ANNEX 84

EBC

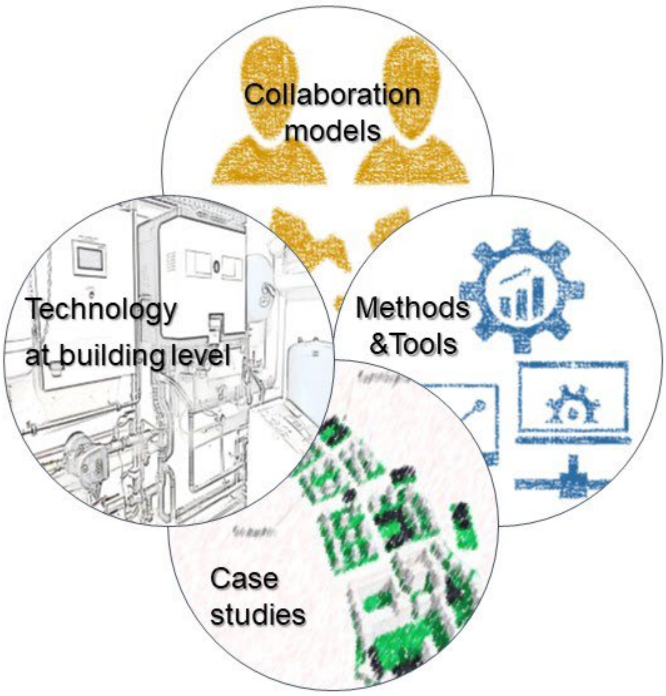
Energy in Building and Communities Programme

International Energy Agency

# Demand management of buildings in thermal networks Project Summary Report (Annex 84)

## Energy in Buildings and Communities Technology Collaboration Programme

May 2025




Technology Collaboration Programme

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ANNEX 84

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## Energy in Buildings and Communities Technology Collaboration Programme

May 2025

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# Preface

## The International Energy Agency

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

## The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)
The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.
At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

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

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

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

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

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

## The Executive Committee

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

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and 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
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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 the Subtask A 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.
**Incentivize Customer Participation:** Use financial, environmental, and energy-saving incentives to engage consumers effectively.

Also, the report aims to summarise the work of Subtask B indicating the complex relationship between building types and district heating and cooling (DHC) systems in Europe, with a focus on demand-side management (DSM), the technologies and strategies that can enhance energy efficiency, sustainability, and demand response in buildings connected to DHC network, the current technical state of DHC substations, and the overarching evaluation all technological elements discussed to assess their impact and significance, as well as to rate the flexibility of a proposed concept.

Moreover, the report aims to provide a comprehensive overview, delivered by Subtask C, of cutting-edge 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 processing and analysis, automated fault detection, and digital twins for orchestrating smart thermal operations and demand response of buildings integrated into thermal grids. The focus is on achieving energy-efficient, cost-effective, and sustainable district heating and cooling systems.

The report presents the key findings from the questionnaire developed for Subtask D, which served as a standardised framework for collecting and documenting relevant information about 29 DSM implementations and projects in district heating (DH) networks.

Finally, this document should guide professionals, researchers, policymakers, and stakeholders interested in the latest advancements in building energy management that benefit district heating and cooling systems.

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# 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/decentralised 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 decentralised 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 indoor environmental quality (IEQ) monitoring equipment for real-time data modelling of thermal demand response potential in buildings and urban districts.
- Disseminate lessons learned from case studies.

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).

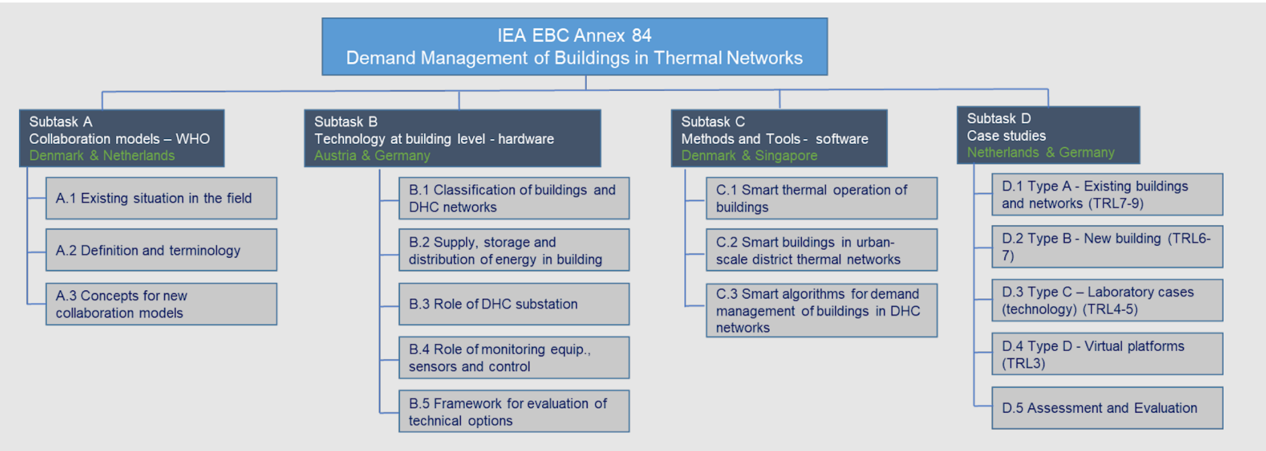


**Figure 1:** Structure of the IEA EBC Annex 84

## 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.

Finally, to address the topic of demand management/response of buildings in thermal networks comprehensively and uniformly the Annex 84 has adopted the terminology, which is technology agnostic and presented in Figure 2.

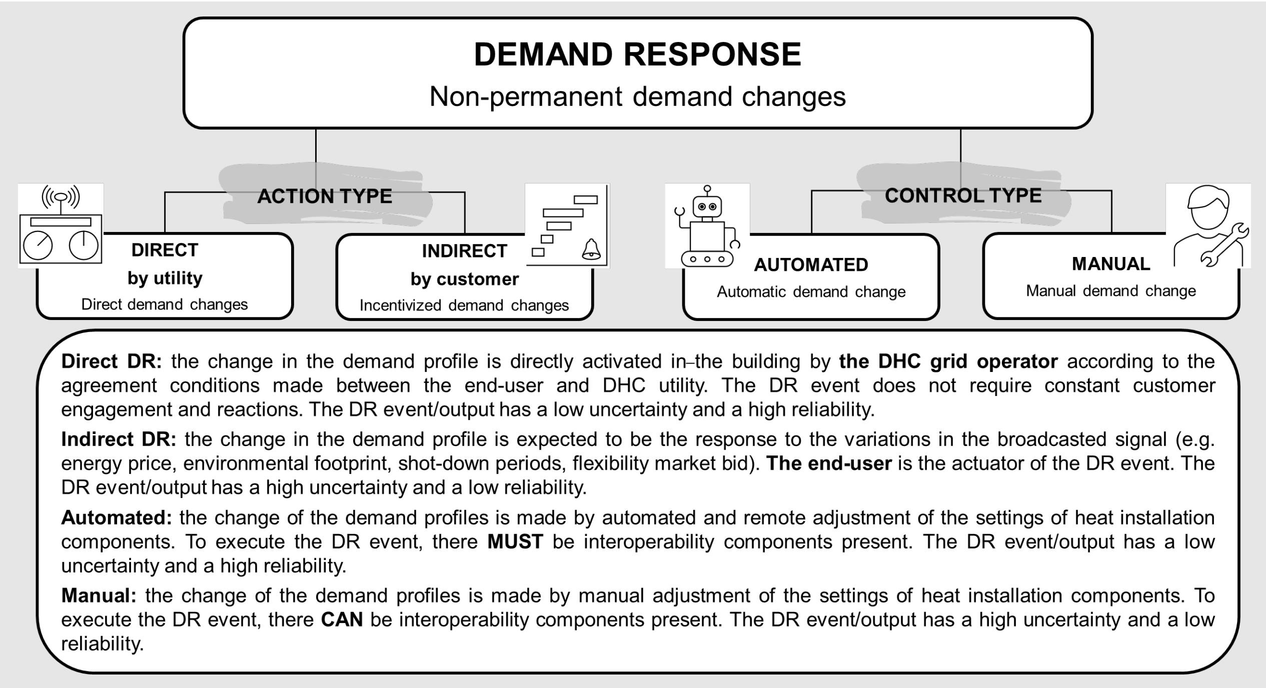


**Figure 2:** Terminology applied in IEA EBC Annex 84

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), action and control types are characterised by high reliability; 2) **Indirect Automated** (e.g. model predictive control in the building reacting to the DHC broadcasted signal), action and control types are characterised by low & high reliability, respectively; 3) **Direct Manual** (e.g. DHC operator vising the house or sitting in the control room and pressing the button), action and control types are characterised by high & low reliability, respectively; 4) **Indirect Manual** (e.g. end users changing the settings physically of via using the remote technology (walking in the house, sitting on the sofa and using app)  as the reaction to the broadcasted signal), action and control types are characterised by low reliability. Figure 3 presents the visualisation of the four DR types.

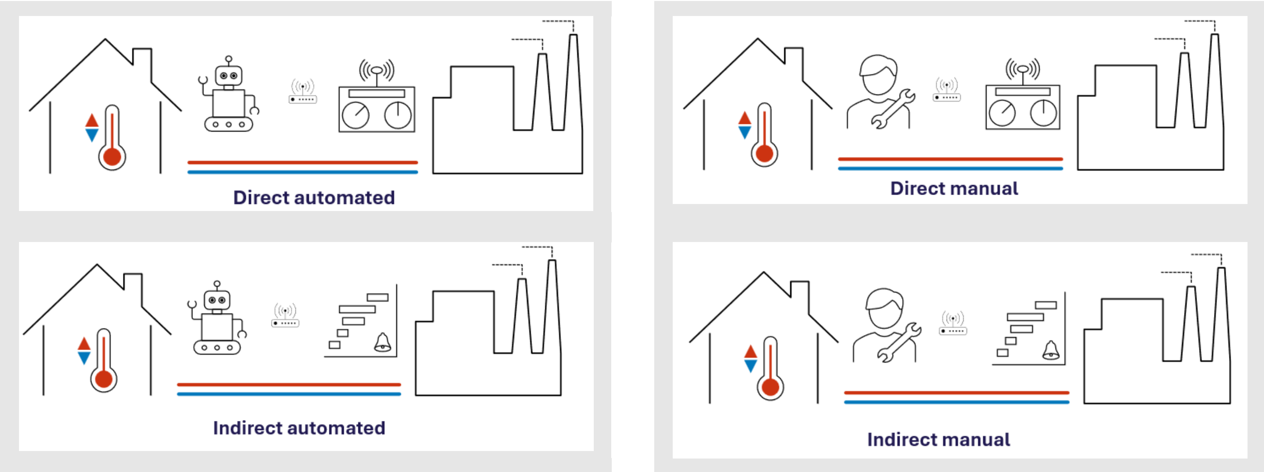


**Figure 3.** Illustration of the four types of DR according to Annex 84

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.

# 2. Subtask A: Collaboration Models

Within Annex 84 “Demand management of buildings in thermal networks”, Subtask A 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

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.

# 3. Subtask B: Technology at Building Level

Within Annex 84 "Demand management of buildings in thermal networks", the objective of Subtask B was to:

- Collect information on which technological options exist to enable demand response in buildings connected to thermal grids
- Evaluate their current market readiness or research status
- Evaluate their technical and economic potential
- Highlight limitations and bottlenecks
- Collect examples
- Evaluate to what extent demand response by selected technical options – in combination with each other and with a control strategy and system – improves the performance of a DHC system

**B.1 – Classification of building types connected to DHC systems** aimed to explore the complex relationship between building types and district heating and cooling (DHC) systems in Europe, with a focus on demand side management (DSM). The work item investigates the adoption of DHC systems across European nations, highlighting regional variations in efficiency and development, and emphasizing the potential for DSM within DHC networks, which is influenced by network infrastructure properties. The study also delves into the utilization of building structures as heat storage media, considering factors like thermal capacity and conductivity. Through a case study in Aalborg, Denmark, it underscores the importance of high-resolution data in understanding heat consumption patterns and the impact of building characteristics. The research aims to inform strategies for more sustainable energy management in Europe by leveraging building-specific attributes.

**B.2 – Supply, storage, and distribution of heat, cold, domestic hot water, and electricity at the building level for demand response and flexibility options** aimed to comprehensively investigate and understand the technologies and strategies that can enhance energy efficiency, sustainability, and demand response in buildings connected to DHC networks. Therefore, this work item includes the collection of case studies and best practices, the evaluation of thermal storage, the assessment of distribution technologies, and the examination of supply technologies in buildings. It should be noted that the storage technologies addressed in this work item have no relation to the substation (e.g., PCM, building thermal mass, thermally activated components, etc.)

**B.3 – Role of DHC substations as an element in demand response at the building scale** concentrated on the current technical state of DHC substations. It aims to provide an overview of the technical equipment and components in various substation design options. Special emphasis is placed on national peculiarities, guidelines and technical rules, as well as the legal framework in different countries where DHC is used. A classification of DH substation design is provided, and the minimum requirements for the technical equipment of DHC substations are outlined. With the aim of developing some kind of flexibility readiness measure for the thermal flexibility a particular substation can provide to the thermal grid, the flexibility options of typical substation components are investigated.

**B.4 – Role of monitoring, sensoring, and control technology** aimed to provide an overview and evaluation of the role of Monitoring, Sensoring and Control technology as a demand response option in combination with a DHC system, highlighting their potential and limitations.

**B.5 - Evaluation & Summary** focused on the summary and overarching evaluation of the results from work items B.1 – B.4. The summary highlights the main findings of each work item, while the overarching evaluation identifies synergetic and compatible options. An approach is presented for the systematic evaluation of all elements discussed in Subtask B (and the whole Annex) to assess their impact and significance, as well as to rate the flexibility of a proposed concept.

Key conclusions of Subtask B:

1. **Diverse building stock requires tailored DSM strategies:** The DSM potential varies significantly depending on building typology and construction year. For example, buildings constructed after 1980, typically featuring better insulation and higher thermal mass, offer better conditions for flexibility. In contrast, older buildings often need targeted retrofitting to be viable for demand response.

2. S**ynergies across system levels:** Effective DSM implementation demands coordinated actions across buildings, substations, and the network. Optimising at the building level alone often results in suboptimal outcomes unless guided by central orchestration and a shared data infrastructure.

3. **High-quality data underpins reliable flexibility:** Control strategies and predictive models depend heavily on precise, high-resolution data. The limited granularity and availability of operational data from substations and end-user devices significantly hinder the effectiveness of flexibility activation and measurement.

4. **Gap between technological potential and control systems:** Although DSM-enabling technologies like phase change material (PCM) storage and smart heat interface units (HIUs) are technically advanced, their capabilities are often underutilized due to a lack of responsive and mature control algorithms aligned with DHC signals.

5. **Integration of heterogeneous technologies remains challenging:** The absence of standardized communication protocols and limited interoperability between devices hamper large-scale DSM deployment. This is particularly problematic in building portfolios that include a mix of modern and legacy systems.

# 4. Subtask C: Methods and Tools

Within Annex 84 “Demand management of buildings in thermal networks”, Subtask C provided a comprehensive 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, automated fault detection and digital twins for the orchestration of the smart thermal operation, and demand response of buildings integrated into thermal grids.

Key conclusions of Subtask C:

1. **Only a few of the existing commercial modelling tools used by engineers and operators are suited for the simulation, study and optimisation of cluster of buildings performing demand response and building-to-grid services for thermal networks**. Advanced multi-domain modelling and co-simulation frameworks capable exist and can handle many aspects of the coupling between the indoor thermodynamics of the buildings, heating and cooling networks, and advanced control strategies. However, they come with a sharp learning curve. Moreover, despite the growing adoption of the Functional Mock-up Interface and the development of application programming interfaces for general-purpose programming languages like Python or MATLAB, interoperability issues remain and hinder seamless integration between different domain-specific modelling tools. Furthermore, model scalability remains a challenge in terms of computation time and solver stability. At the moment, it is difficult to run large-scale dynamic simulations with thousands of buildings operating under hourly time steps to provide demand response services to a thermal grid over a full year. Future development of building and thermal network modelling tools should be more user-friendly, simplifying co-simulation frameworks and improving documentation to lower the entry barrier for engineers and utility operators, while maintaining a balance between accuracy and computational efficiency when scaling up in building cluster size.

2. **Several solutions and research directions are gaining traction and popularity as they present great potential to improve efficiency of district heating and cooling networks and the smart operation of building clusters providing building-to-grid services**. The increasing availability of smart heat meter data with hourly temporal resolution unlocks new opportunities to gain key insights on the building end-users for district heating utility companies. Detailed knowledge about space heating and sanitary hot water demand profiles in large clusters of buildings is necessary to detect underperforming systems, optimize the operation of the entire thermal network, and develop new business models and advanced control strategies to improve supply/return fluid temperature and mitigate peak production bottlenecks. Active research is being carried out to ease and advance big data analytics for district heating and cooling systems, to tackle pre-processing challenges such as imputation of missing data, low measurement resolution of energy demand, or disaggregation of space heating and domestic hot water production from total main smart heat meter data.

3. **The continuous stream of high-resolution building data can also be leveraged to generate and run digital twins of district heating and cooling systems (Virtual replicas of physical systems with two-way communication to the latter).** Digital twins can help with real-time performance assessment and forecasting, energy and cost optimization of thermal network operation, peak load management, integration of renewable energy sources and fault detection and diagnosis. Regarding the

latter, increasing efforts are dedicated to the development of AI- and machine learning-based algorithms for the automated detection and diagnosis of faults in district heating and cooling networks and their related sub-systems inside the buildings. The systematization of such frameworks would unlock predictive maintenance at scale and greatly contribute to the overall energy and cost efficiency and service reliability of thermal networks. However, the main challenge in the further development of automated fault detection and diagnosis algorithms remains to be the lack of high-quality data with standardized labeled ground truth on fault status, origine and consequences.

4. **Greater efforts should be dedicated to real-world implementation, deployment and demonstration of these aforementioned applications and demand response strategies across the large diversity of data structures, hardware, software, systems, customers, control strategies and communication protocols.** Currently, their interoperability, portability, and scalability are limited, hindering business models supporting them. The use of standardized ontologies, building information models, and semantic principles are seen as key technologies to tackle these challenges and unlock seamless deployability.

# 5. Subtask D: Case studies

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

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

In total 29 case studies on DSM in DH networks have been collected and analysed. Each case study is associated with a distinct research project involving various stakeholders, including universities, research institutions, and private companies, often collaborating in consortiums. The projects span from 2010 to 2025, predominantly located in European countries, particularly Denmark and Germany, reflecting a strong interest in implementing DSM within buildings connected to DH networks. A concise summary of each project, highlighting key information together with a classification of the status of the research project and the DSM implementation progress.To facilitate the dissemination of the case study analysis a case study brochure and a presentation with case study profiles have been created [21]. The primary intent of the case study brochure is to showcase practical implementations and facilitate stakeholder understanding of successful projects through visually engaging and accessible content on a higher level.

The comparative analysis of the collected case studies within this report provides insights into various approaches and best practices. Among the 29 case studies, 23 are from completed projects, with an average project duration of three years. The case studies encompass a variety of scales, including individual buildings and larger networks, with seven focused on single buildings and the remainder involving multiple structures, often utilizing only a portion of the connected heating networks for experimental purposes.
The thermal energy storage is the predominant storage type utilized, with a total of 27 systems identified. Among these, 21 are decentralized, with 17 leveraging building mass as part of their storage strategy. Only one project is dedicated to supplying space cooling, which is located outside the district heating network context.

Furthermore, the analysis shows that load shifting is the primary purpose of the DSM measures investigated, with 55% of the case studies focused on this aspect. Other objectives include load shedding and efficiency improvements, with 29% of case studies incorporating load shedding as a goal. The anticipated benefits of the DSM measures mainly extend to the DH grid operator and indirectly to customers, with 13 case studies benefiting this way. Additionally, six case studies provide direct benefits to both the DH grid operator and customers. There are five case studies where only the DH grid operator benefits, and just one case study exclusively benefits customers. Cost reduction is a common objective, as seen in 14 case studies aimed at decreasing expenses associated with peak boiler operation, while seven seek to lower CO2 emissions. Approximately half of the case studies investigate DSM measures activated by the DH operator. Various approaches to DSM implementation are observed, including active and indirect measures, collective measures (such as installing smart home technology), and tariff structures. Most studies focus on the interaction between buildings and the grid, with daily load management being the standard timescale for implementation.

Key lessons learned and recommendations for stakeholders involved in DSM implementation in buildings connected to DH grids are:

1. **Building and System Considerations**: Implement decentralized room-level control strategies and recognize heavy buildings as valuable thermal storage assets. Quantify thermal storage capacity in degree hours and prioritise targeted preheating in specific zones. Short intervention periods can achieve peak reductions, and hybrid networks should be explored for summer shutdowns to reduce energy losses.

2. **Control Strategies and Technology:** Coordinate DSM triggers with energy management systems and extend prediction horizons in demand forecasts. Avoid partial control of radiators in economic model predictive control (E-MPC) implementations and prioritise domestic hot water during peak periods. Ensure thermostats remain on to prevent condensation and maintain minimum temperatures.

3. **Occupant Engagement and Communication:** Clearly explain DSM functions and benefits to occupants before implementation. Frame participation as a collective achievement and emphasise economic and environmental benefits. Allow occupants some control over temperature settings and provide app notifications with personalised recommendations.

4. **DSM Implementation Approach:** Address building-related issues before implementing DSM and design shorter demand response events for high override risk buildings. Simple, cost-effective data-driven DSM solutions should be prioritised, and thorough stakeholder consultation is essential.

5. **Pitfalls to Avoid:** Avoid treating buildings as simple load points, creating new demand peaks, and ignoring occupant engagement. Do not reduce temperatures during already cold periods, and refrain from overly complex solutions when simpler alternatives exist.

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ANNEX 84

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