ANNEX 84

EBC

Energy in Building and Communities Programme

International Energy Agency

Demand management of buildings in thermal networks: Description and Comparative Analysis of Case studies (Annex 84, Subtask D)

Energy in Buildings and Communities Technology Collaboration Programme

May 2025

Technology Collaboration Programme by iea

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Preface

The International Energy Agency

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

The IEA Energy in Buildings and Communities Programme

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

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

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

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

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

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

- the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
- benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;
- improving smart control of building services technical installations, including occupant and operator interfaces;
- addressing data issues in buildings, including non-intrusive and secure data collection;
- the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

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

The Executive Committee

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

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation 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 and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO_2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO_2 Equivalent Emissions for Building Construction (*)

Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings (*)
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale (*)
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements (*)
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings (*)
Annex 73: Towards Net Zero Energy Resilient Public Communities (*)
Annex 74: Competition and Living Lab Platform (*)
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables (*)
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions (*)
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting (*)
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation (*)
Annex 80: Resilient Cooling (*)
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings
Annex 87: Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems
Annex 88: Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
Annex 89: Ways to Implement Net-zero Whole Life Carbon Buildings
Annex 90: Low Carbon, High Comfort Integrated Lighting
Annex 91: Open BIM for Energy Efficient Buildings
Annex 92: Smart Materials for Energy-Efficient Heating, Cooling and IAQ Control in Residential Buildings
Annex 93: Energy Resilience of the Buildings in Remote Cold Regions
Annex 94: Validation and Verification of In-situ Building Energy Performance Measurement Techniques
Annex 95: Human-centric Building Design and Operation for a Changing Climate
Annex 96: Grid Integrated Control of Buildings
Annex 97: Sustainable Cooling in Cities

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities
Working Group - Building Energy Codes

Summary

Buildings are increasingly becoming smarter due to the widespread availability of connected devices, sensors, and actuators. These technologies enhance indoor comfort while reducing operational costs, energy consumption, and environmental footprints. However, space and domestic hot water heating continue to significantly contribute to CO_2 emissions in the building sector. This emphasizes the urgent need to decarbonize energy systems and transition from fossil fuels toward renewable energy sources to mitigate climate change, improve energy supply security, reduce pollution, and address sustainability challenges necessitates a significant paradigm shift in the building sector, which is the largest energy end-user. Buildings are evolving into more responsive loads with decentralized energy production and storage capabilities. This transformation allows buildings to operate in synergy with various energy sectors, adapting their short-term energy demand profiles, thereby helping to align energy demand with the intermittent supply from renewable energy sources.

District heating and cooling (DHC) systems are recognized as sustainable solutions for meeting heating and cooling needs in densely populated areas, playing a pivotal role in global decarbonization efforts by promoting the use of renewable energy and enhancing the flexibility of energy supply. Within the context of DHC the concept or energy-flexible buildings, which utilizes buildings as decentralized solutions for thermal storage, is also gaining traction. Despite the potential of DSM and the utilization of buildings for energy storage within DHC systems, several challenges hinder large-scale implementation, necessitating close collaboration among various stakeholders with sometimes conflicting goals. These factors underscore the need for innovative approaches in DSM to facilitate an effective energy transition and achieve climate targets.

The IEA EBC Annex 84, titled “Demand Management of Buildings in Thermal Networks,” aims to develop comprehensive guidelines for the successful activation of Demand Response (DR) in District Heating and Cooling (DHC) systems. It addresses both social and technical challenges while leveraging digitalization, such as smart meters and sensors, to enhance large-scale DR implementation with minimal investment. Specific objectives include providing knowledge on key stakeholders, proposing design solutions for building heating and cooling installations, and developing methods to utilize data from monitoring equipment for real-time modelling of thermal demand response.

Within Annex 84, Subtask D focuses on reviewing existing buildings that can deliver thermal storage to DHC systems, examining the technological solutions and collaboration strategies in place. Through these efforts, Annex 84 aims to promote best practices and facilitate the effective integration of demand response in thermal networks. To achieve this, the case study questionnaire developed for Subtask D serves as a standardized framework for collecting and documenting relevant information about DSM implementations and projects in district heating (DH) networks.

The questionnaire systematically gathers comprehensive and comparable data from diverse case studies, enabling the analysis and assessment of DSM methods and their effectiveness across various projects. By providing researchers and practitioners with a structured format to submit key parameters, the questionnaire facilitates comparative analysis and knowledge transfer between different implementations. It consists of several thematic chapters that include both open and multiple-choice questions, collecting information about the buildings investigated, the energy storage technologies used, the thermal grid characteristics, and the specific type of DSM applied, along with its intended purpose and expected benefits.

In total 29 case studies on DSM in DH networks have been collected and analysed. Each case study is associated with a distinct research project involving various stakeholders, including universities, research

institutions, and private companies, often collaborating in consortiums. The projects span from 2010 to 2025, predominantly located in European countries, particularly Denmark and Germany, reflecting a strong interest in implementing DSM within buildings connected to DH networks. A concise summary of each project, highlighting key information, is presented in Table 2, together with a classification of the status of the research project and the DSM implementation progress.

To facilitate the dissemination of the case study analysis a case study brochure[1] and a presentation with case study profiles[2] have been created. The primary intent of the case study brochure is to showcase practical implementations and facilitate stakeholder understanding of successful projects through visually engaging and accessible content on a higher level. The case study profiles on DSM in DH networks serve to provide a standardized and categorized summary of all 29 case studies, promoting consistent analysis and comparison across various projects. Each profile is visually structured for enhanced readability, covering essential categories such as project overview, objectives, system boundaries, and results. This systematic documentation facilitates effective analysis and application of STD findings, making the profiles a valuable resource for understanding DSM in practice.

The comparative analysis of the collected case studies within this report provides insights into various approaches and best practices. Among the 29 case studies, 23 are from completed projects, with an average project duration of three years. The case studies encompass a variety of scales, including individual buildings and larger networks, with seven focused on single buildings and the remainder involving multiple structures, often utilizing only a portion of the connected heating networks for experimental purposes. The analysis reveals that most projects pursue technical objectives, emphasizing the testing of new innovations to mitigate peak loads commonly occurring in the morning. Seven projects utilize predictive control strategies to optimize energy demand forecasts and manage loads effectively. Additionally, seven case studies examine the thermal mass of buildings as a resource for load shifting, while ten projects specifically engage consumers to investigate acceptance and user behaviour related to demand response measures. Additionally, the comparative analysis highlights the technology readiness levels (TRL) of the projects, with the majority at TRL seven, also indicating a focus on existing buildings and networks rather than new constructions. Residential buildings dominate the research, with a notable emphasis on apartments and single-family homes. Furthermore, the types of DH networks utilized vary, with a significant number focusing on second and third generation networks that cater to both space heating and domestic hot water needs.

The comparative analysis of the collected case studies regarding Demand-Side Management (DSM) reveals that thermal energy storage is the predominant storage type utilized, with a total of 27 systems identified. Among these, 21 are decentralized, with 17 leveraging building mass as part of their storage strategy. Only one project is dedicated to supplying space cooling, which is located outside the district heating network context.
Furthermore, the analysis indicates that 22 case studies, focus, among other aspects, on load shifting as a primary purpose of the investigated DSM measures. Other objectives include load shedding and efficiency improvements, with 12 of case studies incorporating load shedding as a goal. The anticipated benefits of the DSM measures mainly extend to the DH grid operator and indirectly to customers, with 13 case studies benefiting this way. Additionally, six case studies provide direct benefits to both the DH grid operator and customers. There are five case studies where only the DH grid operator benefits, and just one case study exclusively benefits customers. Cost reduction is a common objective, as seen in 14 case studies aimed at decreasing expenses associated with peak boiler operation. In case 14, 14.36% of energy could be saved leading to cost reductions. 7 case studies aim to lower CO_2 emissions. For example, case 23 is expecting to save 25.000 tons of CO_2 by reducing peak boiler operation run by gas. Approximately half of the case studies investigate DSM measures activated by the DH operator. Various approaches to DSM implementation are observed, including active and indirect measures, collective measures (such as installing smart

[1] "IEA EBC Annex 84 - Demand Management of Buildings in Thermal Networks" published at https://annex84.iea-ebc.org/publications
[2] "Case Study Profiles" published at https://annex84.iea-ebc.org/publications

home technology), and tariff structures. Most studies focus on the interaction between buildings and the grid, with daily load management being the standard timescale for implementation.

The lessons learned from the case studies are categorized into two groups: 1) User behaviour, thermal comfort, and acceptance, and 2) Flexibility sources, DSM strategies and technical aspects.
Successful implementation of DSM requires a nuanced understanding of buildings and occupants as unique entities rather than simple load points. Temperature conditions can vary significantly within a building, necessitating decentralized control strategies that manage room-level variations while ensuring occupant comfort. Effective communication about the functions and benefits of demand response (DR) interventions enhances acceptance, with key factors influencing acceptance including appropriate indoor climate conditions, timing of load shifts, and individual control options for occupants. Occupants are more likely to accept DSM measures when they are well-informed about the benefits, including economic savings and contributions to collective societal goals. Financial incentives also play a crucial role in motivating participation in DSM programs, particularly when combined with environmental benefits. The analysis emphasizes the importance of maintaining temperatures within comfort boundaries, as residents generally accept fluctuations as long as they remain comfortable.
Additionally, successful DSM implementation hinges on collaboration among multiple stakeholders, with thorough communication and consultation processes deemed essential. The technical aspects highlight that utilizing building thermal mass effectively increases flexibility in district heating systems, while specific strategies for peak load management can significantly reduce demand during critical periods. Advanced control systems and economic model predictive control can enhance the effectiveness of load shifting strategies but must be tailored to individual room requirements to prevent issues like overheating. Overall, a holistic approach that incorporates user preferences and technical innovations is crucial for the success of DSM initiatives in thermal networks.

Based on the lessons learned from the case studies, several key recommendations for stakeholders involved in DSM implementation in buildings connected to DH grids are proposed. By following these recommendations, stakeholders can enhance the effectiveness of DSM initiatives, improving energy efficiency in district heating systems.
Building and System Considerations: Implement decentralized room-level control strategies and recognize heavy buildings as valuable thermal storage assets. Quantify thermal storage capacity in degree hours and prioritize targeted preheating in specific zones. Short intervention periods can achieve peak reductions, and hybrid networks should be explored for summer shutdowns to reduce energy losses.
Control Strategies and Technology: Coordinate DSM triggers with energy management systems and extend prediction horizons in demand forecasts. Avoid partial control of radiators in E-MPC implementations and prioritize domestic hot water during peak periods. Ensure thermostats remain on to prevent condensation and maintain minimum temperatures.
Occupant Engagement and Communication: Clearly explain DSM functions and benefits to occupants before implementation. Frame participation as a collective achievement and emphasize economic and environmental benefits. Allow occupants some control over temperature settings and provide app notifications with personalized recommendations.
DSM Implementation Approach: Address building-related issues before implementing DSM and design shorter demand response events for high override risk buildings. Simple, cost-effective data-driven DSM solutions should be prioritized, and thorough stakeholder consultation is essential.
Pitfalls to Avoid: Avoid treating buildings as simple load points, creating new demand peaks, and ignoring occupant engagement. Do not reduce temperatures during already cold periods, and refrain from overly complex solutions when simpler alternatives exist.

Table of content

Abbreviations

Abbreviations	Meaning
DHC	District Heating and Cooling
DH	District Heating
DHW	Domestic Hot Water
DR	Demand Response
DSM	Demand-Side Management
E-MPC	Economic model predictive control
HEMS	Home Energy Management System
H/C	Heating / Cooling
HP	Heat pumps
MPC	Model predictive control
RES	Renewable Energy Sources
SH	Space Heating
SC	Space Cooling
TES	Thermal energy storage
TRL	Technology Readiness Level

1. Introduction

1.1 General Context

Buildings are becoming smarter due to the widespread availability of connected devices, sensors, actuators and appliances, which can improve the indoor comfort of occupants while reducing total building operational costs, energy, and environmental footprint. At the same time, space and water heating contribute to 45% of CO_2 emissions in the building sector, accounting for 12% of global energy-related CO_2 emissions [1]. Space cooling, which currently represents only 15% of the energy used for heating [1], along with heating, makes up the largest portion of carbon emissions in buildings. Over the next 30 years, building floor areas are expected to double by 2070, cooling demand is projected to grow by 3% annually, but heating demand is not expected to balance out this increase, thus these energy uses are key targets for interventions aimed at a swift and effective transition to zero-carbon energy systems [2].

District heating and cooling (DHC) systems are recognized as the most sustainable solutions for meeting heating and cooling needs in densely populated areas where individual heat pump installations are impractical [2,3]. It is estimated that district heating (DH) systems supply 9% of the global heating demand in buildings and industry [4]. According to the IEA's "Net Zero by 2050" strategy [5], DH is expected to supply over 20% of the global space heating demand. The district cooling (DC) systems are in the development stage delivering around 300 PJ/year globally [2]. Yet, they are gaining the interest of the international community since the impact of climate change on global warming is now clearly visible, and the cooling demand increases even in heating-dominated locations, e.g. Austria, the Netherlands, Poland, and Canada. Additionally, the European Union has raised its CO_2 emissions reduction target for 2030 from 40% to 55%. The EU's "Fit-for-55" proposal aims to achieve this goal through enhanced energy efficiency and increased reliance on renewables. As a result of these international targets, both the DHC and electrical power sectors are undergoing significant transformations, striving to eliminate fossil fuels and boost the share of renewable energy sources (RES).

The planned decarbonization of the energy system necessitates a revolution across all energy sectors and a shift towards smart energy systems, markets, and social restructuring [6–9]. A high integration of RES, such as geothermal, solar, and wind energy, either directly at DHC production units or indirectly through the electricity grid via large-scale heat pumps (HPs), may result in fluctuating heat production [10]. Consequently, DHC systems could play a critical role in buffering energy system intermittency. However, this variability presents additional challenges in DHC system operation and planning, increasing the need for long- and short-term energy storage and flexibility and, thus, interoperability between the existing and new components and functionalities located at the production and demand sides. Thus, DH systems are undergoing major changes to meet decarbonization goals and manage intermittent heat supplies to ensure consistent heat availability while stable operation and cost-optimal performance.

Thermal energy storages (TESs) offer a promising solution to enhance the controllability of DHC systems during short- and long-term operational challenges [11,12]. According to [13], TES in DHC systems can be classified by a) physical phenomenon: sensible, latent, and chemical; b) storage duration: short-term and long-term; c) location: distributed/decentralized and localized/centralized; and d) transportability: fixed and mobile. TES can be integrated into the production unit or strategically placed within the distribution network, centrally controlled by DHC operators. Water circulating in DHC network pipelines has also been explored as a source of thermal storage or driven in a decentralized manner via broadcasted incentive signals [14,15]. These TES solutions involve actions and investments on the primary side.

At the same time, every building connected to the DHC network can be seen as a decentralized TES solution with characteristics fluctuating according to the heat demand profile of the building. The main concept behind utilizing buildings for energy storage is that for a specific time, the heat supply to the building exceeds current demand, with the stored heat used later [16]. This concept, known as energy-flexible building or demand response (DR), has been studied by international experts for over a decade, focusing on initial concept definition, formulation, simulation studies [17], general discussions on applications and challenges [18,19], and extensive reviews of evaluation metrics [20]. However, these studies are mostly academic, with generic definitions and evaluation metrics applied across different scopes, mainly in the electricity sector, without accounting for hydronics in thermal DHC systems. Despite its potential, large-scale implementation of demand response and utilisation of buildings for energy storage in DHC systems has not yet materialised, as utilities are hesitant to adopt it in daily operations. Integrating solutions for flexibility activation and control into existing DHC systems and building heating installations while ensuring customer satisfaction, economic viability, interoperability and regulatory compliance is a complex task that requires collaboration among various stakeholders with sometimes conflicting goals. These challenges limit the large-scale adoption of the demand response concept in DHC systems.

The overarching goal of IEA EBC Annex 84 "Demand Management of Buildings in Thermal Networks" is to develop comprehensive knowledge used as guidelines for the successful activation of the DR in DHC systems. The work of IEA EBC Annex 84 explores both the social and technical challenges and how they can be overcome, as well as how digitalization of the demand side (e.g., smart meters, sensors, monitoring equipment) can further facilitate large-scale DR utilization with the minimum investments.

To fulfil the aim the following specific objectives were defined for IEA EBC Annex 84:

- Provide knowledge on partners/actors involved in the energy chain and on collaboration models/instruments for successful demand management.
- Classify, evaluate and provide design solutions for new and existing building heating and cooling installations for successful demand management in various DHC networks.
- Develop methods and tools to utilize data from energy and IEQ monitoring equipment for real-time data modelling of thermal demand response potential in buildings and urban districts.
- Disseminate lessons learned from case studies collected by the Annex.

To address these objectives, the research and development work in the Annex is divided into four subtasks, each of which is further divided into several specific work items (see Figure 1 below).

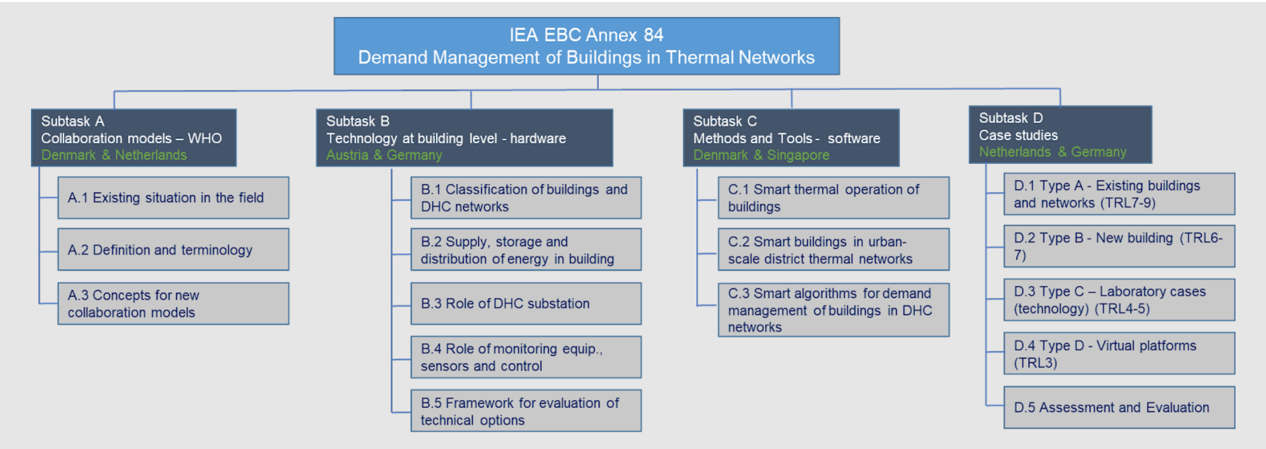


Figure 1: Structure of the IEA EBC Annex 84

Subtask A: Collaboration Models

It investigates the motivations, challenges and limitations of key actors involved in DR. It reviews existing terminology and indicators describing the DR concept followed by the development of a common language understandable for all involved actors. It reviews the existing collaboration models and provides recommendations for the commercial utilisation of the DR concept by DHC utilities in the case studies in Subtask D.

Subtask B: Technology at Building Level

It investigates the technological options integrated at the building level to enable DR. Special attention is given to the evaluation of their ability to maintain the thermal and DHW comfort demands of the end-users while reacting to the DHC signals, to their market readiness level, and to their economic and adaptation potential in different generations of DHC systems.

Subtask C: Methods and Tools

It develops new data-driven algorithms for modelling the smart thermal operation of individual buildings and for aggregation, orchestration and feasibility studies of individual smart buildings in urban DHC systems and techno-economic system-wide optimization of DHC systems.
It provides an overview of state-of-the-art methods, frameworks, software, numerical tools and algorithms relevant to smart thermal management of individual buildings and building clusters connected to district heating and cooling networks. It covers aspects such as dynamic modelling, large data treatment and analysis, techno-economic optimization, fault detection and orchestration of the smart thermal operation and demand response of buildings integrated into thermal grids.

Subtask D: Case studies

It reviews the existing real-life and virtual buildings or cluster of buildings delivering thermal storage to DHC systems and thereby being demand-response-ready. The investigation includes the applied technological solutions, control strategies, collaboration agreements between DHC utilities and the customers, and finally the motivation of the actors to initiate the DR action.

Finally, to address the topic comprehensively and uniformly the Annex 84 has adopted the terminology, which is technology agnostic and presented in Figure 2.

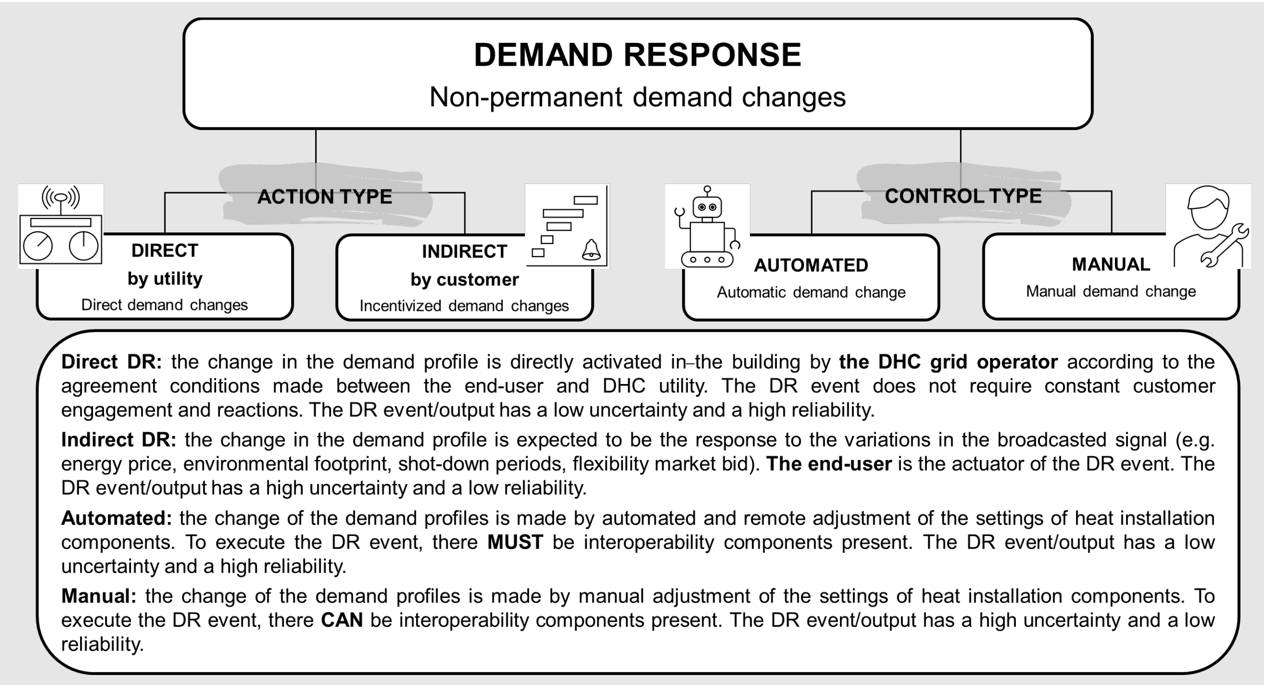


Figure 2: Terminology applied in IEA EBC Annex 84

Combining the two action and control types there can be four different demand response types: 1) **Direct Automated** (e.g. model predictive control in the building executing a forecast of the DHC grid operator), it is characterised by high & high reliability; 2) **Indirect Automated** (e.g. model predictive control in the building reacting to the DHC broadcasted signal), it is characterised by low & high reliability; 3) **Direct Manual** (e.g. DHC operator vising the house or sitting in the control room and pressing the button), it is characterised by high & low reliability; 4) **Indirect Manual** (e.g. end users changing the settings physically of via using the remote technology (walking in the house, sitting on the sofa and using app) as the reaction to the broadcasted signal), it is characterised by low & low reliability. Figure 3 is presenting the visualisation of the four DR types.

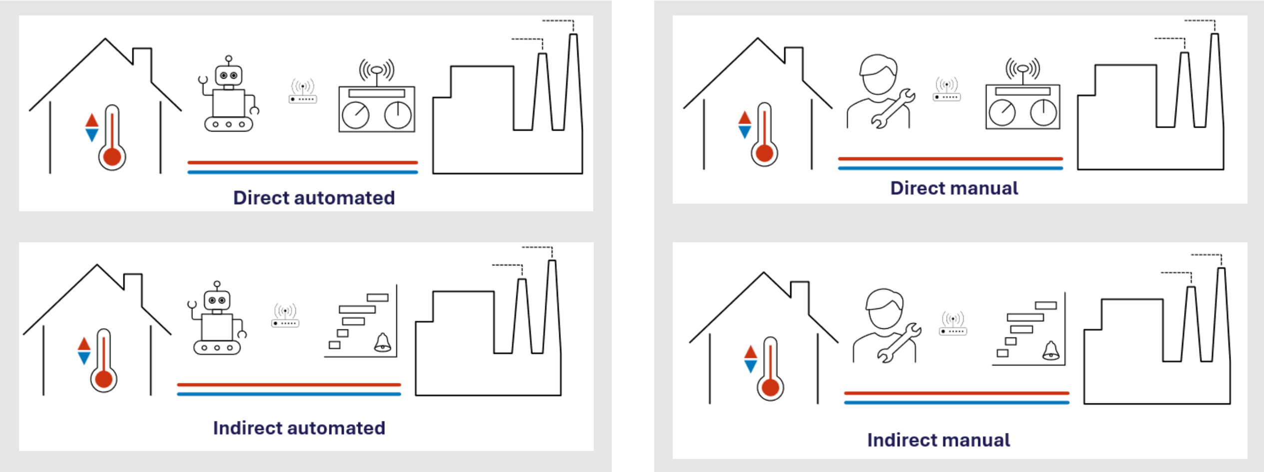


Figure 3. Illustration of the four type of DR according to Annex 84

Finally, the direct and indirect action types proposed by Annex 84 are preferable DR mechanisms employed by the DHC operators; they indicate the level of operator involvement in the DR programme. From the customers' perspective, i.e. more sociological viewpoint, these action types can be classified as explicit or implicit DR mechanisms. In the explicit DR, the customers receive a direct payment from the DHC utility for shifting their demand as part of the DR programme. In implicit DR, various incentives, e.g. price or CO_2 signals, are used to encourage the customers to modulate their demand.

1.2 Introduction to Subtask D

Subtask D of IEA EBC Annex 84 focuses on the examination of real-life and virtual case studies utilizing Demand-Side Management (DSM) in buildings or clusters of buildings that provide thermal storage to district heating and cooling (DHC) systems.

This report presents a collection of 29 detailed case studies that exemplify diverse approaches to implementing DSM in buildings connected to thermal networks. Each case study is analysed comprehensively, addressing key elements such as research objectives, collaboration models, building characteristics and demand response control mechanisms. Furthermore, the report outlines the results and conclusions drawn from case studies, emphasizing valuable lessons learned and best practices identified throughout the research project. This comprehensive examination not only contributes to the understanding of demand response in DHC systems but also serves as a practical guide for future implementations in similar contexts.

2. Objectives and Means

This subtask aims to analyse various technological solutions, control strategies, and collaboration agreements between DHC utilities, building occupants, and other stakeholders. Additionally, it explores the motivations driving these stakeholders to engage in demand response (DR) initiatives. The primary objective of this subtask is to compare how flexibility in building heat demand can be harnessed through DSM by performing a comparative and descriptive analysis. Specifically, this involves the implementation of DSM strategies, such as load shedding (also known as peak shaving), load shifting, and on-site generation utilization, as defined in section 2.1. These strategies are crucial for enhancing demand-response capabilities, increasing the proportion of renewable energy in the overall energy mix, and reducing dependence on fossil-fuel-based peak-only boilers.

2.1 Types of Demand-Side Management

Demand-Side Management (DSM) refers to permanent or temporary changes in consumption patterns on the consumer side of the energy system. Unlike traditional supply-side management, which focuses on adjusting generation capacity to meet demand, DSM approaches target the modification of consumer demand to better align with available energy resources and grid capabilities. In the context of district heating (DH) networks, DSM strategies are particularly valuable for addressing challenges such as peak demand management, integrating renewable energy sources, reducing return temperatures, and optimizing operational efficiency. [21,22]

The following categorization of DSM types in Table 1 is based on the framework developed by Li et al. (2021) [21], adapted specifically for district heating applications. Within chapter 5 “Evaluation Framework” of the questionnaire the following four different DSM types are distinguished.

These four DSM types provide a comprehensive framework for understanding and categorizing the various demand-side strategies that can be implemented in DH networks. Each type offers distinct advantages and operational characteristics, and often a combination of multiple approaches is employed to maximize system flexibility and efficiency. The questionnaire utilizes this classification to systematically document the specific DSM measures implemented in each case study, thereby facilitating analysis of their effectiveness and applicability across different contexts.

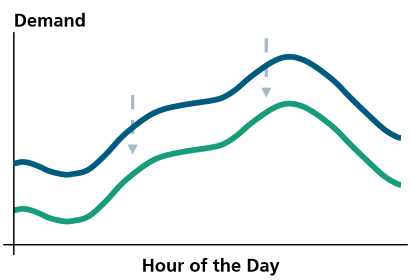
Table 1: Types of Demand Side Management (Own representation based on [21])

Efficiency (passive DSM)

Definition: Persistent heat demand reduction regardless of time.

Key characteristics: Long-term, continuous reduction, Independent of timing, focus on reducing overall energy consumption.

Example of Application in DH: Building envelope refurbishment, equipment efficiency upgrades, smart control systems, implementation of heat recovery systems, reduced distribution losses.

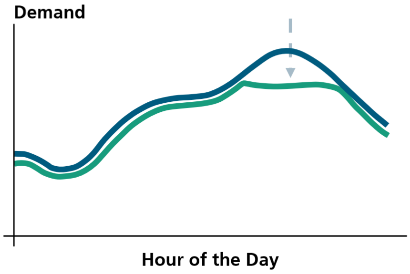


Load Shedding (active DSM)

Definition: Short-term heat demand reduction during peak demand periods or emergency events.

Key characteristics: Heat demand reduced within minutes and usually last for up to one hour. Temporary reduction in service quality may occur.

Example of Application in DH: Temporary setback of room temperatures, limiting maximum flow rates during peak hours, short term shutdown of non-critical systems, strategic prioritization of buildings / zones.

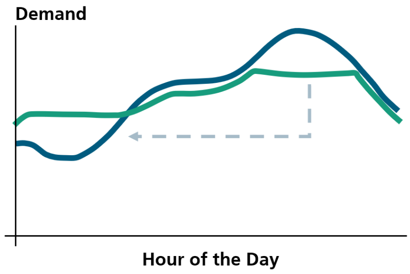


Load Shifting (active DSM)

Definition: The building changes the energy use timing to reduce the heat demand during peak demand periods or to exploit renewable generation.

Key characteristics: Heat demand reduced within minutes and usually lasts for two to four hours.

Example of Application in DH: Pre-heating of buildings before peak demand periods, utilizing building thermal mass as storage, pre-charging of thermal storage tanks before peak demand periods, adjusting operation schedules based on price signals.

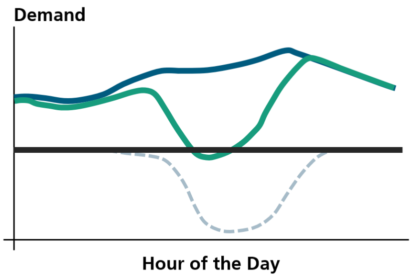


On-Site Generation (active DSM)

Definition: The building generates heat for on-site use or dispatch to the DH network during peak demand periods.

Key characteristics: Heat demand from the network reduced within minutes or heat generation activated within minutes and usually lasts for two to four hours.

Example of Application in DH: Local solar thermal systems, second energy source next to DH network in the building, bidirectional substations enabling feed-in, waste heat recovery from building processes.



2.2 Description of Questionnaire

The case study questionnaire developed for IEA EBC Annex 84 Subtask D serves as a standardized framework for collecting and documenting relevant information about demand-side management (DSM) implementations and projects in DH networks. This questionnaire was designed to systematically collect comprehensive and comparable data from diverse case studies, enabling analysis and assessment of the methods and effectiveness of DSM measures across various projects. By enabling researchers and practitioners to submit key parameters in this structured format, the questionnaire facilitates comparative analysis and knowledge transfer between different implementations.

The questionnaire establishes a standardized foundation for analysing case studies and developing a comprehensive database. This approach allows Subtask D to document various strategies for enhancing energy flexibility in district heating systems and derive insights that could contribute improving collaboration and business models, application and control methods in the field of load management in buildings connected to DH networks.

The questionnaire consists of several thematic chapters containing open and multiple-choice-questions. The questionnaire can be found in the annex to this report. The chapters are structured as follows:

1. **Organizational Parameters:** This section collects core information about the research project in which the case study has been conducted, including its identification details (case study number, title), geographic location (city, country), project timeline (schedule, implementation year), and organizational framework. It documents the participating organizations and their roles, contact information for key personnel, related publications, and web resources. Visual documentation such as pictures or maps of the project is also included in this section to provide context and aid in understanding the project setup. Furthermore, the current phase of the project, distinguishing between the research status (idea, preparation, in progress, completed) and the implementation status (preparation, in progress, completed, or no implementation). This information helps to classify case studies according to their maturity and allows for appropriate comparison between projects at similar development stages.
2. **Building Parameters:** This chapter characterizes the building context of the case study, including the study's scope and Technology Readiness Level (TRL). It captures information about the type of use (residential, non-residential, mixed), building condition (existing/renovated, new, generic), and specific residential building types if applicable (apartment, terraced, semi-detached). These parameters provide details for understanding the technical and operational constraints that may influence the DSM implementation.
3. **Energy Storage:** This chapter details the energy storage technologies employed to implement DSM in the case study. It documents the storage location (from a DH network perspective: decentralized inside buildings or centralized), types of thermal energy storage used (short-term buffer storage, seasonal storage, phase change materials, building mass), and the services provided by the thermal storage (space heating, cooling, domestic hot water). It also categorizes the types of demand-side management strategies that utilize the energy storage: 1) passive and permanent DSM, 2) active and direct DSM, 3) active and indirect DSM, and 4) no DSM. Finally, it seeks to determine the specific applications of thermal energy storage, including whether it is used for space heating, cooling, domestic hot water, and/or other types of energy use.
4. **Thermal Grid Parameters:** This chapter collects the characteristics of the heating or cooling network. It documents the energy sources (renewable, waste heat, fossil-based) and types of energy converter (heat pump, combined heat and power, boiler). It details the type of network by DH generation classification (from 1st to 4th generation), cold network or a district cooling network. Additionally, it captures information about the demand types (heating only, heating dominated, balanced, cooling dominated, cooling only) and heat supply services (space heating only or including domestic hot water).
5. **Evaluation Framework:** This section serves as the core of the questionnaire, assessing on the relevance, implementation type, and type of the DSM measure implemented. It categorizes the purpose of DSM measures (efficiency, load shed, load shift, generation) (more information in section 2.2), and identifies the operational strategies, distinguishing between four different types: 1) user-triggered communication, 2) collective measures (such as smart home technology), 3) introduction of tariff structures, and 4) heating/cooling as a service (where the grid operator uses control strategies). Further, it also captures approaches to customer involvement (implicit, explicit, mixed) and defines the system boundaries (whether it involves only the building, only the thermal grid, or both) and the time scale of the implemented measures (whether the demand shift occurs on a daily, weekly, or seasonal basis).
6. **Detailed Information:** This chapter allows comprehensive descriptions of the case study, including the project's background and objectives, building and system specifications, energy supply schemes, and flexibility and DSM strategies. It documents the business and collaboration models used, any barriers encountered, and if available project results in terms of energy savings, cost

reductions, CO_2 emission reductions, and renewable energy integration. This section allows for more narrative explanation of aspects that cannot be adequately captured in multiple-choice fields.

3. Description of collected Case Studies

3.1 Case Study Overview

This section provides a comprehensive overview of 29 projects within which the case studies were conducted as part of the Subtask D research on demand-side management (DSM) in district heating (DH) networks. Each case study is part of a distinct research project involving various stakeholders including universities, research institutions, and private companies, often working in collaborative consortiums.

The case studies span from 2010 to 2025, with the majority located in European countries, particularly Denmark and Germany, with only case study 27 situated outside Europe. This geographical distribution reflects the strong interest and implementation of research projects of applying DSM in buildings connected to DH networks across Europe, especially in Northern and Central European regions.

The projects are classified into several categories in the further chapters. Within this overview, case studies are comparatively described considering the project status and implementation status of the DSM strategy, categorized as "In Preparation," "In Progress," "Completed," or "No Implementation." Additionally, system boundary conditions for the focus of the case study research are provided.

Table 2 presents a concise summary of each project within which the case studies were conducted, highlighting key information that is further expanded in the case study Brochure and individual case study profiles in subsequent sections. This comprehensively offers a clear and concise overview of each project's key aspects and outcomes. Further information and references regarding every case study and research project can be found in the Annex to this report.

Table 2: Case Study Overview with case study number, short description, status of research project and practical implementation of DSM as well as system boundary of the investigation.

Nr	Title and Short Description	Research Project	DSM Implementation	System Boundary
1	**Peak shaving in Turin District Heating** Italy The project analysed some buildings connected to Turin's district heating grid to determine optimal anticipation time of each substation for minimum peak demand in the network. The study aimed to eliminate or reduce morning peak loads due to nighttime heating system switch-offs and performed successful practical tests.	completed	completed	thermal grid
2	**Data-driven automated DSM technology** Austria This project aimed to reduce peak loads through the development of automated, data-driven DSM technology for small district heating networks. The solution required no hardware retrofits and was developed to be easily deployable and suitable for rapid transition to renewables.	completed	completed	building + thermal grid

No.	Project	Research Project	DSM Implementation	System Boundary
3	**100% renewable District Heating** Austria	completed	completed	thermal grid

The project implemented substation model control to increase flexibility and an energy management system to optimize supply in the district heating network of Leibnitz, Austria. The objective was to facilitate the use of 100% renewable energy and examine a DSM method which uses a model to calculate limits on supply capacity for each substation.

No.	Project	Research Project	DSM Implementation	System Boundary
4	**Flexible energy system integration** Austria	completed	completed	building + thermal grid

The study utilized demand forecast and optimized dispatch to increase and leverage building flexibility in the district heating grid of Maria Laach, Austria. The project aimed to optimize flexibility in the district energy sector, testing flexibility through building thermal inertia controlled by remote settings of substation controllers.

No.	Project	Research Project	DSM Implementation	System Boundary
5	**Smart energy in homes** Denmark	completed	completed	building

This end-user-driven project utilized smart home thermostats and energy consumption monitoring in an online portal to enable energy savings. The goal was to improve energy saving potential for households and investigate occupants' involvement in demand response activities.

No.	Project	Research Project	DSM Implementation	System Boundary
6	**Substitution of conventional controllers** Germany	in Progress	completed	building

The project tested the potential of modern radiator thermostats to reduce heat consumption with low investment costs in an office building. Particular attention was paid to motivating users to adopt energy-saving behavior, with load shifting realized by preheating thermal mass before working hours on selected days.

No.	Project	Research Project	DSM Implementation	System Boundary
7	**DSM in Danish single-family house** Denmark	completed	completed	building

The study modulated indoor air temperatures according to a schedule mimicking economic model-predictive control (E-MPC) behavior, then analyzed load shifting potential. The objective was to increase and optimize load shifting potential under the use of an E-MPC.

No.	Project	Research Project	DSM Implementation	System Boundary
8	**Geo-solar low-temperature DH network** Germany	completed	no implementation	building + thermal grid

This project examined load management and optimized use of central heat pump in low-temperature district heating for energy and economic savings. The objective was to develop a predictive control system to balance morning peak load by preheating thermal energy storage with a central heat pump during the night.

No.	Project	Research Project	DSM Implementation	System Boundary
9	**Digitizing DH supply infrastructure** Germany			

		Research Project	DSM Implementation	System Boundary
	The project investigated digitalization possibilities and potential in the Hannover district heating grid. It aimed to identify peak loads of individual properties, validate historical data through thermal simulations, and quantify flexibility potentials in buildings connected to the grid.	completed	completed	building + thermal grid
10	**DH networks within hybrid energy systems** Germany This study examined operational optimization potential of heating networks within hybrid energy systems during transformation of district heating networks. The project focuses on developing grid-friendly operation of two existing physically separated energy systems in electricity and heat sectors.	in Progress	in preparation	building + thermal grid
11	**Renewable energy integration in DH grid** Germany The project explored the transformation potential of district heating infrastructure for renewable energy integration. It aimed to develop new design criteria for district heating systems and network components as well as novel operating and control strategies for heating networks.	in Progress	in preparation	building + thermal grid
12	**Flexible and innovative DH grid operation** Germany This case examined flexible operation of local district heating network with integrated decentralized solar thermal systems and central combined heat and power plant. The primary aim was to implement, verify and derive general rules for long-term use and integration of solar thermal energy in comparable urban residential districts.	completed	completed	building + thermal grid
13	**Acceptance of fluctuating indoor temperatures** Denmark The project examined occupant acceptance of fluctuating indoor temperature behavior caused by economic model-predictive control of the space heating system. Four different temperature boost interventions were tested to assess residents' reactions to temperature fluctuations and derive demand response peak shifting effects.	completed	completed	building
14	**Remote control of radiator thermostats** Denmark This study implemented demand-side management in private households using smart thermostats controlled during morning peak periods and evaluated occupant acceptance. The objective was to shift load and reduce morning peak without reducing occupant comfort by briefly switching off radiator thermostats.	completed	completed	building + thermal grid

15

Temperature optimization for LTDH
Italy

Research Project	DSM Implementation	System Boundary
completed	completed	building

The project assessed the impact of dynamic supply temperature control with the STORM (Self-Organising Thermal Operational Resource Management) controller on an apartment building's heating supply within Brescia’s DH network. The objective was to reduce peak energy consumption of the district heating network branch through demand response, as these power peaks are expensive to provide by peak production plants.

16

Energy and cost savings in office building
Denmark

Research Project	DSM Implementation	System Boundary
completed	completed	building

This study investigated energy and cost savings by changing control of an existing heating system in an office building. The research compared night setback control and continuous heating with minimized supply temperature curves in a Danish office building.

17

DSM in smart homes: living-lab experiments
Denmark

Research Project	DSM Implementation	System Boundary
completed	completed	building

The project implemented rule-based demand-side management to shave peak demand in morning hours using remote control in individual rooms in apartments. The goal was to demonstrate how to remotely control heating systems in individual rooms to lower heating demand during peak hours.

18

Energy flexibility of low-energy buildings
Denmark

Research Project	DSM Implementation	System Boundary
completed	completed	building

This study utilized building mass as thermal storage to shift heat load, reduce peak load, and lower energy costs. The aim was to evaluate potential for low-energy residential buildings to operate flexibly according to heating system needs through various temperature set-point schedules.

19

Buildings as thermal energy storage in DH grids
Sweden

Research Project	DSM Implementation	System Boundary
completed	completed	building

The project investigated buildings' capacity to serve as thermal energy storage in district heating systems through a pilot test. The objective was to evaluate the magnitude of thermal energy storage capacity that can be utilized in residential buildings while maintaining good indoor climate.

20

Thermal conditions and flexibility potential
Denmark

Research Project	DSM Implementation	System Boundary
completed	completed	building

This research analyzed quantitative and qualitative data on thermal conditions and heating practices in apartment households. The aim was to examine variations of temperature conditions using multiple methods and assess if current modeling approaches for thermal conditions are realistic for evaluating flexibility potential.

No.	Project	Research Project	DSM Implementation	System Boundary
21	**Occupant fade-out from demand response** Denmark The study evaluated the persistence of occupant participation in demand response over long-term periods. In this field study of 72 single-family houses, the "night setback" demand response strategy was applied for two heating periods with occupants controlling DR event settings.	completed	completed	building
22	**Application of the STORM controller in Rottne, Sweden** Sweden This project tested and evaluated the peak shaving algorithm of the STORM (Self-Organising Thermal Operational Resource Management) controller in Rottne district heating network. The objective was to reduce peak energy consumption above a prescribed threshold through demand response in nine buildings.	completed	completed	thermal grid
23	**Optimal dispatch of heat in DH grid** Switzerland The study focused on optimizing heat dispatch in a new district heating grid to reduce CO_2 emissions and fossil-based boiler use. The objectives included reduction of CO_2 emissions and increased waste heat use and district heating customer connections.	in Progress	in preparation	thermal grid
24	**Load shifting in buildings connected to DH** England This project utilized a Home Energy Management System (HEMS) for demand-side management in residential buildings connected to district heating. The primary aim was to understand the impact of HEMS and demand coordination service on heat demand profiles and thermal comfort.	completed	completed	building
25	**Perceptions of indoor climate during DR** Sweden The study investigated tenants' thermal perceptions in apartment buildings connected to district heating during demand-side management. The objective was to evaluate thermal perception among tenants during periods with centrally controlled load shifts.	completed	completed	building
26	**DR in Student Apartment Buildings** Finland This project examined the potential of prioritizing domestic hot water demand over space heating in apartment buildings. The main objective was to test the feasibility of DHW prioritizing as a demand response method in apartment buildings.	completed	completed	building

No.	Case study	Research Project	DSM Implementation	System Boundary
27	**Thermostats overrides during DR events** Canada, USA This data-driven research analyzed thermostat override behavior during demand response events targeting air conditioners in summer. The objective was to provide knowledge on acceptability of demand response by remote control of air conditioners and inform design of more successful demand response events.	completed	completed	building
28	**DR events in a university building** Finland The project field-tested demand response algorithms to flexibly set space heating supply temperature in a university building. Goals included examining how much deviation could be incurred in inlet water temperature, how it affected occupant perceptions, and evaluating different DR strategies.	completed	completed	building
29	**Smart grid flexibility in single-family houses** Denmark This study theoretically analyzed thermal flexibility capacity of typical Danish single-family houses. The aim was to quantify the amount of energy and electricity that can be shifted away from daily peak periods while maintaining acceptable indoor temperatures.	completed	completed	building

3.2 Case Study Brochure

The case study brochure on DSM in buildings connected to DH network is designed to provide an overview and concise descriptions of selected case studies that perfectly align with the scope and goals of this annex. The primary intent behind the brochure is to offer stakeholders a curated collection of the "best" case studies, showcasing practical implementations and facilitating the understanding of successful projects. Visually, the brochure is designed to enhance the readability and engagement of the brochure, making it easier to grasp the essential information quickly. The brochure is published on the annex webpage, ensuring easy accessibility for all interested parties. The case study brochure is published on the Annex Web Page[3].

The brochure features selected case studies that are well aligned with the annex's scope and goals. These case studies are chosen because they demonstrate practical implementations of heating networks, highlighting successful strategies and outcomes that can serve as best practices for future projects.

Each case study in the brochure is thoroughly documented and follows a structured format to ensure consistency and comprehensiveness. The structure of each case study includes:

1. **General Information:**
    a. Project Overview: A brief sentence providing general information about the project.
    b. Scope and Focus: A sentence outlining the extent, subject matter, or specific focus of the project.
2. **Status Quo, Problem Statement, and Objectives:**

[3] IEA EBC Annex 84 Webpage: https://annex84.iea-ebc.org/publications

a. Status Quo: Description of the current situation before the project.
b. Problem Statement: Identification of the key issues the project aims to address.
c. Objectives: Clear objectives that the project seeks to achieve.

3. **Project Details:**
    a. Collaboration with Customers: Information on how customers were involved in the project.
    b. Technology and Hardware: Details about the technologies and hardware used.
    c. Control Software: Description of the control systems and software implemented.
    d. Additional Details: Any other relevant details pertinent to the project.
4. **Outcome and Results:**
    a. Results: Specific outcomes and achievements resulting from the project.
    b. Impact: The broader impact of the project's results on the heating network and stakeholders.
5. **Lessons Learned, Best Practices, and Conclusion:**
    a. Lessons Learned: Insights and knowledge gained from the project.
    b. Best Practices: Effective strategies and practices identified during the project.
    c. Conclusion: A summary of the project's success and its implications for future initiatives.

These structured categories ensure that each case study is comprehensively documented, providing valuable insights and practical examples that can inform and inspire future heating network projects. As a visual example, the page of the brochure detailing information about case study 1 is represented in Figure 4.

By presenting selected, high-quality case studies in a visually appealing and organized manner, the brochure serves as an essential resource for stakeholders seeking to understand and implement effective heating network solutions.

Peak shaving in Turin District Heating

With the development of a genetic optimizer algorithm, the optimal anticipation time could be found to reduce the morning peak loads.

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The district heating network in Turin is the largest in Italy. This project tested load shifting with some of the buildings connected to a distribution network in the Turin DH grid. The heat is generated in two large, combined heat and power plants and in various boilers.

The heating systems in most of the buildings are turned off overnight and reactivated in the morning between 5 and 6 am. This results in a load peak due to the system cooling down overnight. The peak is characterized by the mass flow rate and, consequently the thermal profile.

The implementation of demand response aims to reduce the peak load and the proportion of heat generated by the heat-only boilers. To mitigate peak loads, an optimizer has been designed to adjust the schedules of the heating systems installed in buildings to flatten the total thermal load as much as possible. The primary aim was to find the best timing for activating a building's heating system to achieve maximum peak shaving.

The best anticipation time is found by using a genetic algorithm optimizer. The optimization considers the predicted thermal demand for each building, utilizing data collected at substation level.

The genetic algorithm is incorporated to a network simulator. Combined, these tools can determine the optimal time for activating the heating systems.

Peak can be reduced by 5 % when fewer than 30 % of the buildings are considered, with a maximum anticipation of 20 minutes. Generally, these results support the inclusion of demand response strategies in DH networks.

Throughout the project, the maximum anticipation time was limited to 20 minutes to minimize effects on the internal temperature. However, simulation analyses show the peak effects can be entirely avoided by setting the maximum anticipation to 60 minutes.

6 PEAK SHAVING IN TURIN DISTRICT HEATING EBC ANNEX 84 CASE STUDIES

Figure 4: Visual representation of Case Study Brochure, as an example Case Study 1.

3.3 Case Study Profiles

The case study profiles on DSM in DH networks are designed to provide a standardized and categorized summary of all 29 case studies. The primary intent behind these profiles is to facilitate consistent analysis and comparison across various projects, enabling stakeholders to gain a comprehensive understanding of different approaches and outcomes related to research in DSM in DH networks. Each profile is visually structured to enhance readability and accessibility. This visual presentation helps users quickly grasp the essential elements and findings of each case study. The profiles are published on the annex webpage, ensuring easy access for all interested parties[4].

Within each case study, several categories are thoroughly described to ensure comprehensive documentation. These categories include:

1. **Overview:** Provides general information about the project and the problem it addresses.
2. **Objective:** Outlines the main goals of the case study or project.
3. **Scope:** Details the extent and setting of the case study, including specific boundaries and parameters.
4. **System Boundary & Time Scale:** Describes whether the study focuses solely on the building, the thermal grid, or both, and the timeframe for implementing DSM measures, categorized as daily, weekly, or seasonal.
5. **Building:** Specifies the type and use of buildings participating in the DSM.
6. **Network:** Details the generation and supply temperature of the DH grid.
7. **Heat Source of DH Network:** Identifies the heat sources used within the DH network.
8. **Storage:** Explains the storage solutions employed for implementing DSM.
9. **Demand-side management:**
    a. **Type and Purpose:** Describes whether the DSM is active or passive, its role in increasing efficiency, shifting or shedding load, or utilizing on-site generation.
    b. **Customer Involvement:** Specifies the level of customer participation in activating DSM methods, whether limited, indirect, or direct.
10. **Intended Benefits:** Explains the reasons for implementing the DSM measures.
11. **Who Benefits:** Identifies the beneficiaries of the DSM implementation.
12. **Results:** Presents the specific outcomes observed after implementing the DSM measures.
13. **Collaboration Detail:** Provides information on collaborations involved in the implementation and activation of DSM measures, if available.
14. **Technology Detail:** Describes the technologies used, including sensors, controls, IT infrastructure, and more, if available.
15. **Control Detail:** Details the control mechanisms, inputs, and outputs associated with the DSM measures, if available.

These structured categories ensure that each case study is thoroughly documented, making it easier to analyse and apply the findings to various heating network projects effectively. The Categories help to make the case studies comparable to each other. A visual representation of the case study profile is exemplary presented in Figure 5 for case study 1.

The structured case study profiles ensure comprehensive documentation and enable effective analysis and comparison of the case studies, providing valuable insights in the field of DSM in DH networks.

[4] IEA EBC Annex 84 Webpage: https://annex84.iea-ebc.org/publications

Figure 5: Visual representation of the first two pages of a Case Study Profiles, as an example Case Study 1.

4. Comparative Analysis of Case Studies

4.1 General Comparison

The objective of this chapter is to achieve a deeper understanding of the diverse approaches and best practices in the field of DSM of DH networks through a comparative analysis of case studies within the projects. Figure 6 displays the cumulated case studies by year. The case studies examined were conducted between 2010 and 2025, with the majority of cumulated case studies taking place between 2018 (12) and 2022 (9).

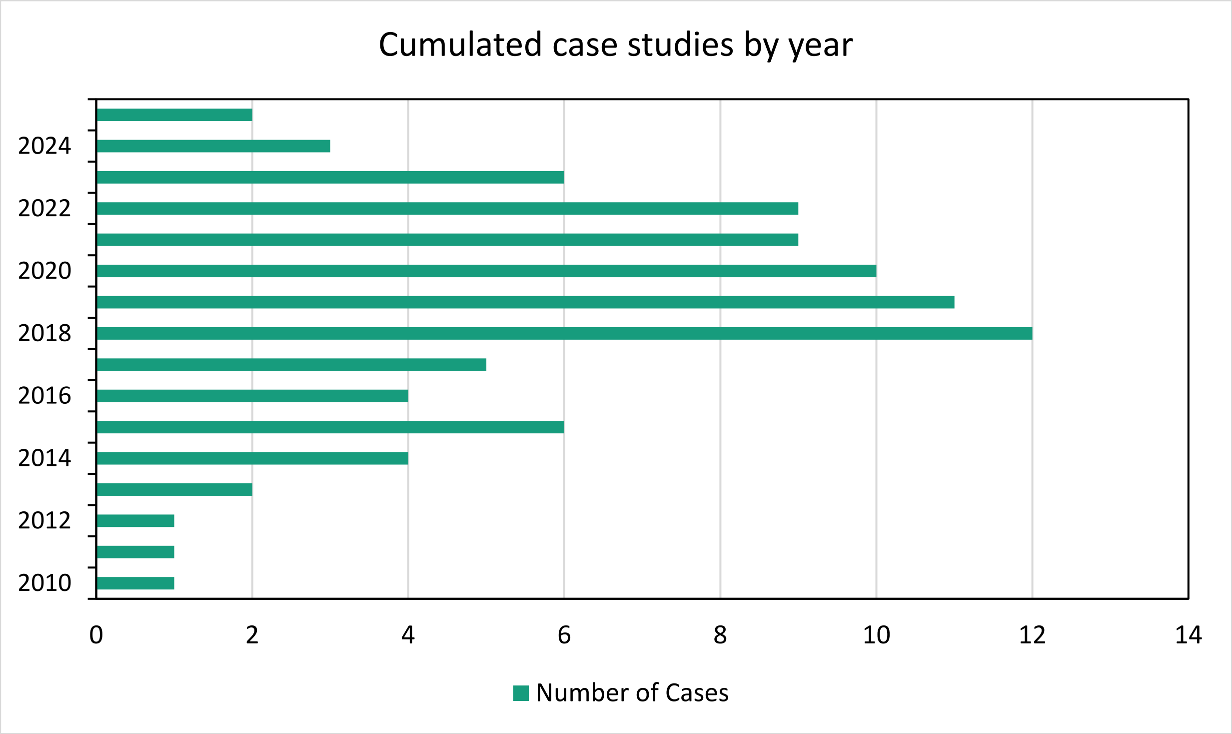

Figure 6: Number of Case Studies per year of the research project

Among the total of 29 examined case studies, as seen in Figure 7, 23 are from completed projects. The average duration of the projects is three years, with durations ranging from one to eight years. Most projects (9) have a duration of one year, followed by seven cases lasting four years and six cases lasting two years. Except for one, all completed projects have undergone practical implementation.

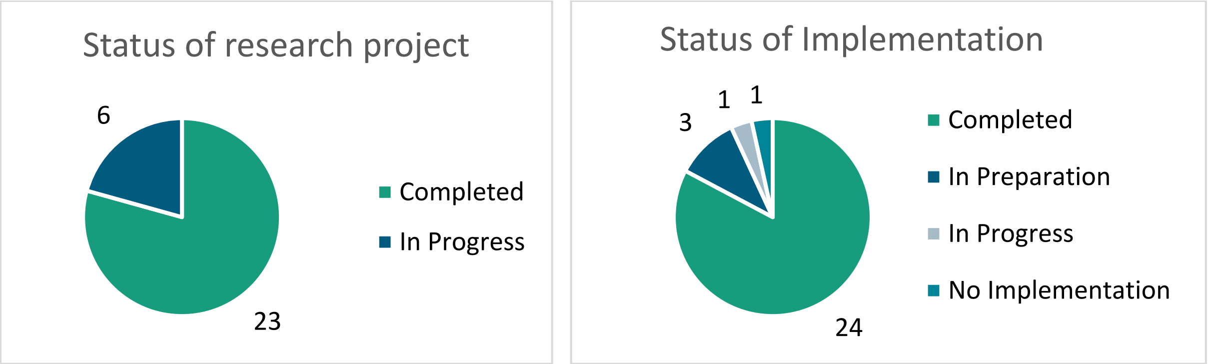

Figure 7: Status of research projects and implementation of concept

Six of the projects are currently still in progress. Two of the six projects have completed their practical implementation, three are in the preparation phase, and one remains ongoing. Figure 7 shows that from all projects, 24 and therefore the majority of projects have completed their practical implementation. Geographically, all projects are situated in Europe, except for one project located in the USA and Canada. As can be seen in Figure 8, most projects are implemented in Denmark (10 case studies), followed by Germany (6 case studies). Additionally, there are three projects each in Austria and Sweden, two in Finland and Italy, and one each in Switzerland and England.

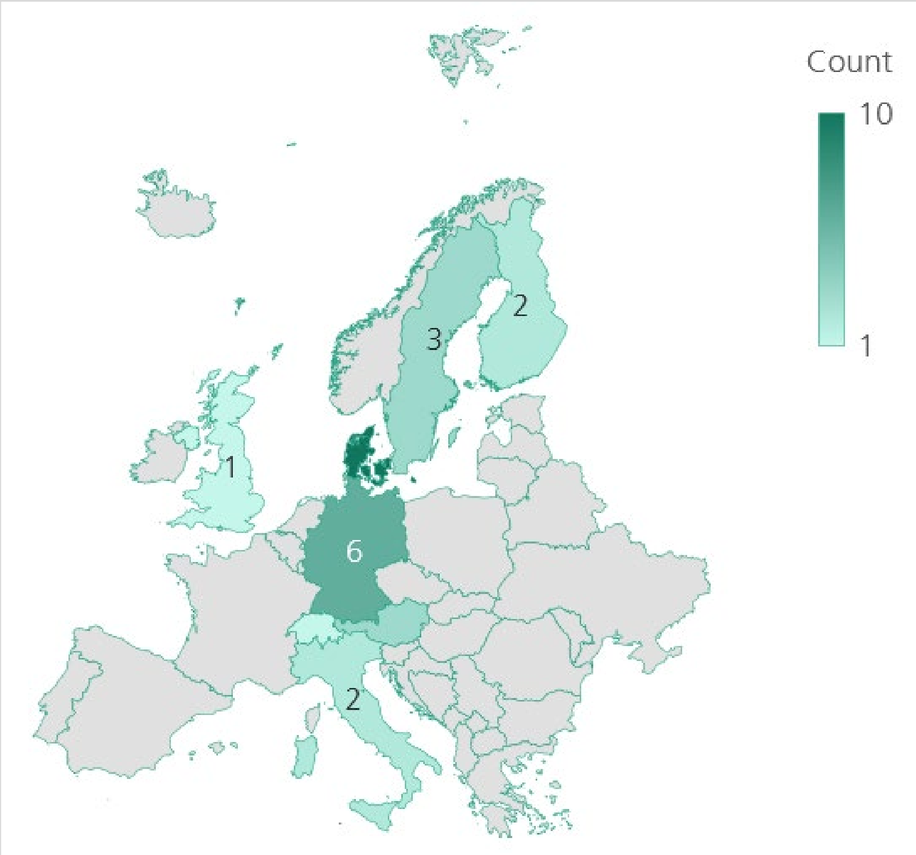

Figure 8: Location of DSM implementation

The case studies covered a range of scales, including individual buildings, residential blocks, neighborhoods, and districts. A general overview, detailing the number of buildings, is illustrated in Figure 9.

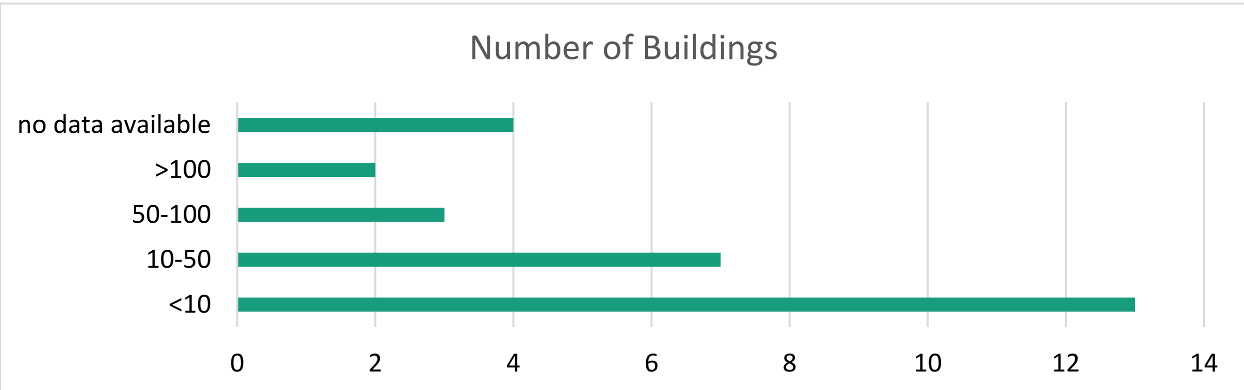

Figure 9: Number of cases per number of buildings connected to DH grid investigated.

Four cases do not provide any data regarding the number of supplied buildings, specifically case studies 3, 4, 8 and 11. Seven case studies examine one single Building focusing on individual structures. These projects include two office buildings, one university, one single-family home, and apartment buildings with multiple living units. However, most of the studies involved multiple buildings with several apartments. Notably, one study involving over 100 buildings took place in the USA and Canada, concentrating on user behavior related to demand response measures for air conditioning systems, rather than examining a DH network. In many case studies, the actual DH grids are supplying more customers, only a portion of the heating networks were utilized for experimental purposes.

The examined projects show diverse research objectives. Fifteen case studies pursued technical research objectives, focusing on testing new technical innovations, particularly in DR measures, often utilizing novel mathematical or physical models. Specific technical goals included the investigation of measures to address peak loads, which frequently occur in the morning due to night setback and high demand in the morning. These peak loads often necessitate the use of expensive, CO_2-intensive peak boilers. Strategies to mitigate these peaks include preheating the network or temporarily shutting down specific loads in the morning, supported with model predictive control (MPC) to forecast the energy demand being a key area of study. For example, the project in which case study one is conducted examines the DH grid in Turin. Certain loads are turned off during specific morning periods to reduce peak loads. Case study 8 involves using predictive control to forecast morning loads and preheat the heating network overnight using heat pumps.

As illustrated in Figure 10, among the case studies with technical research objectives, three focused on control strategies at the network level, while 12 examined building-level controls, such as dynamically adjusting the supply temperature of an apartment building using a smart controller. Additionally, five studies explored control options for individual consumers, including room-level temperature regulation through thermostats.

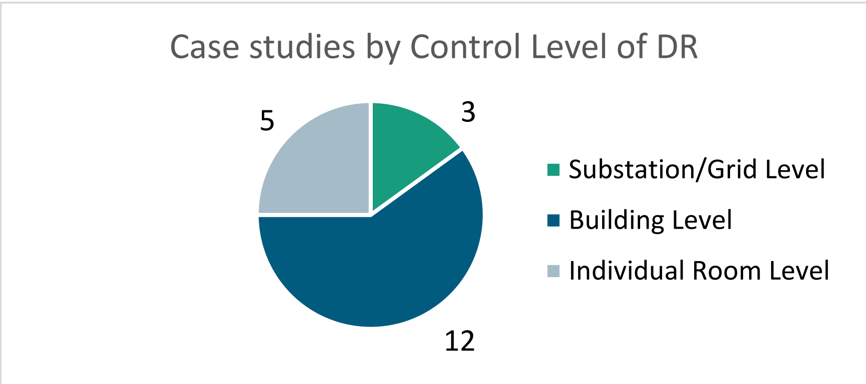

Figure 10: Levels of control of DR measures

Seven cases analyze the utilization of the thermal mass of buildings as thermal storage, which also aims to avoid peak loads. For instance, case study 18 investigated how the building structure can be used for flexible operation and load shifting by evaluating ten temperature set-point schedules. Other objectives included expanding the heat network with green energy sources, integrating new customers, and reducing operational costs.

12 projects were implemented in collaboration with consumers, focusing on key investigation topics such as acceptance, user behavior, and thermal perception (see**Fehler! Verweisquelle konnte nicht gefunden werden.**). For example, case study 20 examined the actual temperature conditions in households by analyzing data from 17 households through thermostat measurements and interviews, aiming to illustrate the range of temperature conditions present.

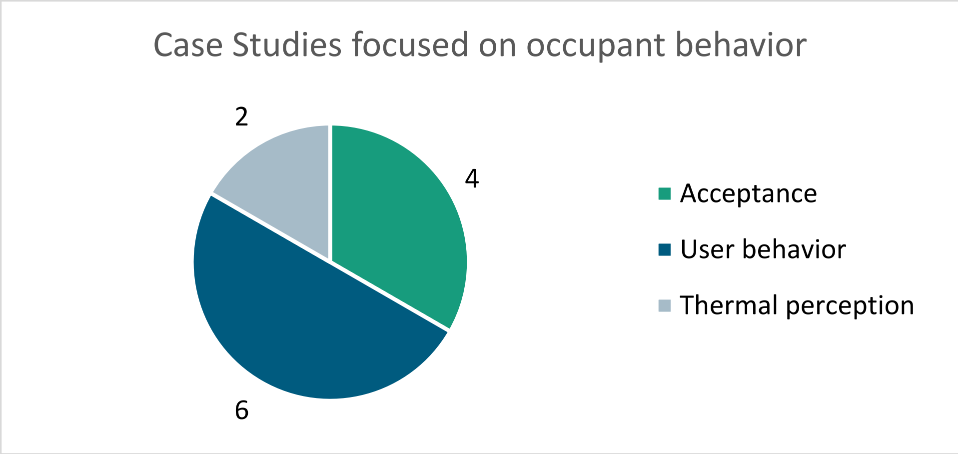

Figure 11: Number of case studies with focus on Acceptance, User behaviour and Thermal perception

Several studies also investigated how residents respond to DR measures, including case study 21 where night setback was applied over two heating seasons. Residents had control over the DR event settings and could stop the events independently at any time. In four projects, there was cooperation with consumers, though not through active user participation, but rather by their involvement in technical measures. This often includes projects where customers are engaged by installing sensors in their homes or modifying transfer stations.

For instance, case study two aimed to avoid peak loads by classifying customers based on their flexibility, with a data-driven MPC generating thermal loads for users. The building thermostat was manipulated to influence the heating curve and reduce thermal peaks from flexible customers.

Both user experience and technical possibilities are important areas of investigation. In terms of user experience, research questions are sometimes fundamental, such as heating habits of customer and how they respond to external heating controls. Technical innovations can occur at many levels, such as at the network, building, or room level, or using new hardware or software to support load distribution and forecasting. Overall, the combination of user interaction and technical development is crucial for the successful implementation of energy-efficient solutions.

4.2 Comparison of building and grid-details

The comparison of building and grid details across the case studies reveals several key insights. The majority of case studies are within projects exhibiting a technology readiness level (TRL) of seven (11 projects), followed by TRL six (5 projects). Additionally, three projects each are categorized under TRL four and TRL eight, while only two projects have achieved the highest TRL of nine. Notably, one of these TRL nine projects is located in North America and does not involve a DH network. As shown in Figure 12, 23 case studies focus on projects with existing buildings and networks, while only three projects involve new buildings and networks. Furthermore, three cases examine different combinations of network and building types.

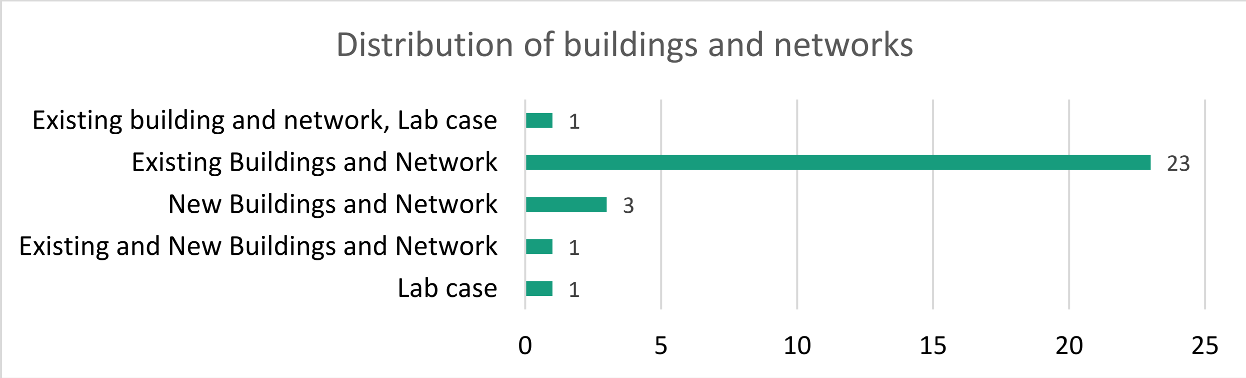

Figure 12: Distribution of existing and new buildings and networks

Regarding building types, Figure 13 illustrates that most case studies (18) investigate residential buildings. Four case studies explore mixed types of building usage, and three each examine non-residential and combined residential and non-residential building types. Additionally, one case study focuses on residential and mixed types of use. Eight of the case studies address apartments, townhouses, and single- and two-family homes, while another eight exclusively examine apartments. Five case studies are dedicated solely to single- and multi-family houses, and two focus on apartments and multi-story residential buildings. Each of the remaining case studies investigate offices, laboratories, lecture halls, single-family homes combined with townhouses, apartments combined with multi-story residential buildings, and offices. This indicates a strong research emphasis on residential buildings, albeit with diversified sub-focuses within this category.

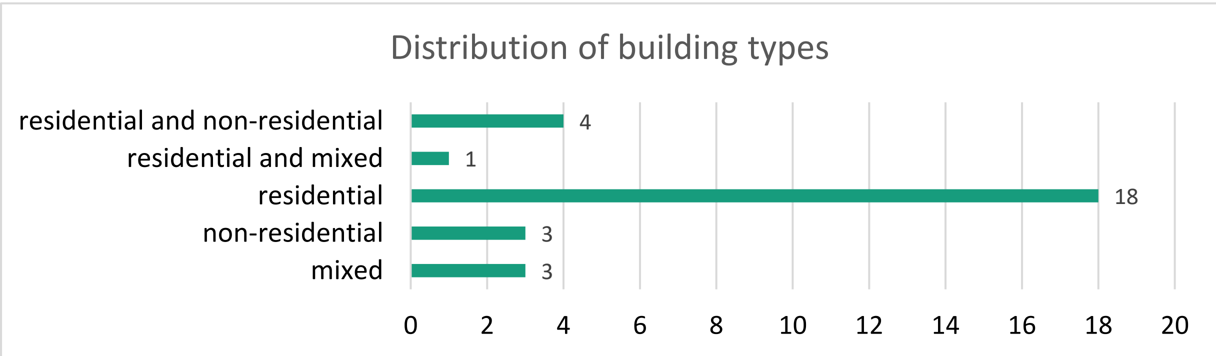

Figure 13: Distribution of building types

In terms of network utilization, 20 case studies research on heating networks for both space heating (SH) and domestic hot water (DHW), while six case studies are within projects utilizing the network exclusively for SH only. The types of heating networks used across the projects vary based on their generation and supply temperatures. Four projects utilize 2nd Generation DH networks with supply temperatures exceeding 100°C. Additionally, one project employs a combination of 2nd Generation DH (>100°C) and 4th Generation DH (40–70°C) networks. Most projects, totaling ten, use 3rd Generation DH networks with supply temperatures ranging from 70 to 100°C. Five projects rely solely on 4th Generation DH networks with supply temperatures between 40 and 70°C, while one project uses a 5th Generation DH network with a supply temperature below 40°C. Finally, eight cases have no data available regarding the DH network supply temperature, specifically case studies 14, 19, 20, 24-27 and 29.

4.3 Evaluation of Demand-Side Management

In the DSM measures analyzed, the predominant type of energy storage utilized is thermal energy storage, with a total of 27 systems identified. There is one system that combines battery and thermal energy storage, and one instance where no data was provided regarding the type of storage.

21 of the storage systems are decentralized. Among these, 17 systems utilize building mass as part of their storage strategy. Furthermore, two of these systems incorporate both short-term storage and building mass. Additionally, there are five projects that feature both centralized and decentralized energy storage, while two projects rely solely on centralized storage. Thus, the emphasis is on decentralized thermal energy storage that leverage building mass.

The primary application of the storage systems is for space heating (SH), with 19 out of the total case studies focusing on this function. Out of these 19 case studies, 15 case studies utilize the building mass as a thermal energy storage. Additionally, 9 case studies serve both space heating and domestic hot water (DHW) needs, while only 1 project is dedicated to supplying space cooling (SC), which is located in North America and does not involve a district heating network.

As seen in Figure 14, the majority of case studies investigate active and indirect measures (12 projects) alongside active and direct DSM measures (10 projects).

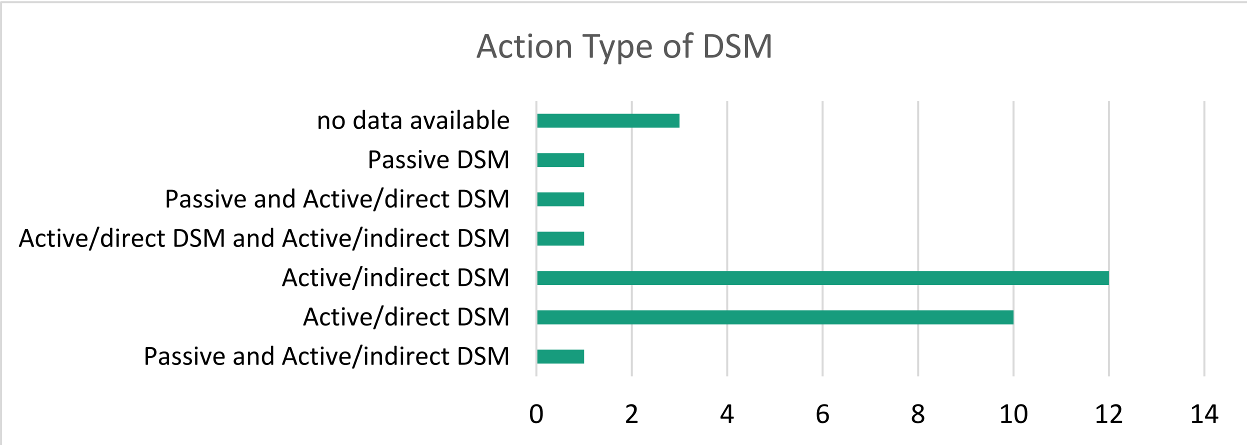

Figure 14: Action Type of DSM measure

Load shifting is the predominant purpose of the DSM measures investigated. If all purposes of Load shifting in Figure 15 are combined, 22 of the 29 case studies focusing primarily on this aspect. Several case studies examined DSM implementation with multiple purposes, allowing combinations like load shifting and shedding. Twelve of all case studies included load shedding as a purpose, while efficiency and on-site generation were the least common objectives (see Figure 15).

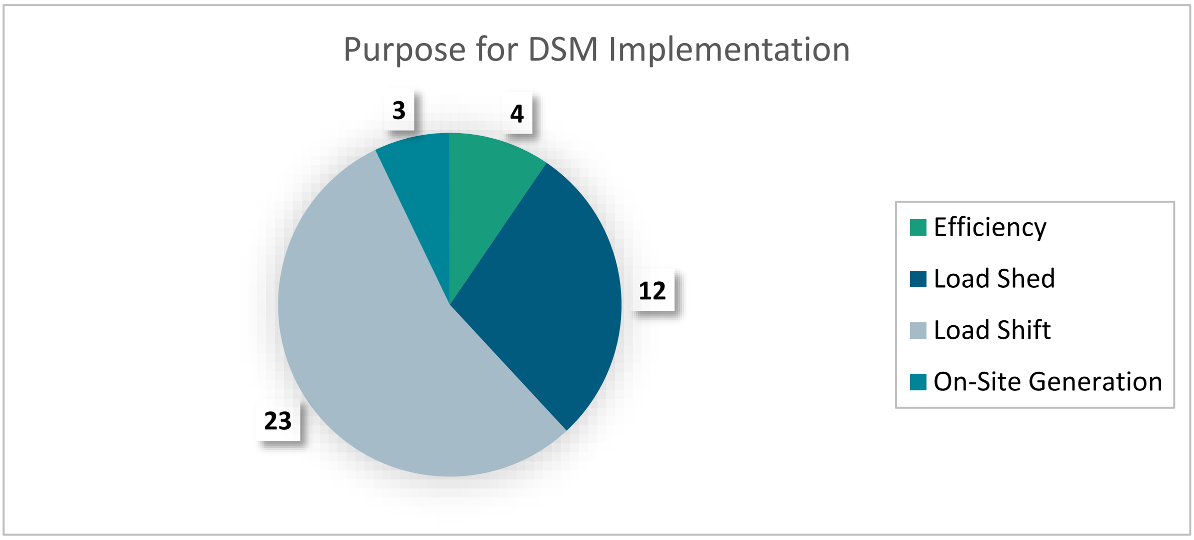

Figure 15: The purpose of DSM implementation stated in the questionnaire for the investigated case studies

The anticipated benefits of the DSM measures mainly extend to the DH grid operator and indirectly to customers, with 13 case studies benefiting this way as seen in Figure 16. Additionally, six case studies provide direct benefits to both the DH grid operator and customers. There are four case studies where only the DH grid operator benefits, and just one case study exclusively benefits customers.

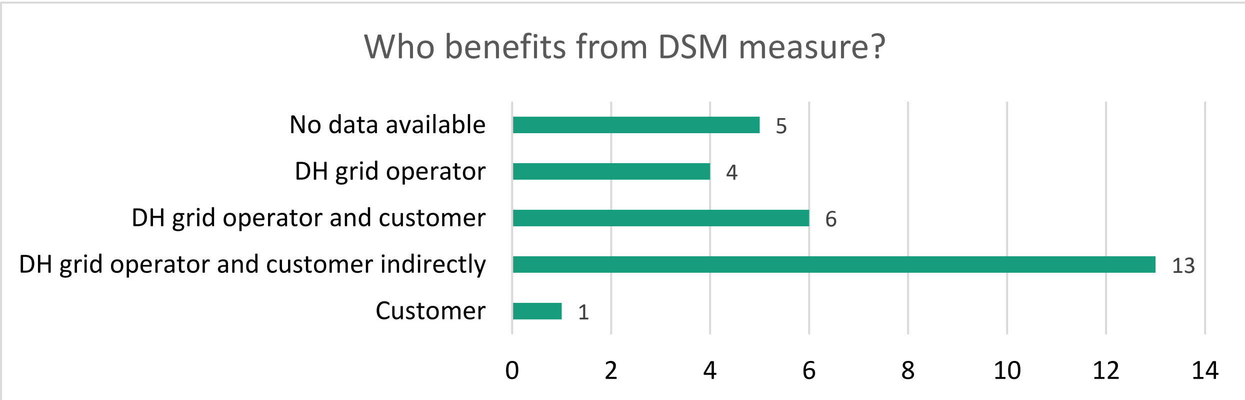

Figure 16: Beneficiary of DSM measures

Regarding the benefits, Figure 17 illustrates that 14 case studies aim to reduce costs, often by reducing expensive peak loads, peak boiler operation or reducing the overall energy demand. Another benefit seven case studies seek to achieve is lowering CO_2 emissions. For instance, in case 3, a DH grid will be expanded, and an EMS will be implemented. It is planned to use nearly 100% renewable energy from biomass and waste heat. The intended benefit in this case is to lower CO_2 emissions as well as avoid large load peaks in the morning.

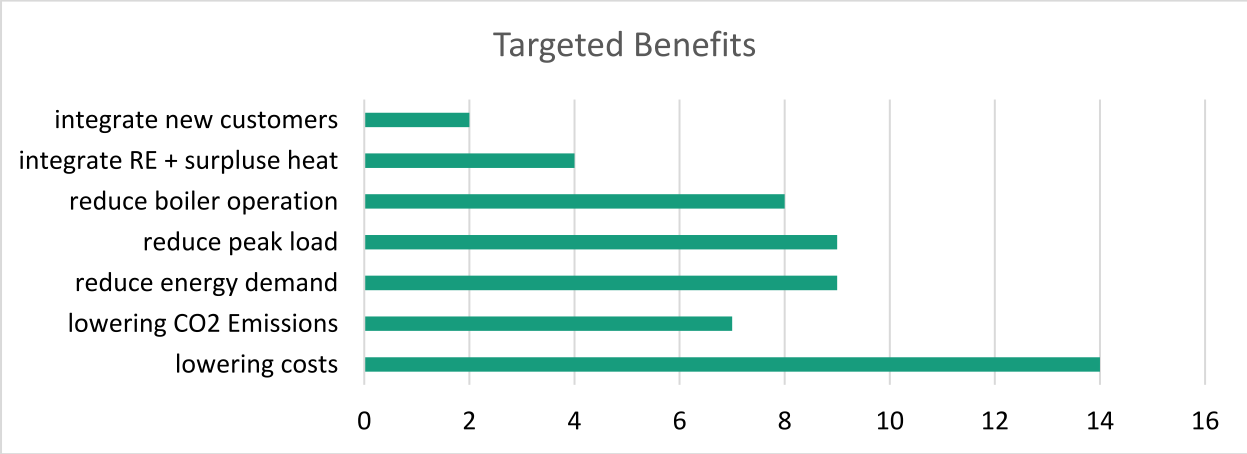

Figure 17: Targeted Benefits to achieve with DSM measures

Approximately half of the case studies (14) realize a DSM measure as heating/cooling (H/C) as a service, meaning the DH operator controls the DR, often at the substation level. Five case studies utilize collective measures, such as installing smart home technology, while another five employ tariff structures on network level, such as day-night or capacity rate. Two case studies are communication-based, meaning the occupant triggers the demand response, and one case study combines H/C as a service with tariff structure.

Regarding the system boundaries for the investigation, most of the case studies focus on the building (14) and on the interaction between building and grid (10). A specific focus on the thermal grid is in five case studies. All projects implement load management over a daily timescale.

4.4 Description of Lessons Learned

4.4.1 Classification and Overview to Lessons learned

The analysis of the lessons learned from the case studies can be divided into two groups: 1) User behavior, thermal comfort and acceptance and 2) technical aspects (see Figure 18).

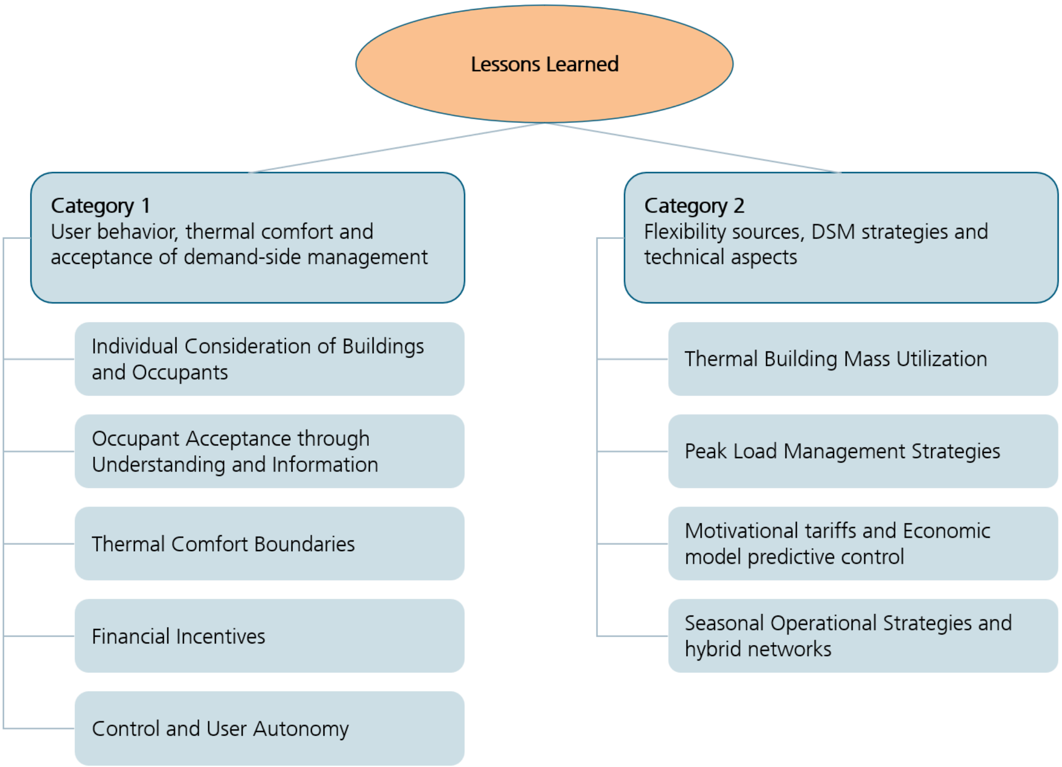

Figure 18: Overview of categories and subcategories of the collected lessons learned

4.4.2 User behavior, thermal comfort and acceptance of demand-side management

Individual Consideration of Buildings and Occupants

Successfully implementing demand side management (DSM) requires considering buildings and their occupants as individuals rather than simple load points (Case 5, 21). Temperature conditions vary significantly with space and time both within and between dwellings, with differences reaching up to 7K between spaces. Living rooms typically maintain the most homogeneous temperatures, while bedrooms exhibit the most significant variations (Case 20). This understanding challenges the conventional approach of modeling uniform temperature conditions throughout buildings when evaluating flexibility potential. Consequently, approaches that treat buildings as simple load points or demand-side variables fail to recognize occupants as individuals capable of enabling systemic interventions and delivering short-term storage flexibility (Case 21).

Preheating the entire building during nighttime to modulate heat demand during daytime have proven unrealistic for an apartment building (Case 20). Instead, decentralized control strategies on room level better manage temperature variations across different rooms, ensuring occupant comfort while maximizing energy flexibility (Case 28), compared to the centralized control strategy on building level. To achieve the full flexibility potential of buildings, including occupants in decision-making and management processes is essential (Case 20, 21).

Occupant Acceptance through Understanding and Information

Acceptance of demand response (DR) interventions significantly improves when functions and benefits are thoroughly explained to occupants (Case 13). Effective communication should consider the knowledge level of users and emphasize both economic savings and environmental benefits (Case 13). Communication about upcoming load shifts can help promote acceptance of DSM and ensuring a well-functioning heating system (Case 25).

Four key factors consistently emerged as determinants for occupant perception and acceptance: 1) setting appropriate indoor climate conditions, 2) careful timing and magnitude of load shifts, 3) provision of individual control options and 4) effective communication with occupants (Case 21, 25).

Providing app notifications with recommendations on DR actions has proven helpful in engaging occupants (Case 14). Additionally, framing participation as part of a collective achievement toward societal goals like avoiding the need for upgrading district heating pipes or mitigating climate change increases acceptance (Case 14). Most importantly, occupants should be considered as individuals capable of enabling systemic interventions and delivering short-term storage and flexibility, rather than passive consumers (Case 21).

Residential acceptance of demand response interventions represents a critical factor in implementation success. Studies reveal that residents experience loss of control negatively during demand response events, with particularly strong objections to losing control over bathroom heating during morning hours (Case 17). This highlights the importance of room selection when implementing partial heating control strategies.

Multiple stakeholders must be involved in practical DSM implementation, with thorough communication and consultation processes essential for successful adoption (Case 15). Studies demonstrate that cooperation between energy providers and service users significantly impacts the effectiveness of automation systems (Case 26).

Thermal Comfort Boundaries

Occupant acceptance of flexible heating operations depends largely on maintaining temperatures within comfort boundaries. As long as residents do not perceive room temperatures as too cold, they generally accept temperature fluctuations (Case 13). However, major temperature reductions during times already perceived as cold should be avoided, as should temperature increases during periods already perceived as warm (Case 25).

For practical implementation, it's important to note that thermostats should never be completely turned off to ensure temperatures don't fall "too low," both for user acceptance and to avoid condensation on walls and mold growth (Case 14). Building-related problems such as inadequate insulation should be addressed prior to implementing DSM strategies to ensure baseline thermal comfort (Case 25).

In buildings with higher override risk by tenants, shorter DR events have proven more effective, as they have a lower chance of being overridden and less impact on thermal comfort (Case 27). Interestingly, certain DR implementations have even seemed to improve occupant perceptions rather than deteriorate them (Case 28).

Financial Incentives

Economic incentives play an important role in motivating participation in DSM programs (Case 13, 14). Most participants indicate willingness to participate in commercial DSM schemes for relatively small financial rewards (Case 24). When combined with environmental benefits, these incentives become particularly effective in gaining occupant acceptance (Case 13). With the right incentives, even manual measures can encourage participants to adapt their daily activities to achieve energy savings (Case 14). This suggests that financial motivation, while not the only factor, remains a significant driver for participation in demand response programs.

Control and User Autonomy

The perception of control significantly impacts occupant acceptance of DSM interventions. Lack of control over temperature is a common issue reported by participants (Case 25). DSM schemes should be designed to allow occupants some freedom to adjust temperature levels according to their individual needs (Case 14).

DSM strategies based on individual thermostat control imply a high level of technical complexity that needs to be weighed against simpler and more robust solutions (Case 14). However, providing users with some degree of control increases their willingness to accept larger temperature variations (Case 25).

For optimal implementation, it's advisable to select active and passive rooms for DR according to expected load shifting potential and occupants' comfort preferences (Case 8). Additionally, avoiding control of sensitive spaces such as bathrooms, particularly during morning hours, has proven important for user acceptance (Case 17).

Summary
Through these lessons learned, it becomes evident that successful DSM in thermal networks requires a holistic approach treating buildings and occupants as individuals rather than simple load points, with room-level control strategies proving more effective than building-wide approaches. Clear communication about DSM functions and benefits substantially improves acceptance, particularly when emphasizing both economic savings and environmental benefits. Maintaining temperatures within comfort boundaries is crucial, avoiding temperature changes during already uncomfortable periods, while providing some degree of user control significantly enhances willingness to participate. Financial incentives remain powerful motivators, especially when combined with environmental benefits and framed as contributing to collective societal goals. Successful implementation ultimately depends on thorough stakeholder collaboration and consultation processes that respect occupants as active participants capable of enabling flexibility rather than passive consumers.

4.4.3 Flexibility sources, DSM strategies and technical aspects

Thermal Building Mass Utilization
Utilizing building thermal mass serves as an effective method for load shifting and increasing flexibility in DH systems. Heavy buildings with concrete structural cores demonstrate significantly greater capacity to tolerate heat delivery variations while maintaining acceptable indoor climate conditions compared to lighter structures (Case 19). The thermal energy storage capacity is most effectively measured in degree hours rather than using fixed time constants, as the latter proves insufficient for accurately describing indoor temperature variations during flexible operations (Case 19). Case 29 indicates for single-family houses in Denmark that up to 99% of energy demand during peak hours can be shifted outside these periods by leveraging thermal mass.

Building mass utilization software integrated with optimization tools helps district heating operators operate their systems more efficiently, with demonstrated peak load reductions of approximately 6% (80 kW) in field implementations (Case 4). While such thermal mass activation can reduce energy consumption during target periods by 40-87%, it may cause wider temperature ranges and more frequent fluctuations indoors (Case 18). The benefits often outweigh these effects since shifted heat loads typically occur when city demand is lower, making the energy less expensive and less carbon-intensive (Case 18).
As buildings undergo renovations, their flexibility potential typically increases due to improved insulation and heat retention properties (Case 29). However, further investigations are needed to fully characterize the differences in thermal energy storage potential between "light" and "heavy" building constructions (Case 19).

Peak Load Management Strategies
Several effective approaches for managing peak loads, particularly demand peaks in the morning, have been demonstrated across case studies. Delaying heating system activation times can achieve peak

reductions of 5% when applied to 30% of buildings connected to the grid for just 20 minutes, with complete peak elimination possible when extended to all buildings with 60-minute anticipation times (Case 1).

Strategic utilization of thermal networks as storage by preheating during off-peak hours has proven successful, with central heat pump preheating increasing overall system efficiency and enabling more flexible operations while reducing expensive operating costs (Case 8). Dynamic supply temperature control in apartment buildings has shown similar benefits, nearly eliminating morning peak loads (Case 15).

Room-specific control strategies offer another effective approach, with selective temperature control in residential apartments reducing morning peak demand by 85% compared to control groups (Case 17). Similarly, prioritizing domestic hot water over space heating can decrease peak loads by 14-15% (Case 26), with even older buildings showing substantial potential despite newer buildings demonstrating greater flexibility (Case 26).

Advanced control systems like the STORM controller effectively shift heat loads below predefined thresholds, replacing expensive peak heat production with cheaper base load generation (Case 22). Data-driven demand-side management solutions offer cost-effective infrastructure utilization without hardware investments, though their economic feasibility may be limited for larger networks (Case 2).
Despite these successes, load shifting strategies often create new, albeit smaller, peaks at different times (Cases 17, 29). Additionally, implementation requires careful coordination between energy providers and service users, with significant benefits realized when DSM triggers are coordinated by energy management systems or linked to thermal energy storage management (Case 3). Furthermore, extending prediction horizons and differentiation between working and non-working days in the forecast can significantly improve the performance of the DSM strategy (Case 3).

Motivational tariffs and Economic model predictive control
Economic Model Predictive Control (E-MPC) measures for load shifting require comprehensive control of all heating elements within a building; partial control of selected radiators has demonstrated limited effects on overall heat consumption and may lead to issues such as room overheating for a single-family house (Case 7). Implementation effectiveness improves when considering individual room thermal demand and comfort requirements rather than treating buildings as homogeneous units (Case 7).

Motivation tariff policies for low-temperature operations can provide additional economic incentives beyond direct energy savings (Case 16). This approach supports continuous low-temperature heating that maintains the required comfort levels while reducing heating costs (Case 16).

Seasonal Operational Strategies and hybrid networks
Alternative operational modes and technologies can be deployed to completely shut down thermal networks during summer months, avoiding distribution losses (Case 10, 12). Integration of decentralized solar thermal collector systems enables temporary grid shutdowns, representing a significant option particularly for urban areas with high land costs (Case 12).

In districts with low population density, heat losses can constitute 15-35% of network supply (Case 10). Field implementations have demonstrated that shutting down networks during summer and implementing sliding temperature control can reduce heat losses by 26% and pump operation electricity consumption by 22% (Case 10).

Also, hybrid energy systems, which combine heat and electricity, offer opportunities for operational optimization. In case 10 for instance, shutting down heating networks during low-demand periods in rural areas can reduce heat losses by up to 26% and decrease pump energy consumption by 22%.

Summary
In summary, it becomes evident that thermal building mass offers substantial flexibility potential in DH systems, with heavy concrete buildings tolerating greater heat delivery variations than lighter structures while maintaining indoor comfort. Peak load management can be achieved through various approaches including delayed heating activation, thermal network preheating during off-peak hours, room-specific temperature control, and prioritizing domestic hot water over space heating. Economic Model Predictive Control requires comprehensive control of all heating elements to be effective, while motivation tariff policies provide additional economic incentives beyond direct energy savings. Alternative operational strategies like shutting down thermal networks during summer months can significantly reduce heat losses, especially in low-density areas where losses constitute 15-35% of network supply, while hybrid energy systems combining heat and electricity networks offer additional optimization opportunities.

4.5 Conclusion and Recommendations

Based on the described lessons learned in the subsection before, the following actions are recommended for stakeholders involved in DSM implementation in buildings connected to DH grids:

Building and System Considerations
- ✓ Implement decentralized room-level control rather than centralized building-level strategies
- ✓ Recognize heavy buildings with concrete structural cores as superior thermal storage assets
- ✓ Quantify thermal storage capacity in degree hours rather than fixed time constants
- ✓ Prioritize targeted preheating in specific zones, instead preheating entire buildings uniformly
- ✓ Even short intervention periods (20 minutes) can deliver peak reductions of 5-6%
- ✓ Consider hybrid networks, combining heat and electricity, allowing for complete summer shutdown where appropriate, yielding energy loss reductions

Control Strategies and Technology
- ✓ Coordinate DSM triggers with energy management systems or thermal storage management
- ✓ Extend prediction horizons and differentiate between working/non-working days in demand forecasts
- ✓ Implement sliding temperature control in networks with significant distribution losses
- ✓ If applicable, strategies utilizing heat pulses to share heat between buildings with decentralized storage can be beneficial
- ✓ E-MPC implementations with partial control of only some radiators in a single-family house yield limited effects on heat demand
- ✓ Prioritizing DHW over space heating during peak periods can already yield 14-15% peak reduction
- ✓ Ensure thermostats are never completely turned off to prevent condensation and mold growth, maintaining minimum room temperature thresholds

Occupant Engagement and Communication
- ✓ Thoroughly explain DSM functions and benefits to occupants before implementation
- ✓ Frame participation as part of collective achievement toward societal goals
- ✓ Emphasize both economic savings and environmental benefits in communications
- ✓ Select active/passive rooms for DR based on load shifting potential and occupant preferences
- ✓ Exclude bathrooms from DR control, especially during morning hours
- ✓ Allow occupants some freedom to adjust temperature settings within system parameters
- ✓ Provide app notifications with personalized recommendations on DR actions
- ✓ Consider implementation of motivation tariff policies for low-temperature operations

DSM Implementation Approach
- ✓ First address building-related problems, e.g. poor insulation or system operation, before implementing DSM
- ✓ Design shorter DR events for buildings with higher override risk (less likely to be overridden)

- ✓ Develop simple, cost-effective data-driven DSM solutions that don't require hardware retrofits
- ✓ Implement thorough stakeholder consultation processes before deployment
- ✓ Use dynamic supply temperature control to eliminate morning peak loads
- ✓ Provide small but meaningful financial incentives for participation (even modest rewards are effective)
- ✓ Consider the building's renovation status when estimating flexibility potential

Pitfalls to Avoid

- Treating buildings as simple load points without considering occupant behaviours
- Creating new demand peaks when shifting loads from peak periods
- Implementing load shifting without considering temperature variations across different rooms
- Ignoring rebound effects after DR events
- Failing to engage occupants in the decision-making process
- Reducing temperatures during periods already perceived as cold
- Implementing complex technical solutions when simpler robust alternatives would suffice

Literature

[1] Is cooling the future of heating? – Analysis. IEA 2020. https://www.iea.org/commentaries/is-cooling-the-future-of-heating (accessed March 28, 2025).
[2] Werner S. International review of district heating and cooling. Energy 2017;137:617–31. https://doi.org/10.1016/j.energy.2017.04.045.
[3] Mazhar AR, Liu S, Shukla A. A state of art review on the district heating systems. Renew Sustain Energy Rev 2018;96:420–39. https://doi.org/10.1016/j.rser.2018.08.005.
[4] District Heating - Energy System. IEA n.d. https://www.iea.org/energy-system/buildings/district-heating (accessed March 28, 2025).
[5] Net Zero by 2050 – Analysis. IEA 2021. https://www.iea.org/reports/net-zero-by-2050 (accessed March 28, 2025).
[6] Lund H, Andersen AN, Østergaard PA, Mathiesen BV, Connolly D. From electricity smart grids to smart energy systems – A market operation based approach and understanding. Energy 2012;42:96–102. https://doi.org/10.1016/j.energy.2012.04.003.
[7] Li Y, Rezgui Y, Zhu H. District heating and cooling optimization and enhancement – Towards integration of renewables, storage and smart grid. Renew Sustain Energy Rev 2017;72:281–94. https://doi.org/10.1016/j.rser.2017.01.061.
[8] Sorknæs P, Lund H, Skov IR, Djørup S, Skytte K, Morthorst PE, et al. Smart Energy Markets - Future electricity, gas and heating markets. Renew Sustain Energy Rev 2020;119:109655. https://doi.org/10.1016/j.rser.2019.109655.
[9] Reda F, Ruggiero S, Auvinen K, Temmes A. Towards low-carbon district heating: Investigating the socio-technical challenges of the urban energy transition. Smart Energy 2021;4:100054. https://doi.org/10.1016/j.segy.2021.100054.
[10] Sayegh MA, Danielewicz J, Nannou T, Miniewicz M, Jadwiszczak P, Piekarska K, et al. Trends of European research and development in district heating technologies. Renew Sustain Energy Rev 2017;68:1183–92. https://doi.org/10.1016/j.rser.2016.02.023.
[11] Verda V, Colella F. Primary energy savings through thermal storage in district heating networks. Energy 2011;36:4278–86. https://doi.org/10.1016/j.energy.2011.04.015.
[12] Olsthoorn D, Haghighat F, Mirzaei PA. Integration of storage and renewable energy into district heating systems: A review of modelling and optimization. Sol Energy 2016;136:49–64. https://doi.org/10.1016/j.solener.2016.06.054.
[13] Guelpa E, Verda V. Thermal energy storage in district heating and cooling systems: A review. Appl Energy 2019;252:113474. https://doi.org/10.1016/j.apenergy.2019.113474.
[14] Vandermeulen A, Reynders G, van der Heijde B, Vanhoudt D, Salenbien R, Saelens D, et al. Sources of Energy Flexibility in District Heating Networks: Building Thermal Inertia Versus Thermal Energy Storage in the Network Pipes. 2018.
[15] Gu W, Wang J, Lu S, Luo Z, Wu C. Optimal operation for integrated energy system considering thermal inertia of district heating network and buildings. Appl Energy 2017;199:234–46. https://doi.org/10.1016/j.apenergy.2017.05.004.
[16] Van Der Meulen SF. Load management in district heating systems. Energy Build 1988;12:179–89. https://doi.org/10.1016/0378-7788(88)90063-1.
[17] Jensen SØ, Marszal-Pomianowska A, Lollini R, Pasut W, Knotzer A, Engelmann P, et al. IEA EBC Annex 67 Energy Flexible Buildings. Energy Build 2017;155:25–34. https://doi.org/10.1016/j.enbuild.2017.08.044.
[18] Li R, Satchwell AJ, Finn D, Christensen TH, Kummert M, Le Dréau J, et al. Ten questions concerning energy flexibility in buildings. Build Environ 2022;223:109461. https://doi.org/10.1016/j.buildenv.2022.109461.
[19] Goy S, Ashouri A, Maréchal F, Finn D. Estimating the Potential for Thermal Load Management in Buildings at a Large Scale: Overcoming Challenges Towards a Replicable Methodology. Energy Procedia 2017;111:740–9. https://doi.org/10.1016/j.egypro.2017.03.236.
[20] Li H, Johra H, de Andrade Pereira F, Hong T, Le Dréau J, Maturo A, et al. Data-driven key performance indicators and datasets for building energy flexibility: A review and perspectives. Appl Energy 2023;343:121217. https://doi.org/10.1016/j.apenergy.2023.121217.
[21] Li H, Wang Z, Hong T, Piette MA. Energy flexibility of residential buildings: A systematic review of characterization and quantification methods and applications. Adv Appl Energy 2021;3:100054. https://doi.org/10.1016/j.adapen.2021.100054.

[22] Satchwell A, Piette MA, Khandekar A, Granderson J, Frick NM, Hledik R, et al. A National Roadmap for Grid-Interactive Efficient Buildings 2021.

Annex

Case Study Questionnaire (Example: Case Study 1)

IEA EBC - Annex 84 Demand Management of Buildings in Thermal Networks

Energy in Buildings and Communities Programme

Date: *2022-05-11*

1) Organisational parameters

Case-Study No.:	**Location/City:** Turin	**Country:** Italy
Title (short and full title): Demand response in Turin District Heating, Italy		
Schedule of the demo project (research study): 2014 - 2017		**Year of implementation:** 2016
Leader organisation (owner, constructor, solution developer, research inst., etc.): IREN (company)		
Participating organisations – demonstration project part (involved other organisations): Politecnico di Torino		
*** Budget of the demo (invest/monitoring etc.):**		
Published articles (paper, article etc.): • Guelpa, E., Marincioni, L., Deputato, S., Capone, M., Amelio, S., Pochettino, E., & Verda, V. (2019). Demand side management in district heating networks: A real application. *Energy*, *182*, 433-442.		
Contact/name: Elisa Guelpa, Vittorio Verda		
*** Homepage (if available):**		

Picture/Map (eye catcher)

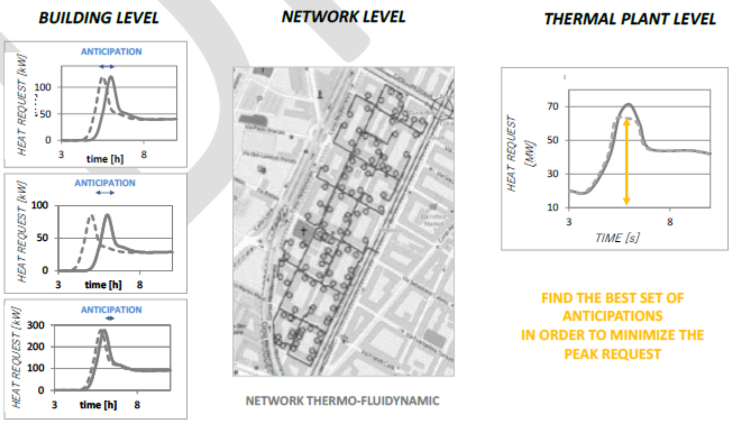

Figure 1 Load shifting approach applied to the Turin network (image with representative purpose)

Funding status (research)

Secured	Pending	Planned
☐	☐	☐

Status of project / case study

Idea	In Preparation	In Progress	Completed
☐	☐	☐	☒

Implementation Concept

In Preparation	In Progress	Completed	No Implementation
☐	☐	☒	☐

2) Building parameters

Case study scope and indication of TRL level

Type A Existing buildings and networks	**Type B** New Building and networks[1]	**Type C** Lab Cases	**Type D** Virtual platforms
☒	☐	☐	☐

Indication of TRL level[2] of case study type								
TRL 1	**TRL 2**	**TRL 3**	**TRL 4**	**TRL 5**	**TRL 6**	**TRL 7**	**TRL 8**	**TRL 9**
☐	☐	☐	☐	☐	☒	☐	☐	☐

Customer type (Customer is more applicable to a person, maybe we could use simply *Building typology*)

Existing/Renovated Existing or renovated buildings, no deep renovation	**New** Deeply renovated or new buildings	**Generic** Case study applicable to both
☒	☐	☐
Residential	**Non-residential**	**Mixed use**
☐	☐	☒

Building type

Apartment	Terraced	(semi)-Detached
☒	☐	☐

3) Energy storage

Type of energy storage

Battery storage		Thermal energy storage	
Centralized	Decentralized	Centralized	Decentralized
☐	☐	☒	☒

Type of thermal energy storage

Water-based (short-term buffer storage)	Water-based (seasonal storage)	PCM storage	Building mass
☒	☐	☐	☒
Other thermal energy storage:			

Type of demand-side-management using energy storage[3]

Passive DSM (permanent)	Active DSM (Market demand response)	Active DSM (Physical demand response)	No DSM
☐	☐	☐	☒

Use of thermal energy storage for DSM

Space heating	Space cooling	Domestic hot water	Other
☒	☐	☐	☐

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4) Thermal grid parameters

Energy source(s) of thermal grid

Renewable heat	Waste heat	Fossile-based heat
☐	☐	☒
Please specify energy source and owner of energy source: the company own 2 large cogeneration units (natural gas)		

District heating or cooling network

2nd Gen. DH T_{supply} > 100 °C	3rd Gen. DH T_{supply} > 90 °C	4th Gen. DH T_{supply} = 55 - 75 °C	5th Gen. DH T_{Supply} = 5 - 35 °C	District cooling
☒	☐	☐	☐	☐

Demand types of thermal grid

Heating only No cooling	Heating dominated Heating >> Cooling	Both heating and cooling Heating and cooling demand in the same order	Cooling dominated Cooling >> Heating	Cooling only No heating
☒	☐	☐	☐	☐

Heat supply of thermal grid

Space heating only	Space heating and domestic hot water
☒	☐

5) Evaluation Framework

Importance of DSM

DSM is a must-have	**DSM is nice-to-have**
☒	☐

Purpose of DSM measure

Please specify why DSM measures are taken in the thermal grid? peak shaving
Which benefit is intended and who benefits from DSM measure? avoid the morning peak (very large) to avoid use of heat only boiler

How is the DSM measure implemented?

Communication is the dominant strategy to activate demand response	**Collective measure** to save energy and improve grid temperatures; e.g. provide smart home technology	**Tariff structure** measures to activate demand response, such as day-night rate, capacity rate, water volume rate	**H/C as service** Grid operator uses control strategies to deliver thermal comfort
☐	☐	☐	☐

Involvement of customers and end users

Explicit involvement limited/indirect involvement of the customers (i.e. acceptance of participation in the DSM initiative)	**Implicit involvement** requires from the customers direct reaction to the sent activation signal (e.g. price, CO2 emissions)	**Mix involvement** Building operator/owner as implicit and occupants/tenants as explicit involvement
☐	☐	☐

System boundary and time scale

Building Focus on building performance	**Thermal grid** Focus on grid performance	**Building + thermal grid** Focus on building-grid interaction
☐	☒	☐
Daily	**Weekly**	**Seasonal**
☒	☐	☐

6) Detailed Information

General description of the project

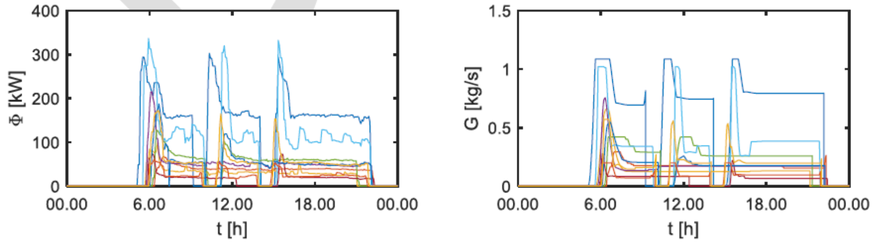
Suggested content: background/location/main objectives of the project / project organisation / budget and schedule, etc. / general description of the system

The Turin district heating is the largest in Italy. The district heating network is characterized by 1) a transport network, which is the main pipeline connecting the plants to the various areas of the town and 2) 182 distribution networks, connecting the transport network to the buildings. One of the 182 distribution networks is adopted for the test. The thermal demand is characterized by a significant peak in the morning. This is due to the fact that heating systems are generally switched off during the night. In the morning when these are switched on, the thermal load dramatically increases, due to the thermal masses that during the night cool down (e.g. water in distribution network, heat exchangers, buildings). The goal of the analysis is to find the best anticipation of the switching on time for a building in order to achieve the best peak shaving. The best anticipation is found by using a genetic algorithm optimizer. The optimization is done considering the predicted thermal demand of each building, which is done by exploiting data gathered at the substations. (described in the next section)

Building and system description of the project

Suggested content: system concept and optimization / innovative components /description of measurement data or simulation results / software tools etc.

The Turin district heating system supplies heat to about 56 million m3 of buildings (corresponding to about 6500 substations). The distribution network considered supply about 100 buildings.
Only a fraction of the buildings is considered for demand response. Therefore the load shifting is applied only to a fraction of buildings connected. The assignment of the anticipation time to the various buildings can be done using the remote control system. This has been used in the experimental tests to directly manage the scheduling of buildings. The maximum allowed anticipation was set to 20 min, in order to limit the effects on the indoor temperatures. The measured quantities in the buildings are: the mass flow rate at the primary side of the heat exchanger, the temperature at the inlet section of the primary side, temperature at the outlet section of the primary side, the temperature at the inlet section of the secondary side, the temperature at the outlet section of the secondary side, the environmental temperature. The figure shows the evolution of data gathered in various buildings in the network of the Turin system (mass flow rates and thermal power). Most of the heating systems are switched off during the night and switched on between 5 a.m. and 6 a.m. When a system is switched on, the mass flow rate and, consequently, the thermal profile present a peak.



Energy supply – scheme of the heat supply system

Suggested content: description of the heat supply system (including strategies for the transformation of district heating system - especially for existing district heating systems)

Heat is generated in two large cogeneration plants (located in the north and the south of the city) and various heat-only boilers. Four large storage systems are also installed; these allow one increasing the heat fraction produced through cogeneration. Water supply temperature is constant at about 120°C while the return temperature is between 70 °C and 50 °C. Demand response is adopted to further reduce the fraction of heat produced by heat only boilers.

Flexibility and demand response – scheme and control strategy of the system:

Load shifted by demand response	-	kWh
Peak load before usage of demand response	8	MW
Peak load after usage of demand response	7.6	MW

Suggested content: Scheme of data collection and handling

The goal of the analysis is to shave the thermal peaks due to the switching off of the heating systems in buildings. In order to avoid the adoption of a heat only boiler, the demand response is adopted. For this reason, an optimizer is built to manage the changes in schedules of heating systems installed in the buildings, specifically to achieve the optimal peak shaving. The model allows one evaluating the best rescheduling for the heating systems of the building installed in a network. The load shifting is done by adopting an anticipation in the switching on time. Delays are not considered in order to not produce discomfort indoor conditions. The optimal rescheduling is performed by means of an optimization approach, based on the demand forecast. The demand forecast is done by exploiting data collected at the thermal substation. The goal of the optimizer is to flatten the total thermal load as much as possible. A genetic algorithm that includes a network simulation model (to take into account the thermal inertia, losses and time delay phenomena) was developed to reach this aim.

Description of the business model

Suggested content: energy saving potential / cost saving potentials (investment and operating cost) etc.

Still has to be studied..

Description of the collaboration model and barriers

Suggested content: drivers for demand management, actors involved, applied models (objectives + incentives), barriers and limitations: human aspects, e.g. heating practices, night/weekend set-back routine; technology aspects, e.g. equipment, control; business aspects; legal framework

No collaboration

Results of the project

Suggested content: energy saving potential / cost saving potentials (investment and operating cost) /CO2 Reduction / integration of renewable sources etc.

The effects of the load management in the overall demand peak are analyzed. Experimental results shows that a non-negligible peak reduction can be achieved: peak reduction of about 5%, when a fraction of buildings lower than 30% is considered for a maximum anticipation of 20 min. A simulation analysis has shown that when all the buildings are considered and the allowed anticipation reaches 60 min, the peak can be completely shaved (adopting anticipations larger than 40 min only in 15% of buildings). Results encourage in the adoption of demand response in DH networks for a better exploitation of the energy resources.

7) Additional information

Contents: district heating network

Land area for buildings served by heat distribution network	ca. 210,000 (in the distribution net considered)	m²
Trench length for heat distribution network	ca. 2500 (in the distribution net considered)	m
Heating capacity	-	kW
Heat annually supplied into the heat distribution network	about 10000 (in the distribution net considered)	MWh/a

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Heat annually delivered from the heat distribution network	-	MWh/a
Annual average supply temperature in the heat distribution network	120	°C
Annual average return temperature in the heat distribution network	60	°C
Heat generation based on renewable sources	0	MWh/a
Share of renewable sources	0	%

Contents: description of energy storage system

Energy storage type:	-
Storage size (capacity):	-
Term of flexibility:	-
Storage temperature (thermal energy storage)	-

Contents: simulation study

Simulation software used	**Matlab (software developed by the university)**

Contents: buildings

Construction year period	-	
Number of buildings connected	About 30 considered in the analysis	
Total heated floor area in buildings connected	-	m²
Number of inhabitants living in all buildings	-	
Total heating capacity of all buildings	-	kW

Further information and references on all case studies

Add a table with further information and references/publications to every case study.

Nr	Title and References/Further Information
1	**Peak shaving in Turin District Heating** • Guelpa, E., Marincioni, L., Deputato, S., Capone, M., Amelio, S., Pochettino, E., & Verda, V. (2019). Demand side management in district heating networks: A real application. Energy, 182, 433-442
2	**Data-driven automated DSM technology** • Presentation: http://aee-intec.at/download/DataDrivenLM_Final_Presentation_2022-07.pdf • General project information: https://projekte.ffg.at/projekt/3205634 • Project website: URL. • Final project report "DataDrivenLM": URL.
3	**100% renewable District Heating** • Valentin Kaisermayer, Jakob Binder, Daniel Muschick, Günther Beck, Wolfgang Rosegger, Martin Horn, Markus Gölles, Joachim Kelz, Ingo Leusbrock. Smart control of interconnected district heating networks on the example of "100% Renewable District Heating Leibnitz". Smart Energy, Volume 6, 2022. (https://doi.org/10.1016/j.segy.2022.100069) • Intelligente Regelungen zum optimierten Betrieb von Wärmenetzen. Nachhaltige Technologien 2022-02, Page 9-11. (https://www.aee-intec.at/zeitung/nachhaltige_technologien-2-2022/8/) • Final project report "ThermaFLEX": Link • https://greenenergylab.at/projects/100-renewable-district-heating-leibnitz/
4	**Flexible energy system integration** • Conference Presentation: S. Demet, Flexible and synchronized local energy systems-concept development and demonstration – A case study of a rural district heating network in Austria: https://www.tugraz.at/fileadmin/user_upload/tugrazExternal/738639ca-39a0-4129-b0f0-38b384c12b57/files/pr/Session_E5/551_PR_Schmid.pdf • Conference Presentation: C. Fuchs, Electricity Market Participation of Flexible District Heating Networks in Austria – A case study of a rural district heating network in Austria: https://www.tugraz.at/fileadmin/user_upload/tugrazExternal/738639ca-39a0-4129-b0f0-38b384c12b57/files/pr/Session_A5/155_PR_Fuchs.pdf • Webinar: Flexi-Sync Webinar #7: Cost-optimal flexibility and flexibility price models: https://www.ivl.se/projektwebbar/flexi-sync/webinars/220510-webinar-7.html • Webinar: Flexi-Sync Webinar #6: Demo of district energy flexibility optimization tool: https://www.ivl.se/evenemang/2022-02-08-flexi-sync-webinar-6-demo-of-district-energy-flexibility-optimization-tool.html • Webinar: Flexi-Sync Webinar #5 Austrian rural district heating at the power market: https://www.ivl.se/evenemang/2021-10-20-flexi-sync-webinar-5-austrian-rural-district-heating-at-the-power-market.html • Webinar: Flexi-Sync webinar 2: Austrian and Swedish demos: https://www.ivl.se/projektwebbar/flexi-sync/webinars/2020-05-26--flexi-sync-webinar-2.html • T. C. Ernström, 'How to optimise district energy flexibility', Celsius Initiative: https://celsiuscity.eu/how-to-optimise-district-energy-flexibility • Deliverables: https://www.ivl.se/projektwebbar/flexi-sync/publications.html • Homepage: https://www.ivl.se/projektwebbar/flexi-sync.html – J. Peacock and J. Kensby, 'DELIVERABLE 4.1 - PLATFORM INTEGRATION' – Johansson and J. Kensby, 'DELIVERABLE 4.2 – DEMAND FLEXIBILITY CONNECTED THROUGH SMART HEAT GRID'

	– J. K. Utilifeed, 'DELIVERABLE 4.3 – MINIMUM VIABLE OPERATIONAL CO-OPTIMIZATION TESTED IN LIVE OPERATION' – J. K. Utilifeed, 'DELIVERABLE 4.4 – FEATURE COMPLETE OPERATIONAL CO-OPTIMIZATION'
5	**Smart energy in homes** • Project report "Smart Energi i Hjemmet": URL. • Nielsen, 2013, https://de.slideshare.net/slideshow/smart-energyhome-a-project-that-lives-by-data/18006257#3
6	**Substitution of conventional controllers** • Homepage: https://tu-dresden.de/ing/maschinenwesen/iet/gewv/forschung/forschungsprojekte/projekt-camper
7	**DSM in Danish single-family house** • Amato V., Hedegaard R.E., Knudsen M.D., Petersen S. Room-level load shifting of space heating in a single-family house – a field experiment (2022). In review at Energy and Buildings • Project website "PreHeat": URL.
8	**Geo-solar low-temperature DH network** • I. Best, J. Orozaliev, K. Vajen, M. Schurig, D. Schmidt, O. Reul, T. Ebert: Geosolare Wärmeversorgung für die Neubausiedlung „Zum Feldlager" in Kassel, 26. Symposium Thermische Solarenergie 20.-22. April 2016, Bad Staffelstein. • J. Orozaliev, I. Best, K. Vajen, D. Schmidt, M. Schurig, A.M. Kallert, O. Reul, J. Bennewitz, and P. Gerhold: Development of an Innovative Heat Supply Concept for a New Housing Area – A Case Study of IEA EBC Annex 64, CLIMA 2016 - proceedings of the 12th REHVA World Congress. • O. Reul; H. Räuschel; D. Schmidt; J. Orozaliev; P. Gerhold; J. Bennewitz: Coupling of borehole heat exchangers with solarthermal systems. Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul 2017. • O. Reul; H. Räuschel; D. Schmidt; J. Orozaliev; P. Gerhold; J. Bennewitz: Kopplung und Optimierung von Erdwärmesonden-Speichern mit solarthermischen Systemen. Fachsektionstage Geotechnik 2017/09 – 7. Symposium Umweltgeotechnik Abstract eingereicht – mündl. Vortrag. • Best I., Orozaliev J., Vajen K.: Central versus Semi-decentralized Solar District Heating for Low Heat Demand Density Housing Developments in Germany, Proc. ISES Solar World Congress, Abu Dhabi, UAE, 29.10.-02.11.2017 • Best I., Orozaliev J., Vajen K.: Low-temperature versus ultra-low-temperature solar district heating for low heat demand density housing developments in Germany, 3rd International Conference on Smart Energy Systems and 4th Generation District Heating, Copenhagen, Proc., DK, 12.09.-13.09.2017
9	**Digitizing DH supply infrastructure** • https://www.agfw.de/smartheat • https://www.iee.fraunhofer.de/de/projekte/suche/2019/smartheat.html
10	**DH networks within hybrid energy systems** • BMWK FKZ: FKZ 03EN3041 A bis F • https://www.agfw.de/forschung/hybridbot • Wett (2023), Master thesis: "Simulationsgestützte Analyse und Bewertung ausgewählter Versorgungsvarianten eines multivalenten Wärmenetzes unter Berücksichtigung der Sektorenkopplung in Neuburg an der Donau". https://publica-rest.fraunhofer.de/server/api/core/bitstreams/934c9c95-95f0-472d-915f-915bfc30e0e5/content

11	**Renewable energy integration in DH grid** • A. Kallert, D. Lottis, M. Shan, and D. Schmidt, ‘New experimental facility for innovative district heating systems—District LAB’, Energy Reports, vol. 7, pp. 62–69, Oct. 2021, doi: 10.1016/j.egyr.2021.09.039. • S. Hay, A. Kallert, D. Lottis, R. Ziegler, I. Weidlich, and S. Dollhopf, ‘Existing District Heating Networks in Context of German Climate Goals: Potentials for “UrbanTurn”’, in Conference Proceedings ISEC 2nd Sustainable Energy Concerence 2022, Congress Graz Austria, pp. 196–203. • A. Kallert and D. Lottis, ‘Praxisnahe Fernwärmeforschung im Quartiersmaßstab - Versuchs- und Experimentiereinrichtung District LAB’, bbr, no. 03–2022, pp. 24–29. • Fraunhofer IEE: https://www.iee.fraunhofer.de/de/presse-infothek/Presse-Medien/Pressemitteilungen/2021/UrbanTurn.html • AGFW: https://www.agfw.de/forschung/urbanAturn
12	**Flexible and innovative DH grid operation** • Dissertation: Mehmet Elci, Smarte und Dezentrale Solare Fernwärme, ISBN: 978-3-8396-1397-9, http://publica.fraunhofer.de/dokumente/N-515184.html • IEA SHC Task 52, Solar Heat and Energy Economics in Urban Environments, http://task52.iea-shc.org • Project report, http://publica.fraunhofer.de/documents/N-549554.html • Presentation on the “Berliner Energietage 2021”: https://www.energie.fraunhofer.de/content/dam/energie/de/documents/03_PDF_Messen-Veranstaltungen/dokumente_messen_2021/2021-04-21-BET_Innovative_Betriebsfuehrungsstrategien.pdf • Homepage: https://www.ise.fraunhofer.de/de/forschungsprojekte/enwisol.html
13	**Acceptance of fluctuating indoor temperatures** • Louise R.L. Christensen, Thea Hauge Broholt, Verena M. Barthelmes, Dolaana Khovalyg, Steffen Petersen. A mixed-methods case study on resident thermal comfort and attitude towards peak shifting of space heating. Energy and Buildings 276 (2022), 112501, https://doi.org/10.1016/j.enbuild.2022.112501. • Louise R.L. Christensen, Thea Hauge Broholt, Steffen Petersen. Are bedroom air temperatures affected by temperature boosts in adjacent rooms? 2022: CLIMA 2022 The 14th REHVA HVAC World Congress, Link. • Louise R.L. Christensen, Steffen Petersen. Mixed-methods case studies on residents’ acceptance of temperature fluctuations from model predictive control. Energy & Buildings, https://doi.org/10.1016/j.enbuild.2023.113405.
14	**Remote control of radiator thermostats** • https://cordis.europa.eu/project/id/768619/reporting • https://cordis.europa.eu/project/id/768619/results • EU Project website „RESPOND“: URL.
15	**Temperature optimization for LTDH** • EU Project website: URL. • Project website TEMPO: URL. • Demonstration site in Brescia: URL. • T Van Oevelen, L Scapino, J Al Koussa, D Vanhoudt. A case study on using district heating network flexibility for thermal load shifting. Energy Reports. 7, 4, 2021, 1-8, https://doi.org/10.1016/j.egyr.2021.09.061. • T Van Oevelen, T Neven, A Brès, R-R Schmidt, D Vanhoudt. Testing and evaluation of a smart controller for reducing peak loads and return temperatures in district heating networks. Smart Energy 10, 100-105. • D Vanhoudt. Digitalisation in district heating networks: the TEMPO-project. European Energy Innovation, Autumn 2019

	• D Vanhoudt, J Desmedt. New Management Systems for DHC Networks, HOT | COOL, Spring 2019.
16	**Energy and cost savings in office building** • Benakopoulos et al. (2022): Energy and cost savings with continuous low temperature heating versus intermittent heating of an office building with district heating. https://doi.org/10.1016/j.energy.2022.124071
17	**DSM in smart homes: living-lab experiments** • Christensen et al. (2020): Demand side management of heat in smart homes: Living-lab experiments https://doi.org/10.1016/j.energy.2020.116993 • Project website "EnergyLab Nordhavn": URL.
18	**Energy flexibility of low-energy buildings** • Foteinaki et al. (2020) - Evaluation of energy flexibility of low-energy residential buildings connected to district heating. https://doi.org/10.1016/j.enbuild.2020.109804 • Project website "EnergyLab Nordhavn": URL.
19	**Buildings as thermal energy storage in DH grids** • Kensby et al. (2015) - Potential of residential buildings as thermal energy storage in district heating systems – Results from a pilot test. http://dx.doi.org/10.1016/j.apenergy.2014.07.026
20	**Thermal conditions and flexibility potential** • Marszal-Pomianowska et al. (2021) - Thermal conditions in households and assessment of building's flexibility. https://doi.org/10.1016/j.buildenv.2021.108353 • Project website "INTERHUB": URL.
21	**Occupant fade-out from demand response** • Marszal-Pomianowska et al. (2023) - Do the customers remember? The fade-out effect from the demand response applied in the district heating system in Denmark. https://doi.org/10.1088/1742-6596/2600/13/132003
22	**Application of the STORM controller in Rottne, Sweden** • EU Project website "Self-organising Thermal Operational Resource Management": URL. • Case study description: URL. • T Van Oevelen, D Vanhoudt, C Johansson, E Smulders. Testing and performance evaluation of the STORM controller in two demonstration sites. Energy 197, 2020 https://doi.org/10.1016/j.energy.2020.117177
23	**Optimal dispatch of heat in DH grid** • Boghetti, R and Kämpf, J H. "Verification of an Open-Source Python Library for the Simulation of District Heating Networks with Complex Topologies". Energy 290 (March 2024): 130169. https://doi.org/10.1016/j.energy.2023.130169

24	**Load shifting in buildings connected to DH** • Sweetnam et al. (2019) – Domestic demand-side response on district heating networks. https://doi.org/10.1080/09613218.2018.1426314
25	**Perceptions of indoor climate during DR** • Hagejärd et al. (2021) - My apartment is cold! Household perceptions of indoor climate and demand-side-management in Sweden. https://doi.org/10.1016/j.erss.2021.101948
26	**DR in Student Apartment Buildings** • Ala-Kotila et al. (2020) - Demand Response in District Heating Market - Results of the Field Tests in Student Apartment Buildings. https://doi.org/10.3390/smartcities3020009
27	**Thermostats overrides during DR events** • Sarran et al. (2021) - A data-driven study of thermostat overrides during demand response events. https://doi.org/10.1016/j.enpol.2021.112290
28	**DR events in a university building** • Mishra et al. (2019) – Demand response events in district heating: Results from field tests in a university building. https://doi.org/10.1016/j.scs.2019.101481
29	**Smart grid flexibility in single-family houses** • Wittchen et al. (2020) - Analyses of thermal storage capacity and smart grid flexibility in Danish single-family houses. BuildSim-Nordic 2020

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