ANNEX 84

EBC
Energy in Building and Communities Programme

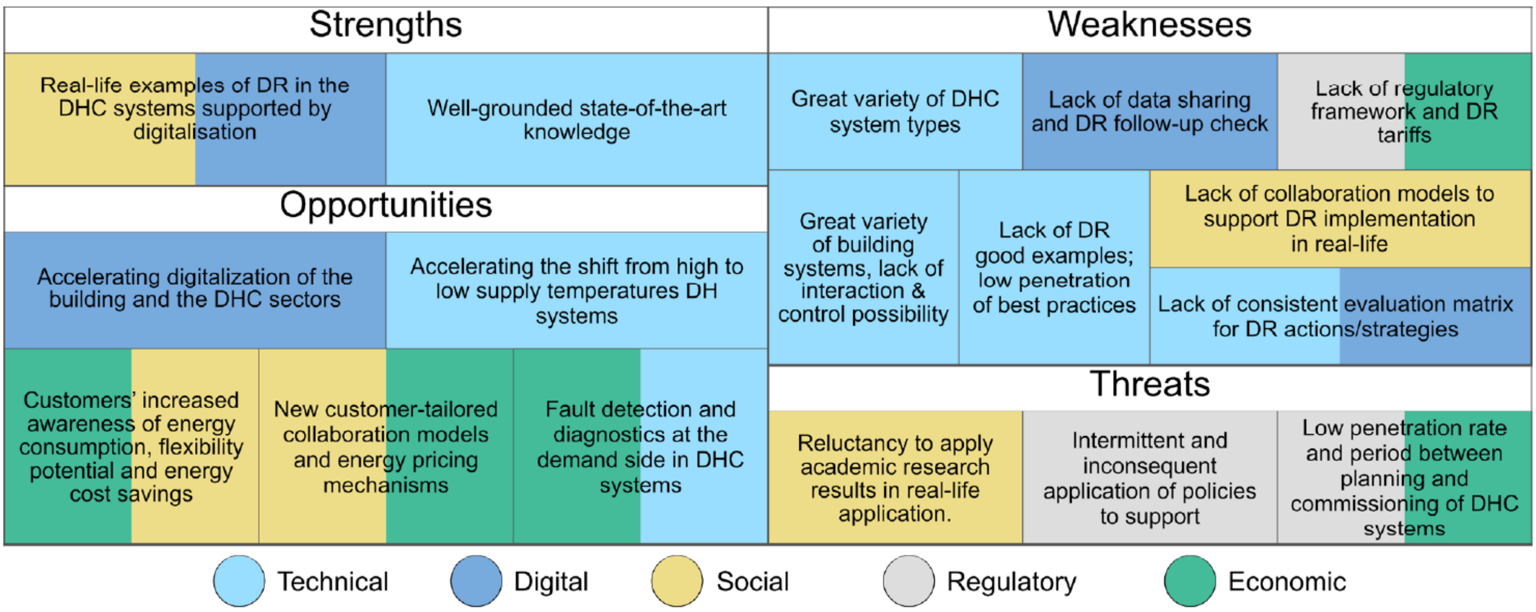
International Energy Agency

Demand management of buildings in thermal networks: Collaboration models – overview of involved actors, existing practices, potential barriers and limitations, recommendations (Annex 84, Subtask A)

Energy in Buildings and Communities Technology Collaboration Programme

April 2025

Demand Response in District Heating and Cooling Systems



ANNEX 84

EBC

Energy in Building and Communities Programme

International Energy Agency

Demand management of buildings in thermal networks: Collaboration models – overview of involved actors, existing practices, potential barriers and limitations, and recommendations (Annex 84, Subtask A)

Energy in Buildings and Communities Technology Collaboration Programme

April 2025

Authors

Anna Marszal-Pomianowska, Aalborg University, Denmark (ajm@build.aau.dk)
Christopher Graf, Fraunhofer, IEE, Germany (christopher.graf@iee.fraunhofer.de)
Markus Schaffer, Aalborg University, Denmark (msc@build.aau.dk)
Toke Haunstrup Bach Christensen, Aalborg University, Denmark (thc@build.aau.dk)

Contributing Authors

Benedetto Nastasi, Sapienza University of Rome, Italy (benedetto.nastasi@uniroma1.it)
Clemens Felsmann, Engineering and Heat Supply, TU Dresden (clemens.felsmann@tu-dresden.de)
Emilia Motoasca, DAIKIN EUROPE (motoasca.e@daikineurope.com)
Elisa Guelpa, Department of Energy, Politecnico di Torino, Italy (elisa.guelpa@polito.it)
Hicham Johra, SINTEF Community, Norway (hicham.johra@sintef.no)
Ingo Leusbrock, AEE Intec, Austria (i.leusbrock@aee.at)
Joaquim Romaní Picas, IREC, Spain (jromani@irec.cat)
Michele Tunzi, Technical University of Denmark DTU (mictun@dtu.dk)
Per Heiselberg, Aalborg University, Denmark (pkh@build.aau.dk)
Vittorio Verda, Department of Energy, Politecnico di Torino, Italy (vittorio.verda@polito.it)

Published by Aalborg University, Fredrik Bajers Vej 7K 9220 Aalborg East Denmark

ISBN: 978-87-94561-41-9

DOI:10.54337/aau978-87-94561-41-9

Participating countries in the EBC TCP: Australia, Austria, Belgium, Brazil, Canada, P.R. China, Czech Republic, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Republic of Korea, the Netherlands, New Zealand, Norway, Portugal, Singapore, Spain, Sweden, Switzerland, Turkey, United Kingdom and the United States of America.

Additional copies of this report may be obtained from: EBC Executive Committee Support Services Unit (ESSU), C/o AECOM Ltd, The Colmore Building, Colmore Circus Queensway, Birmingham B4 6AT, United Kingdom
www.iea-ebc.org
essu@iea-ebc.org

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 CO2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO2 Equivalent Emissions for Building Construction (*)

Annex 58: Reliable Building Energy Performance 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

The integration of buildings into the energy system introduces both opportunities and challenges for district heating and cooling (DHC) utilities. While demand response (DR) strategies and new pricing models can improve efficiency, barriers such as split incentives, regulatory constraints, and information asymmetries hinder their implementation. Additionally, knowledge gaps exist regarding cost-effective deployment and stakeholder engagement.

Research and interviews presented in this deliverable indicate that households generally support DR schemes as long as comfort and control are maintained. A lack of transparency in DR programs can lead to frustration, emphasising the need for better communication. While many DHC providers acknowledge the potential of DR, they focus more on supply-side measures due to regulatory and knowledge barriers.

Key Recommendations combining both ends of the DR value chain (i.e. DHC customers and DHC utilities) for successful implementation of the DR programs, leading to a more sustainable and energy efficient DHC sector are:
Improve Communication: Ensure clear information about DR programs to enhance participation and user satisfaction.
Development of Fair Pricing Models: Gradually introduce variable tariffs with protections for low-income households and support for energy-efficient renovations.
Stronger promotion of Knowledge Sharing: Facilitate collaboration and best practice exchanges among DHC utilities.
Addressing Regulatory Barriers: Advocate for policy adjustments to enable demand-side flexibility.
Incentivise Customer Participation: Use financial, environmental, and energy-saving incentives to engage consumers effectively.

Table of content

Preface 5

Summary 8

1. Introduction 11

1.1 General Context 11

1.2 Introduction to Subtask A 14

2. End-users’ engagement in DR programmes 17

2.1 Engagement of the residents in DR programmes (literature review) 17
- 2.1.1 Meaningfulness 19
- 2.1.2 Competences and Know-how 19
- 2.1.3 Technological design 20
- 2.1.4 Conclusions 20

2.2 Demand response experiment with district heating customers living in apartment units (Aarhus, Denmark) 21
- 2.2.1 Quantitative results 22
- 2.2.2 End-users feedback on DR programmes 23
- 2.2.3 Interviews with selected households 23

3. District heating and cooling professionals' perspective towards DR programmes 26

3.1 Description of the questionnaire with DHC professionals 27

3.2 Results 27
- 3.2.1 Load management: challenges and experience 28
- 3.2.2 Relevance of the electricity market 28
- 3.2.3 Familiarity with DR concept and willingness for upgrades 28
- 3.2.4 DR control limitations: data privacy, thermal comfort, legal responsibilities 29
- 3.2.5 Benefits and barriers from DR and their importance 30
- 3.2.6 Incentives for customers to participate in DR programmes 31
- 3.2.7 Relevance of DR programmes to future developments of DHC systems and importance of policy measures to enable DR programmes 31

3.3 Conclusions 32

4. Collaboration models and existing tariffs 33

4.1 Literature review 33

4.2 Experience from Annex 84 case studies collected in subtask D. 33
- 4.2.1 Case study 2: Data-driven automated DSM technology (“DataDrivenLM” by AEE Intec) 34
- 4.2.2 Case study 9: Digitizing DH supply infrastructure (Project “Smart Heat” by Fraunhofer IEE, Germany) 35
- 4.2.3 Case study 25: Perceptions of indoor climate during DR (by Chalmers University, Sweden) 35
- 4.2.4 Case study 28: DR events in a university building (by Aalto University, Finland) 35

5. **Conclusions and recommendations** 37

6. **References** 39

7. **Appendix 1** 42

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 [1]. 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 maintaining stable operation and cost-optimal performance.

Thermal energy storages (TES) 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).

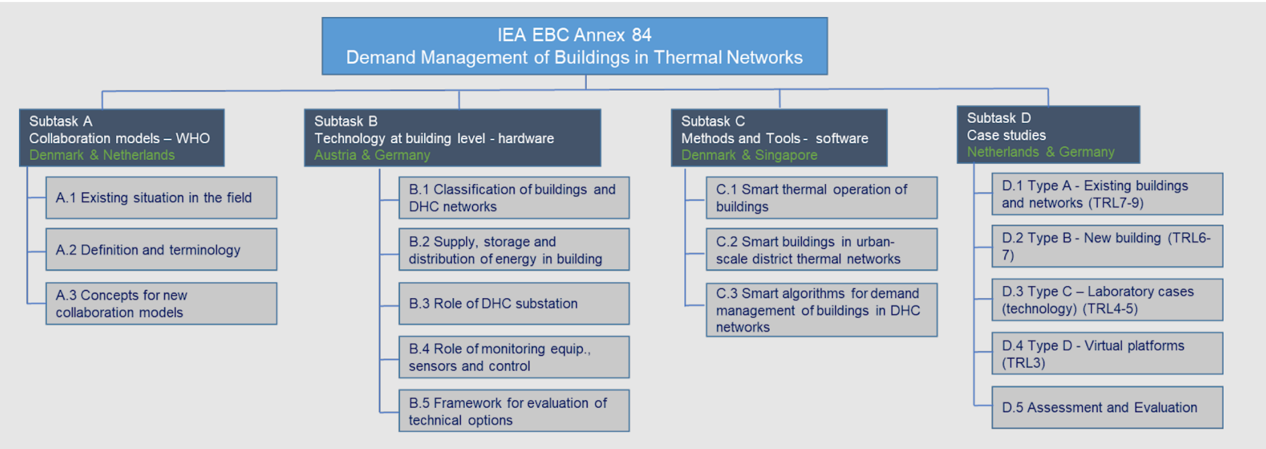


Figure 1: Structure of the IEA EBC Annex 84

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 domestic hot water (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.

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

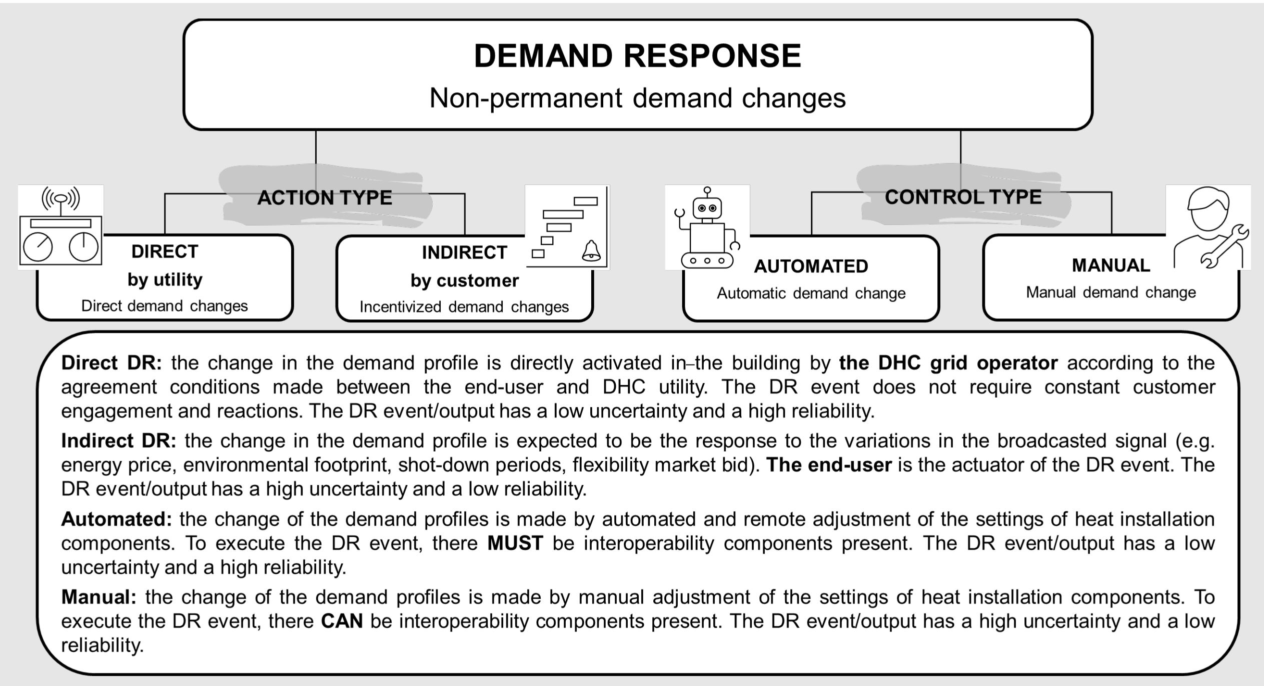


Figure 2: Terminology applied in IEA EBC Annex 84

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 or 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 presents the visualisation of the four DR types.

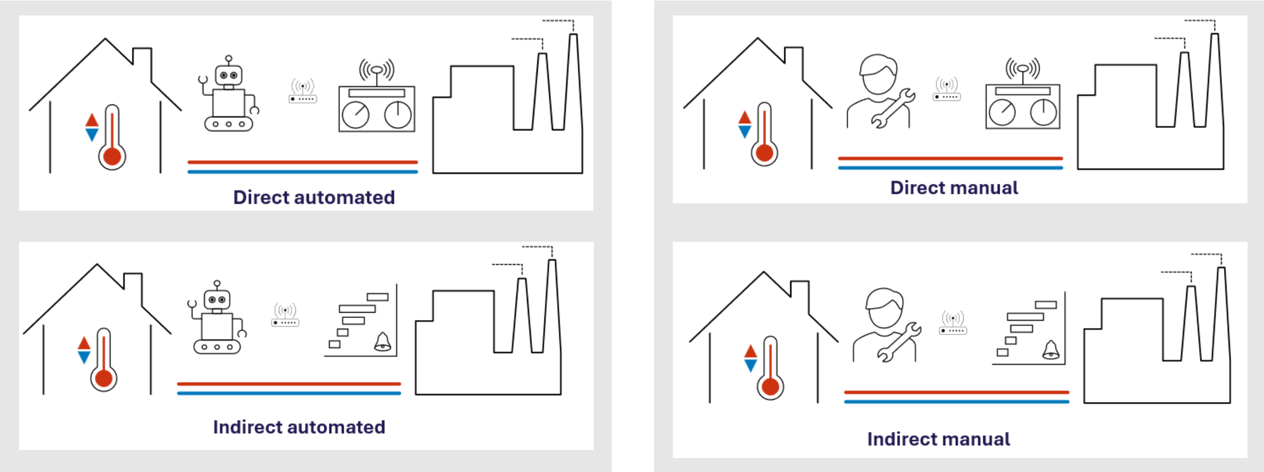


Figure 3. Illustration of the four types of DR according to Annex 84

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 A

The integration of buildings in the energy system brings new opportunities but also new complexities for energy service companies, such as district heating and cooling (DHC) utilities, regarding addressing customers' and stakeholders' needs [21]. The adaptation of new communication and collaboration models is often confounded by significant split incentive barriers and information asymmetries between stakeholders (i.e. customers and utility operators). There is also a significant knowledge gap on the aspects of cost-effective implementation and increasing customer and stakeholder involvement.

There exist two opposing approaches to involve customers in the activation of demand response (DR) assets [22]. The end-users can either be active participants by adjusting the timing of energy use according to the received signal (price, CO_2 emissions, etc.) or be passive participants, where the change/adjustment of energy use is executed by automatic system remotely controlled by DHC system operators.

Knowledge of energy demand is pertinent when integrating buildings in DHC systems. For end-users, energy is mostly invisible and consumed in the course of performing practices in everyday life. Experiments with the electric grid have shown that customers are to some extent flexible in their electricity consuming practices and react to e.g. time-of-use pricing. Heating/cooling demand response is very different and relates to questions of thermal comfort and control of space heating and cooling, as well as to patterns of domestic hot water (DHW) use. Knowledge on how end-users can be engaged is crucial for improving heating/cooling control and demand response and its potential for minimizing bottlenecks in the DHC system. Moreover, these insights are significant for developing relevant new services and products.

The development of DHC systems varies significantly across the globe, adding further complexity [2]. The establishment period of DHC systems differs from one country to another. Older thermal networks were designed solely for heating or cooling, whereas newer collective thermal networks provide both. The age of DHC networks often determines the heat/cold carriers and operating temperatures. Table 1 presents the characteristics of different generations of DHC systems as proposed in [2, 23-25].

Table 1 Features of the DH and DC system generations developed using information from [2,23,24,30-32].

	Period	**heat/cold carrier**	**Supply Temp.(ºC)**	**Extra features**
DH system				
First generation (1GDH)	> 1880	steam	>200	concrete ducts
Second generation (2GDH)	> 1930	pressurised water	> 100	in-suit elements
Third generation (3GDH)	> 1980	pressurised water	< 100	prefabricated elements
Fourth generation (4GDH)	> 2008	pressurised water	< 70	2-way DH
Fifth generation or Cold District Heating (5GDH&C or CDH)	> 2010	water	< 25	Combined heating and cooling; individual heat pumps or boosters
DC system				
First generation (1GDC)	> 1890	refrigerant or brine	-4 to +7	centralised chillers
Second generation (2GDC)	> 1960	cold water	2 to 8	large mechanical chillers
Third generation (3GDC)	> 1990	cold water	0.5 to 8	diversified cooling technologies and cooling sources; storage; coupling to DH
Fourth generation (4GDC)	> 2020	multi-source	4 to 24	Centralised and decentralised solutions; integration with Electricity, DH, and gas systems

Moreover, each DHC system has a unique local signature, influenced by factors such as the geographical distribution of its components, technical characteristics, and the mix of buildings with various heating/cooling installations and consumer demands. Recent reports on DHC system digitalisation [26,27] highlight the rapid evolution of technologies, offering new management solutions that enhance performance and flexibility.

DC systems are not yet as well established as DH systems. However, they have the potential to play a major role in reducing environmental impacts in a cost-efficient manner. Compared to individual solutions, DC systems offer lower environmental footprints, higher energy efficiency, improved flexibility for electricity grids, cross-sector synergies, and mitigation of the urban heat island effect [24, 28]. Currently, they primarily provide space cooling for commercial buildings in major urban areas across Europe, the Middle East, Asia, and Canada [29].

Therefore, up-to-date knowledge of DHC utility operators' approaches to utilizing buildings as decentralized storage assets is crucial for successfully integrating buildings into the daily operation of DHC networks.

Therefore, within the scope of subtask A, which aimed to study the motivations, challenges, and constraints faced by key actors involved in demand response (DR) and to analyse current collaboration models and to offer recommendations for the commercial implementation of the DR concept by DHC utilities, the following activities were conducted and are described in this deliverable:

– Customers' engagement in DR programs and their perspectives on the DR concept, based on findings from the RESPOND project.
– Survey of DHC professionals on their views regarding the integration of buildings into the daily operation of DHC networks.
– Analysis of existing tariffs and collaboration models, including a literature review and case study analysis.

2. End-users’ engagement in DR programmes

The Horizon 2020 Integrated Demand Response Solution Towards Energy Positive Neighbourhoods (RESPOND) project (grant agreement No 768619) [33] took a very ambitious challenge of investigating how to ensure user engagement in demand response (DR) strategies. The RESPOND project aimed to fill the gap between the ongoing DR initiatives often focusing on the biggest customers with high energy demand and households with small demand. The objective of RESPOND was to design, implement and test DR solutions for small dwellings which, acting like a large group, can change their heating consumption load during a certain period to decrease the peak in the usage curve, without affecting users' comfort while benefiting from cheaper and cleaner energy. Therefore, the target citizens in RESPOND were the end-users living in apartments in multi-story buildings. The RESPOND project leveraged a holistic approach to the demand response concept working with societal challenges from a social practice perspective, which emphasizes the role of meaning, competences, materiality and technical design in energy-consuming practices and in changing these through DR programmes, and technical challenges such as interoperability between smart home devices and automation systems, reliable energy data analytics and real-time forecasting to foster execution of DR strategies.

The methodologies applied in the project were also very comprehensive including a thorough theoretical study of how to achieve the long-lasting engagement of the end-users in the DR programmes followed by a 10-week-long experimental investigation of different DR control strategies in social housing buildings (in the Danish pilot) and finished with in-person interviews with end-users to collect their feedback on the conducted experiment and potential improvements of the DR strategies.

In the RESPOND project, residents were considered a key demand-side variable capable of enabling systemic demand response interventions thus speeding up the process towards carbon-neutral societies. This scope and the mixed methods applied to design, demonstrate and validate the DR concept are unique among known real-life DR cases described in the Annex 84 subtask D deliverable [ref]. Therefore, the knowledge and experience collected during the RESPOND provide the fundaments for Annex 84 recommendations for the successful engagement of residents in the demand response programmes in the district heating sector.

The following sections are developed using the results collected in eight deliverables developed during RESPOND and primary in WP3 User Engagement Process and WP6 Validation and replication of project results: D.3.1 *Criteria and framework for participant recruitment* [34], D3.2 U*ser engagement strategy* [35], D.3.3 *Findings and recommendations from focus groups on user context* [36], D3.4 *Personal energy performance assistant design* [37], D6.2 *Validation analysis of operation scenarios* [38], D6.3 *User engagement assessment* [39], D6.4 *RESPOND replication plan* [40], and D6.5 *Best practices and lessons learnt* [41].

2.1 Engagement of the residents in DR programmes (literature review)

This section is developed using the content of the RESPOND project's deliverable D3.2, which is the *User engagement strategy* [35].

Demand Response (DR) solutions, as components of smart energy systems, have often been perceived and implemented as primarily technical or infrastructural initiatives. However, it is crucial to integrate knowledge about customers/residents and their everyday practices into these solutions. For DR solutions to be successful and functional in practice, two key criteria must be met:

– **Meaningfulness**: The solution must resonate with people and align with their values or motivations.
– **Practicality**: The solution should be easy for users to engage with, ensuring it is both functional and user-friendly.

The practicality criterion can be further broken down into two essential aspects that shape the usability of a DR solution: the technological design and the users' competences or know-how for operating the DR solutions. These two criteria are closely interconnected. For instance, how people ascribe meaning to a certain technology —such as DR solutions—depends partially on their technical proficiency and familiarity with it. Similarly, what users find meaningful is shaped by a range of socio-economic factors and individual, culturally influenced preferences. For example, some individuals might find DR solutions meaningful because they offer financial benefits, while others may engage with them for their environmental benefits.

Demand Response (DR) strategies often adopt an approach termed by Shove [42] as the ABC model, where ABC stands for Attitude, Behaviour, and Choice. Strengers [43] extended this model by adding a "D" for Demand, forming the ABCD model. This framework suggests that demand-side solutions should be grounded in an analysis of customers' attitudes, values, choices, opinions, barriers, and drivers. The underlying assumption in ABCD model is that demand can be influenced by mapping and understanding the ABCD of end-users, and then applying appropriate strategies. This model operates on the premise that people's behaviour is determined by their attitudes (e.g., environmental values) and that people's decisions are conscious and deliberate, informed by their knowledge, such as the environmental impact of certain behaviours.

However, the ABCD approach is criticised by social science research for overlooking the dynamic and evolving nature of practices. Rather than viewing energy demand as a result of rational, individual choices shaped by attitudes, the practice theory approach recommends energy consumption as the outcome of collective and habitual practices. Practices are shared activities that individuals perform, influenced by various elements, including technical factors like the design of energy-consuming products.

Strengers also challenges the assumption that energy consumers (e.g. occupants) are perceived as "micro resource managers" who make rational, daily decisions about their energy use based on information given by, for instance, smart meter feedback. This perspective fails to account for two key realities:

– Energy consumption emerges from daily practices such as cooking, cleaning, and showering, which are driven by need of comfort and convenience rather than energy efficiency.
– People's energy-related habits are shaped by a complex interplay of factors, including materials (e.g., appliances), meanings, and competences, rather than by deliberate decision-making.

These observations form the foundation for the subsequent analysis and the development of the RESPOND user engagement strategy:

– Energy consumption results from everyday practices such as household chores and personal care.
– People generally do not focus on energy consumption itself; it is a outcome of their daily routines.
– These practices are shaped by a combination of elements, including materials (technologies and products), meanings (cultural and personal significance), and competences (skills and know-how).

- Simply providing information is insufficient to change practices. Effective strategies must address the meanings and competences that underpin these practices and influence energy consumption.

2.1.1 Meaningfulness

RESPOND project has come up with following key findings for how to make the DR programmes meaningful for the DH customers:

- Variable pricing (dynamic tariffs) can be an effective incentive for shifting energy consumption, but the tariff scheme must be simple, provide timely notifications of price changes, and include large price differences to motivate behaviour change.
- When asked, customers rate environmental concerns (e.g.”saving the environment”) higher than social influence in clarifying their behaviour and domestic energy consumption, however …
- Research shows that normative social influence, the tendency to align with perceived societal norms, has a higher impact on energy-related behaviour than personal beliefs or stated values.
- Policies, campaigns, and initiatives should prioritize influencing shared practices over targeting individual beliefs.
- Energy feedback increases households’ awareness of their energy use but does not necessarily translate into changes in their routines or practices.
- Domestic energy consumption is the result of routinized practices.
- Designing interventions to change practices and thereby shift energy consumption requires identifying and addressing all elements that shape practices: materials, meanings, and competences.
- Promoting new practices should be supported through hands-on demonstrations of new (e.g., more energy-efficient or time-shifted) ways to perform everyday activities.
- Demand Response (DR) programmes must ensure that customers’ thermal comfort is not compromised, as this could compromise their acceptance of DR programmes.
- Incorporating information about the indoor environment and recommendations for improvement in DR solutions can make these programs meaningful and encourage the engagement of people.

2.1.2 Competences and Know-how

- Competences (skills) play a crucial role in shaping practices, influencing energy consumption, and effectively utilizing feedback and DR programmes.
- Competences (know-how) are transferable between practices. Therefore, DR solutions should leverage skills familiar from other practices, e.g. use of mobile applications for DR strategies, as most people are accustomed to this solution.
- Competences (e.g. use of smartphones and mobile apps) vary among individuals, which must be accounted for in the design of DR solutions.
- Within households, competences can differ among occupants, leading to variations in how easily individuals adopt DR solutions and recommendations. These differences may create imbalances, where some household members become more adept at managing these systems, causing conflicts within the household about who is controlling what (and how).
- To develop the necessary competences for using DR solutions and recommendations, hands-on demonstrations are recommended. These demonstrations should clearly show users how to interact with new technologies.
- DR solutions should offer easy-to-understand, specific, timely, and household-tailored recommendations to guide occupants in adjusting their practices to time-shift energy consumption.
- Community-based approaches can foster long-term engagement of customers in DR programmes.
- While feedback data helps users gain insights into their energy use patterns, it does not necessarily result in practice changes. Tailored recommendations on how to modify practices may be helpful.

2.1.3 Technological design

- Technology is embedded in social practices and daily routines, and it has the potential to alter these routines.
- While technology is designed with a specific purpose in mind, its interpretation and use remain flexible and open to individual adaptation.
- Educational and social background impacts the effect of DR management technology.
- Providing historical feedback can encourage long-term user engagement.
- Frequent feedback provides the best results. However, it is important to include an option for adjusting the frequency of feedback
- Comparing energy usage with that of neighbours yields good results.
- DR technologies should be integrated with existing systems and technologies.
- Everyday practices involving automation (e.g. remote control of the setpoints) are typically easier to time-shift.

2.1.4 Conclusions

Based on the previous sections and the social practice theory, briefly mentioned in the introduction to section 1.1 and further elaborated in deliverable D3.2 *User engagement strategy* [35], the RESPOND project proposed the following strategy for end-user engagement with DR programmes:

Inclusive Design of Digital Solutions for End-Users

Well-designed and functional digital solutions with user-friendly interfaces are key to ensuring the successful and long-term engagement of customers in DR programmes. Incorporating focus groups and mock-ups during the development process is recommended to achieve this goal.

End-User Control for Overriding Settings

Customers must always have the option to override automated Demand Response settings. Providing this level of control is essential for ensuring user satisfaction and allowing them to address any thermal discomfort or inconvenience caused by automation. The absence of such a feature may undermine the success of the DR programmes.

Tailored DR Action Recommendations for End-Users

DR technological solutions should offer timely and personalized recommendations on when and how to shift energy consumption. These recommendations are critical for maintaining user engagement and should be adjustable in frequency to meet individual preferences.

User-Friendly and Simple Data Presentation

A clear and simple graphical representation data is crucial for helping users understand the information being shared.

Promoting Engagement Through End-User Competition

Displaying individual customer performance in comparison to others in the neighbourhood can sustain user interest in DR programmes. This approach leverages the dynamics of normative social influence and competition to drive engagement. However, all implementations must strictly align with GDPR to ensure data privacy.

Workshops and Meetings for End-Users

In-person engagement, such as workshops and meetings, provides an effective way to introduce DR programmes and familiarize users with technological solutions. These interactions help to enhance user engagement and disseminate knowledge about energy consumption practices, including time-shifting strategies.

End-users inclusive design of digital solutions

Well-designed and operating digital solutions with user-friendly interfaces and functionalities is a key to successful and long-term engagement of customers. The use of focus groups and mock-ups in the development process is recommended.

2.2 Demand response experiment with district heating customers living in apartment units (Aarhus, Denmark)

This section is developed using the content of the RESPOND project's deliverable D6.2, which is the *Validation analysis of operation scenarios* [38].

In RESPOND project, the main drivers to use the DR strategies among the DH customers were the capacity issues and high peaks in various areas (e.g. residential area expansion) in the morning due to people showering nearly simultaneously and adding this consumption to existing space heating demand. By application of DR strategies, the DH supplier would like to eliminate the investment in upgrading the pipes in the ground and the cost of activation of peak boilers, which might lead to higher heat prices for the customers.

The DR experiment took place for 10 weeks in February and March 2020 in 10 three-storey apartments owned by the social housing association in Aarhus, see Figure 4. All units were occupied by two adults and between zero and three children, who lived there for over one year.

Figure 4 Picture of the case study building (left). Location of the radiators (red circle), temperature sensor (green circle), fireplace (purple circle), and DH substation (yellow) (right). [34-41]

The DR control strategies included only the direct automated types, where the thermostatic valve settings were changed remotely without the end-user actions. The end-users could always override the DR event settings. The characteristics of the DR strategies and their schedules are presented in Figure 5. The end-users were not introduced to the DR events' characteristics or the schedule. DR events were tested in five working days, weekends were excluded from DR events. It should be noted that the DR events were not activated by the DH utility but by the project participants.

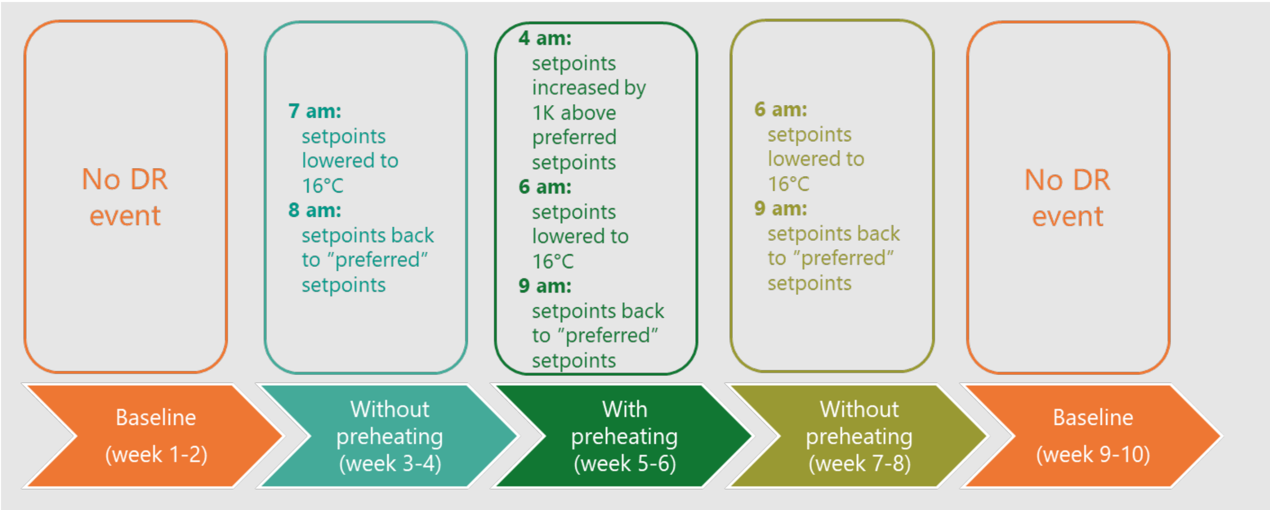


Figure 5. Overview of the DR strategies during the 10-week experiments and their characteristics.

The thermostat set-point is 16°C and not lower during the DR event for the following reasons: a) to maintain a temperature that is within the occupants' acceptable range for thermal comfort, and b) to prevent the dwelling's temperature from dropping to a level that could cause condensation on walls, leading to mould growth and potential building damage

Before each DR event, the RESPOND DR system remotely read the thermostat set point values, using them as the baseline for the event. Once the DR event finished, the thermostat set points were reverted to their pre-event settings, i.e. set points defined by the occupants.

The DR events were executed separately in every room in the apartment. The bathrooms were excluded from the studies since occupants are more sensitive to temperature changes in these spaces than in other rooms.

Finally, before starting the DR events, new digital thermostats were installed in every room of the 10 apartments and connected to new gateways. This work was done in mid-November to give the occupants 2,5 months to get familiar with new technology (Danfoss ECO thermostats) and integrate it into their everyday routines for adjusting thermal comfort in their homes. In this way, the baseline observations in weeks 1&2 were not biased due to lack of experience with new hardware.

2.2.1 Quantitative results

The reduction of energy use at the community level varied between the three DR control strategies. The biggest savings of 27,5% were achieved in weeks 7&8, where no preheating was used. In weeks 5&6 with 1h preheating, the energy use decreased by 9.4%. The smallest energy savings of 6.3% were achieved in weeks 3&4, where the temperature setpoint was lowered for just 1 hour.

The results of the peak load reduction had a slightly different pattern. The biggest peak load reduction of 90 kWh was also achieved in weeks 7&8. However, the DR preheating strategy applied in weeks 5&6 resulted in a peak increase of 30 kWh. The DR strategy of 1h temperature decrease applied in weeks 3&4 led to a peak decrease of 33 kWh.

The load rescheduling, i.e. moving energy use from peak to off-peak periods, was most beneficial in weeks 3&4, where the consumption during DR event was reduced 50% compared to the baseline. In weeks 5&6 load reduction of 25% was achieved and no load was rescheduled in weeks 7&8 compared to the baseline weeks.

2.2.2 End-users feedback on DR programmes

This section is developed using the content of the RESPOND project's deliverable D6.3, which is *User engagement assessment*.

During the 10-weeks of the DR experiments, after every week occupants were asked to provide feedback on the previous week. 20 persons received questions in weeks 1-6 and 19 in weeks 7-10. The response rate was 76% (149 answers out of 196 questionaries sent). The detailed questions used in the questionnaires can be found in Appendix 11 in D6.3 *User engagement assessment* report [39].

The age distribution of respondents was < 18 years old - 1, 30-49 years old – 6; 50-70 years old – 9; >70 years old – 4. The COVID-19 situation in winter 2020 (test weeks 6-10), and the respondents' age distribution affected the stay-at-home time, which was 89%, 55%, 85% and 88% during periods morning 6-10, noon/afternoon 10-16, evening 16-22 and night 22-6, respectively.

The overall results show that during the 10-week DR experiment, 76% of assessments expressed satisfaction with temperature conditions, and 24% were dissatisfied. It was identified that too-low temperatures were a problem for 37% of respondents, and too-high temperatures were troublesome for only 15%. Occupant feedback about excessively low temperatures highlighted issues such as cold radiators, difficulty regulating the temperature, and temperature fluctuations between rooms and over time.

By comparing responses between the four baseline weeks and the six weeks with DR events, it was found that over half of the occupants experienced excessively low temperatures during periods without DR actions. In contrast, the percentage of dissatisfied occupants decreased to 37% during the DR event periods. However, as shown in Figure 6, the mornings when DR events occurred proved to be the most challenging. This suggests that the DR actions, such as reducing the heating set-point temperature to a minimum, contribute to an increase in cold-related discomfort. The discomfort was consistent across different rooms, except for the bedroom, where only one person (5%) reported issues with low temperatures.

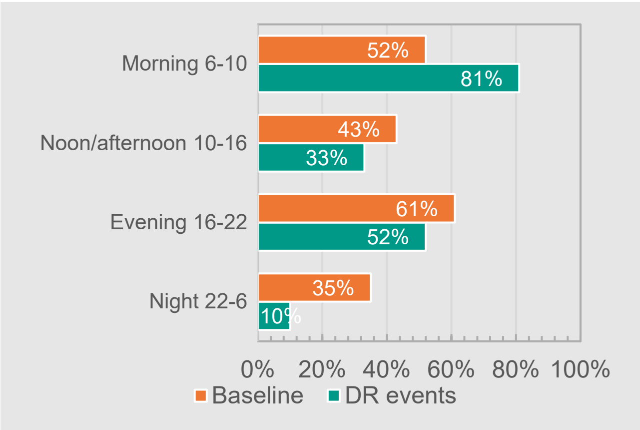


Figure 6. Distribution of answers to the question: what time of the day do you experience problems with too low temperatures? (Baseline weeks 1,2,9,10; DR period weeks 3-8).

2.2.3 Interviews with selected households

The interviews were conducted after the completion of the DR trial, focusing on four apartments. The planned DR protocol was partially implemented in households Aa01, Aa04, and Aa06, while it was fully implemented in Aa05.

The results are presented in three sections. Part 1 provides an overview of the interviewees' experiences with the indoor environment and temperatures during the DR trial. Part 2 explores the interviewees' perceptions of their level of control over their home's indoor environment during the trial. Part 3 summarizes the interviewees' attitudes toward participating in future DR schemes in district heating networks and outlines the conditions under which they would consider participating in such programs.

Part 1: Experience of the indoor environment during DR trial

Household Aa01 (a couple 60+, preferred room temperature 20 °C, differentiation of temperature between rooms, with unused spaces not heated).
The couple generally felt that the temperatures in their home were lower than they preferred, both during and outside of the DR trial. On two mornings in week 7 (set-point 16°C between 6-9 a.m.), they experienced particularly low temperatures in the bathroom and their bedroom. During these experiences and other moments of feeling cold, the couple typically explained that they had touched the radiators and felt that they were cold. As the participants had not been informed about the DR event schedule prior to the trial, experiencing cold radiators lead to some speculation and uncertainty of the couple with regard to whether this was due to the experiment or could be a failure of the thermostat. Similar stories of cold radiator surfaces were also mentioned in interviews with households Aa04 and Aa06.

The couple rarely adjusted the new thermostats after their installation. They believed it was important to avoid changing the set-point temperatures to prevent interfering with the DR experiment. This thoughtful approach to adjusting the thermostats may have contributed to their perception of too-low temperatures.

Household Aa04 (a female 50+ and teenage male, preferred room temperature is high)
Generally, the lady found the indoor temperatures less stable during the DR experiment period compared to a typical winter. Therefore, she had to adjust the thermostats more frequently than usual. However, there is no evident pattern regarding when she felt cold, as these experiences have occurred both in the morning and at various times throughout the day.

Household Aa05 (a couple 40+ and two young children, preferred room temperature 22-23°C, uniform temperature across rooms)
Compared to previous years, the family noticed a greater need to frequently adjust the thermostat set-points to maintain a comfortable indoor temperature. It might partly be due to the 6-year-old son, who found it exciting to interact with the thermostats as they light up when the set-point temperature is changed.

In the evenings, they experienced excessively high temperatures (e.g. 25-26°C) in the master bedroom and excessively low temperatures in their son's bedroom
Overall, there is no clear pattern when the rooms feel too warm or too cold, suggesting that these fluctuations are less related to the DR experiment and more likely caused by other factors, such as unpredictable thermostat behavior or their son adjusting the temperature settings.

Household Aa06 (a retired couple)
The couple did not indicate during the interview that the experiences of excessive heat or cold are linked to the DR experiment. Their experience appeared to be related to the change in thermostats, which function differently from the ones the couple was familiar with before.

The interviews showed that the RESPOND DR experiment had a limited impact on how the interviewed occupants perceived the thermal conditions in their homes. The negative experiences reported by the households are connected to the performance of the thermostats rather than the DR experiment. Household Aa01 and Aa05 members only experienced feelings of cold or warmth directly related to the DR Experiment.

Part 2: Perceived level of control of temperature in home.

The frustration with the new thermostats was a key factor to consider when assessing the interviewees' perceptions of their control over the indoor temperature during the DR experiment. The thermostats' “sensitivity” in regulating temperature may be the reason why four out of the five households felt a loss of control over their thermal conditions in the house.

Moreover, the interviews pointed to that having a clear understanding of the plan and objectives behind a DR strategy may significantly influence how households will experience indoor temperature variations. Thus, the design of the trials, where the participants were not informed about the exact trial protocol (e.g. when thermostat set-points would be regulated), seemed to result in more frustration among the participants than if they had been informed about the trial schedules.

These findings underlined the importance of users' long-term experience with technology used for controlling heating in their homes and of dialogue between the DHC utilities and their customers to enhance occupants' acceptance of DR solutions and potential indoor conditions inconveniences.

Part 3: Attitudes towards participating in DR programmes in DH networks

The interviews revealed that house owners were generally positive about their participation in future Demand Response schemes. Especially the couple in Aa01 household was very enthusiastic about it and indicated that avoiding digging *up all the roads in the neighbourhood to install new pipes is an acceptable incentive to participate in DR programs.* For this couple, price was not a decisive factor in their acceptance; the primary motivation was avoiding the need for costly and disruptive pipeline upgrades.

Beyond avoiding the inconvenience of DH piping upgrades an important incentive, shared by several interviewees, was the cost savings. Yet, the interviewees found it difficult to estimate how much they would need to save to make participation in DR programs worthwhile. Additionally, Aa06 occupants mentioned environmental benefits as a motivating factor for accepting DR control.

Several interviewees emphasized that a DR scheme should not come at the risk of too low indoor temperatures and occupants feeling too cold. Most households seemed willing to accept a temperature setback of 1-2°C but not beyond that. Additionally, two interviewees proposed a solution where only in part of the house/apartment the DR scheme is activated and room, such as the kitchen and bathroom are excluded.

Overall, the interviews reveal a generally positive attitude toward heat DR (specifically peak shaving in the morning hours). However, this acceptance is conditional on maintaining some level of control, particularly regarding (a) the extent of temperature reductions during setbacks and (b) the ability to customize DR control for different rooms.

3. District heating and cooling professionals' perspective towards DR programmes

In the recent scientific publication [44] analysing the strengths, weaknesses, opportunities and threats (SWOT analysis) of the demand response (DR) in DHC systems, the authors have listed the following 17 elements, presented also on Figure 7:

Strengths:

1) well-grounded state-of-the-art knowledge
2) real-life examples of DR in the DHC systems supported by digitalisation;

Weaknesses:

3) great variety of DHC system types
4) great variety of building systems, lack of interfaced interaction, and control possibilities
5) lack of good DR examples; low penetration of best practices
6) lack of data sharing and DR follow-up check
7) lack of collaboration models to support DR implementation in real-life
8) lack of consistent evaluation metrics for DR actions/strategies
9) lack of a regulatory framework and DR tariffs

Opportunities:

10) accelerating digitalisation of the building and the DHC sectors
11) accelerating the shift from high to low supply temperatures in DH systems
12) fault detection and diagnostics at the demand side in DHC systems
13) new customer-tailored collaboration models and energy pricing mechanisms
14) customers' increased awareness of energy consumption, flexibility potential and energy cost savings

Threats:

15) low penetration rate and period between planning and commissioning of DHC systems
16) intermittent and inconsequent application of policies to support DR, RES, DHC
17) reluctance to apply academic research results in real-life applications. However, these are just theoretical studies using literature and expert knowledge as the background.

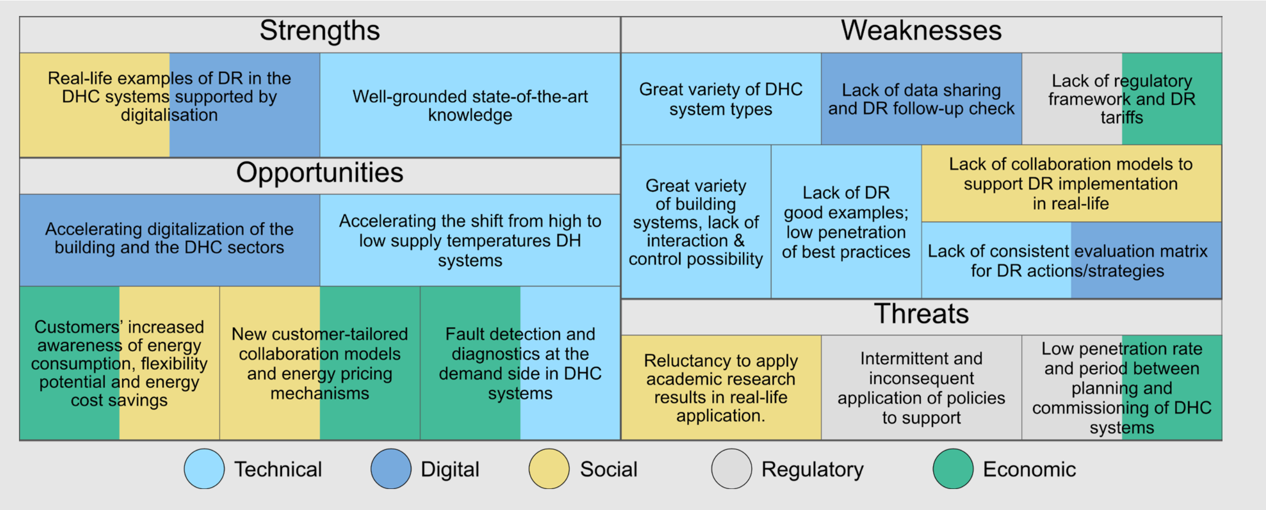


Figure 7: Summary of the SWOT analysis with indication of different elements groups

Therefore, the following work of IEA EBC Annex 84 aimed at conducting a survey with DHC professionals to collect insights on strengths, weaknesses, opportunities and threats associated with DR from stakeholders daily working with DH customers, operational challenges and future developments in the DHC systems.

3.1 Description of the questionnaire with DHC professionals

The survey was designed to gauge the opinions and attitudes of DHC professionals towards the DR concept. Therefore, the survey included 17 Likert Scale questions with a five-point agreement scale, 2 open-text questions, and 1 close-ended question. The background data of the respondents, such as age, education, expertise in the DHC utility, daily tasks and responsibilities, were collected at the end of the survey. The survey was originally developed in English and translated by the Annex 84 participants into Danish, French, German, Italian and Spanish. The questions were grouped into the following categories:

– Load management: challenges and experience
– Relevance of the electricity market
– Familiarity with DR
– Willingness for system upgrades and investment enabling DR
– DR control limitations: data privacy, thermal comfort, legal responsibilities
– Benefits and barriers from DR and their importance
– Incentives for customers to participate in DR programmes
– Relevance of DR to future developments of DHC systems
– Importance of policy measures to enable DR programmes

The questions used in the survey can be found in Appendix 1.

The questionnaire was distributed by the Annex 84 participants in their networks and the DHC+ platform [45] has disseminated the survey on their webpage and included it in the newsletter to increase the outreach of the survey.

3.2 Results

46 respondents answered the survey. Taking into consideration that the district heating and cooling sector is rather conservative, hermetic and not easy to collaborate with, this response rate is satisfactory. Also, since there are 46 answers from 8 countries, the analysis is performed globally, which means no results or conclusion is drawn at the country level but only commonly for the whole survey.

Figure 8 presents the background information of the survey respondents. Eight countries were represented in the survey with a good mix of only district heating (46%) and district heating & cooling (46%) utilities. The district cooling utilities constitute only 8%.

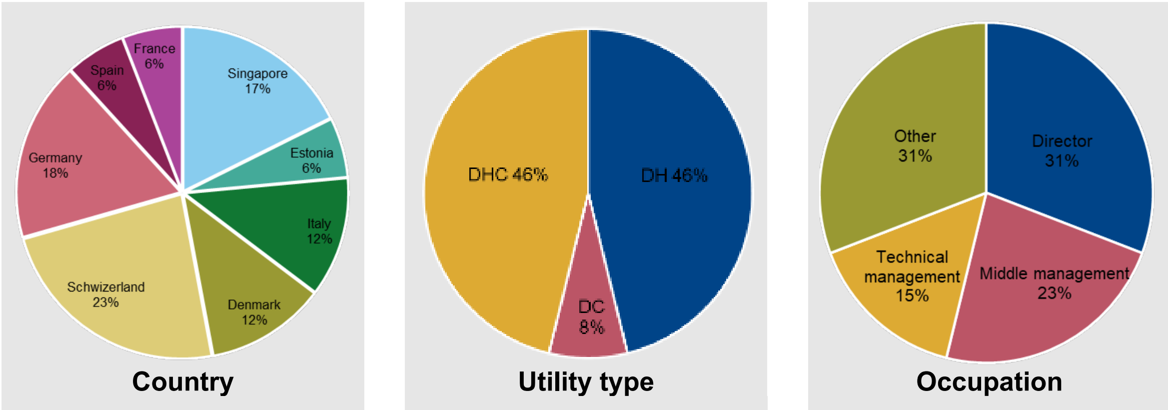


Figure 8. Characteristics of the survey respondents.

3.2.1 Load management: challenges and experience

Above 60% of respondents indicate that already today they face challenges in load management. However, 75% do not take any measure to change the load curve during critical moments, such as morning peaks during the heating season, where the production of DHW water tops the space heating demand.

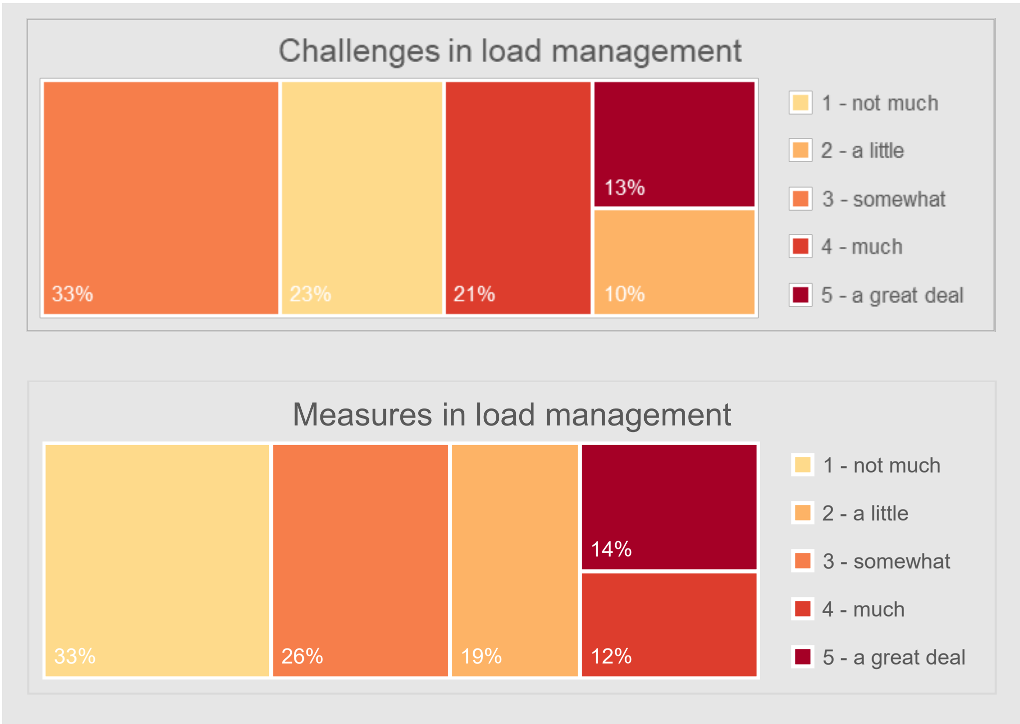


Figure 9. Distribution of answers for the first group of questions.

3.2.2 Relevance of the electricity market

For 50% of respondents, the price of electricity plays a crucial role in the daily control of the system, particularly in DHC networks with CHP units and heat pumps.

3.2.3 Familiarity with DR concept and willingness for upgrades

The survey revealed that 90% of respondents are familiar with the concept of shifting customer loads to enhance system operation. Similarly, 84% are open to implementing control updates necessary for activating demand-side management to optimize the system.

However, only 30% of respondents, equivalent to 15 utilities, currently apply DR strategies in their daily DHC operations. Unfortunately, the survey did not include a question about the specific strategies they use.

When asked about the importance of DR-ready customers, 50% of utility operators indicated that they consider them important for future system optimization.

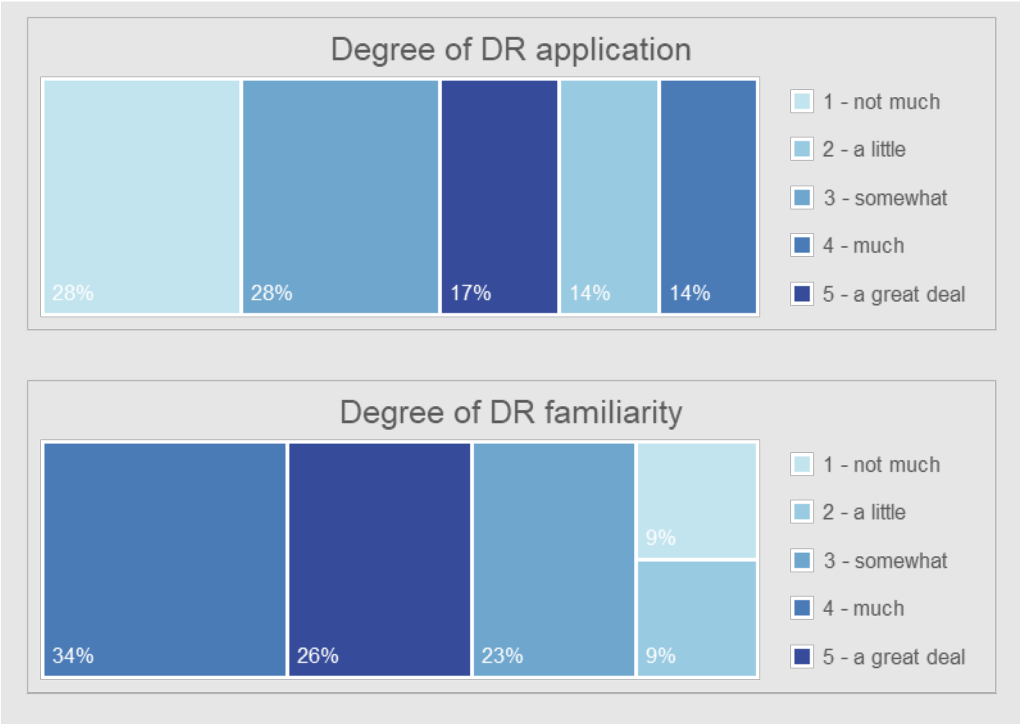


Figure 10. Distribution of answers for the third group of questions.

3.2.4 DR control limitations: data privacy, thermal comfort, legal responsibilities

The next set of questions focused on the restrictions that could limit the application of DR in DHC systems. When asked, “Would you see any legal or organisational restrictions when controlling the heating/cooling consumption of your customers to solve challenges in your network?”, DHC professionals provided varied responses.

Data privacy was identified as a restriction by 50% of respondents, but legal responsibilities were seen as an even greater limiting factor (Table 1). Thermal comfort was perceived as both a concern and a non-issue, indicating differing perspectives among professionals. Additionally, respondents had the opportunity to list other restrictions in an open-text field, where the following additional concerns were highlighted:

- “Mostly contractual obligations than legal” (SIN)
- “The electricity grid must have already put in place a demand response mechanism”
- “Old structure and known and safe practices” (DK)
- “Split of cost customer/network operator” (DE)
- “The technical effort is too great” (DE)
- “Customer-facing marketing” (SP)
- “Tariffs” (SP)

Table 2. Distribution of answers on restrictions for DR concept.

Likert Scale	Data privacy	Customers thermal comfort	Legal responsibilities
Absolutely not	38%	21%	25%
Mostly not	17%	20%	13%
Probably	33%	25%	38%

Mostly yes	8%	21%	17%
Absolutely yes	4%	13%	7%

3.2.5 Benefits and barriers from DR and their importance

The implementation of new concepts and changes to "business-as-usual" routines requires a clear understanding of the benefits that follow these changes. To assess this, DHC professionals were asked to evaluate the importance of environmental, monetary, energy mix, and operational benefits.

Monetary savings in production, peak load reduction, and the increased integration of renewable energy sources were identified as highly important by DHC professionals. However, all six benefits were considered significant, with only minor percentage differences in their evaluations. This supports the idea that the DHC sector is undergoing a major transformation, where reducing environmental impact and eliminating fossil fuels, especially those used during peak periods, is a top priority.

Additionally, DHC utilities are beginning to recognize the secondary benefit of the application of DR concept, namely the possibility to detect faults in domestic heating installations.

Table 3. Distribution of answers on benefits of DR concept.

Likert Scale	**CO_2 savings**	**Cost savings: production**	**Cost savings: distribution**	**Peak load reduction**	**Increase of renewable sources**	**Fault detection**	**Prestige**
Not important	6%	6%	11%	11%	6%	22%	32%
Of little importance	17%	6%	22%	11%	6%	11%	37%
Moderately important	11%	11%	11%	6%	11%	6%	10%
Important	28%	**44%**	28%	28%	**44%**	39%	11%
Very important	39%	33%	28%	**44%**	33%	22%	10%

Similar to the benefits, the barriers to implementing DR were also examined. DHC professionals were asked to evaluate the importance of six key barriers.

The results showed that the high cost of technology is considered a significant barrier. The complexity of control was rated as moderately important by some professionals, while others viewed it as a major challenge. Unclear benefits were not seen as a significant obstacle to DR implementation.

Data privacy concerns varied across regions. For German DHC professionals, data privacy was rated as important or very important, whereas professionals from other countries were generally less strict about this issue.

Table 4. Distribution of answers on barriers of DR concept.

Likert Scale	High cost of technologies	High complexity level of control	Insufficient or unclear benefits	Data privacy	Reduced market potential
Not important	13%	13%	20%	27%	13%
Of little importance	7%	7%	**40%**	13%	33%

Moderately important	27%	**33%**	6%	20%	**40%**
Important	**40%**	20%	27%	20%	13%
Very important	13%	27%	7%	20%	0%

All four aspects of the DR concept that are unclear or currently unavailable are considered important by DHC professionals. Real-life experience with DR programmes does exist, subtask D has collected 30 case studies, but it is not well communicated within the sector.

Additionally, the lack of regulations and technical standards was identified as a significant obstacle. Another key challenge is customer acceptance and trust in DR solutions, which was rated as important by nearly half of the surveyed DHC professionals.

Table 5. Distribution of answers on the aspects not available or not enough elaborated for DR concept success.

Likert Scale	Lack of customer acceptance and trust	Lack of appropriate regulations	Lack of real-life experience	Lack of technical standardisation
Not important	13%	27%	13%	7%
Of little importance	20%	20%	13%	20%
Moderately important	20%	0%	14%	20%
Important	**32%**	13%	**60%**	**33%**
Very important	15%	**40%**	0%	20%

3.2.6 Incentives for customers to participate in DR programmes

Monetary savings were identified as the most important incentive for motivating DHC customers to participate in DR schemes. Additionally, CO_2 savings were considered more significant than energy savings. DHC professionals indicated that customers do not place a high value on their comfort and are willing to compromise it in favour of the social benefits of the DR initiatives. This aligns with the findings of the RESPOND project survey described in section 1.2.3, which showed that most households would accept a temperature decrease of 1–2 K but not beyond that.

Likert Scale	Monetary savings	CO_2 savings	Energy savings	High thermal comfort
Not important	7%	7%	7%	14%
Of little importance	0%	7%	0%	20%
Moderately important	27%	33%	**40%**	**33%**
Important	20%	**47%**	27%	20%
Very important	**47%**	0%	20%	7%

3.2.7 Relevance of DR programmes to future developments of DHC systems and importance of policy measures to enable DR programmes

The future development of DR schemes is considered important by 65% of DHC professionals. This is seen as a promising opportunity and a key driver for technology providers in the DHC sector, as well as for researchers exploring the use of buildings as decentralized storage facilities.

The significance of policy regulations varies depending on how regulated the DHC market is in each country and the level of freedom utilities have. For example, in Denmark, where the market is highly regulated, utilities will only integrate DR schemes if they are proven to be highly reliable to avoid compromising the customer-utility relationship. In contrast, other markets may operate under regulations similar to those in the electricity sector, allowing for greater flexibility in implementing DR schemes. As a result, policy regulations will differ across DHC markets and countries.

3.3 Conclusions

The survey results from DHC professionals indicate that most DHC utilities currently do not implement significant measures to shift demand-side loads to manage daily load fluctuations in the network. Instead, their main strategies focus on the primary side, involving the control of production units and the optimization of distribution networks. However, the survey confirmed that many DHC utilities are familiar with the demand response (DR) concept.

The primary restrictions preventing the large-scale application of DR are legal and contractual responsibilities. Another major barrier is the lack of experience and knowledge transfer on DR applications between DHC utilities. Responses from professionals suggest a shortage of real-life DR application examples, despite subtask D in Annex 84 having collected multiple DR trial cases.

Regarding customer participation in DR schemes, monetary incentives are considered the most effective motivation. However, there is also potential for leveraging environmental benefits and energy savings to engage DHC customers.

4. Collaboration models and existing tariffs

4.1 Literature review

There are two main types of district heating and cooling markets: regulated and deregulated [46]. In a regulated market, the government sets the rules for calculating the price, and all DH plants and distribution networks are owned and operated by municipalities. Companies do not generate profits, and DH pricing follows a "cost-plus" method, where the price covers operating costs, annual depreciation, and a permitted profit. In a deregulated market, the marginal-cost pricing method is commonly used, encouraging cost reduction, efficiency improvements, and investment in advanced technologies. This pricing model is generally more supportive of demand response than the cost-plus approach.

However, to the authors' knowledge, no DHC supplier currently employs a pricing model that enables demand response or allows buildings to actively participate in the DHC market by delivering energy flexibility.

Recent research has examined the impact of DH tariff structures on the profitability of building renovations. Findings suggest that fully flexible tariffs, which accurately reflect heat supply costs, combined with low-interest loans for energy conservation measures, provide a strong economic incentive for retrofitting most existing buildings [47–50]. However, one critical but often overlooked aspect is the social compatibility of such tariffs, which may penalize energy-inefficient buildings. Since housing prices and rents tend to be positively correlated with energy efficiency [51,52] the introduction of variable DH tariffs, potentially triggering a retrofitting wave, could have negative effects on housing affordability [53]. Additionally, these tariffs may disproportionately affect low-income households, which struggle to reduce energy consumption [54], as well as low-income homeowners, who have lower adoption rates for energy retrofits compared to high-income building owners [55]. Thus, while variable DH tariffs could serve as a powerful tool to address the persistently low building retrofitting rates, their successful implementation would require substantial policy adjustments to ensure social fairness [54]. Consequently, such tariff structures should be seen as a medium to long-term solution rather than a quick fix.

4.2 Experience from Annex 84 case studies collected in subtask D.

A total of 30 case studies were analyzed in Subtask D of IEA EBC Annex 84, focusing on the integration of demand-side management in buildings connected to thermal networks. Among these, 13 case studies explicitly described active collaboration between stakeholders, and eight implemented practical solutions in either individual buildings or entire districts. Four of these cases, characterized by diverse stakeholder engagement, are described in detail here.

The case studies cover a wide range of building types, including residential and non-residential properties, such as single-family houses, multi-story buildings, and both tenant-occupied and owner-occupied dwellings. However, specific details regarding building types and ownership or rental arrangements were not consistently provided across all studies. The duration of the studies varied considerably, ranging from a few weeks to over a year, reflecting the diverse methodologies and contexts employed.

A key aspect of these collaborations was the collection of qualitative data, particularly regarding thermal perception, which cannot be directly measured. Several studies used surveys to evaluate thermal perception, shedding light on user acceptance thresholds. Notably, one case study utilized data from the electrical grid rather than thermal networks, investigating user behavior in overriding thermostats during demand response events. Table 6 provides an overview of the case studies, describing aspects related to collaboration between stakeholders.

Table 6. Overview of relevant case studies from subtask D. Case Study Nr. equivalent with consistent with numbering of cases within Subtask D. Involvement of the customer in de/activating the demand response is indicated.

Case Study Nr.	Title of Case Study / Research Project	Involvement of the customer
2	Data-driven automated DSM technology (“DataDrivenLM” by AEE Intec, Austria)	Automated - Direct
9	Digitizing DH supply infrastructure (Project “Smart Heat” by Fraunhofer IEE, Germany)	Automated-Indirect
25	Perceptions of indoor climate during DR (by Chalmers University, Sweden)	Automated-direct
28	DR events in a university building (by Aalto University, Finland)	Direct

4.2.1 Case study 2: Data-driven automated DSM technology (“DataDrivenLM” by AEE Intec)

This case study explores the implementation of an automated-direct, data-driven load management in a typical Austrian medium-sized district heating (DH) network. The network, located in a rural area, serves a few hundred customers and utilizes a biomass/wood chip boiler as its primary heat source, with an oil boiler for infrequent peak demands. The primary objective of the DR utilisation is to flatten the overall load, thereby avoiding peaks and very low partial loads.

Participating customers are assigned to one of two groups: (a) Flexible customers, who actively participate in the DR program with their load flexibility, mainly in space heating for residential buildings, and (b) Fixed customers, who participate in DR but have no own flexibility, such as industries with fixed production plans. All participating customers have space heating systems controlled by a heating curve (supply temperature as a function of the ambient temperature). For flexible customers, by introducing a temperature offset to the actual ambient temperature in the heating curve, the load management potential is increased. This intervention allows the adjustment of the heating curve of the flexible customers according to the DH network needs. All customers contribute to load management by providing life data to the DH operator on supply and return temperatures, set points, volume flow, power and energy, valve positions, pressure, and ambient temperature.

This collaboration type benefits both existing and new customers. New customers can be relatively quickly connected to the grid and existing customers might profit from indirect cost savings as a result of the possibility of reusing existing infrastructure (boilers, storage) when connecting new customers. Without the system, new customers' peak loads might necessitate retrofits in boilers and piping; however, this can be avoided due to shifts and reductions in peak loads. Additionally, customers could benefit from improved long-term stability of their heat prices, due to reduced dependency on fossil energy price increases.
The results of this case study indicate that the implementation of a fully data-driven DR solution constitutes a straightforward and cost-effective strategy for mitigating peak demand and flattening the heating curve. Segmenting customers into two groups, those with load flexibility and those without, facilitates load management for the grid operator. Given that customer participation is primarily indirect through data provision,

minimal engagement from customers is required. This circumstance fosters high levels of acceptance and willingness to cooperate. Furthermore, customers benefit indirectly from the DR initiative, as no additional hardware or equipment, and thus no investment is necessary to enhance grid capacity.

4.2.2 Case study 9: Digitizing DH supply infrastructure (Project “Smart Heat” by Fraunhofer IEE, Germany)

This case study examines a case in Hannover involving 20 buildings connected to the DH system. These buildings include single-family houses (SFH), multi-family houses (MFH), and non-residential buildings such as kindergartens, hotels, and offices, each with varying building standards. Three of these buildings are used to test different control mechanisms. A key objective of this case study is load smoothing by engaging customers through variable heating tariffs, which allow customers to benefit from temporarily lower heat prices.

The collaboration involved the following three components: (1) the implementation of variable heat tariffs as customer incentives, (2) the optimization of customers’ installations, and (3) the establishment of interoperability protocols for data and control signals exchange.

A customer survey is used to analyze the acceptance of the dynamic tariffs. The results (very similar results for customers living in SFH and MFH) show that 70% of customers accept dynamic tariffs if there is a chance of lower prices during low-demand periods. However, only 10% of the customers accept higher prices during peak-demand periods.

4.2.3 Case study 25: Perceptions of indoor climate during DR (by Chalmers University, Sweden)

This case study based on Hagejärd et al. (2021) [56] investigates tenant perceptions of indoor climate and demand-side management (DSM) in Malmö, Sweden. The research focuses on 93 participants residing in 33 multi-residential buildings, constructed between 1949 and 1973, with three buildings having undergone refurbishment. Of these, eight buildings implemented power control and load shifts, involving 40 tenants. The study explores the impact of direct automated and centrally controlled load shifts on thermal sensation and satisfaction, utilizing the thermal inertia of buildings to facilitate load shifting. Indoor temperatures were allowed to fluctuate by ±0.5°C, enabling a 75% power reduction for two hours or a 25% power reduction for six hours.

The study was conducted in three phases: an initial registration and survey, a two-week trial with demand control and diary entries on indoor temperature perception, and a closing survey. Six different load shift tests were executed between November 18th and December 1st, 2019, including variations such as -50% for 1 or 3 hours, -100% for 0.5 hours, -25% for 3 hours, and +25% for 1 hour.

The collaboration involved dividing participants into two groups: Group A received notifications 30 minutes before load shifts, while Group B did not receive notifications. Results show four factors influencing the perceptions and acceptance of DR: the possibility to set indoor climate conditions, timing and magnitude of load shifts, individual control and communication. Overall, between days with and without load shifts, no difference in thermal comfort and satisfaction was identified. However, fewer participants can imagine allowing more variation in temperature at home to save energy after the trial. Furthermore, mornings are perceived as colder than other times of the day. Temperature reduction during times perceived as cold and temperature increase during times perceived as warm should be avoided. Additionally, there is a positive correlation between perceived control and willingness to accept larger temperature variations.

4.2.4 Case study 28: DR events in a university building (by Aalto University, Finland)

The case study based on Mishra et al. (2019) [57] explores the implementation of demand response events within a district heating network at the U-Wing of a large building on Aalto University’s Espoo campus in

Helsinki, Finland. The building, originally constructed in 1975 and refurbished in 2014, spans 13,800 m² and operates within a district heating network with supply temperatures ranging from 75 to 115°C.

In this case study a price-based DR control is applied, where the inlet temperature of the heating water substation is adjusted in response to pricing models. The primary objectives include facilitating load shifting by utilizing the building mass as thermal energy storage, reducing peak load boiler operations, and achieving lower energy prices. The study investigates the extent of permissible deviations in inlet water temperature and their impact on occupant perceptions. Field tests of demand response strategies were conducted to evaluate their effects on both the building and its occupants.

The collaboration involved implementing price-based demand response while monitoring occupant satisfaction, providing insights into the balance between energy efficiency and occupant comfort. This research contributes to the development of effective demand response strategies in district heating systems, highlighting the potential for energy savings and enhanced occupant satisfaction.

During the test, several different ranges of deviation of the inlet water temperature are achieved. The reduction of the inlet water temperature is between -2.7°C and -21.1°C. The Increase of water inlet temperature is between 0.8°C and 10.9°C. Regarding the occupants, the perception of the indoor thermal environment did not deteriorate during the DR implementations. Certain DR implementation periods even seemed to improve occupant perception over the reference periods.

5. Conclusions and recommendations

The integration of buildings into the energy system presents both opportunities and challenges for district heating and cooling (DHC) utilities. While new pricing models and demand response (DR) strategies can enhance efficiency and sustainability, significant barriers such as split incentives, information asymmetries, and regulatory constraints hinder their widespread implementation. Additionally, the knowledge gap regarding cost-effective deployment and stakeholder engagement remains a critical issue.

Findings from research and interviews highlight that while DR mechanisms can be beneficial, their successful implementation requires careful consideration of social equity, affordability, and user experience. Customers generally support DR programmes if they do not compromise comfort and allow for a degree of control. Moreover, the lack of clear communication and transparency in DR strategies can lead to frustration among end-users, emphasizing the need for improved stakeholder engagement.

On the utility side, many DHC providers acknowledge the potential of DR programmes but focus primarily on supply-side measures to solve the future challenges rather than demand-side flexibility. Key barriers include regulatory limitations, insufficient knowledge transfer, and a lack of real-world DR application cases.

To narrow the existing gap and foster the roll-out of DR programmes application among DHC utilities following recommendations were formulated:

1. **Enhance Communication and Customer Engagement**
   - Clearly inform customers about DR programme objectives, schedules, and expected impacts to mitigate frustration and increase participation.
   - Provide user-friendly interfaces and controls that allow households to customize DR participation, ensuring comfort and convenience.
2. **Develop Socially Equitable Pricing Models**
   - Introduce variable DH tariffs gradually, ensuring safeguards for low-income households to prevent affordability issues.
   - Implement financial support mechanisms such as subsidies or low-interest loans to encourage energy-efficient renovations, mitigating negative social impacts.
3. **Promote Knowledge Sharing and Best Practices**
   - Establish platforms for DHC utilities to exchange experiences and lessons learned from DR implementations.
   - Encourage pilot projects and demonstration cases to showcase the benefits and feasibility of DR schemes.
4. **Address Regulatory and Contractual Barriers**
   - Advocate for policy adjustments that facilitate demand-side flexibility while ensuring legal and contractual clarity.
   - Develop standardized DR frameworks to support consistent implementation across different market structures.
5. **Leverage Multiple Incentives for Customer Participation**
   - Combine financial incentives with environmental and energy-saving motivations to appeal to a broader range of customers.

- Offer tiered DR participation options, allowing customers to choose their level of engagement based on their preferences and needs.

By addressing these challenges through policy adjustments, improved communication, and knowledge transfer, DHC utilities can successfully integrate demand response mechanisms, leading to more efficient and sustainable energy systems.

6. References

[1] IEA [2020], Is cooling the future of heating?, IEA, Paris https://www.iea.org/commentaries/is-cooling-the-future-of-heating
[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] https://www.iea.org/energy-system/buildings/district-heating
[5] IEA [2021], *Net Zero by 2050*, IEA, Paris https://www.iea.org/reports/net-zero-by-2050, Licence: CC BY 4.0
[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. 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. 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. 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 networks pipes. *In: Proceedings of the urban energy simulation conference* 2018; 2018. p. 1–9.
[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;3: 179-189. 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. https://doi.org/10.1016/j.enbuild.2017.08.044
[18] Li R, Satchwell AJ, Finn D, Christensen TH, Kummert M, Le Dr´eau J, et al. Ten questions concerning energy flexibility in buildings. *Build Environ* 2022;223. https://doi.org/10.1016/j.buildenv.2022.109461

[19] Goy S, Ashouri A, Mar´echal F, Finn D. Estimating the potential for thermal load management in buildings at a large scale: overcoming challenges towards a replicable methodology. *Energy Proc* 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 Dreau J, Maturo A, et al. Data-driven key performance indicators and datasets for building energy flexibility: a review and perspectives. Appl Energy 2023;343. https://doi.org/10.1016/j.apenergy.2023.121217
[21] Specht, J. M., Madlener, R., 2019. Energy Supplier 2.0: A conceptual business model for energy suppliers aggregating flexible distributed assets and policy issues raised, *Energy Policy* 2019; 135, 110911.https://doi.org/10.1016/j.enpol.2019.110911
[22] M. Goulden, B. Bedwell, S. Rennick-Egglestone, T. Rodden, A. Spence, Smart grids, smart users? The role of the user in demand side management, *Energy Res. Social Sci*. 2014; 21–29, https://doi.org/10.1016/j.erss.2014.04.008
[23] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. *Energy* 2014;68:1–11. https://doi.org/10.1016/j.energy.2014.02.089
[24] Østergaard PA, Werner S, Dyrelund A, Lund H, Arabkoohsar A, Sorknæs P, et al. The four generations of district cooling - a categorization of the development in district cooling from origin to future prospect. *Energy* 2022;253.https://doi.org/10.1016/j.energy.2022.124098
[25] Stichting Warmtenetwerk/Dutch New Energy Research. In: Nationaal warmtenet trendrapport 2021; 2020, 2 november [n.d]
[26] IEA DHC Annex TS4: Digitalisation of district heating and cooling https://www.iea-dhc.org/the-research/annexes/2018-2024-annex-ts4
[27] Digitalisation in district heating and cooling systems. Euroheat & Power; May 2023 https://prod.euroheat.org/dhc/knowledge-hub/dhc-report-on-digitalisation-in-dhc-systems
[28] Calderoni M, Babu Sreekumar B, Dourlens-Quaranta S, Lennard Z, Rama M, Klobut K, et al. Sustainable district cooling guidelines. IEA DHC/CHP Report; 2019. 2019.
[29] IRENA, IEA and REN21 [2020], 'Renewable Energy Policies in a Time of Transition: Heating and Cooling'. IRENA, OECD/IEA and REN21. https://www.irena.org/Publications/2020/Nov/Renewable-Energy-Policies-in-a-Time-of-Transition-Heating-and-Cooling
[30] Averfalk H, Benakopoulos T, Best I, Dammel F, Engel C, Geyer R, et al. Low-Temperature District Heating Implementation Guidebook. Final Report of IEA DHC Annex TS2. Implementation of Low-Temperature District Heating Systems. 10.24406/publica-fhg-301176
[31] Buffa S, Cozzini M, D'Antoni M, Baratieri M, Fedrizzi R. 5th generation district heating and cooling systems: a review of existing cases in Europe. *Renew Sustain Energy Rev* 2019;104: 504–522. https://doi.org/10.1016/j.rser.2018.12.059
[32] Lund H, Østergaard PA, Nielsen TB, Werner S, Thorsen JE, Gudmundsson O, et al. Perspectives on fourth and fifth generation district heating. *Energy* 2021;227. https://doi.org/10.1016/j.energy.2021.120520
[33] Horizon 2020 Integrated Demand Response Solution Towards Energy Positive Neighbourhoods (RESPOND) project (grant agreement No 768619) https://cordis.europa.eu/project/id/768619
[34] Christensen, T. H., Knudsen, H. N., Shearcaigh, A. N., Lopez, R., & Rasmussen, L. S. [2018]. *D3.1 Criteria and framework for recruiting and engaging*. https://vbn.aau.dk/ws/portalfiles/portal/291744639/RESPOND_D3.1_Criteria_and_framework_for_recruiting_and_engaging_Final.pdf
[35] Larsen, S. P., Christensen, T. H., & Knudsen, H. N. [2018]. *D3.2 RESPOND user engagement strategy*. https://vbn.aau.dk/ws/portalfiles/portal/291744377/RESPOND_D3.2_User_engagement_strategy_Final.pdf
[36] Christensen T.H., Knudsen H.N., Shearcaigh A N., Lopez R., Yara A. [2019} *D3.3 Findings and recommendations from focus groups on user context.*
[37] Esnaola I., Diez F. J., Cruz M., Martinez L., Christensen T.H. [2019] *D3.4 Personal energy performance assistant design.*
[38] D6.2 *Validation analysis of operation scenarios*,

[39] Christensen T.H., Knudsen H.N., Yara A.,Serrano M.L., Fhlaithearta L.N., Correa D.P., [2020] D6.3 *User engagement assessment.*
[40] Bescós J., Serrano M.L., Pla O., Starostová T., Kirketerp P., *D6.4 RESPOND replication plan*
[41] D6.5 *Best practices and lessons learnt*.

[42] Shove, Elizabeth, Beyond the ABC: Climate Change policy and theories of social change. *Environment and Planning* A 2010; 42(6). 1273 – 1285. https://doi.org/10.1068/a4228
[43] Strengers, Yolande, Peak electricity demand and social practice theories: Reframing the role of change agents in the energy sector. *Energy Policy* 2012;44(1). 226-234. https://doi.org/10.1016/j.enpol.2012.01.046
[44] Marszal-Pomianowska, A., Motoasca, E., Pothof, I., Felsmann, C., Heiselberg, P., Cadenbach, A., Leusbrock, I., O'Donovan, K., Petersen, S., & Schaffer, M. Strengths, weaknesses, opportunities and threats of demand response in district heating and cooling systems. From passive customers to valuable assets. *Smart Energy* 2024, 14,100135. https://doi.org/10.1016/j.segy.2024.100135
[45] DHC+ knowledge platfrom https://www.euroheat.org/dhc/about-dhc
[46] Li H, Sun Q, Zhang Q, Wallin F. A review of the pricing mechanisms for district heating systems. Renew *Sustain Energy Rev* 2015;42:56–65. https://doi.org/10.1016/j.rser.2014.10.003
[47] Baldini M, Brøgger M, Jacobsen HK, Wittchen KB. Cost-effectiveness of energy efficiency improvements for a residential building stock in a Danish district heating area. *Energy Effic* 2020;13:1737–61. https://doi.org/10.1007/s12053-020-09889-x
[48] Djørup S, Sperling K, Nielsen S, Østergaard PA, Thellufsen JZ, Sorknæs P, et al. District heating tariffs, economic optimisation and local strategies during radical technological change. *Energies* 2020;13. https://doi.org/10.3390/en13051172
[49] Hvelplund F, Krog L, Nielsen S, Terkelsen E, Madsen KB. Policy paradigms for optimal residential heat savings in a transition to 100% renewable energy systems. *Energy Pol* 2019;134. https://doi.org/10.1016/j.enpol.2019.110944
[50] Ziemele J, Cilinskis E, Blumberga D. Pathway and restriction in district heating systems development towards 4th generation district heating. *Energy* 2018;152: 108–18. https://doi.org/10.1016/j.energy.2018.03.122
[51] Næss-Schmidt S, Heebøll C, Fredslund NC. Do homes with better energy efficiency ratings have higher house prices?. In: Econometric approach. Danish Energy Agency; 2015.
[52] Fuerst F, Haddad MFC, Adan H. Is there an economic case for energy-efficient dwellings in the UK private rental market? *J Clean Prod* 2020;245. https://doi.org/10.1016/j.jclepro.2019.118642
[53] Haffner MEA, Hulse K. A fresh look at contemporary perspectives on urban housing affordability. *Int J Unity Sci* 2021;25:59–79. https://doi.org/10.1080/12265934.2019.1687320
[54] Trotta G, Hansen AR, Sommer S. The price elasticity of residential district heating demand: new evidence from a dynamic panel approach. *Energy Econ* 2022;112. https://doi.org/10.1016/j.eneco.2022.106163.
[55] Schleich J. Energy efficient technology adoption in low-income households in the European Union – what is the evidence? *Energy Pol* 2019;125:196–206. https://doi.org/10.1016/j.enpol.2018.10.061
[56] Hagejard S, Dokter G, Rahe U, Femenías P. My apartment is cold! Household perceptions of indoor climate and demand-side management in Sweden. *Energy Res Social Sci* 2021;73. https://doi.org/10.1016/j.erss.2021.101948
[57] Mishra AK, Jokisalo J, Kosonen R, Kinnunen T, Ekkerhaugen M, Ihasalo H, et al. Demand response events in district heating: results from field tests in a university building. *Sustain Cities Soc* 2019;47. https://doi.org/10.1016/j.scs.2019.101481.

7. Appendix 1

Questions used in the DHC survey

1 Do you face major challenges with regard to the load profile of your district heating/ district cooling network?

	1 - not much	2 - a little	3 - somewhat	4 - much	5 - a great deal
Challenges in load management	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑

2 Do you take measures to change the load curve (e.g. load shift in the morning during the heating season)?

	1 - not much	2 - a little	3 - somewhat	4 - much	5 - a great deal
Measures in load management	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑

3 How important is the electricity price in your daily control of the district heating/district cooling system?

	1 - not important	2 - of little importance	3 - moderately important	4 - important	5 - very important
Importance of electricity price	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑

4. Do you already apply demand response concept in your district heating/district cooling network operation?

	1 - not much	2 - a little	3 - somewhat	4 - much	5 - a great deal
Degree of demand response application	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑

5. How familiar have you been with the advantages of the demand response concept, as short-term storage before this questionnaire?

	1 - not much	2 - a little	3 - somewhat	4 - much	5 - a great deal
Demand response concept/technologies	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑

6. How important are demand-response-ready customers allowing for shifting heating/cooling peaks or for decentralized storage of heat/cold from the grid?

	1 - not important	2 - of little importance	3 - moderately important	4 - important	5 - very important
Importance of demand-response-ready customers	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑

7. Would you be willing to upgrade the control system of the heating/cooling network and customers' heating/cooling installations in such a way that the control of the heating/cooling consumption of your customers would be usable and help in solving challenges in your network?

	1 - absolutely not	2 - mostly not	3 - probably	4 - mostly yes	5 - absolutely yes
Control optimization	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑

8. Would you see any legal or organizational restriction when controlling the heating/cooling consumption of your customers in order to solve the challenges in your network?

	1 - absolutely not	2 - mostly not	3 - probably	4 - mostly yes	5 - absolutely yes
Data privacy	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑
Ensure thermal comfort	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑
Legal responsibilities	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑

Other (please specify below)

______

9. Are there any national rules/guidelines/standards/technical specs defining minimum requirements for substations?

____
____
____
____
____
____

10. What amount of energy or load - as a share of your total generated - would be beneficial to be shifted and/or saved?

____
____
____
____
____
____

11. Would you be willing to invest in the district heating/district cooling system to implement the option to control the heating/cooling consumption of your customers?

	1 - absolutely not	2 - mostly not	3 - probably	4 - mostly yes	5 - absolutely yes
Investments	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑

12. How important are following benefits for you to implement demand response concept in your district heating/district cooling system?

	1 - not important	2 - of little importance	3 - moderately important	4 - important	5 - very important
CO2 emissions savings	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑
Production cost savings	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑
Distribution cost savings	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑
Peak load reduction	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑
Renewable energy share increase	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑
Possibility of fault detection at customers' heating/cooling installations	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑

Prestige among competitors	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑

Other (please specify below)

______

13. How important are barriers that could hinder the deployment of demand response concept in your district heating/district cooling system?

	1 - not important	2 - of little importance	3 - moderately important	4 - important	5 - very important
High cost of technologies	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑
High complexity level of control	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑
Insufficient or unclear benefits	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑
Lack of customers' acceptance and trust	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑
Lack of appropriate regulation	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑
Lack of real-life experience	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑
Lack of technical standardisation	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑
Data privacy and protection problems	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑
The reduced potential market makes it unattractive to develop them	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑

Other (please specify below)

______

14. Would the following incentives be able to convince your customers to engage in the demand response concept?

	1 - absolutely not	2 - mostly not	3 - probably	4 - mostly yes	5 - absolutely yes
Monetary savings	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑
CO2 emission savings	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑
Energy savings	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑
Higher comfort	(1) ❑	(2) ❑	(3) ❑	(4) ❑	(5) ❑

Other (please specify below)

______

15. How relevant to the market is the development of concepts and technologies for intelligent heating/cooling grids - will they have a direct influence on your planning or operation in the future?

	1 - not much	2 - a little	3 - somewhat	4 - much	5 - a great deal
Influence on future decisions	(1) ❍	(2) ❍	(3) ❍	(4) ❍	(5) ❍

16. Have you heard about or do you see any business model of the demand response concept in district heating/district cooling systems? If yes, could you shortly describe it?

____
____
____
____
____
____

17. How important for you would be policy measures or directives for the dissemination of demand response concept in district heating/district cooling systems?

	1 - not important	2 - of little importance	3 - moderately important	4 - important	5 - very important
Policy measures and laws for implementation	(1) ❑	(3) ❑	(2) ❑	(4) ❑	(5) ❑

18. Which country do you come from?

____
____
____
____
____
____

19. What is your gender?

(1) ❍ Male
(2) ❍ Female
(3) ❍ Non-binary

20. What is your age

(1) ❍ Below 30 years
(2) ❍ 30-39 years
(3) ❍ 40-49 years
(4) ❍ 50-59 years
(5) ❍ 60-69 years
(6) ❍ Above 70 years

21. What is your highest (finished) education level?

(1) ❍ Secondary School
(2) ❍ High School
(3) ❍ University level

22. In which branch do you work? (e.g. planner, grid operator, contact with customers)

____
____
____
____
____
____

23. What kind of position do you have in your company?

(1) ❍ Director
(2) ❍ Middle management
(3) ❍ Technical management
(4) ❍ Controlling
(5) ❍ Team leader
(6) ❍ Other

24. Is your company dealing with anything else than the supply and distribution of district heating/cooling?

____
____
____
____

25. Is your company in District heating OR District cooling OR District heating & cooling sector?

(1) ❑ District heating sector
(2) ❑ District cooling sector
(3) ❑ Both sectors

26. If you feel comfortable with it, please give the name of your company
NB! This information will be used only for describing statistics behind the survey, NO specific names will be public available!

ANNEX 84

EBC

Energy in Building and Communities Programme

www.iea-ebc.org