ANNEX 84

EBC

Energy in Building and Communities Programme

International Energy Agency

Demand Management of Buildings in Thermal Networks: Evaluation and Summary (Annex 84, Subtask B)

Energy in Buildings and Communities Technology Collaboration Programme

May 2025

Technology Collaboration Programme

by iea

ANNEX 84

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Demand Management of Buildings in Thermal Networks: Evaluation and Summary (Annex 84, Subtask B)

Energy in Buildings and Communities Technology Collaboration Programme

May 2025

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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.

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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
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: EBC Annex 90 / SHC Task 70 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 objective of Subtask B of the IEA EBC Annex 84 is 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

Subtask B is organized into five work items:
B.1 – Classification of building types connected to DHC systems
B.2 – Supply, storage, and distribution of heat, cold, domestic hot water, and electricity at the building level for demand response and flexibility option
B.3 – Role of DHC substations as an element in demand response at the building scale
B.4 – Role of monitoring, sensoring, and control technology
B.5 – Evaluation & Summary

The key conclusions of Subtask B are:

- **Building stock diversity requires tailored DSM strategies:** The DSM potential varies significantly across building typologies and construction periods. For instance, post-1980 buildings with improved insulation and higher thermal mass offer better conditions for flexibility, while older stock may require targeted retrofitting to be viable for demand response.
- **Building-level heat load profiles are key indicators for DSM potential:** High-resolution consumption data reveals that heat demand variability—especially peak loads—is closely linked to specific building characteristics. This underscores the importance of using typology-specific load profiling as a precondition for identifying viable DSM candidates within a DHC network.
- **Synergies across system levels:** Effective DSM requires coordination across building, substation, and network levels. Isolated optimization at the building scale often leads to suboptimal system-wide outcomes unless supported by central orchestration logic and shared data infrastructure.
- **Data quality is critical for actionable flexibility:** Many control strategies and predictive models rely heavily on accurate, high-resolution data. The limited availability and granularity of operational data from substations and end-user devices significantly constrain the reliability of flexibility activation and measurement.
- **Mismatch between hardware potential and control logic:** While many DSM-enabling technologies (e.g. PCM storage, smart HIUs) are technically mature, their benefits are often underexploited due to missing or underdeveloped control algorithms that respond dynamically to DHC signals.
- **Heterogeneous technology integration remains a challenge:** The lack of standardized communication protocols and device interoperability poses a barrier to wide-scale DSM deployment, especially in mixed building portfolios with legacy equipment.

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Abbreviations

Abbreviations	Meaning
AI	Artificial Intelligence
DH	District heating
DHC	District heating and cooling
DHN	District heating networks
DHW	Domestic hot water
DSM	Demand-side management
EU	European Union
KPIs	Key performance indicators
IoT	Internet of Things
MFH	Multi-family houses/homes
ML	Machine Learning
PCM	Phase change material
SFH	Single-family house/homes
SH	Space heating
TRL	Technology Readiness Level
TH	Terraced house
U-values	Thermal transmittance values

1. Introduction

1.1 General Context

Buildings are becoming smarter due to the widespread availability of connected devices, sensors, actuators and appliances, which can improve the indoor comfort of occupants while reducing total building operational costs, energy, and environmental footprint. At the same time, space and water heating contribute to 45% of CO2 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 CO2 emissions reduction target for 2030 from 40% to 55%. The EU's "Fit-for-55" proposal aims to achieve this goal through enhanced energy efficiency and increased reliance on renewables. As a result of these international targets, both the DHC and electrical power sectors are undergoing significant transformations, striving to eliminate fossil fuels and boost the share of renewable energy sources (RES).

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

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

At the same time, every building connected to the DHC network can be seen as a decentralized TES solutions 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 [20-21]. 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 sub-tasks, each of which is further divided into several specific work items (see Figure 1 below).

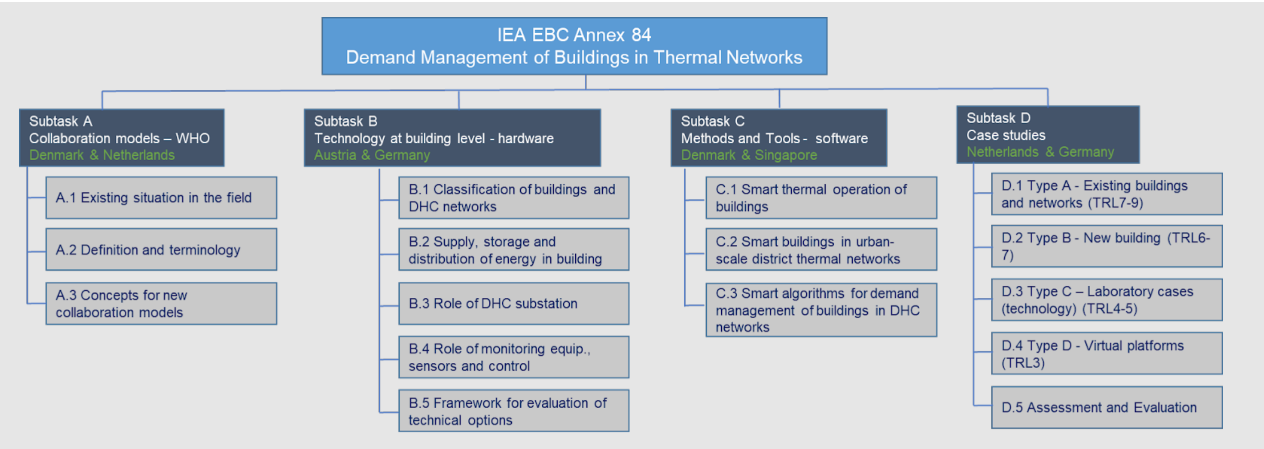

Figure 1: Structure of the IEA EBC Annex 84.

Subtask A: Collaboration Models

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

Subtask B: Technology at Building Level

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

Subtask C: Methods and Tools

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

Subtask D: Case studies

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

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

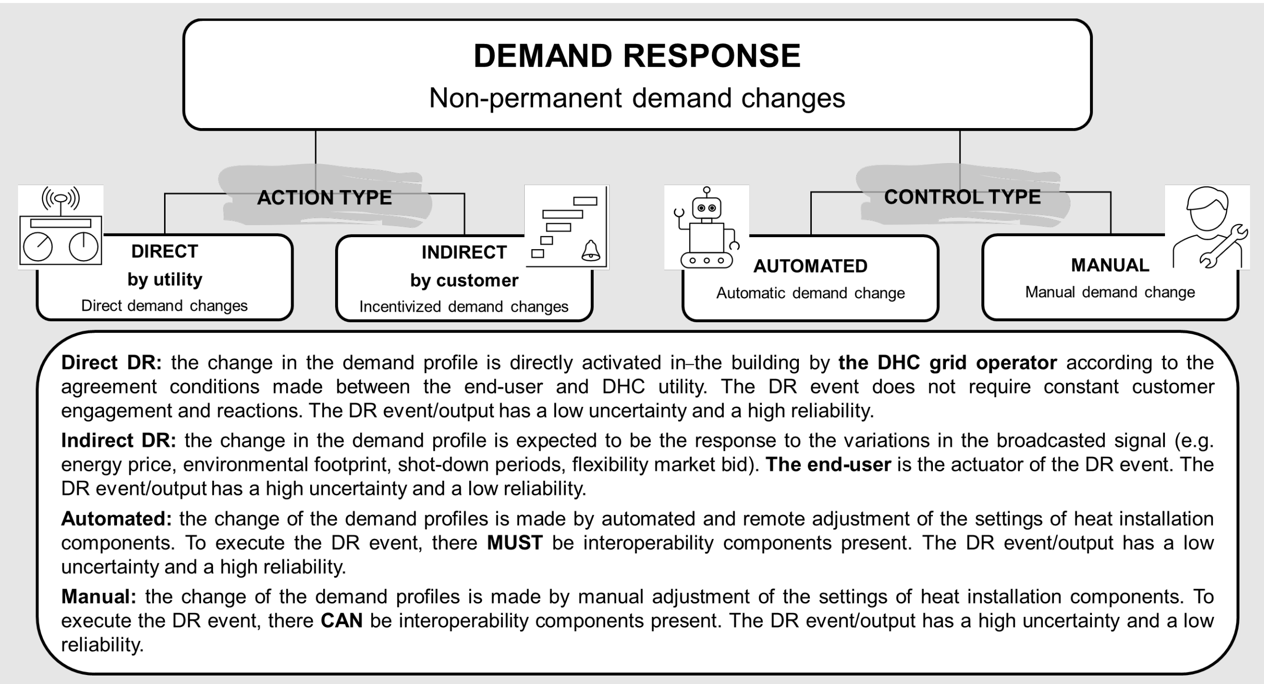

Figure 2: Terminology applied in IEA EBC Annex 84.

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

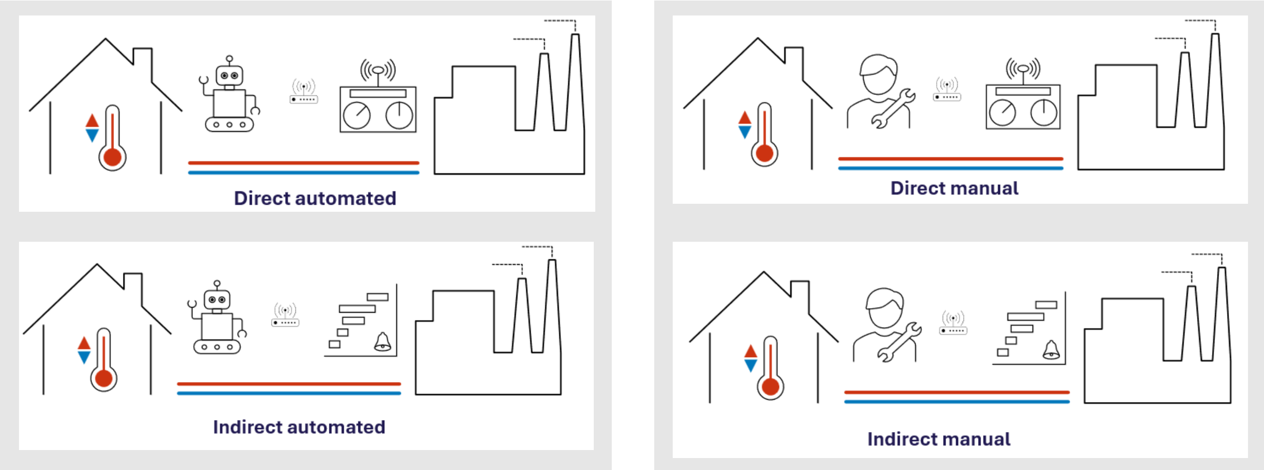

Figure 3. Illustration of the four types of DR according to Annex 84.

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 Overview of Subtask B and the Work Items B.1 – B.5

The objectives of Subtask B are 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

Subtask B is organized into five work items:

- B.1 – Classification of building types connected to DHC systems
- B.2 – Supply, storage, and distribution of heat, cold, domestic hot water, and electricity at the building level for demand response and flexibility option
- B.3 – Role of DHC substations as an element in demand response at the building scale
- B.4 – Role of monitoring, sensoring, and control technology
- B.5 – Evaluation and Summary

Work item B.1 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 Aal-borg, 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.

Work Item B.2 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.)

Work Item B.3 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.

Work item B.4 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.

Work Item B.5 focussed 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.

All work items have individual deliverables, in which the topics mentioned above are discussed in greater detail.

2. Content – Highlights from Work Item B.1 to B.5

The evaluation and summary of Work Item B.1 to B.5 provide a comprehensive synthesis of the findings of Subtask B on demand-side management potential in district heating and cooling networks. The results highlight key technological, operational, and structural aspects that influence DSM effectiveness, as well as the limitations and opportunities for future improvements.

2.1 Work Item B.1 – Classification of building types connected to DHC systems

Work Item B.1 focused on the classification of building types connected to DHC systems and their potential for demand response. The analysis considered buildings from seven European countries (Sweden, Norway, the Czech Republic, Bosnia and Herzegovina, Denmark, Germany and Slovenia), assessing their thermal mass characteristics, historical construction trends, and connection rates to DHC networks. Four types of buildings (single-family houses (SFH), terraced houses (TH), multi-family houses (MFH), and apartments) constructed in different periods (from 1850 to 2016) were examined to determine their suitability for DSM.

Among the studied countries, Denmark has the highest connection rate of SFH to the networks compared to the other countries, while Slovenia and Norway have the lowest connections (see Figure 4). Although SFH and TH may have a lower DSM potential compared to MFH and apartments, the actual energy savings achievable depend on factors such as the prevalence of these building types and their construction timelines within a city.

The findings show that while MFH and apartment buildings generally exhibit the highest connection rates to DHC networks, SFH in certain regions, such as Denmark and Sweden, still represent a significant share of district heating consumers. The study also identified that the potential for demand response varies with the thermal properties of buildings. Structures built before 1980 often have lower thermal mass storage capabilities, whereas newer buildings with improved insulation offer better conditions for DSM implementation. SFH and TH have a lower DSM potential compared to MFH and apartments. Among the seven countries analysed, the Czech Republic exhibits the highest potential for DSM activities due to having the largest proportion of MFH, with 35% connected to DH. Bosnia and Herzegovina and Germany follow, each with 13%. Despite this, the actual energy savings depend on factors such as the prevalence of these building types and their construction periods within a city [22], [23].

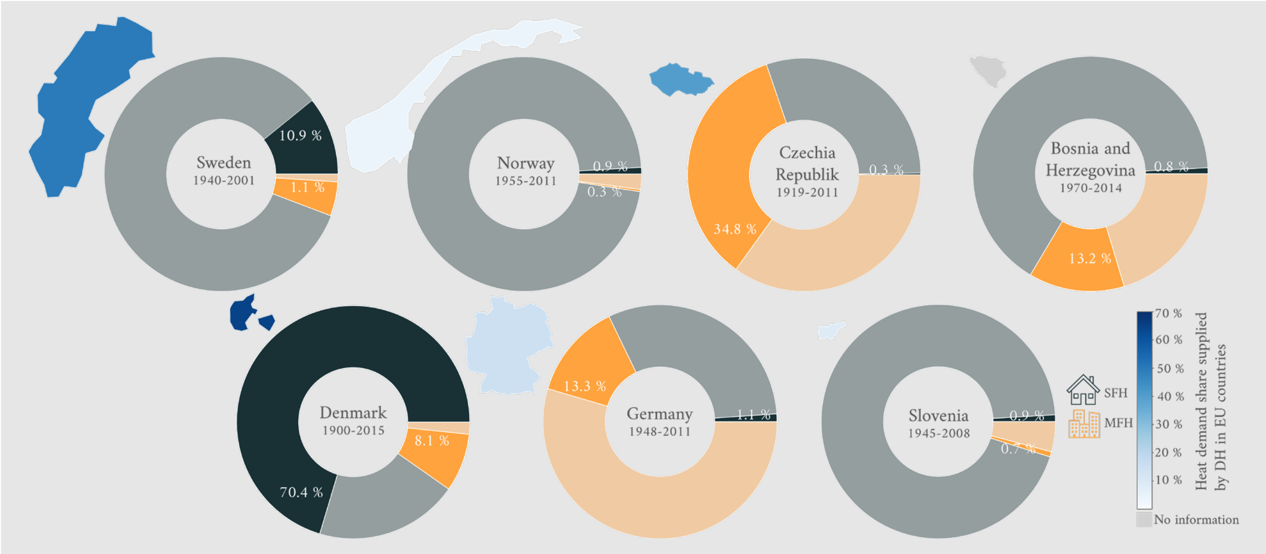

Figure 4: The total proportion of buildings in the seven countries that have SFH and MFH connections to district heating networks (AEE INTEC, Data: [22], [23])

Apartment blocks and MFH generally have the highest connection rates (percentage) in each EU country. However, the absolute number of SFH connected to district heating networks is higher than that of MFH in Sweden and Denmark. Slovenia and Norway have the lowest connection rates since these two countries have low DHN connectivity. Denmark has one of the highest connection rates to district heating grids in Europe in the range of 30% to 40%.

In Germany, large multi-family homes (i.e., apartment blocks) from the post-war period between 1949–1978 have high connection rates. Apartment blocks built between 1949 and the present have a connection rate of approximately 25–35%. Single family homes have a significantly lower connection rate of between 2–3%, though newer SFH (post 2011) have a connection rate of approximately 7%. The overall connection rate of residential buildings is relatively low, with only 12% of single-family homes (detached/terraced) connected to district heating networks [22], [23].

In district heating systems, balancing energy demand and production is often managed by storing generated energy for later use. One approach uses the building's structure as a heat storage medium, leveraging its thermal mass – walls, roofs, and furniture – to store and slowly release heat, although this varies with building characteristics [24]. A building with high thermal capacity offers greater heat storage potential, while high thermal conductivity leads to significant heat losses. However, this approach is not straightforward due to the wide variety of building characteristics, such as volume, shape, construction materials, and insulation [25].

To address the U-values for different buildings and construction years in seven different countries, spanning from 1850 to 2016, were collected to examine the heat thermal capacity and conductivity of the buildings. The analysis of buildings in various European countries showed improvements in insulation standards over time, affecting their suitability for DSM. It was concluded that building constructed before 1980 have a limited capacity for heat storage and rapid heat exchange. In contrast, buildings constructed after 1980 are to be situated in the region characterized by the gradual storage of a larger amount of energy over time, thus offering the highest potential for thermal mass utilization [23].

A case study of Aalborg's district heating network highlighted the importance of high-resolution heat meter data in understanding and predicting heat consumption, influenced by both climate and occupant behaviour. Key performance indicators (KPIs) such as daily and seasonal heat load variations, help identify buildings more likely to contribute to peak loads, with older buildings showing less variation than newer, highly insulated ones. These insights aid in assessing the suitability of buildings for demand response measures based on their heat demand profiles [26], [27].

2.2 Work Item B.2 – Supply, storage and distribution of heat, cold, domestic hot water, and electricity on building level for demand response and flexibility option

In Work Item B.2, the focus shifted to the technological solutions available at the building level that can support DSM. The evaluation included a detailed examination of supply, storage, and distribution technologies, with an emphasis on their technical feasibility and economic implications. The report provides a comprehensive analysis of case studies, research projects, and best-practice examples focused on these technologies. It summarizes outcomes of these case studies, emphasizing their applicability to demand response, technical and economic performance, and required technologies.

Table 1 highlights the limitations of the technologies studied in Work Item B.2.

Table 1: Summary of the technologies based on case studies

Technology	TRL	Flexibility enabler	Load-Shifting period	Limitations	Hardware	Building Type
PCM (Storage) [28]	7–9	Cooling, DHW Electricity	Daily - Weekly	Higher investment costs	Available IoT integrated components	126 apartments (South Korea)
Decentralized Substation (Distribution) [29], [30]	9	Cooling, DHW	Daily	High upfront costs for equipment, installation, and infrastructure. Requires regular maintenance. Lack of secondary-side data. Country-dependent feasibility.	Smart heat meter (at least at the primary side)	11 buildings (Sweden) / real-world villa
Smart heat interface units (Distribution)	7–9	Heating, DHW, Electricity	Daily	Expensive intelligent control concepts. Shortage of monitoring data regarding rebound effects and rental models.	Smart devices	Multi-storey residential apartment building (Denmark)
Hydronic Radiator (Distribution) [31]	9	Cooling	Daily	Low thermal mass, limiting long-term load shifting feasibility.	Availability of IoT for advanced automated control	Detached SFH (Denmark)
Electric Resistance Heater (Supply) [32]	9	Heating, Cooling, DHW, Electricity	Hourly	Lack of communication between thermal and electrical grids. Electricity use may not always be cost-effective or sustainable for the DH grid. Ownership of power and heating grids is often not shared.	Available IoT integrated components SCADA system, smart heat electricity meters	23 terraced and SFH (simulation, LTDH, Denmark)
PreHeat Control in substation (Supply) [33]	7–9	Heating	Daily	Requires individual agreements with customers.	IoT unit, motorised control valve, 4G SIM card	90 apartments (Denmark)

				Experience mainly limited to houses with underfloor heating		

Phase Change Materials, for example, were identified as effective for shifting heating and cooling loads on a daily to weekly basis. However, their adoption is currently hindered by high initial investment costs and limited real-world applications [28]. Decentralized substations and smart heat interface units showed promise in enabling more flexible heating and domestic hot water management, but their performance remains highly dependent on intelligent control strategies and the availability of real-time monitoring data [29], [30].

The heat meter collects combined DHW and space heating load information, requiring statistical methods to separate the two loads. Instead of each building having its own outdoor temperature sensor, a centralized system collects outdoor temperature data for a group of buildings. This approach helps to mitigate control errors that arise from issues such as malfunctioning or inaccurately positioned sensors.

The analysis also highlighted a lack of integration between thermal and electrical grids, particularly with electric resistance heaters, which – while providing short-term flexibility – do not always align with the cost and sustainability objectives of DHC operators. Lessons learned from Work Item B.2 emphasize the importance of adaptive control mechanisms, improved thermostat compatibility for retrofitting, and centralized outdoor temperature measurement to enhance system efficiency and prevent overheating. Additionally, a key recommendation emerging from this work is the need for standardized communication protocols between smart devices and DHC systems to enable real-time optimization and dynamic control.

The following recommendations for DSM application were derived:

- Develop better adapter systems for mounting modern thermostats on old radiator valves.
- Customize radiator set points to balance energy flexibility and return temperature.
- Implement weather compensation and flow rate adjustments to prevent overheating.
- Explore alternative methods for separating space heating and domestic hot water data.

2.3 Work Item B.3 – Role of DHC substations as element in demand response option on building scale

Work Item B.3 explored the role of DHC substations as critical elements in demand response at the building scale. The findings confirmed that, historically, DHC substations were designed primarily to ensure secure and stable heat supply rather than to enable flexible operation. As a result, existing substations often lack the necessary control mechanisms to facilitate active demand response participation. The study highlighted the need for improved substation design, including advanced control strategies, remote monitoring capabilities, and predictive algorithms that can dynamically adjust to fluctuating heating and cooling demands. Additionally, various retrofitting options were explored, with particular attention given to the integration of small-scale heat pumps to improve sector coupling between heating and electricity networks. The introduction of a standardized framework for assessing substation flexibility readiness was also recommended to support DHC operators and policymakers in prioritizing investment decisions. One critical takeaway from this study was the role of network-wide coordination in maximizing the flexibility potential of individual substations, as isolated optimization efforts at the building level may not yield substantial system-wide benefits (more details to be found in Deliverable Annex 84 Work Item B.3).

Further analysis revealed that the flexibility of a DHC substation depends on multiple factors, including the type of heat exchanger used, the availability of variable-speed pumps, and the integration of advanced control systems. Current substations are typically designed to operate with fixed supply temperatures and flow rates, which limits their ability to adjust dynamically to real-time heating and cooling demands. A more adaptive approach that integrates smart control solutions would allow substations to respond to varying loads and optimize system performance based on real-time data. For example, incorporating weather-compensation algorithms could adjust supply temperatures according to outdoor conditions, improving energy efficiency while maintaining comfort levels in connected buildings [34], [35], [36], [37] .

One of the key technological advancements discussed in Work Item B.3 was the role of smart thermostats and indoor temperature sensors in improving substation performance. By utilizing real-time occupancy and temperature data, substations could distribute thermal energy more effectively, preventing overheating or underheating. However, implementing such solutions requires overcoming challenges related to data integration and ensuring interoperability between different building management systems and DHC network control platforms. Establishing standardized communication protocols between substations and buildings is crucial for enabling seamless data exchange and optimal operation.

The study also examined the potential of demand-side thermal storage integration within substations, such as utilizing domestic hot water storage tanks to shift heating loads or employing phase-change materials to buffer short-term fluctuations. Substations that incorporate such thermal storage solutions could help mitigate peak loads, reduce energy costs, and enhance overall network resilience. The feasibility of implementing these technologies varies depending on building typology and occupant heating patterns, highlighting the need for case-specific assessments before widespread deployment (Deliverable Annex 84 STB.3 Section 2.4).

From a regulatory perspective, Work Item B.3 emphasized the necessity of policy measures to incentivize the adoption of flexibility-enhancing technologies in DHC substations. Current regulatory frameworks primarily focus on supply-side efficiency but often lack mechanisms to promote active demand-side flexibility. Incentive programs, such as time-of-use pricing and demand-response compensation schemes, could encourage building owners and DHC operators to invest in smart substation upgrades. Furthermore, new market structures that enable greater interaction between electricity and thermal grids would allow substations to participate in balancing markets, creating additional revenue streams for network operators.

Lastly, the report stressed the importance of real-world demonstration projects to validate the proposed substation flexibility strategies. While theoretical models and simulations provide valuable insights, field experiments are essential to understand practical implementation challenges and to refine optimization algorithms. Pilot projects in urban DHC networks could demonstrate the benefits of intelligent substation management, providing concrete evidence for policymakers and stakeholders considering large-scale adoption.

In conclusion, Work Item B.3 demonstrated that transitioning DHC substations from static heat supply units to dynamic demand response enablers requires a combination of technological, regulatory, and operational advancements. Implementing advanced control strategies, leveraging smart sensors, integrating thermal storage, and aligning policy incentives are critical steps toward unlocking the full flexibility potential of DHC substations. Future research should focus on refining interoperability standards, exploring AI-driven optimization techniques, and expanding pilot programs to demonstrate real-world benefits.

2.4 Work Item B.4 - Role of monitoring, sensoring and control technology

Work Item B.4 examined the critical role of monitoring, sensing, and control technologies in enabling DSM. The study found that while digitalization in the building sector has advanced significantly in recent years [38], the full potential of smart meters, sensors, and Internet of Things (IoT)-based control systems remains largely underutilized [39], [40], [41].

A key challenge identified was that existing metering infrastructure is primarily used for billing purposes rather than for real-time optimization of heating and cooling operations. The evaluation highlighted opportunities for leveraging artificial intelligence (AI)-driven fault detection to improve predictive maintenance and prevent system inefficiencies. Additionally, improvements in battery life and connectivity stability for wireless sensors were noted as essential for ensuring reliable long-term operation [38], [39].

The results suggest that a more systematic integration of smart monitoring and control technologies could substantially enhance demand response capabilities in buildings connected to DHC networks. One of the key insights was that utilizing existing infrastructure, such as heat meters, for real-time control and performance monitoring could provide a cost-effective pathway to unlocking additional demand-side flexibility. Furthermore, case studies demonstrated that real-time data analytics could be instrumental in identifying and addressing inefficiencies, such as suboptimal setpoints or malfunctioning components, before they lead to significant energy waste (more details to be found in Deliverable Annex 84 Work Item B.4).

2.5 Work item B.5 – Evaluation & Summary

Taken together, the findings from Work Item B.1 to B.4 provide a holistic view of the current state of demand-side management in district heating and cooling networks and lay the foundation for developing a comprehensive evaluation framework in Work Item B.5 (more details to be found in Deliverable Annex 84 Subtask B.5). The analysis underscores the importance of combining technological advancements with improved operational strategies, regulatory support, and market incentives to unlock the full potential of demand-side flexibility in district heating and cooling systems. The key conclusions of Subtask B are:

- **Building stock diversity requires tailored DSM strategies:** The DSM potential varies significantly across building typologies and construction periods. For instance, post-1980 buildings with improved insulation and higher thermal mass offer better conditions for flexibility, while older stock may require targeted retrofitting to be viable for demand response.
- **Building-level heat load profiles are key indicators for DSM potential:** High-resolution consumption data reveals that heat demand variability—especially peak loads—is closely linked to specific building characteristics. This underscores the importance of using typology-specific load profiling as a precondition for identifying viable DSM candidates within a DHC network.
- **Synergies across system levels:** Effective DSM requires coordination across building, substation, and network levels. Isolated optimization at the building scale often leads to suboptimal system-wide outcomes unless supported by central orchestration logic and shared data infrastructure.
- **Data quality is critical for actionable flexibility:** Many control strategies and predictive models rely heavily on accurate, high-resolution data. The limited availability and granularity of operational data from substations and end-user devices significantly constrain the reliability of flexibility activation and measurement.
- **Mismatch between hardware potential and control logic:** While many DSM-enabling technologies (e.g. PCM storage, smart HIUs) are technically mature, their benefits are often underexploited due to missing or underdeveloped control algorithms that respond dynamically to DHC signals.
- **Heterogeneous technology integration remains a challenge:** The lack of standardized communication protocols and device interoperability poses a barrier to wide-scale DSM deployment, especially in mixed building portfolios with legacy equipment.

While DSM potential exists across multiple building typologies and technical solutions, its large-scale activation requires an integrated approach that aligns technological innovations with policy frameworks, user engagement strategies, and economic incentives. Future efforts should focus on standardization, interoperability, and multi-stakeholder collaboration to ensure that the benefits of demand response are realized across entire DHC networks rather than in isolated pilot projects.

Recommendations for Additional Research and Demonstration Needs

- From Work Item B.1
  - Further studies on the impact of different building materials and insulation strategies on DSM potential across climate zones
  - Large-scale demonstration projects assessing the impact of different DSM strategies in diverse building typologies
  - Research on user behavior and incentives to increase participation in DSM programs
  - Development of policy frameworks that support building retrofitting measures for DSM
  - Exploration of business models for DHC operators to leverage DSM opportunities
- From Work Item B.2
  - Field studies on the real-world performance of PCM for thermal storage in DHC-integrated buildings
  - Investigation into interoperability and standardized communication protocols for smart heating devices
  - Development of cost-effective solutions for integrating small-scale thermal storage into existing building stock
  - Demonstration projects on dynamic pricing models incentivizing demand flexibility
  - Regulatory analysis on policy incentives for adopting decentralized substations
- From work item B.3
  - Development of a standard flexibility readiness assessment framework for substations
  - Large-scale pilot projects testing different smart substation configurations
  - Evaluation of the potential for integrating small heat pumps into existing DHC substations
  - Research on business models supporting the transition toward smart substations
  - Policy recommendations for incentivizing substation retrofitting with flexibility-enabling technologies
- From work item B.4
  - Development of AI-driven predictive maintenance tools tailored for DHC networks
  - Large-scale deployment of real-time monitoring and fault detection systems in existing DHC infrastructure
  - Regulatory analysis on data-sharing frameworks between buildings and DHC operators
  - Research on privacy and cybersecurity measures for smart monitoring systems
  - Investigation into scalable business models for third-party providers offering demand response analytics

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