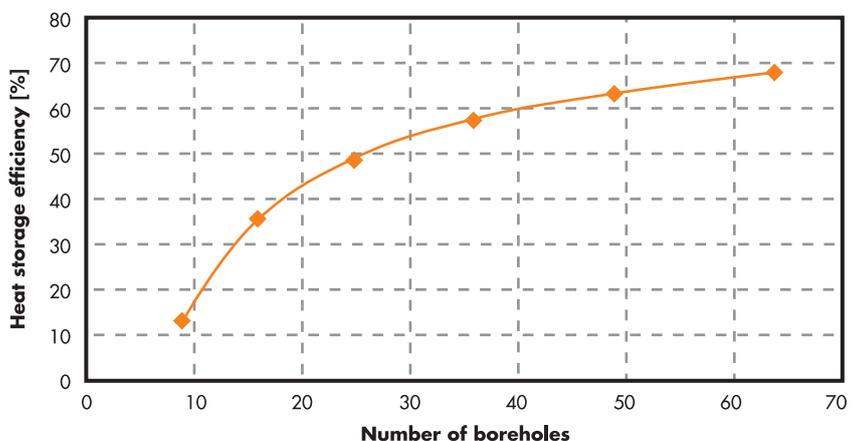


Figure 6.5: Estimated heat storage efficiency.

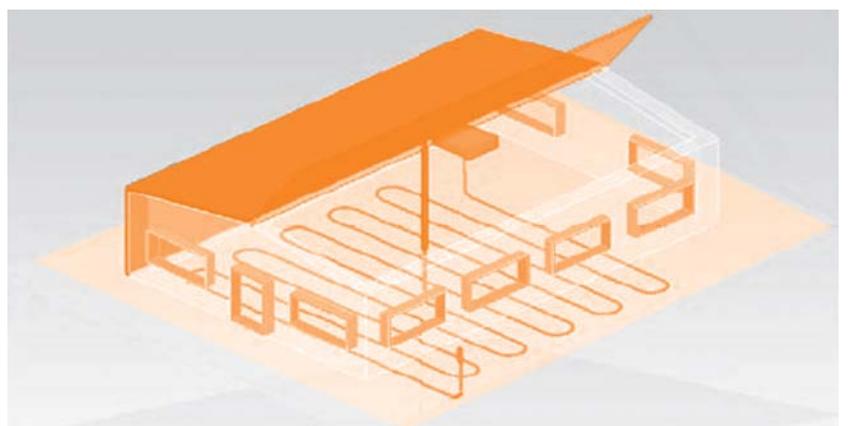


Figure 6.6: General view of the system.

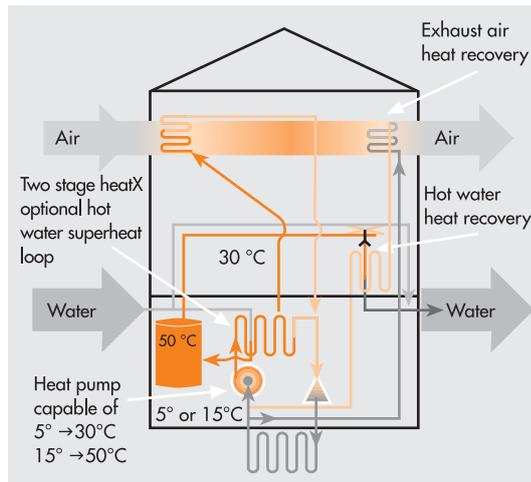


Figure 6.7: View of the system

ment, as well as the warm water. Recovery systems for exhaust air are already common, but wastewater has been overlooked. Most well insulated high performance buildings now have nearly half of their heat demand coming from hot water production. In this system, a recovery system is being analysed to maximise the potential of warm wastewater to augment the performance of a heat pump. The heat from showers and other hot water demands is captured at the highest possible temperature and used to reduce the temperature lift needed for the heat pump to produce hot water. Thereby, a low lift compressor can be used in the production of both low temperature (LowEx) space heating as well as hot water, which requires a higher production temperature, but now receives a higher source temperature. This concept is depicted below (see Figure 6.7) and the potential change in COP is demonstrated in the T-S diagram (Figure 6.8).

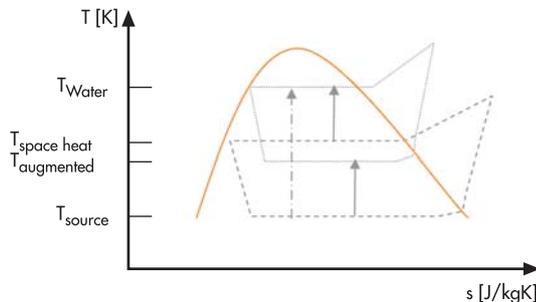


Figure 6.8: T-S diagram of the heat recovery process

Relevance as low-exergy technology

In this study case, the recovery of waste energy has a strong influence on the performance of the heat pump, By increasing the source temperature, and consequently the COP, the demand of electricity decreases.

Innovative configuration for cooling purposes: series design for chillers

Although a few companies supply chilled water at two temperatures, the industry standard design is to provide a single temperature chilled water supply. Water cooled chillers are normally configured with evaporators in parallel and condensers in parallel. The supply to return temperature differential for both evaporator and condenser water chiller flows is typically between 5.6°C and 6.7°C. The industry large scale chiller plants average approximately 0.267 system $k_{Welectric}/kW_{cooling}$ at 24.2°C ambient temperature.

The improvement potential achievable with an innovative chiller design consisting on a series connection of several chillers is investigated here.

Figure 6.9 shows schematically the conventional design (left) and the innovative configuration proposed here (right). Temperature levels assumed for the performance of both designs are also shown in the diagram. Ideal exergy efficiencies for both configurations amount 8.33 and 12.14 respectively. This represents an improvement of 47%.

Such an innovative configuration has been checked for the cooling supply of a production plant in Malaysia (Solberg, 2010).

In the innovative configuration chilled water is supplied at 7.2°C and 13.3°C with a common return with 11.1°C temperature differential. The design consists on eight centrifugal refrigeration compressors in series and has four condensers in series for a temperature differential of 8.3 °C. The forecasted electrical energy demand for the chillers is then reduced from the conventional value of 0.267 system $kW_{electric}/kW_{cooling}$ to 0.135 $kW_{electric}/kW_{cooling}$ at 24.2°C ambient air temperature.

Increasing the chilled water temperature differential reduced the total flow of chilled water by 50%, meaning pipes, pumps, and valves were much smaller. A conventional design for the particular case of the investigated production plant required 27 pumps; the innovative design, in turn, required 9 pumps.

In the production facility studied the innovative configuration represents an improvement on the overall exergy efficiency of the production plant from 0.249 to 0.293.

Relevance as low-exergy technology

In this study case, the exergy improvement potential from a cascaded use of thermal energy flows for cooling applications is shown.

Conventional vs. Advanced Cooling System Design

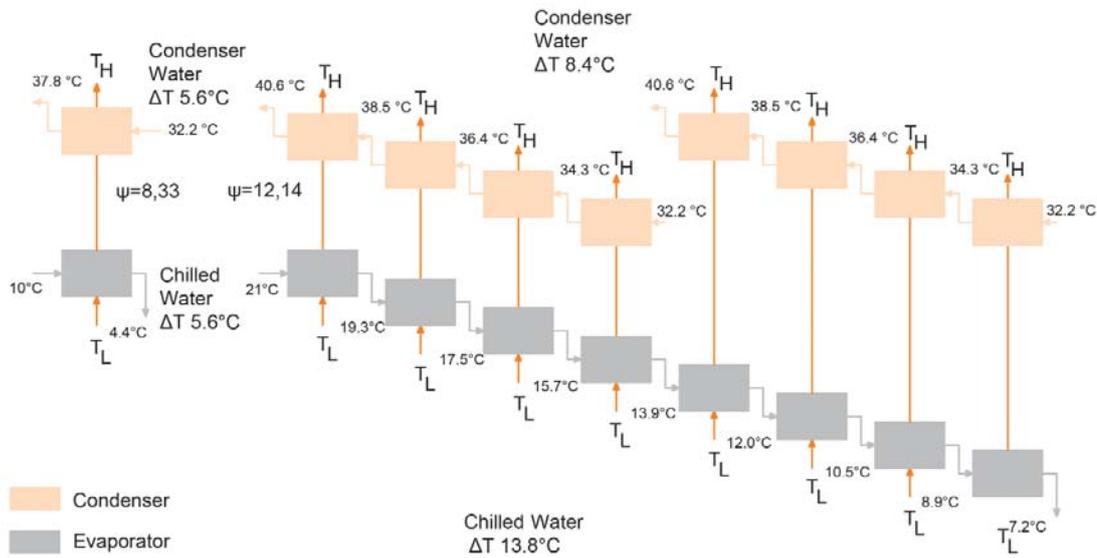


Figure 6.9: Conventional parallel configuration of chillers for cooling energy supply (left) and innovative series configuration for high efficiency cooling supply (right).

¹⁷This case study was kindly submitted to the ECBCS Annex 49 working group by Xiaoyun Xie and Yi Jiang from Tsinghua University (China) as guest participants.

¹⁸This case study was kindly submitted to the ECBCS Annex 49 working group by Xiaoyun Xie, from Tsinghua University (China) as guest participant.

¹⁹This case study was kindly submitted to the ECBCS Annex 49 working group by Tamás Simon, a guest participant, from the Budapest University of Technology and Economics, Budapest (Hungary).

7. APPLICATION OF THE EXERGY APPROACH TO COMMUNITY CASE STUDIES

Managing energy supply and costs within a community requires that community to have a vision for its future development. Plans and strategies for developing energy supply structures for communities would incorporate the development of programs and projects that create resilience within the community and thereby a resistance to the impact of energy market fluctuations.

In this chapter several community case studies which have decided to go through such a planning process and implemented development projects to modify their energy supply structures are presented. Table 7.1 shows an overview of the community case studies included in this chapter. Besides a general description of the community and the innovative supply systems used, the relevance of the deployed technologies as “LowEx” systems is explicitly stated for each case.

Prior to the case studies a general introduction on the community scale is given. Here, the concept of community as used in this report is introduced, followed by some words on the operation and development of community supply structures.

The community

Interestingly the term “community” is commonly used with apparent disregard for a consensus on its meaning. Here, the term community refers to a predetermined study area over which the decision-makers have authority or influence. For a City Hall this may

be an entire municipality, although the evaluation of an entire city might be complex or unwieldy: it could also be a more modest development such as a downtown rejuvenation project. To enable categorisation of demands the study area should be heterogeneous in its design and contain a mixture of building types with a variety of energy uses and demand profiles. Such mixtures could include such properties as residential, commercial, retail, institutional, and even industrial uses.

The planning and decision making process

Figure 7.1 suggests that changes in energy use patterns within a community may be initiated at a variety of levels. At each level the decision-makers are different. The simplest change is often at the level of the end-user. For example a manufacturer might improve the efficiency their refrigerators, his cars or light bulbs. Each end-user would purchase this new product based upon anticipated cost savings, but for significant savings to be made, the number of end-users purchasing this new product must be large.

On the other hand, a change in energy type at the system level would involve fewer stakeholders and theoretically should be easier to initiate, but it would require increased investment. For example, a simple cycle plant might decide to recover its waste heat and employ this within a district energy system, displacing oil heating in community buildings. At the community level, this change would likely be the expensive but also environmentally the most far reaching of the alternatives. It is at this level of change towards which the community case studies presented in this chapter are oriented.

As already stated in this report, exergy is a comprehensive measure of the potential of an energy supply to do work (Shukuya and Hammache, 2002), therefore offering users the ability to manage the availability of energy. By knowing the characteristics of the task to be undertaken (demand), one can select the most appropriate energy stream for it (supply). Energy sources within the community must be separated and categorised according to their quality (i.e. exergy content) before being aggregated to form specific energy supply groups. Similarly, categories for energy demand types can be defined.

With an understanding of the capacity and capability of each category, supply and demand integration can follow, linking energy supplies and demands in the most effective manner and where possible, using local resources to generate that energy.

Often, it is also possible to align tasks in such a manner that the output energy stream from one task becomes the input energy stream for another, there-

Table 7.1: Summary of community case studies.

community	country	LowEx highlights
Alderney Gate	Canada	Sea water cooling coupled with borehole thermal energy storage
Andermatt	Switzerland	geothermal energy systems
Heerlen	Netherlands	low temperature emission systems, low temperature district heat from old coal mines
Letten	Switzerland	geothermal energy systems
Minnesota	USA	co-generation and district heating
Oberzwehren	Germany	utilisation of waste heat from CHP as low exergy supply source
Okotoks	Canada	solar thermal heating systems coupled with seasonal ground thermal energy storage
Parma	Italy	Low temperature heating systems coupled with efficient ventilation systems
Ullerød	Denmark	low energy district heating, ground source heat pump (GSHP) and air-to-water heat pump (AWHP).

by cascading through the activities and maximising the effectiveness of the supply. This line of thinking is similar in some respects to Pinch Technology (Wall and Gong, 1996), as used within an industrial process where the cooling and heating requirements are coordinated to minimise the need for external energy. However, the fundamental difference between the use of exergy and energy in Pinch Technology is that, for energy, a satisfactory solution is obtained when supply and demand are balanced or their difference is minimised. For a satisfactory exergy solution, supply and demand not only have to be balanced, but the exergy level at the final step has to be close to that of the ambient temperature – a much more demanding requirement.

Diagrams for characterising community exergy performance

The characterisation of the exergy performance of different case studies and community concepts is presented here by means of diagrams that enable visualization of the performance of a given case study and make different community energy supply concepts comparable. They are included under the section “LowEx Diagrams” in the respective case study. Arrow diagrams and PER-Exergy efficiency diagrams introduced in chapter 5 are used here to characterise graphically the exergy and energy performance of community supply systems.

There are some projects which have already been implemented. Therefore monitoring results are available and the contribution of different energy sources and technologies used to supply them is known. In this cases the PER and exergy efficiency figures are shown for the mix of the different energy sources used in the supply. Examples of this situation are the Okotoks Drake Landing Solar Community and Alderney Gate projects. Some other projects are still in planning or under development. Here, different options regarded for energy supply are characterised separately. An example of this situation is the City of Parma.

Innovative community case studies

Alderney Gate (CA)

This low-exergy project integrates demand side management within the Alderney Gate Complex in Dartmouth, Nova Scotia, with a renewable energy cooling supply (seawater) and in-ground seasonal thermal storage to eliminate the use of electrically driven chilling equipment.

The overall objective of the project is to develop a cooling system for a municipal building complex that employs the cooling effect of sea-water, either

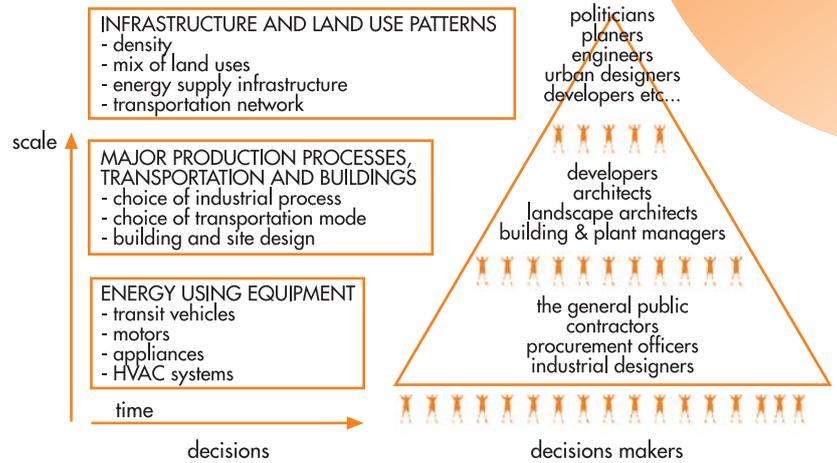
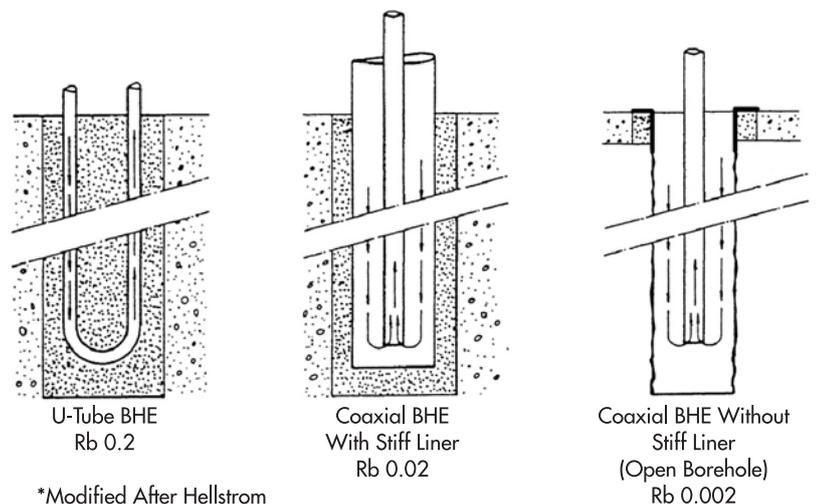


Figure 7.1: Hierarchy of energy-related decisions

directly to the building’s cooling system or indirectly through a Borehole Thermal Energy Storage (BTES) system.

The project demonstrates a systems approach to building energy management. It is the first of its kind of project in Canada, successfully representing the use of borehole thermal energy storage for cooling purposes.

Water is drawn from the harbour adjacent to the project site and passed through a heat exchanger before being returned to the harbour. The extracted cold energy is then passed directly to the building’s own cooling distribution system and, during periods of low cooling loads, passed through a series of vertical borehole heat exchangers and stored in the ground.



*Modified After Hellstrom

Figure 7.2: Advanced coaxial energy storage: heat exchanger design..

The coaxial heat exchanger improves thermal and exergetic efficiency by cutting the temperature difference between the fluid and the ground to 1-2°C, giving the fluid direct access to the borehole wall and providing very low pumping resistance. Figure 7.2 shows schematically the coaxial heat exchanger used. The design results in a smaller storage volume for the same cooling load and eliminates the use of mechanical chillers.

A custom designed control system optimises the system components, the storage temperature distribution, and the activities within the Alderney 5 complex.

LowEx highlights

Sea water cooling coupled with borehole thermal energy storage is planned to be used for cooling purposes in the project. Both thermal energy ground storage as well as the cooling potential from the sea water have low temperature levels and are therefore suitable LowEx sources for supplying cooling demands.

LowEx diagrams

Figure 7.3 shows the Primary Energy Ratio and exergy efficiency for the energy mix used in the Alderney Gate complex.

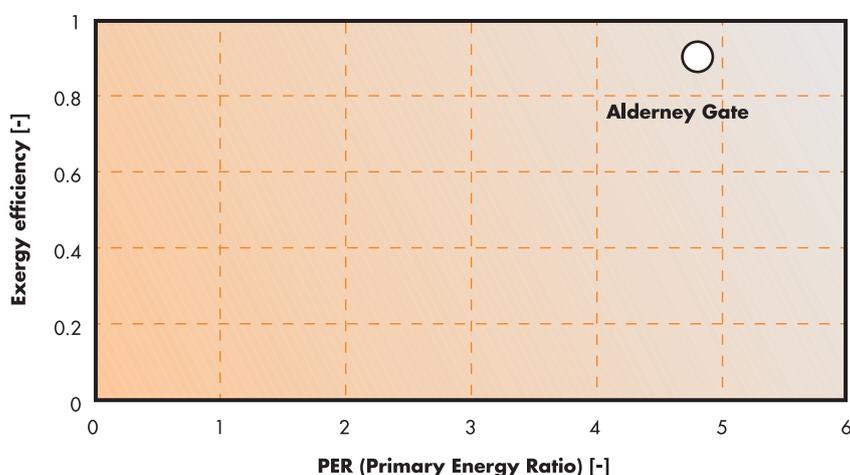


Figure 7.3: PER ratio vs exergy efficiency diagram for the energy supply mix in the Alderney Gate complex.

Andermatt (CH)

Andermatt is an alpine region of Switzerland where an entirely new tourism resort is being built. The cold climate implies a high heating demand with a low cooling demand. One goal of the project is for the energy use at the resort to be CO₂-free.

The energy concept for this resort in the Swiss Alps considers the high potential of deep geothermal energy from mountain tunnels. The temperature level of the heat reservoir is not high enough to supply building energy demands directly. Instead, the concept is to use this low temperature reservoir to minimize temperature gradients in energy supply

systems, thereby minimizing exergy destruction. By incorporating new heat pump technologies, much higher COP's can also be achieved. The viability of the projects depends on the evaluation of the value gained versus the extra infrastructure or transport required for implementation. These aspects are still under evaluation in ongoing research.

This case study demonstrates the transport and utilization of heat at what would be absolutely low temperatures (i.e. being low exergy sources available locally). However, the sources used in this project have still relatively high exergetic potential and minimal environmental impact compared to other ambient sources.

The energy masterplan includes a low temperature loop around the resort with decentralized heat pumps. The loop is fed by a seasonal geothermal storage field of borehole ground heat exchangers of 300m length, with a temperature of 0-5°C. The other source is the Furka tunnel, which has an entrance located 6 km away (see Figure 7.4). It supplies a constant flow of drainage water at 13°C, which can be piped to the resort.

The tunnel water is of special interest in the mountains. Because of the low ambient temperature, the exergetic value of this relatively low temperature source is actually quite high.

This project is ongoing and research includes the feasibility of the low temperature hydronic network supplying the heat pumps. Also of interest is the interplay between the two reservoirs and the relationship between the exergetic value of reservoirs versus the transport cost from the tunnel.

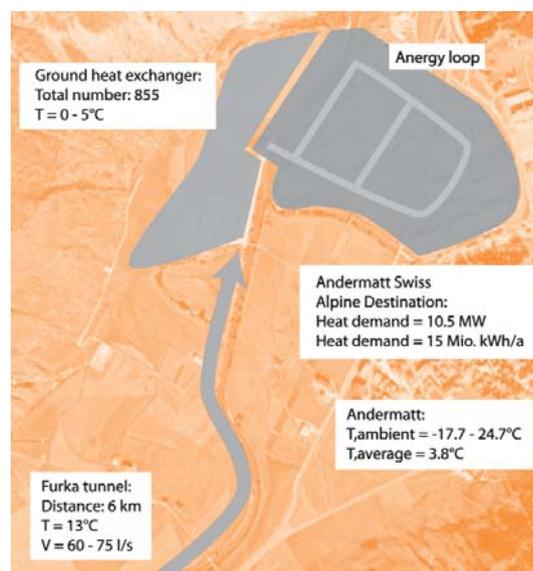


Figure 7.4: Energy plan for the new Andermatt Alpine Resort, at 1447 m altitude.

Heerlen (Netherlands)

This low-exergy project uses warm and cold water volumes from abandoned mines. In the Mine Water Project in Heerlen water from abandoned and flooded mines is used as a new sustainable energy supply for heating and cooling of buildings. The temperatures that have been found (16..30°C) are used in very well insulated buildings, with energy efficient ventilation systems and low temperature emission systems, the thermal comfort is excellent during 365 days/year. At the same time there will be a CO₂ reduction of 50% in comparison with a traditional solution.

The project started in February 2006 in Heerlerheide by drilling the warm wells. In October 2007 the last well was drilled, the cold well.

This project is situated on the concession of the ON III pit in a relatively deep mined area with warm water wells (30..35°C). The area of buildings included in the project are:

- 33,000 m²** dwellings (single family dwellings and residential buildings)
- 3,800 m²** commercial building
- 2,500 m²** public and cultural buildings
- 11,500 m²** health care buildings
- 2,200 m²** educational buildings

The first new building and construction activities in Heerlerheide Centre have started in 2006. the total plan will be realised between 2006 and 2011. All planned buildings will be connected to the energy

supply (heating and cooling) from minewater. All these buildings are planned in a very compact area, which is very favourable for energy distribution. The building location is situated between two warm wells. Next to it, the planned building functions require heating as well as cooling. The energy supply includes the building of an energy station and a small scale distribution grid from this to the build-

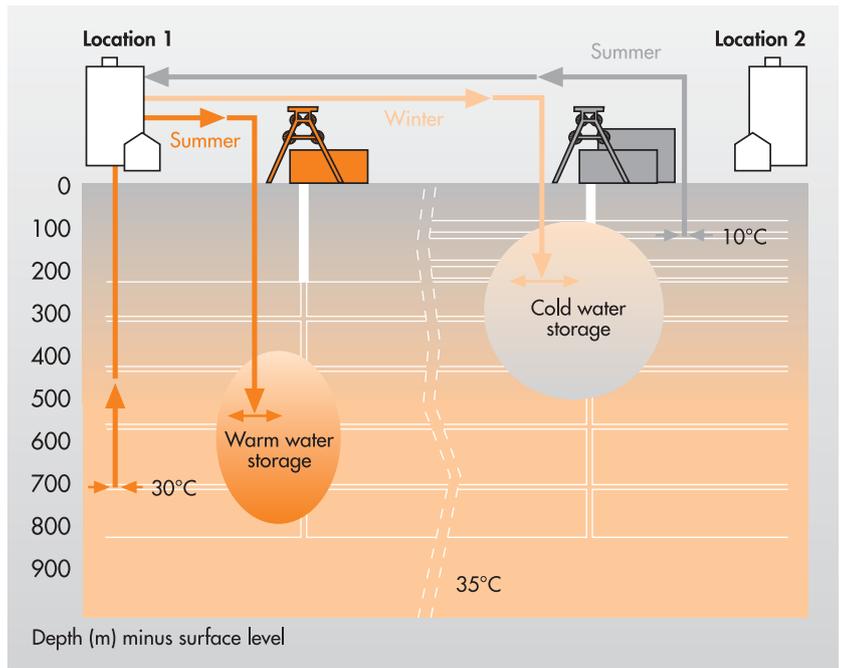


Figure 7.5: Minewater energy concept: depth and temperature level of the wells in the project.

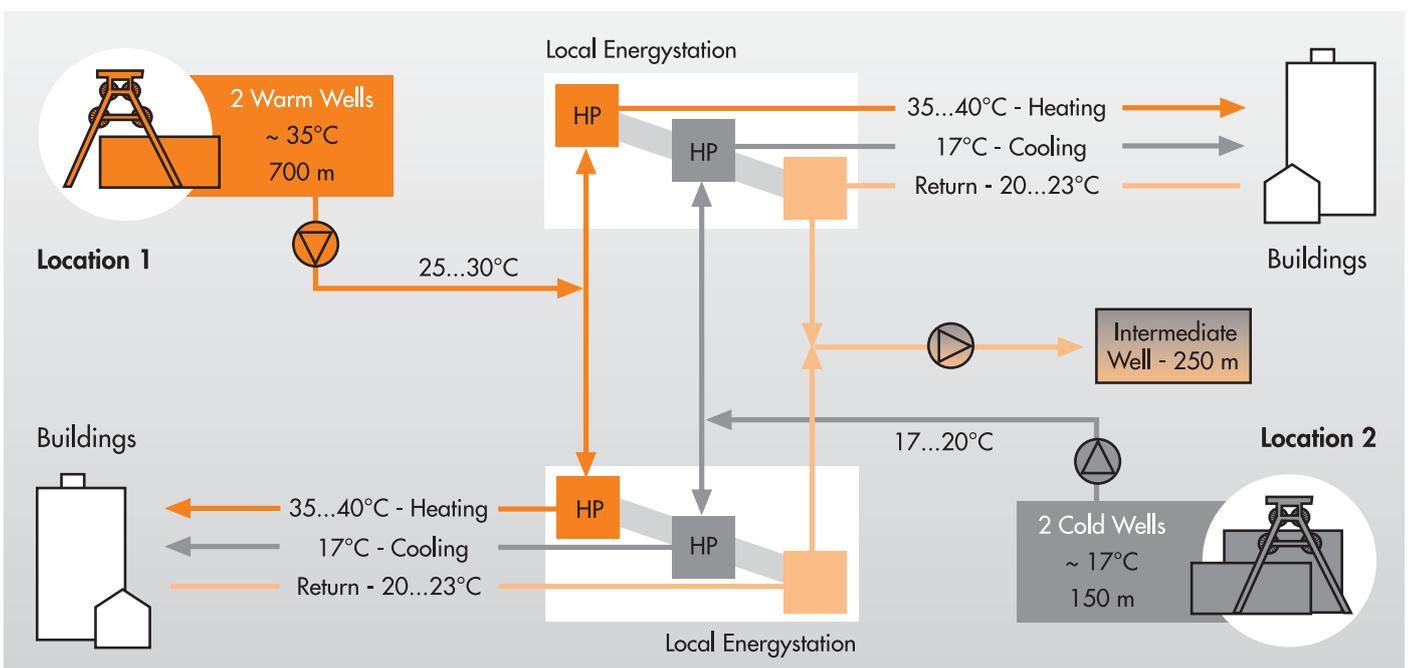


Figure 7.6: Energy management system: temperature levels and lifts in the different parts of the energy supply concept planned in Heerlen.

dings. In the energy station the minewater is brought to the necessary heating and cooling levels by heat pumps. In order to facilitate the process and to guarantee all real estate developers, involved in this building plan, the delivery of energy to the building the main investor, is realising the exploitation of the energy supply, including the building and construction of the energy station and distribution grid. It is important to realise, that with minor modifications this energy supply can also be functional and operational without the application of minewater.

Minewater is extracted in this project from four different wells with different temperature levels. The primary energy grid transports the extracted minewater from the warm wells ($\sim 30^{\circ}\text{C}$) to local energy stations. In these energy stations heat exchange takes place to the secondary energy grid (from the energy station to the buildings). This secondary energy grid provides low temperature heating ($35..45^{\circ}\text{C}$) and high temperature cooling ($16..18^{\circ}\text{C}$) supply and one combined return ($20..25^{\circ}\text{C}$) to an intermediate well. The different temperature levels of the wells considered can be seen schematically in Figure 7.5

The temperature levels of the heating and cooling supply are guaranteed in the local energy stations by a polygeneration concept existing of electric heat pumps in combination with gas fired high-efficiency boilers (see Figure 7.6). The surplus of heat in buildings which cannot used directly in the local energy station can be lead back to the minewater volumes of storage. DHW is prepared in local sub-energy stations in the buildings by heat pumps, small scale CHP or gas fired condensing boiler, depending on type of building and specific energy profile. The

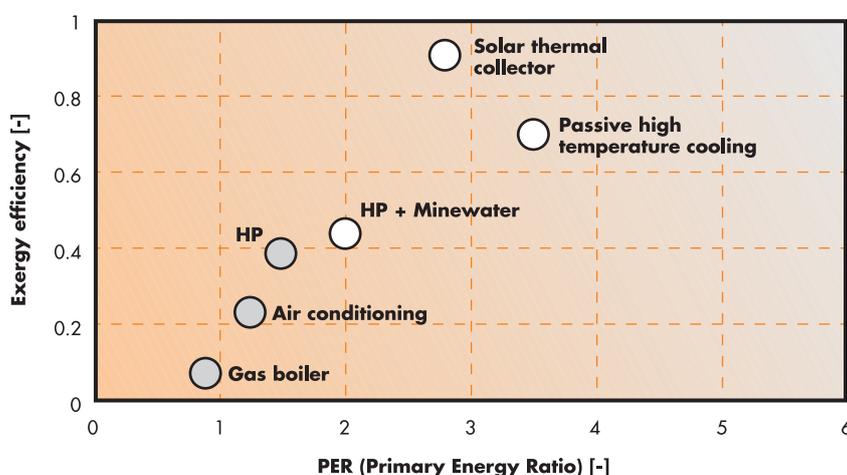


Figure 7.7: PER ratio vs Exergy efficiency diagram for the energy supply options chosen in Heerlen (represented by the white dots). For comparison, grey dots represent the performance of conventional technologies.

total system will be controlled by an intelligent energy management system including telemetering of the energy uses/flows at the end-users.

LowEx highlights

In this project, low temperature heating and high temperature cooling systems are being used in combination with highly insulated buildings. As stated in the design strategies mentioned in chapter 4 for buildings and communities, this makes possible the use of a low exergy source such as minewater at low temperature level for space heating and cooling. Furthermore, as back-up system to guarantee the supply whenever the minewater temperature is not enough to provide direct heating or cooling, heat pumps operating at high COPs are used. These energy systems allow, as stated also in chapter 4, minimizing the high exergy input required to supply the demands.

LowEx diagrams

Figure 7.7 shows the Primary Energy Ratio and Exergy efficiency for the minewater-based supply technologies considered in the community of Heerlen (NL).

Letten (CH)

This case study deals with one energy concept being studied for the supply of the ETH Zurich central campus. One goal of the Energy Strategy to be implemented is to halve the CO_2 -emissions of its structures and buildings by 2020. The energy supply concept focuses on the potential exploitation of the temperature differences between a stratified lake and the mixed river at the lake output. Similarly as case study "Andermatt", the temperatures and temperature differences are not enough for a direct supply of the required energy demands. Again, the idea is to promote and use this low temperature (low exergy) sources available to reduce the temperature differences in common building supply systems, thereby reducing exergy consumption in such systems.

The concept considers reopening an old train tunnel that has been filled in using microtunneling. This tunnel passes underneath the campus. This "Thermotunnel" (see Figure 7.8) would then connect a downstream part of the Limmat river directly with its tributary, the Lake of Zurich. The temperature difference between the two would create an exergy potential at low temperature. Compared to thermal networks with only one reservoir, this system makes use of the temperature differences between the two reservoirs. Due to potential environmental disturbance these sources are not allowed to have their temperatures disturbed. Campus heating and cooling systems from one source would cause a considerable distur-

bance. Instead of disturbing one source, the tunnel can be used to extract or deposit heat between the two thanks to the temperature gradient between the fully mixed river current and the stratified layers in the lake. The energy from the water can be used for direct cooling and for heating with a central heat pump. With a typical extraction temperature of around 6°C combined with low temperature emission systems on the buildings of the campus, high COP systems are expected to minimize the renewable electricity that must be supplied.

LowEx highlights

This project also makes use of a strategy mentioned in chapter 4, namely the reduction of the high exergy input in highly efficient energy systems such as heat pumps. This is achieved by minimizing the temperature difference in the thermodynamic cycle of the heat pump by exploiting the potential of water in a lake as low exergy source.

LowEx diagrams

A graphical representation of the quality levels of the energy supply and end-use categories considered in this case study is shown in the arrow diagram in Figure 7.9.

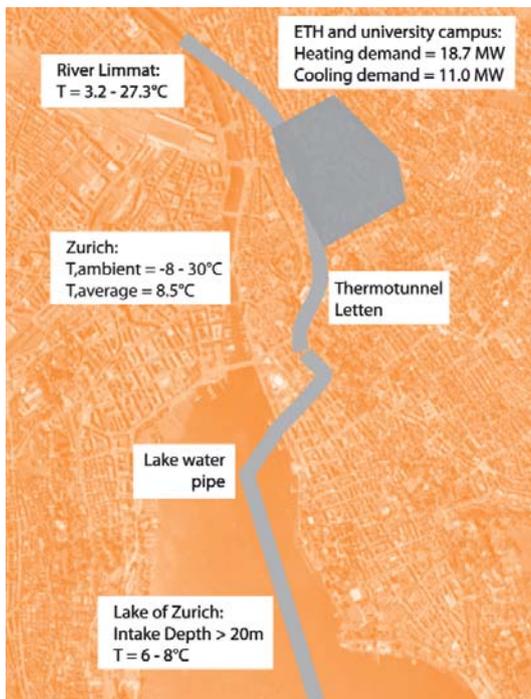


Figure 7.8: Thermotunnel Letten for the potential energy plan of the ETH Zurich.

Oberzwehren (GER)

The city of Kassel, situated in the centre of Germany, is aiming at carrying out an environmentally ambitious housing project within the coming years. The building site is situated on the property of the former School for Horticulture of the University of Kassel in the city district of Oberzwehren. It is bordered by access roads and private estates. To the north, a mixed-use area borders the site. To the northwest, there is a university campus, to the west, multi-family buildings, and to the southwest and east, single-family houses can be found. Floodplains from a small river can be found to the south. Bus and tram connections to the city centre exist.

A district heating pipe from the local utility company circulates close to the residential area. The plan is to use the return line of this district heating connection to supply domestic hot water and space heating demands. District heating in Kassel is mainly waste heat from co-generation power plants. Waste

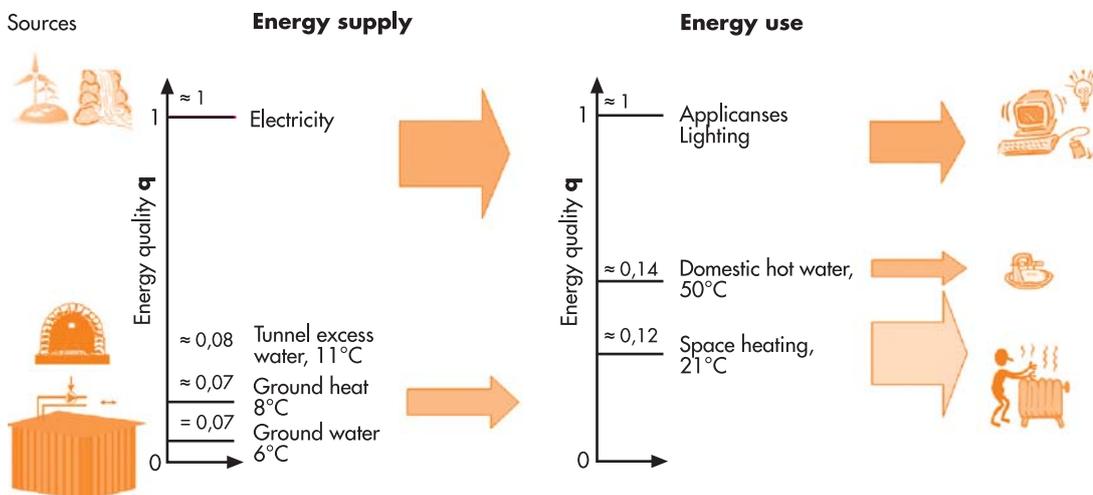


Figure 7.9: Matching of the quality levels of energy demand and supply for the Thermotunnel Letten case study. The different energy supply options regarded as possible supplies are characterised separately.

heat available, e.g. from combined heat and power production (CHP) plants, is a low quality energy flow suitable for supplying the requested energy demands. The use of waste heat with low exergy content allows suitable matching between the exergy level of the demand and supply sides and thus represents a very efficient manner of supplying thermal energy demands in buildings.

For the analysis of this case study dynamic energy and quasi-steady state exergy analysis have been performed using the simulation software TRNSYS (TRNSYS, 2007) with a timestep of 3 minutes.

Space heating (SH) is supplied by floor heating systems operated with supply and return temperatures of 32-27°C. Small DHW storage tanks of 200 litres are considered in each house. This allows a significant reduction in peak loads for DHW supply. For DHW supply in single family houses, a temperature of 50°C at the outlet of the DHW supply element must be ensured at all times (AGFW, 2009). An electric heater located at the outlet of the tank is foreseen for this purpose.

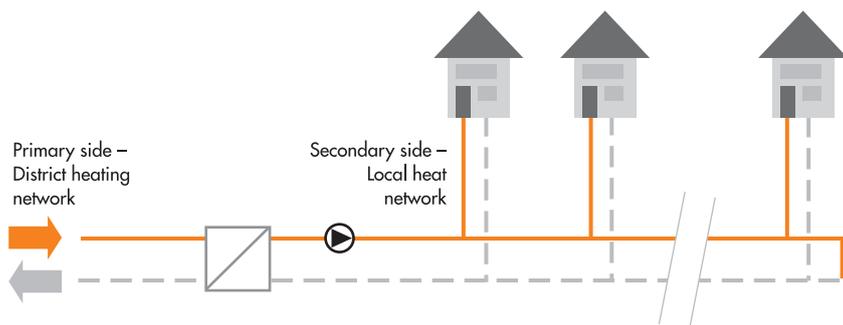


Figure 7.10: Simplified scheme of district heat supply to the studied neighbourhood of Oberzwehren (Germany).

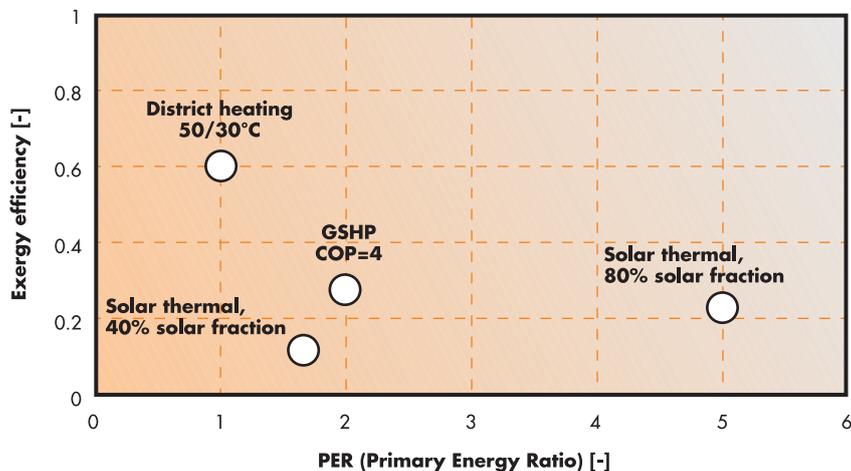


Figure 7.11: PER ratio vs exergy efficiency diagram for the different energy supply options under consideration for the community of Oberzwehren

A centralised heat exchanger unit is being planned for the supply of heat to the small neighbourhood, shown in Figure 7.10. In this way, the district heating network from the local utility company is decoupled from the installed building appliances and systems, i.e. mass flow and temperature drop in the district heating network are not directly determined by the mass flows and temperature drops in the building systems (e.g. floor heating systems). All houses are connected in parallel to the local distribution network (secondary side of the heat supply), as shown in Figure 7.10.

LowEx highlights

In the project, the utilisation of a low exergy supply source, i.e. waste heat from CHP units, is being investigated. Best case scenarios and hydraulic configurations have been derived based on dynamic exergy assessment performed. This clearly shows the added value of exergy analysis in comparison to conventional energy assessment. In order to ensure a minimum supply of high exergy sources for DHW supply, hydraulic configurations which ensure maximum supply from the district heating network for these demands have been analysed. Furthermore, low temperature (floor) heating systems have been implemented in the buildings.

LowEx diagrams

Here, all possible supply options considered at the beginning of the project are analysed. Thereby, the simple graphical representations show, at a glimpse, how well the final supply chosen (district heating return pipe) performs, as compared to other supply options. A graphical representation of the quality levels of the energy demanded (energy use) and supplied is shown in Figure 7.12. The height of the arrows gives an idea of the degree of matching between the energy supplied and demanded. In an ideal case, supply and demand arrows would be equally thick (no energy losses) and equally high (no exergy losses). In Figure 7.11, primary energy ratio and exergy efficiency for the different energy supply options regarded for the community of Oberzwehren are shown.

Quality levels of the energy supplied and demanded are calculated by using simplified steady state equations assuming a reference temperature of 0°C (typical winter space heating conditions in Germany), as well as typical supply temperatures for the technologies, sources and demands under regard. Supply and return temperatures for the solar thermal collectors and district heating return pipe are assumed to be 70/50°C and 50/30°C, respectively. Approximate quality levels under these assumptions are displayed close to the corresponding arrows in the diagram.

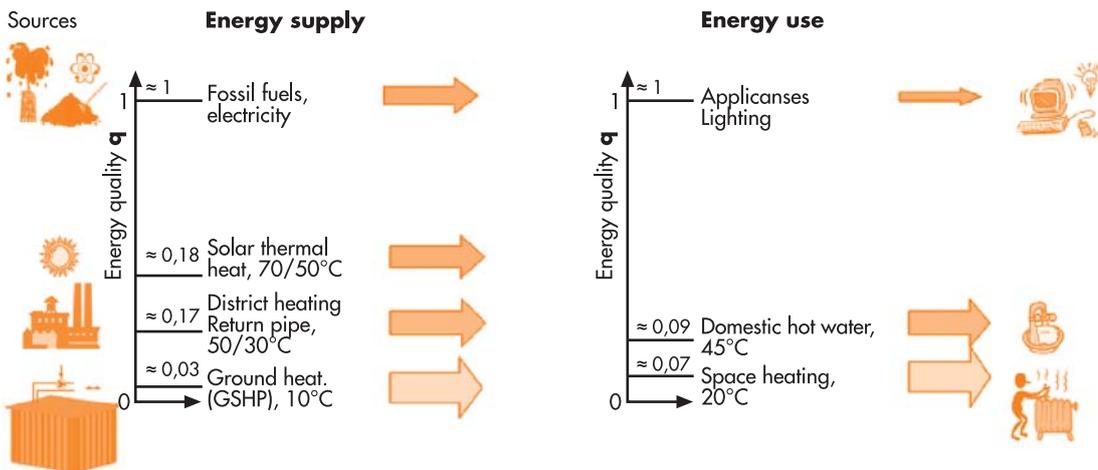


Figure 7.12. Matching of the quality levels of energy demand and supply for the community of Oberzwehren. The different energy supply options regarded as possible supplies are characterised separately.

Okotoks (CA)

The community of Okotoks (Figure 7.13), Alberta, is more than 1,000 m above sea level, but its average summertime temperature exceeds 20°C. This allows solar thermal collectors, facing due South at an angle of 45°, to generate up to 1.5MW (thermal) to heat the buildings at 55°C.

The plant started operation in June 2007 and it is estimated that it will take three years to fully charge the underground storage to 80°C. Construction of the 52 homes is complete and all homeowners have moved in. Performance indications from May 2008 suggest that the solar energy system is performing as designed and that the 90% solar fraction will be achieved by year 5.



Figure 7.13: Okotoks complex (Canada)

The solar water heating system uses flat plate solar collectors and provides at least 90% of the annual space heating and 60% of domestic hot water (DHW) for the 52 individual dwellings. This was achieved, despite winter temperatures of -33°C. In the scheme (Figure 7.14) of the solar thermal system, the borehole seasonal thermal storage and the district heating loop is shown.

The array is mounted on garages, at the rear of the houses, and uses a propylene glycol/water solution, pumped through an underground pipe network to a heat exchanger and a high temperature, short-term thermal store (STTS) located within the 'Energy Centre'.

Two unpressurised epoxy-lined cylindrical steel water tanks form the SSTS and internal baffles encourage thermal stratification. The Energy Centre also houses most of the pumps and controls.

In addition, there is long-term Borehole Thermal Energy Storage (BTES) which encompasses 144 boreholes. Each contains a single U-tube grouted in place. Above them, layers of sand and insulation and a waterproof membrane are topped by clay and landscaping. The BTES is connected as 24 strings of six boreholes in series and divided into

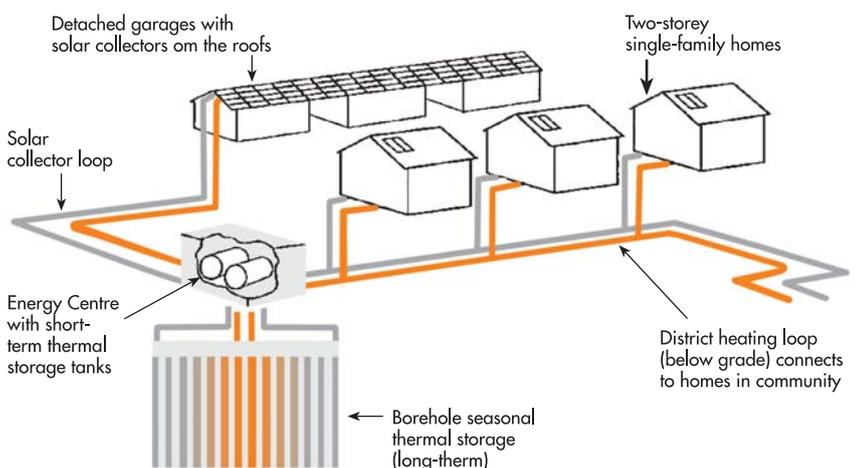


Figure 7.14: Solar seasonal storage and district heating loop used as energy supply system.

four circuits, preventing the loss of any string or circuit from having an impact on storage capacity. By the end of a typical summer, temperature in the earth surrounding the boreholes is expected to top 80°C. When the STTS temperature exceeds that in the BTES, pumps circulate hot water from the STTS through the boreholes. Figure 7.14 shows an scheme of the supply system.

Because a power cut may overheat the glycol loop, an additional photovoltaic (PV) array and battery bank is incorporated to power the pumps.

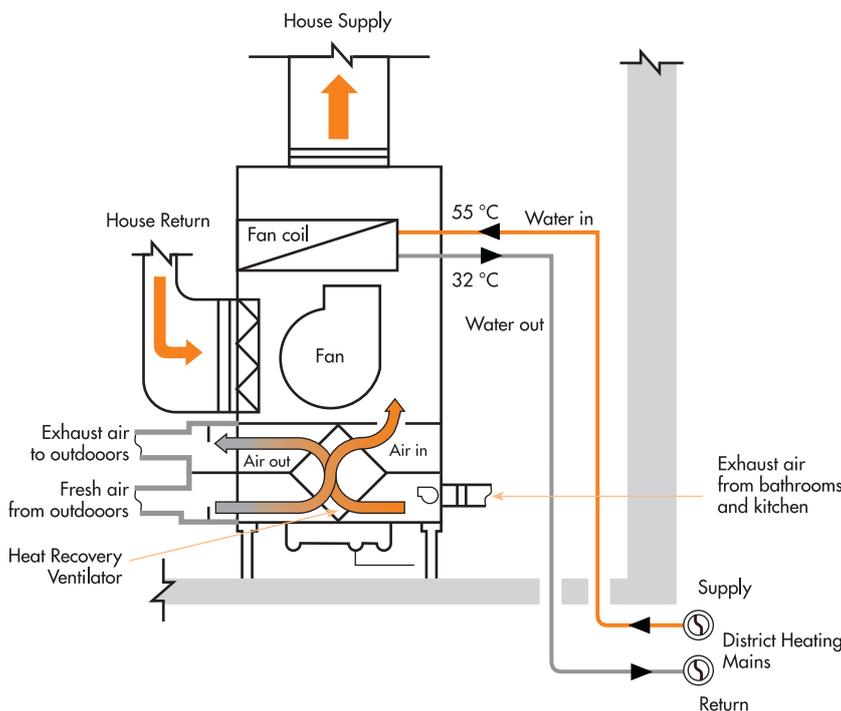


Figure 7.15: Heat emission: low temperature cooling air fan coils

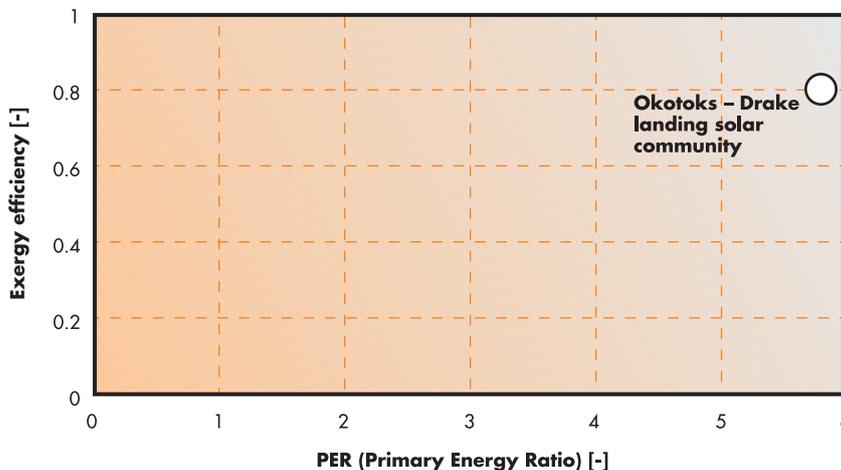


Figure 7.16: PER ratio vs. exergy efficiency diagram for the energy supply mix in the Okotoks Drake Landing solar community.

In winter, with no glycol circulation, parts of the loop can cool down to below freezing. Therefore, on start-up, the glycol solution is recirculated through a bypass loop until its temperature exceeds the STTS. This protects the heat exchanger in the energy centre from freezing.

In winter, whenever the temperature in the STTS is lower than that of the BTES, the system reverses and heat is transferred from the BTES to the STTS, and to a heat exchanger and the district heating loop.

This supplies heated water to individual houses and the specially designed low temperature air-handler units in the basements (Figure 7.15). Warmed air is distributed through the house via internal ductwork.

LowEx highlights

In the project, solar thermal heating systems, coupled with seasonal ground thermal energy storage, are planned to be used for heating purposes in a residential area. Both thermal energy ground storage as well as solar thermal heat have low temperature levels and are therefore suitable LowEx sources for supplying heating demands in buildings.

LowEx diagrams

Figure 7.16 shows the Primary Energy Ratio and exergy efficiency for the energy mix used at the Okotoks Drake Landing solar community.

Parma (IT)

Parma is located in Northern Italy's Emilia-Romagna region and has a population of approximately 178,000 people and a balanced presence of the tertiary, industrial and agricultural sectors, a mild climate and a notable historical buildings stock and cultural heritage. With these features, Parma represents a typical city of the Pianura Padana.

In recent years, Parma has undergone many initiatives related to energy efficiency, with two energy plans (the last dates back to 2006), local regulations for mobility, and a mandatory building energy regulation with advanced quality certification tools and incentives for low energy and the implementation of renewable energy technologies.

An important aim of the present study is to modify energy choices in order to optimize energy and exergy efficiency. Renewable energies, distributed generation, micro-cogeneration and micro-trigeneration may represent important measures to that end.

In order to evaluate the quality and quantity of energy uses within the built environment, the performance of the whole city, sector by sector, must be consi-

dered. This holistic approach implies that during the design process not only single buildings but the whole community must be analyzed.

This approach emphasises the use of low energy systems and leads to better environmental and economic effectiveness, exploiting the potential of distributed local resources. This research project is leading the way in adapting energy systems to this changed paradigm.

New energy systems should address the following issues:

- the use of technologies to minimize primary energy consumption by reducing end-users demand
- the analysis of the whole energy supply chain, from generation through distribution and storage to end-users.

The aim of this study is to provide some representative experience with these issues.

In the future research will address the city of Parma as a whole. So far energy fluxes have been analyzed in detail for three different districts of the town, characterized by different energy end-uses:

- a part of the historical city centre
- an urban neighbourhood
- an industrial and agricultural area.

Exergy loss minimisation will be one of the most important objectives of this study. Here, exergy analysis is only focused on the urban neighbourhood because of its large potential for energy system optimisation.

In a distributed poly-generation system, electricity, high and low temperature heat and refrigerated water are produced locally. In order to efficiently support the transition towards such a system the interaction among customers' demands for energy services, available generation technologies, available renewable energy sources and utility tariffs have to be investigated. For this reason, natural gas and electricity use data was mapped in a GIS to visualise energy use pattern and identify land-use constraints that can prevent the implementation of distributed generation. Based on this real data and constraints, an energy and exergy analysis has been performed in order to define a realistic scenario.

For this purpose, energy demands were split into six main categories based on statistical data: electricity, end-use only (appliances, lighting, etc.), electricity for refrigeration and building cooling, natural gas for water heating, building space heating, process heat (industrial sector), and natural gas only end-use (cooking, etc). Alternative strategies for supplying thermal, electrical and cooling energy demands,

in a poly-generation framework, were highlighted to suggest system concepts that improve energy and exergy efficiency, and reduce emissions and costs. Starting from these initial evaluations, hourly load profiles for electricity (utility statistical data) and thermal energy (simulated heating and cooling demand of buildings) were determined.

A multi criteria procedure, currently in development, will take into account economic, energy and exergy goals in the design and optimisation of energy systems.

In this work, three scenarios have been analysed for the town:

- Scenario 0: Parma 2007. State of the art

The scenario Parma 2007 is based mainly on fossil fuels used for electricity generation and heating. In fact, currently in the city of Parma, fossil fuels are the only energy source. Renewable energies are not used. The average energy demand to be assumed for further planning was based on assumptions of total heat demands and heat loads. With this processed data, we were able to evaluate measures to adopt in the planning scenarios.

- Scenario 1: Parma 2020

Here, the objective is to find a realistic path to reach the 2020 European goals²⁰ by introducing mandatory regulation for local energy planning concerning urban planning and the refurbishment of buildings.

- Scenario 2: Parma 2050

The target is to transform Parma into a renewable city²¹ by the year 2050, adopting today's best available technologies and practices as a benchmark. Here, the optimisation of exergy fluxes is also taken into account.

LowEx highlights

In the building energy regulation developed here, the use of "LowEx" technologies is strongly encouraged. Low temperature heating systems close to room temperature will be used, meaning that the energy and exergy supply to the indoor building spaces will be very efficient, with minimal losses. Low temperature renewable energy sources like solar energy and the heating and cooling potential of underground heat exchangers are also considered as supply sources. As stated in chapter 4, to utilise these sources, the overall building system has to be adjusted to low process temperatures. Radiant heating and cooling systems, ground water heat exchange, solar thermal, as well as building envelope performance improvement (insulation, thermal capacity and natural ventilation) are suggested and economically sustained. The new building energy regulation is an example of the promotion of "LowEx" design strategies mentioned in chapter 4 for both the building and community levels.

- The “LowEx” measures, in this case study, include:
- Low energy demand for heating, good insulation and air-tightness
 - Radiant heating systems like floor and wall heating, slab heating, capillary tube systems
 - Solar energy systems for DHW
 - Heat pumps

LowEx diagrams

A graphical representation of the quality levels of the energy supply and that will be considered in the optimisation study is shown in Figures 7.17 and 7.18.

The scenarios Parma 2020 and Parma 2050, in which district heating and cooling have been planned, refer to hypothetical energy plans that are currently being defined.

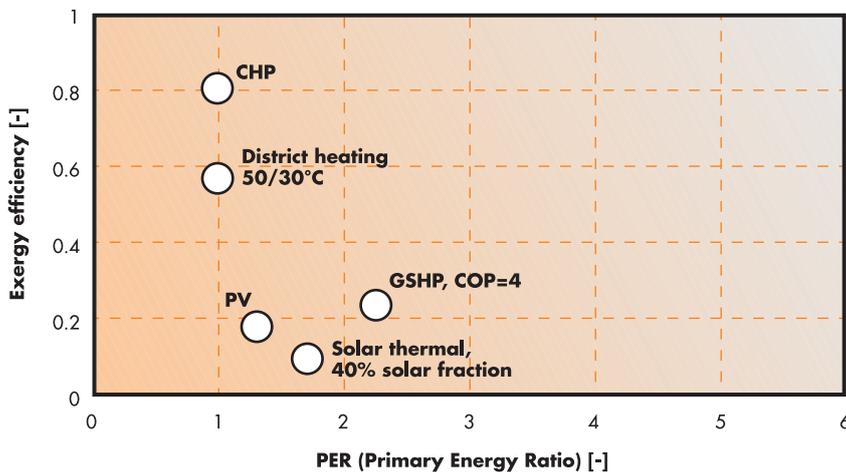


Figure 7.17: Diagram of exergy efficiency of the systems vs. primary energy ratio for scenario 1 - Parma 2020 in winter conditions.

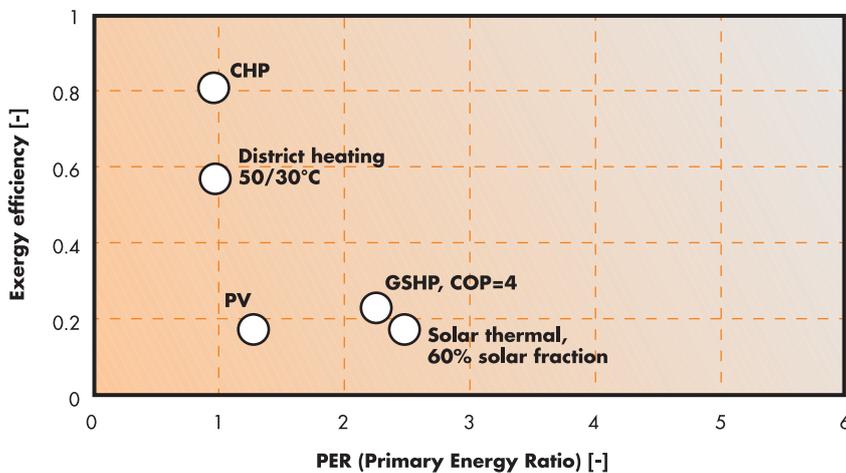


Figure 7.18: Diagram of exergy efficiency of the systems vs. primary energy ratio for Scenario 2 - Parma 2050 in winter conditions.

Quality levels of the demands and energy supplies are calculated by using simplified steady state equations assuming a room temperature of 20°C for heating and 28°C for cooling as well as typical supply temperatures for the technologies, sources and demands evaluated.

All calculations are done assuming a reference temperature of 5°C for winter and 32°C for summer.

Supply and return temperatures considered for the solar thermal collectors and district heating return pipe are assumed to be 70/50°C and 50/30°C, respectively. Supply and return temperatures for the district cooling return pipe are assumed to be 18/25°C.

Twin cities Minnesota (USA)

The energy supply of the Twin Cities of St. Paul and Minneapolis, located in Minnesota (USA) has been analyzed on the light of exergy principle. The energy demands regarded include electrical power generation, home heating and cooling, and automobiles. Besides the analysis of energy flows, harmful emissions and ground water use were also considered.

Minneapolis and St. Paul receive most of their electric power from three Xcel Energy district electric power plants Riverside, Highbridge, and Black Dog. Riverside and Highbridge are natural gas fired combined Brayton and Rankine cycle plants. Black Dog is coal fired Rankine cycle. All condensing heat energy is rejected to the Minnesota and Mississippi Rivers. 25 MW of additional electric power is also generated by Evergreen Energy which supplies downtown St. Paul with electric power, district steam heating, and chilled water cooling. Evergreen Energy currently heats 80% of the commercial, residential and industrial buildings in downtown St. Paul and provides cooling for 60 percent of downtown Buildings.

Minneapolis has district heating and cooling provided by NRG and Hennepin County, and the University of Minnesota also has district heating and cooling for their buildings. Hennepin County burns 1,000 t/d of municipal waste to produce 40 MW of electric power in downtown Minneapolis. No heat is being recovered at the Hennepin County garbage burning facility. Rock-Tenn, a paper recycling plant is in St. Paul, is generating 9 MW for cogeneration. A study (HVAC S.T., 2009) of Rock-Tenn facility indicates that 20.2 MW of heat energy could be recovered from the Rock-Tenn paper exhaust stack.

As a rough approximation, automobile transportation is considered essentially 100% powered by

gasoline, and home heating is considered to be 100% from indirect fired natural gas furnaces.

Based on exergy analysis several recommendations and modifications of the existing energy supply system as explained above have been derived. As a result, a different supply scenario based on electric cars and the use of waste heat from the power plants for district heating purposes has been developed. The main technical characteristics of this supply option are stated below.

Approximately 341 m³/hour of water would be distributed through new distribution piping to homes and buildings throughout the city. With an average yearly temperature of 9.4°C, the Twin Cities requires heating for most of the year. In the winter all the heat rejected to the Minnesota and Mississippi Rivers by Xcel Energy power plants (1049 MW) would be used to heat 300,000 homes (with average loads of 4.4 kW). The power plant steam turbines would produce 41.7 MW less electric power due to increasing condensing temperature from 21.1 °C to 71.1°C. Hot water would be distributed at 71.1 °C and returned at 26.7 °C.

In the summer low exergy cooling technologies such as adsorption chillers or liquid desiccant systems would be used to produce 331,000 MW of cooling. The steam turbine condensing temperature would be increased from 21.1°C to 54.4°C reducing electrical power output by 26.1 MW. Chilled water would be distributed at 7.2°C and returned at 21.1°C. District cooling would be significantly more efficient than air cooled home direct expansion condensers, creating an increase in peak electric capacity of 91 MW, representing 6% of the current capacity.

District electric would charge 88,200 automobiles batteries for 12 h/d at a rate of 1.04 kW/car. This is based on 9.7 km/litre gasoline and an efficiency of 22% fuel/engine power.

Potential heat recovery from Evergreen Energy, Hennepin County, or Rock-Tenn energy plants is not regarded in this retrofit scenario of the energy supply in the communities. Detailed data showing the loads, supply and performance of the Twin cities can be found in (Solberg, 2010).

LowEx Highlights

The performance assessment simulation of the Twin Cities Community of Minneapolis and St. Paul demonstrates that major reductions in energy input and ground water and environmental harmful emissions could be achieved by using electric cars and modifying local power plants to recover waste condenser heat for a district heating and cooling system.

The Twin Cities community systems exergy performance can be increased by 64% from 0.465 to 0.762. Annual carbon emissions can be reduced by 39% or 1,676,000 t/a and ground water use reduced by 73% or 15,870,000 t/a. Reductions in sulphur dioxide and nitrous oxides would be of similar magnitude as carbon. A substantial amount of the emissions reduction is because power plants have significantly less emissions than do automobile engines and home furnaces.

LowEx Diagrams

In Figure 7.19 Primary Energy Ratio and Exergy efficiency for the district heat and electric power supply regarded for the Twin cities are shown. The exergy efficiency figure shown corresponds to a combined analysis of heat and power generation together, with the corresponding heat and electrical demands supplied. A graphical representation of the quality levels of the energy demanded (energy use) and supplied is shown in Figure 7.20. The height of the arrows gives an idea on the degree of matching between the energy supplied and demanded. In an ideal case supply and demand arrows would be equally thick (no energy losses) and at equal height (no exergy losses).

Quality levels of the energy supplied and demanded are calculated by using simplified steady state equations assuming a reference temperature of 9.4°C (average annual outdoor air temperature at the investigated locations), as well as typical supply and return temperatures for the district heating system planned (71/21°C). Resulting quality levels under these assumptions are displayed close to the corresponding arrows in the diagram.

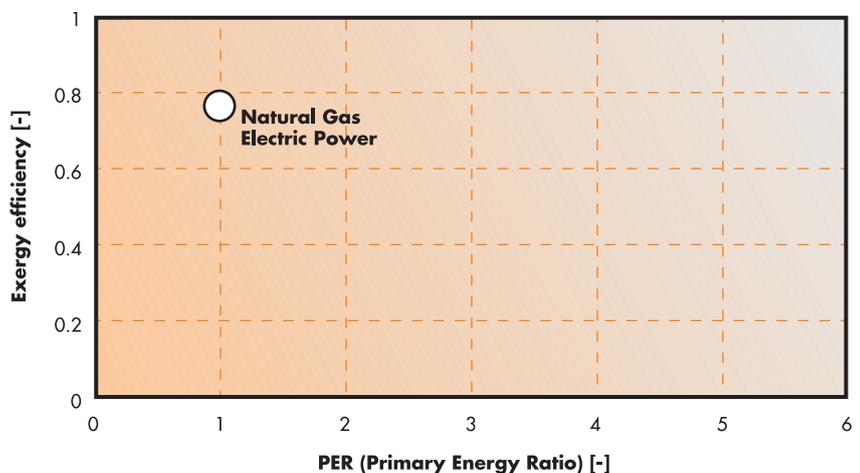


Figure 7.19: PER ratio vs Exergy efficiency diagram for the investigated supply of the Twin cities of St. Paul and Minnesota, based on district heat supply from the power plant.

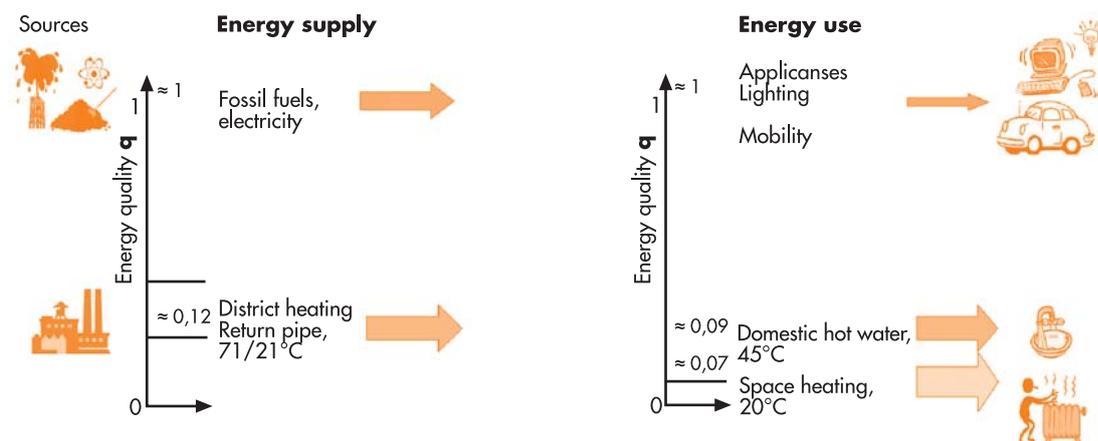


Figure 7.20: Matching of the quality levels of energy demand and supply for the Twin cities of St. Paul and Minneapolis for the described energy supply scenario.

Ullerød (Denmark)²²

In Denmark, the government has decided that energy use in new buildings must be reduced step by step by 25% in 2010, 2015 and 2020. With the increasing number of new low-energy houses, the question is: "What kind of heat supply is economically and environmentally most attractive?" In urban areas with DH, it might be reasonable to connect some new low-energy houses. Yet, in new subdivided areas with lots of or only low-energy houses, it is interesting to know if it is feasible to use DH. Today in Denmark, low-energy houses located in DH districts can be exempted from connection obligation to the DH network. Therefore, it is relevant to research if DH is a good alternative to other heating technologies, e.g. heat pumps.

The low heat demand in low-energy houses means that, with a traditional network design, the network heat loss may be a very significant part of the total heat demand. To solve this problem, the network heat loss and involved costs must be reduced. The solution seems to be a low-temperature DH network with high-class insulated twin pipes in small dimensions, reference (Svendsen, et al. 2005; Svendsen, et al. 2006).

The advantages of a low-energy DH system are:

- DH is a flexible system suitable for all kinds of energy sources
- renewable Energy (RE) sources can be used directly or in combination with large-scale heat storages. This means that DH can be an important part of the future energy supply system fully based on RE
- great potential for utilisation of waste heat from CHP plants, refuse incineration and industrial processes

- DH covers a large part (60%) of Denmark's heating supply and is a well-known technology
- DH is reliable and easy to operate for the consumers.

An urban area has been selected for reference. The area is located in a new district called Ullerød-byen in the municipality of Hillerød, Denmark. The area has a great focus on energy efficiency regarding both buildings and energy supply. This area consists of 92 low-energy houses with an energy demand of 42.6 kWh/m²a including space heating, domestic hot water, cooling and electrical auxiliary energy.

LowEx highlights

In the project, the following "LowEx" technologies are compared: low energy district heating ground source heat pump (GSHP) and air-to-water heat pump (AWHP). Furthermore, these technologies are applied to buildings that fulfil the requirements of low-energy buildings, being already suitable for using low exergy sources in their energy supply.

LowEx diagrams

A graphical representation of the quality levels of the energy demanded (energy use) and supplied is shown in Figure 7.21. The height of the arrows gives an idea of the degree of matching between the energy supplied and demanded. In an ideal case, supply and demand arrows would be equally thick (no energy losses) and equally high (no exergy losses).

Quality levels of the energy supplied and demanded are calculated by using simplified steady state equations assuming a reference temperature of 0°C (typical winter space heating conditions), as well as typical supply temperatures for the technologies, sources and demands taken into consideration.

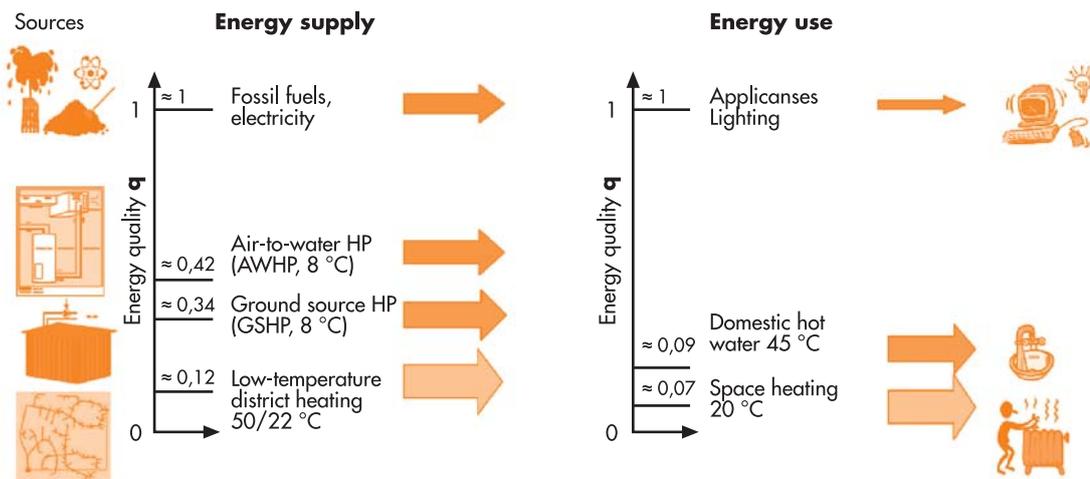


Figure 7.21: Matching of the quality levels of energy demand and supply.

The temperature of the ground for the GSHP system is assumed to be 8°C, equal to the mean annual outside temperature of the air in Denmark. The same temperature of the source is considered for the AWHP system, since the heat pump is used both in winter (for space heating and domestic hot water) and in summer (only for domestic hot water). Supply and return temperatures for the district heating network are assumed to be 50°C and 22°C, respectively. Approximate quality levels under these assumptions are displayed close to the corresponding arrows in the diagram.

The different systems which are assumed to provide the given demand are represented in the exergy efficiency vs. PER below (Figure 7.22).

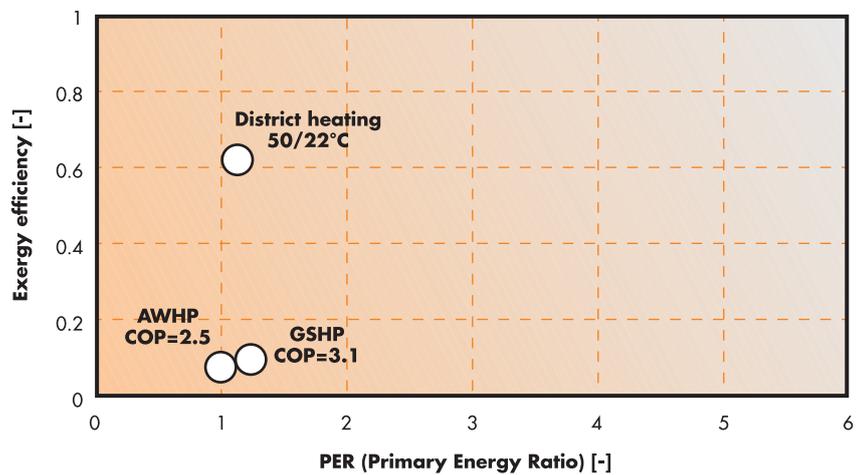


Figure 7.22: Diagram of exergy efficiency of the systems vs. primary energy ratio.

²⁰To reach 2020 goals for EU countries means cutting greenhouse gas emissions by 20% from 1990 levels; a 20% share of renewable energies in EU energy consumption (17% for Italy); cutting energy consumption by 20% through improved energy efficiency.

²¹Not totally but almost entirely fuelled by renewable energy.

²²This case study has been kindly supplied to the ECBCS Annex 49 working group by Sven Svendsen, a guest participant, from the Department of Civil Engineering of the Technical University of Denmark.

8. CONCLUSIONS

The thermodynamic concept of exergy allows depicting how the potential of a given energy flow is used, or lost, respectively, in the course of an energy conversion. Thereby, inefficiencies within energy supply systems can be pinpointed and quantified. Applying the exergy method to energy systems in buildings can contribute to increasing their efficiency significantly.

Within the ECBCS Annex 37 low exergy systems were defined as “heating or cooling systems that allow the use of low valued energy as the energy source” with a focus on space heating applications. However, the scope of ECBCS Annex 49 includes the various energy demands in buildings as well as the integration of multiple buildings in communities or neighbourhoods. Thus, within the course of research activities in ECBCS Annex 49 the definition has been extended to apply to this broader context. In this sense, low exergy systems are defined as “systems that provide acceptable thermal comfort with minimum exergy destruction”. This allows to find the optimal match between quality (i.e. exergy) levels of supply and demand for any use or appliance within buildings.

The basis for exergy analysis in buildings is a commonly accepted and scientifically grounded methodology. Developing such a methodology was one of the main working items within ECBCS Annex 49 activities. Results are presented in chapter 2 including a detailed description of the methodology that can be applied to both, heating and cooling processes analysis.

To obtain coherent and meaningful results, the sign convention adopted for energy and exergy analysis is of great importance. We argue that the thermodynamic reference environment for exergy analysis in building systems should be the ambient air surrounding the building. Climatic data on a time dependent basis are required for dynamic as well as quasi-steady state assessments. Average outdoor air temperatures during the heating season can be used for first estimations on the thermal exergy performance of heating applications following a steady-state method. Simple Input-output approaches (in terms of sources and demands) can also be employed to perform exergy analyses at the community level.

Quasi-steady state approaches for exergy analysis performed on the basis of results from dynamic energy simulations (or measurements) have proven to be reasonably accurate. They require less input data than a fully dynamic approach and, being simpler, are less time consuming. Thereby, quasi-steady state exergy analysis represents a reasonable compromise between accurateness and complexity. It can be used in exergy calculations in buildings aiming at

analyzing the performance of whole building systems. However, if the main goal of the analysis is to optimize or study the performance of storage components dynamic assessments are required.

In any application steady-state exergy assessment can only be used to show the approximate performance of a given system or get first comparisons between systems. Steady-state analysis has proven to be inadequate to obtain the absolute value of the performance of building systems, even for space heating applications. Therefore, quasi-steady state or dynamic exergy analyses are required for an accurate comparison of building energy supply systems.

Space heating and cooling systems in buildings aim to provide comfort for the occupants. Thus besides the energy efficiency, thermal comfort within buildings is the main requirement that they must meet. Due to the importance of human thermal comfort in the built environment, a whole section is devoted to the exergy assessment on thermal comfort in chapter 2.

To make the exergy approach and calculation methodology available to the public, several tools have been developed within the project. A further important step in this direction would be the development of pre-normative proposals including exergy as a performance indicator for building systems. In such a standard, the total exergy input required by a building should be limited according to state-of-the-art technologies available. In chapter 5 several concrete proposals on strategies for characterising the performance of buildings and building systems are presented.

The energy approach, both on a building and community level, intends to reduce energy demands in buildings by increasing insulation levels or increasing the air tightness of the building envelope, i.e. optimizing the building shell. The exergy approach at both levels focuses on matching the quality levels between the energy supply and demand. Therefore, it requires the use of low quality sources for low quality demands like space heating. Demands requiring higher quality levels, such as lighting, electrical appliances or mobility, would in turn need the use of high quality sources.

Exergy analysis shows that combustion processes should not be used for providing the low temperature heat demands in buildings. Fossil fuels have a high energy quality and in intelligent energy systems should be used more rationally and efficiently with respect to exergy. CHP units, providing equally high exergy outputs such as electricity, are a great example of an appropriate use of these energy sources. Similar conclusions to for biomass-based fuels: alt-

though being renewable, their exergy efficiency if directly used for space heating is extremely low. Instead, low exergy sources should be promoted for heat and cold demands in buildings. Examples of such sources are solar thermal or ground source heat.

For the exploitation of low exergy sources often high quality energy is also required, e.g. pumping or fan power, electricity for powering heat pumps, etc. These high exergy inputs also need to be minimized.

Several case studies in this report highlight the differences between energy and exergy performance of building systems such as boilers or heat pumps. They demonstrate the necessity of designing new system concepts based on the use of low temperature heat sources for low temperature applications such as space heating or cooling. Wastewater heat recovery, waste heat in district heating networks or solar thermal heat are some of the sources that should be used for meeting these demands. However, the availability of these sources varies strongly with time and often is not coupled with demand. Intelligent storage concepts, with maximum stratification and minimum mixing are therefore a key component of low exergy supply systems in buildings.

On the other hand, as energy demands for space heating and cooling are reduced, the share of other uses within buildings such as domestic hot water (DHW) demands increases. The exergy quality factor of DHW energy demand is about 13%, almost twice as high as for space heating applications. Energy systems using low exergy sources show lower efficiencies for these demands at higher temperature levels. Further research is required to design system concepts for an exergy efficient supply of DHW.

In addition, higher and lower exergy demands within a building might be supplied in sequence, following cascading principles. Cascading of thermal energy flows in buildings is a promising approach that can be directly derived from the exergy analysis. Here future research is required.

District heating grids are a promising solution for cascading available heat flows to supply different energy demands in an intelligent way. The coordinated management and control of district heating and electricity networks together with state-of-the-art storage systems can be used to maximize the exergy efficiency of the supply. How to design and manage such systems will require further research.

CHP units and heat pumps are very efficient energy systems which allow bridging heat and electricity production, making them promising technologies for future energy systems. Further research is required

to develop suitable storage concepts in combination with local heat and electricity networks on a community scale in order to reduce CO₂ emissions and primary energy use within the built environment using these technologies. The integration of solar thermal systems in local district networks is also a very promising low exergy technology, as shown in the Canadian case study for Okotoks (chapter 7).

Low temperature heating and high temperature cooling systems increase the efficiency of low-exergy sources. Thus, improving building envelopes allows using surface heating and cooling systems and therefore enables the efficient and cost-effective use of low exergy sources available. Therefore the choice of emission system restricts the options for low exergy sources of energy in buildings. For example, the exergy approach shows that water-based systems are able to provide the same thermal comfort as airborne systems. However, they require much lower exergy input for pumps and fans and exergy losses in the emission process are also lower since the emission system and the desired room temperature are very close for water-based system. An exergy efficient design in such cases would necessarily begin with a change of the emission systems – an important insight especially in countries with a strong tradition of airborne systems like the USA or Canada. In turn, in countries using mainly waterborne systems, e.g. most of European, the important choices for exergy efficient building design in the choice of energy sources.

In either case, it has been shown that the exergy performance of a building does not increase significantly if the energy demand is reduced and surface heating systems are used without changing the supply structures and sources used (see chapter 4).

Within this report the methodology for exergy assessment of building systems, which was one of the main items within ECBCS Annex 49 activities, is described and applied to several building and community case studies. This represents a significant step towards a wider application of this method for building related energy uses. The application of this assessment method to further technology concepts (e.g. storage, control, cascading concepts) will help identifying optimum and suitable uses of the analyzed technologies and represents a promising field where further research needs to be conducted.

Designing energy systems with the exergy approach would increase the use of environmental heat and renewable energy sources, leading to lower primary energy consumption and CO₂ emissions. To promote all benefits shown in this report and summarized above, exergy should be included as a further indicator in building and energy regulations.

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APPENDIX B: ADDITIONAL INFORMATION FROM ECBCS ANNEX 49

Brochure

The brochure gives an overview of the activities of the Annex 49 working group and a short introduction of the exergy concept and its utilization within the built environment. The brochure is available in English and German.

Annex 49 guidebook: full version

A printable .pdf version of the full and extended Annex 49 guidebook, the final report of this project, is available for those who prefer to get more detailed information.

Annex 49 guidebook: summary report

The summary version of the Annex 49 guidebook, the full and extended version of the final report is available on the CD-ROM

A framework for exergy analysis at the building and community level

The Annex 49 midterm report entitled: "A framework for exergy analysis at the building and community level" gives an overview of the basic principles of exergy analysis within the built environment and about the used models for the tool development. Furthermore, some case study examples are given.

Human-Body Exergy Balance and Thermal Comfort

The Annex 49 working report on Human-Body Exergy Balance and Thermal Comfort outlines the research work with in the field of exergy and comfort. This report gives detailed information about the basics and about the modelling and the developed calculation tool.

Annex 49 newsletters

All seven issues of the biannual Annex 49 newsletter can be found on the CD-ROM. Starting from the first description of the work in the newsletter no. 1 in March 2007 to the summary of the results of the Annex 49 work in newsletter no.7 in March 2010.

Conference proceedings: The Future for Sustainable Built Environments

- Integrating the Low Exergy Approach

This conference about the future of sustainable built environments was focusing on providing front-edge results on the field of exergy analysis of buildings and communities. It was held in Heerlen/The Netherlands on April, 21st, 2009.

Conference proceedings: The Future for Sustainable Built Environments with High Performance Energy Systems

This conference about the future for sustainable built environments and energy systems integrating a maximum amount of renewable energies provided front-edge technologies and solutions for buildings, communities and energy supply. It was the final Annex 49 conference and took place in Munich/Germany on October 19th-21st, 2010.

Tools

In total, six different tools have been developed during the Annex 49 project. Ranging from a decision support tool, via a tool for a pre-design of a buildings or the assessment of a community district heating structure to a detailed building information model (BIM) based platform. Five of them are enclosed in the CD-ROM, the DPV tool has been developed to a commercial available tool, and you can find an animation about this tool on the CD-ROM.

Tool manuals

User-Guides for the enclosed five tools are available on the CD-ROM.

Technical presentations

A series of technical presentations were prepared for the biannual ECBCS Executive Committee (ExCo) meetings during the working time of Annex 49. The related presentations can be found on the CD-ROM.

Published articles

A list of the exergy related articles published by members of the Annex 49 working group during the course of the project is given on the CD-ROM.

The Network of the International Society for Low Exergy Systems in Buildings (LowExNet)

The International Society for Low Exergy Systems in Buildings (short LowExNet) has been founded on the 13th September 2003 to keep the members of the at that time ending ECBCS Annex 37 together. The main objective of this network is to formulate our interest in the regarded topics beyond the working time of the ECBCS Annex 37 and ECBCS Annex 49 itself. A large number of workshops in connection with other international events have been organised. During this often industry related workshops technologies and applications of LowEx systems on a building and community level have been presented and discussed in detail. LowExNet is intended to cover also applications in countries outside the IEA. All information about this network is available on a website (<http://www.lowex.net/>).

you can find the following additional information on the enclosed CD-ROM and at the homepage www.annex49.com

ECBCS ANNEX 49

Annex 49 is a task-shared international research project initiated within the framework of the International Energy Agency (IEA) programme on Energy Conservation in Buildings and Community Systems (ECBCS).

ECBCS Annex 49 is a three year project. 22 research institutes, universities and private companies from 12 countries are involved.

The main objective of this project is to develop concepts for reducing the exergy demand in the built environment, thus reducing the CO₂-emissions of the building stock and supporting structures for setting up sustainable and secure energy systems for this sector.

Annex 49 is based on an integral approach which includes not only the analysis and optimisation of the exergy demand in the heating and cooling systems but also all other processes where energy/exergy is used within the building stock. In order to reach this aim, the project works with the underlying basics, i.e. the exergy analysis methodologies.

These work items are aimed at development, assessment and analysis methodologies, including a tool development for the design and performance analysis of the regarded systems. With this basis, the work on exergy efficient community supply systems focuses on the development of exergy distribution, generation and storage system concepts.

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Annex 49

Low Exergy Systems for High-Performance
Buildings and Communities

