ANNEX **84**

EBC
Energy in Building and
Communities Programme

International Energy Agency

Demand Management of Buildings in Thermal Networks (Annex 84) – Deliverable WI B.1: Classification of building types connected to DHC systems

Energy in Buildings and Communities Technology Collaboration Programme

March 2025

Technology Collaboration Programme
by iea

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Authors

Keith O’Donovan, AEE INTEC, AT (k.odonavan@aee.at)
Basak Falay, AEE INTEC, AT (b.falay@aee.at)
Ingo Leusbrock, AEE INTEC, AT (i.leusbrock@aee.at)

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essu@iea-ebc.org

Preface

The International Energy Agency

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

The IEA Energy in Buildings and Communities Programme

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

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

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

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

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

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

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

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

The Executive Committee

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

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO2 Equivalent Emissions for Building Construction (*)

Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Resilient Public Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
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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

In the pursuit of more sustainable energy practices, a closer look at the interplay between building typologies and district heating and cooling systems in Europe reveals a complex landscape. This examination emerges from the activities planned under the STB1 initiative, focusing on analyzing heating and cooling systems, reviewing connected buildings, deriving specifics for building types, and evaluating technical options for thermal storage and demand response.

European nations exhibit a wide-ranging connection to district heating and cooling (DHC) systems. While older district heating (DH) networks in Eastern Europe tend to be less efficient, Northern European countries like Denmark, Finland, and Sweden lead in DH adoption. District cooling (DC) networks, on the other hand, are less developed and primarily cater to the service sector. The suitability for demand-side management (DSM) in DH networks is closely tied to infrastructure properties. Older networks with higher operating temperatures often require upgrades before DSM implementation. Conversely, modern DH networks operate at lower temperatures, presenting new possibilities.

The key to utilizing the building's own structure as a heat storage medium lies in building characteristics. By providing heat at off-peak times, the building's mass (walls, roofs, and internal elements) absorbs and stores heat, allowing for gradual temperature adjustments. When aggregating over large clusters of buildings, the thermal storage capacity of the built environment is substantial and can be leveraged to help thermal grids operate more efficiently and integrate a greater share of intermittent renewable energy sources and industrial heat surplus.

The effectiveness of this storage method depends on the building's thermal capacity and conductivity. Buildings with higher thermal capacity offer more storage potential, while those with high thermal conductivity experience greater heat loss. The ratio between stored energy and thermal power needed for temperature control determines the feasibility of this approach. Well-insulated buildings excel in maintaining indoor temperatures, while those with high conductivity can charge their envelopes with excess heat. To assess buildings' suitability for demand-side management (DSM), the specific heat capacity and heat transfer coefficient were analyzed across various building types and construction years in seven European countries. Buildings constructed after 1980 demonstrated higher potential for thermal mass utilization. Single-family homes and townhouses showed lower DSM potential compared to multi-family houses and apartments. This analysis serves as a reference for DSM implementation.

A case study in Aalborg's district heating network in Denmark examined heat meter data from over 3,000 residential buildings. The study emphasized the importance of high-resolution data for understanding and predicting heat consumption patterns. Seasonal variations in heat demand were influenced by climate and building envelope properties. KPIs like Daily and Annual Relative Load Variation provided insights into how buildings contribute to peak loads. Building age, yearly heat demand, and dwelling type were found to influence these KPIs. Older buildings exhibited lower relative daily variations, while newer, better-insulated buildings had higher variability. The study demonstrated the potential of using smart heat meter data to assess a building's suitability for demand response measures.

Looking ahead, as Europe strives for more sustainable energy management, understanding the intricate relationship between building typologies and district heating and cooling systems becomes increasingly vital. It's not just about adopting greener technologies; it's about leveraging the unique attributes of each building to optimize energy use. With smart data analysis and innovative solutions, Europe can pave the way for a more energy-efficient future.

Table of content

Abbreviations

Abbreviations	Meaning
EPC	Energy Performance Certificate
DC	District cooling
DH	District heating
DHC	District heating and cooling
DHW	Domestic hot water
DSM	Demand-side management
Ga	Daily Annual Relative Load Variation
KPI	Key performance indicator
MFH	Multi-family houses/homes
PCM	Phase change material
resp.	Respectively
SFH	Single-family houses/homes
SH	Space heating
TH	Terraced houses
U-value	Thermal Transmittance, transfer of heat through structure

1. Scope and activities

1.1 Overview of Subtask B and Work Item B.1

The objective of Subtask B is to

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

Subtask B is organized in 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 on building level for demand response and flexibility option
- B.3 – Role of DHC substations as element in demand response option on building scale
- B.4 – Role of monitoring, sensoring and control technology
- B.5 – Evaluation and summary

Work item B.1 aims 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 emphasizes 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.

1.2 Activities

The work in Work Item B.1 concentrated on the following aspects:

- **Activity 1: Screening of heating/cooling systems installed in buildings.**
- **Activity 2: Overview of Buildings connected to thermal networks.**
  - Identification of connection rates of buildings to DHC networks for various countries
  - Classification of building stock connected to DH networks per country. Grouped by:
    - Construction period
    - Typology: Single family homes, multi-family homes, apartment blocks, and where applicable, non-residential types such as recreational, offices, industrial buildings etc.
- **Activity 3: Derivation of distinctive specifics in terms of building types identified for countries and regions.**

- Case studies making use of existing datasets (i.e. building smart heat meter data) for different DHC grids to apply KPIs to buildings to characterize their behavior (daily and seasonal load variations)
- Ranking flexibility potential for different building typologies based on:
  - Load profile behavior of building and connected DHC grid
  - Physical properties of the building envelope (thermal mass, insulation)

S*ection 2.1.1* focusses on the role of DHC in different countries.
Section 2.1.2 concentrates on the overview and classification of buildings stocks connected to thermal networks in seven European countries (Denmark, Sweden, Norway, Czech Republic, Slovenia and Bosnia and Herzegovina). The building topologies, classification scheme grouping buildings according to their size, age and further parameters are obtained from international project TABULA.
According to the TABULA project, there are typically representative distinct building archetypes in the given country, each corresponding to a specific type of building age band. These age bands represent changes in building traditions and the implementation of building energy codes over time. Based on this information, the *Section 2.1.3* focuses on the U-values of different age bands of these buildings and assessment of the potentials of different type of buildings on demand side management.

2. Content

2.1 Current Status of District Heating and Cooling Systems in European Countries

On a national level, the share of existing building stock connected to district heating and cooling systems varies significantly across European countries. **In the district heating sector, the highest connection rates are primarily found in northern and eastern Europe** (see Figure 1). In northern Europe, Denmark meets approximately 65% of its heating and domestic hot water demand for residential buildings through district heating, while Finland and Sweden also have high shares of 38% and 50%, respectively. Similarly, many eastern European countries, such as Slovakia, Poland, Estonia, Latvia and Lithuania, have high district heating connection rates, with between 30% and 55% of their heating demand supplied by district heating. Many of these systems have been in operation since Soviet times and are significantly less efficient than those in northern Europe. In central Europe, district heating is less common, though countries such as the Czech Republic, Austria and Germany have relatively high shares between 15 and 40%. In contrast, much of western and southern Europe has very low connection rates, with most countries receiving less than 10% of their residential heating demand from district heating [1].

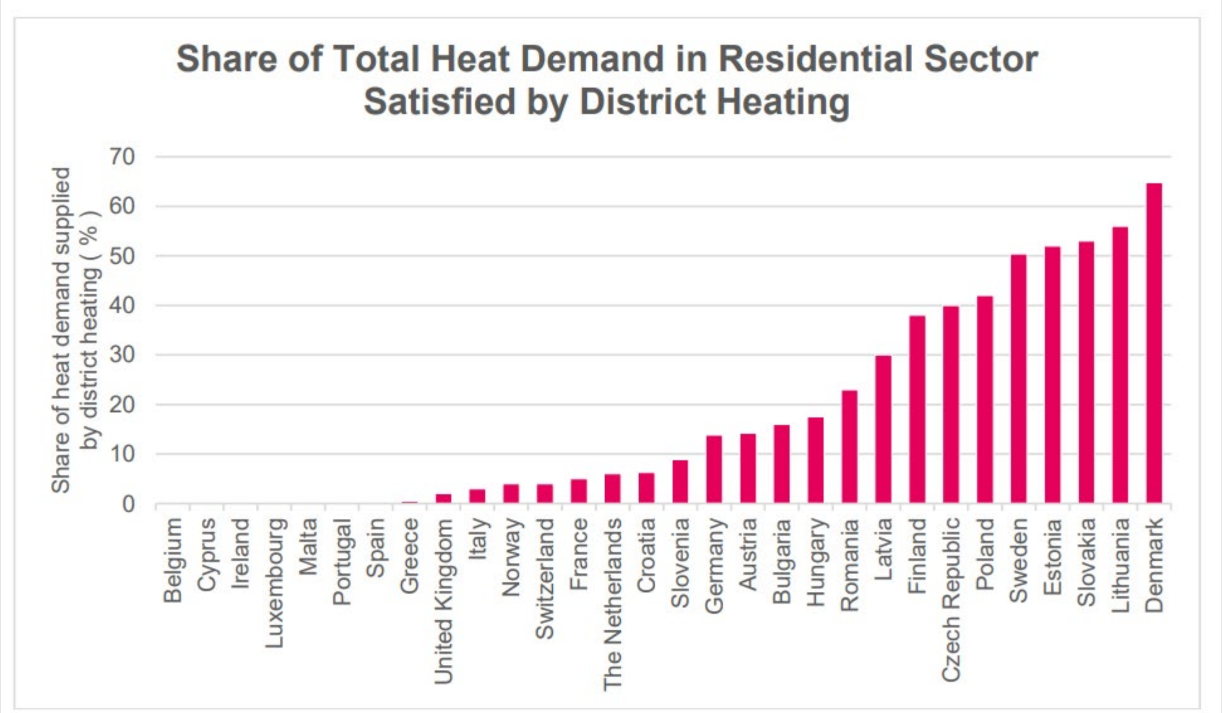


Figure 1: Share of heat demand supplied by district heating in European countries [1]

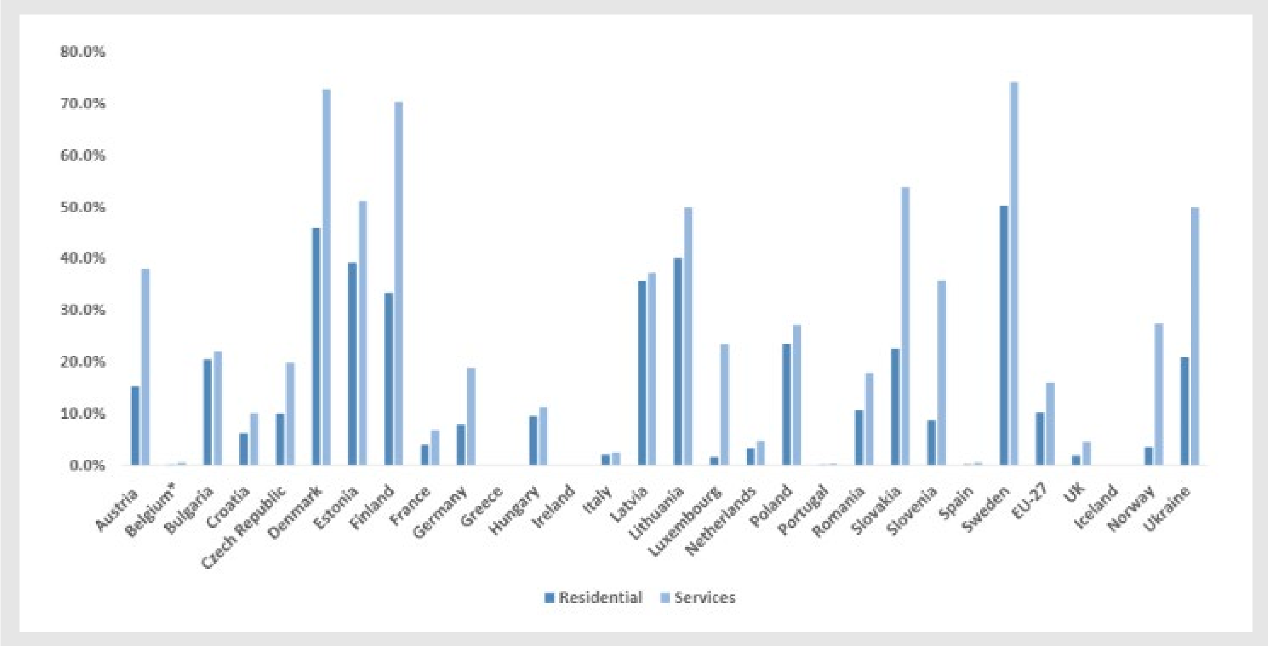


Figure 2: Share of total space heating and domestic hot water demand supplied from district heating for European countries for residential and services applications in 2018 [2], [3]

Figure 2

District cooling networks in Europe on the other hand are far less developed, with no definitive statistical database on the relative cooling demand supplied by cooling networks. In 2018, France was believed to have the highest installed capacity for district cooling in Europe (761 MW), with Finland, Germany, and Italy following with 283 MW, 241 MW and 202 MW installed, respectively. Most other countries have a much smaller or, in some cases, non-existent infrastructure for district cooling. To date, most district cooling networks in Europe are used predominantly in the service sector largely for cooling office blocks, hospitals, shopping centers etc. Only a very small portion is connected to residential buildings, as, unlike district heating systems, there is a lack of adequate cooling distribution systems. [2], [3].

While the overall connection rate and heat consumption from district heating and cooling networks provide an overview of the largest hotspots for implementing innovative demand-side management measures, the suitability for DSM is strongly linked to the properties of the DHC infrastructure. Older district heating networks present in many Eastern European countries typically have very high operating temperatures with high losses, as well as leakages, faulty equipment, and little to no data collection for monitoring purposes. **As a result, carrying out DSM measures on such networks would be, from a technical standpoint, very challenging, and the focus should be placed on improving the network infrastructure before addressing any form of demand response.**

Newer thermal networks are characterised by lower supply and return temperatures, with the most modern 4th and 5th generation DHC networks operating with temperatures below 60°C. 5th generation DHC networks, in particular, operate at ultra-low temperatures (20–30°C), meaning that the interface between the network and connected buildings differs significantly from those in 2nd or 3rd generation networks, often using booster heat pumps in the building substations to reach a minimum necessary temperature for space heating and domestic hot water purposes in the building. Most district heating networks in Europe are of the 2nd or 3rd generation, with operating temperatures ranging from 80°C up to 160°C. To date, only a handful of 4th or 5th generation DHC networks exist in Europe, including those in Belgium, the Netherlands, and Denmark [1].

2.2 Current Status on Building Stock in European Countries

Apart from the existing thermal network infrastructure, the properties of the connected building stock strongly influence the suitability and type of demand-side management measures that can be carried out. A statistical analysis conducted within Annex 67: Energy Flexibility in Buildings [4] identified some of the key building properties that affect their ability to shift thermal loads effectively. The main factors identified were:

1. Level of insulation of the envelope
2. Building thermal inertia
3. Heating system installed: floor heating vs hydronic radiators
4. Additional indoor thermal mass (e.g., PCM – phase change materials)

The most significant factor was found to be the level of insulation of the building envelope. Older, poorly insulated buildings are losing heat faster than newer buildings, which typically adhere to higher insulation standards. Depending on the objective of DSM measures, insulation levels can have a positive or negative impact. Poorly insulated buildings are better suited for fast, transient load shifting, while well-insulated buildings are more suitable for storing heat over a longer period.

Energy Performance Certificate

Within Europe, buildings are ranked by the Energy Performance Certificate (EPC), which is regulated by the European Directive on the Energy Performance of Buildings. The EPC ranking follows a letter scale from A++ (highly efficient buildings – NZEB) to G (high energy consumption – little to no insulation standards). Below is a breakdown of the residential building stock in various European countries as of 2017, categorized by labels A, B, C, D, and >D. For many counties (e.g., Spain, Italy, Bulgaria, Lithuania, Estonia and Wallonia (Belgium)), more than 50% of the existing residential building stock falls into the > D category. The combined share of A or B buildings remainsl relatively small, with shares ranging from <1% (Spain) to a maximum of 20% (France, Flanders (Belgium)).

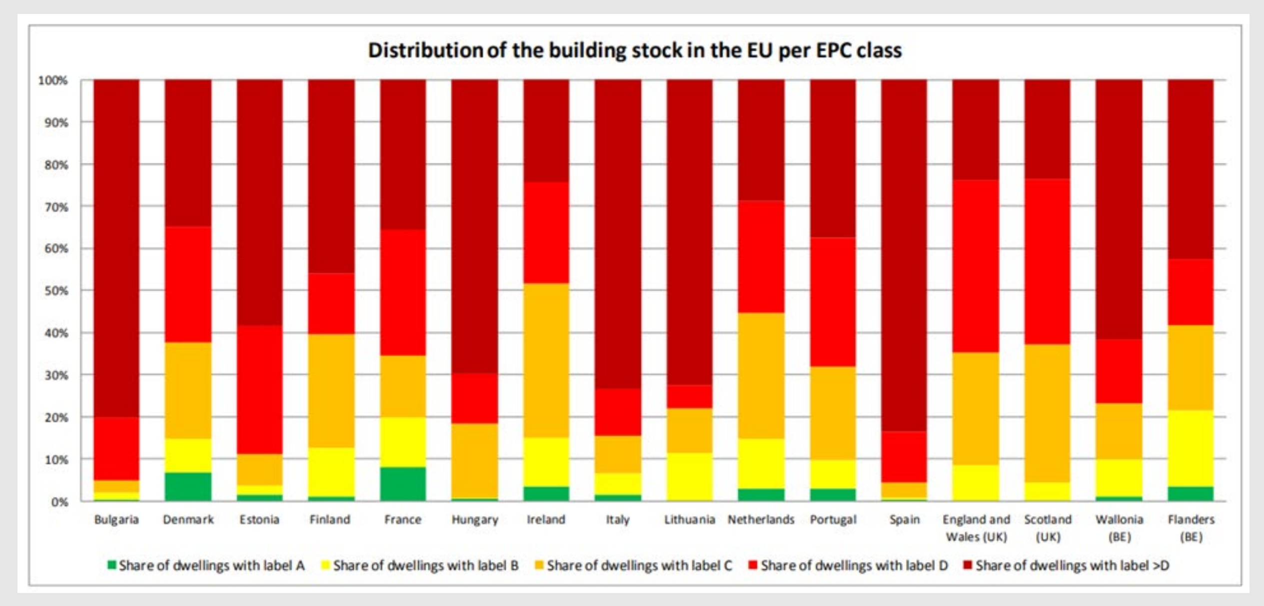


Figure 3: EU Building Stock Breakdown by EPC Label as of 2017 [5]

Most residential buildings in Europe are relatively old (pre-1960), which explains the high share of >D-rated buildings in the existing stock. These older buildings typically have the highest specific heating demands (kWh/m^2/a) and, therefore, contribute disproportionately to the overall heat demand in district heating systems compared to buildings in categories A, B, or C. Consequently, the oldest buildings in a district heating network are likely to experience higher peak loads than newer ones. **For DSM, reducing the peak loads of the "most-problematic" buildings – those with the highest peaks – is a logical starting point if the**

goal is to lower the overall peak load of the grid. This approach is preferable to focusing on newer buildings, which contribute comparatively smaller peaks [5]**.**

2.2.1 Denmark

Denmark's Residential Building Stock

For Denmark, there is an exceptionally good database (Statistics Denmark [6]) on the existing building stock, including data on connections to district heating networks. The plots below show a breakdown of the existing residential building stock for both connected and non-connected buildings by construction year. This includes detached and terraced single-family homes (SFH) as well as multi-family homes (MFH), categorized by total heated floor area and number of buildings.

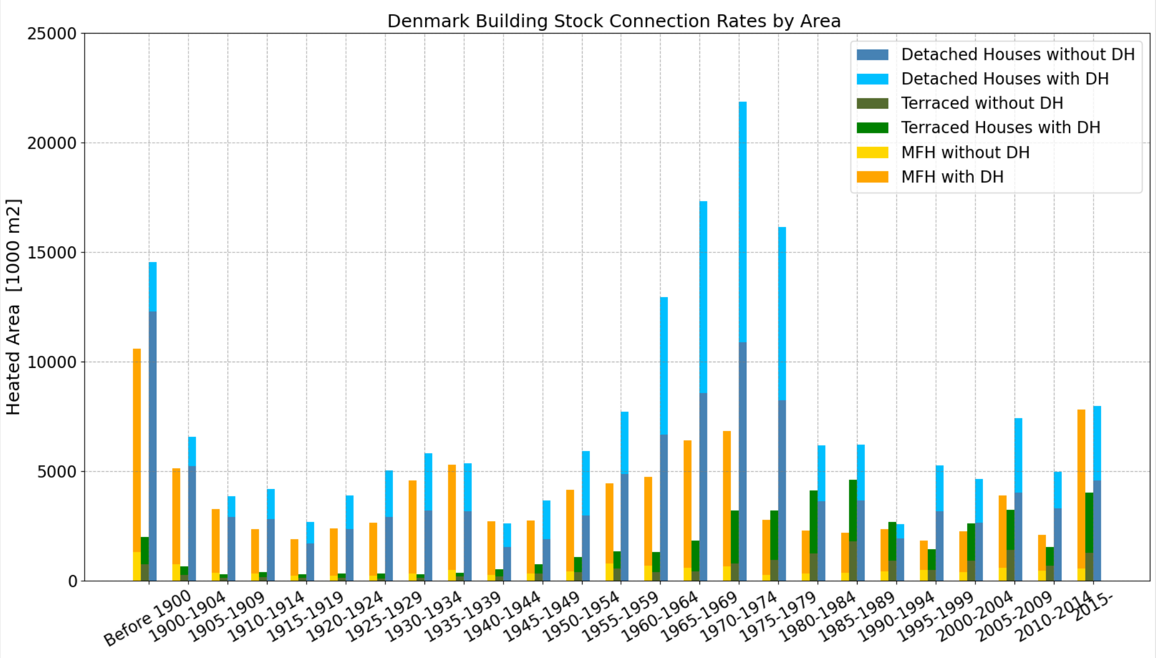


Figure 4: Existing residential building stock in Denmark with and without DH connection by construction periods (five-year intervals) – total number of buildings and total heated area (AEE INTEC, Data: Statistics Denmark [6])

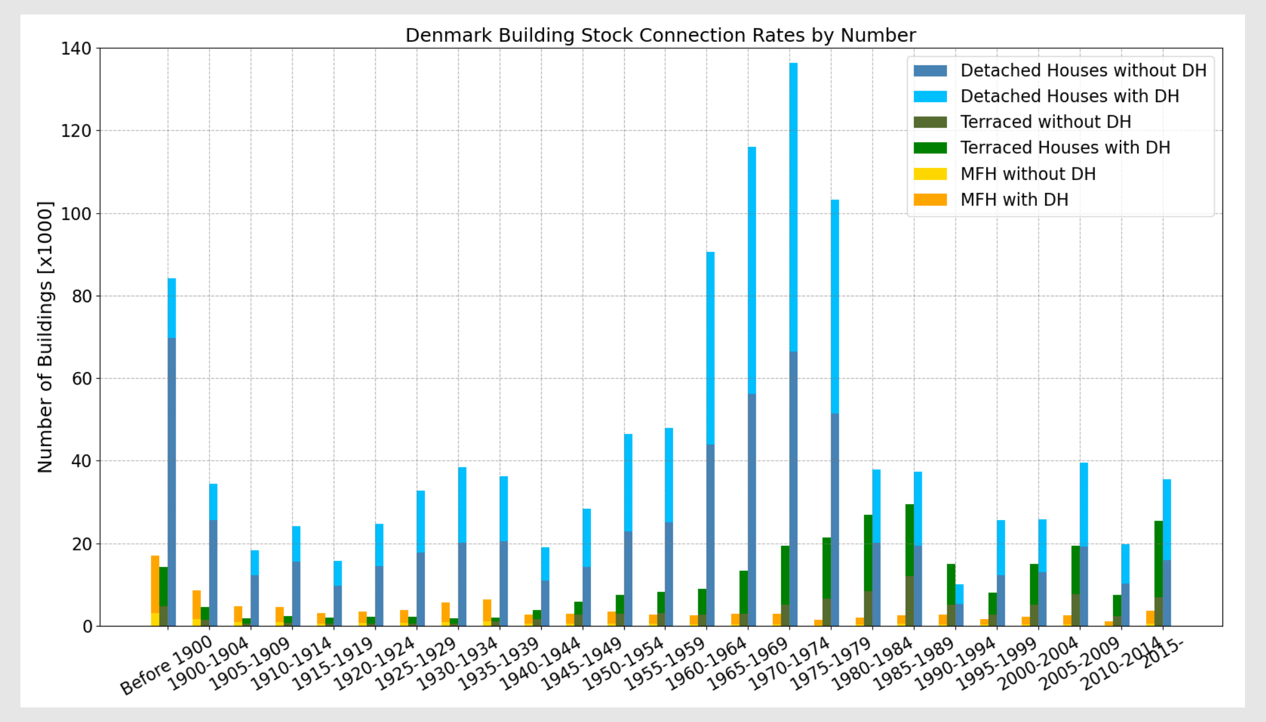


Figure 5: Existing residential building stock in Denmark with and without DH connection for construction periods over five-year intervals – total number of buildings (AEE INTEC, Data: Statistics Denmark [6])

Key observations from the data show that the largest proportion of Denmark's residential building stock was built between 1960 and 1975. Detached SFH constitute the majority of all residential buildings, both in terms of the number of buildings and total heated floor space.

Denmark has one of the highest connection rates to district heating grids in Europe. The plots below indicate connection rates of detached homes ranging from 30% to 40%, for terraced homes from approximately 50 to 60%, and MFH above 80% across all construction years.

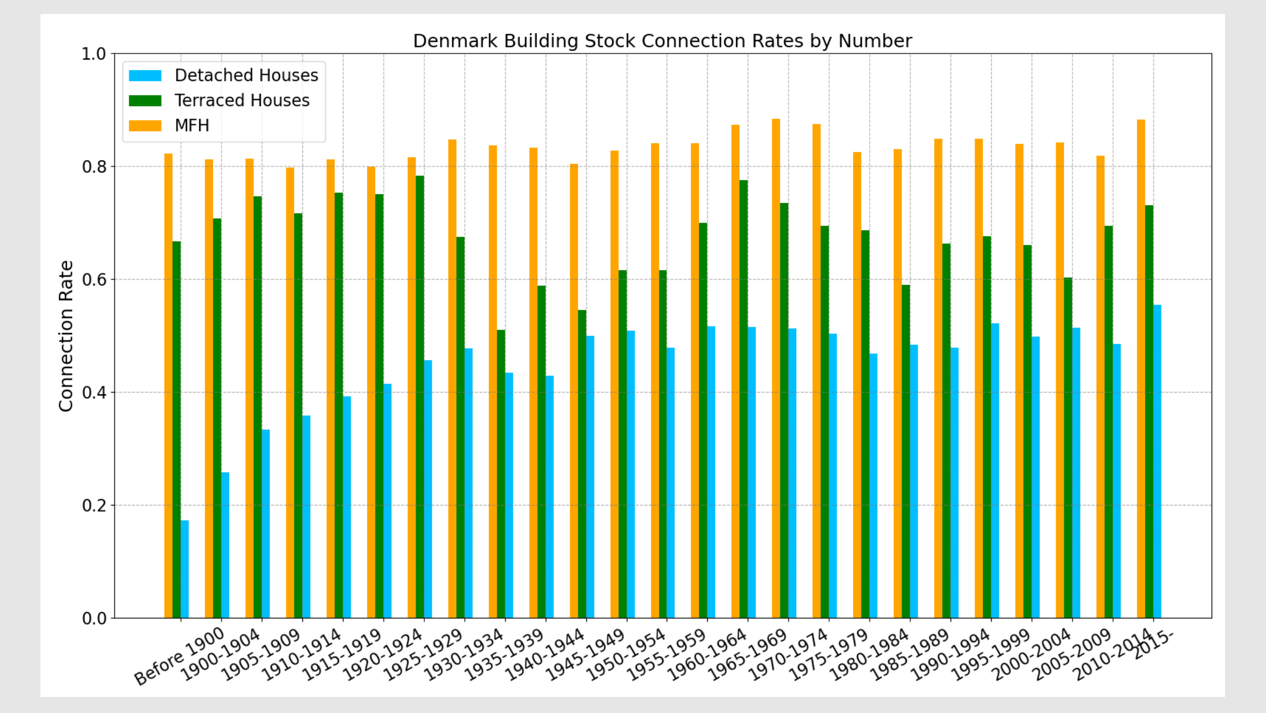


Figure 6: Existing residential building stock in Denmark – DH connection rate for construction periods (five-year intervals) – by building area (AEE INTEC, Data: Statistics Denmark [6])

Denmark's Non-Residential Building Stock

Figure 7 and Figure 8 provide a breakdown of Denmark's non-residential building stock connected to district heating networks. These buildings are categorized by five-year construction periods. The largest category, in terms of both total number of buildings and heated floor area, includes educational and administration buildings (schools, universities, and offices), followed by healthcare, industry, recreational, and transport-related buildings.

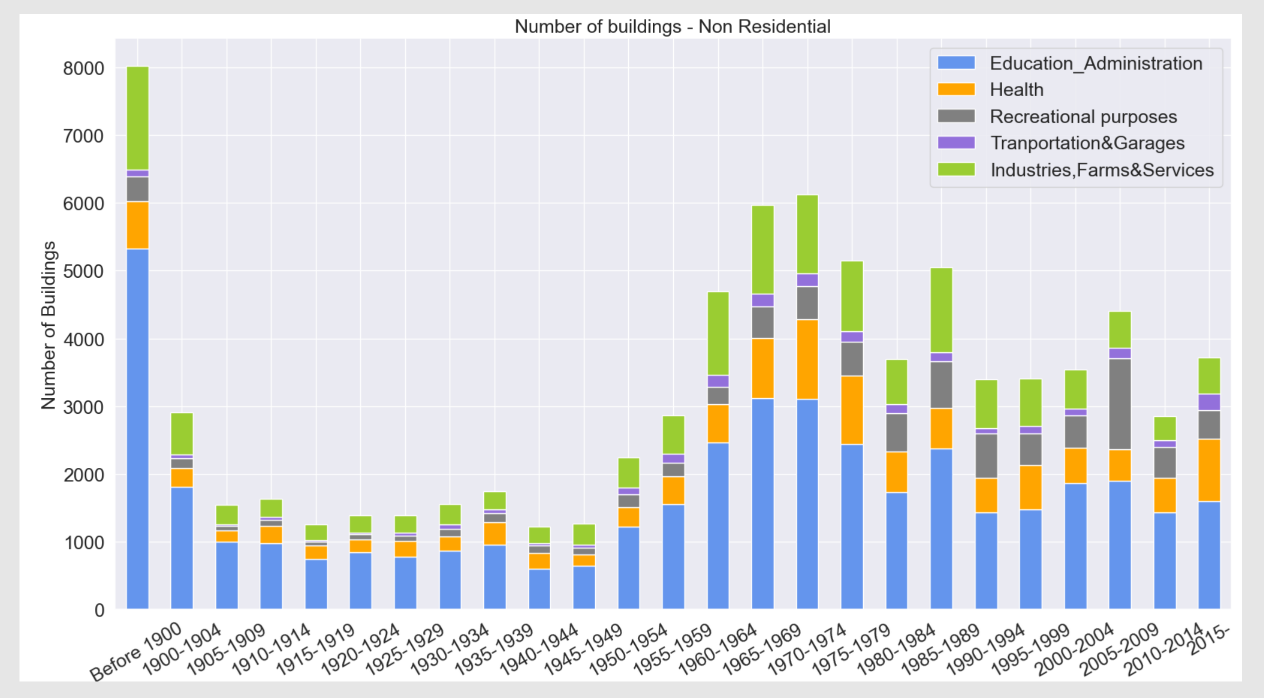


Figure 7: Non-residential buildings connected to district heating networks in Denmark – number of buildings (AEE INTEC, Data: Statistics Denmark [6])

The distribution of construction years shows a significant share of older buildings (pre-1900) being used for non-residential purposes, with fewer buildings constructed from 1900 to 1954. As with the residential building stock, a large proportion of non-residential buildings connected to district heating networks were constructed between 1970 and 1975.

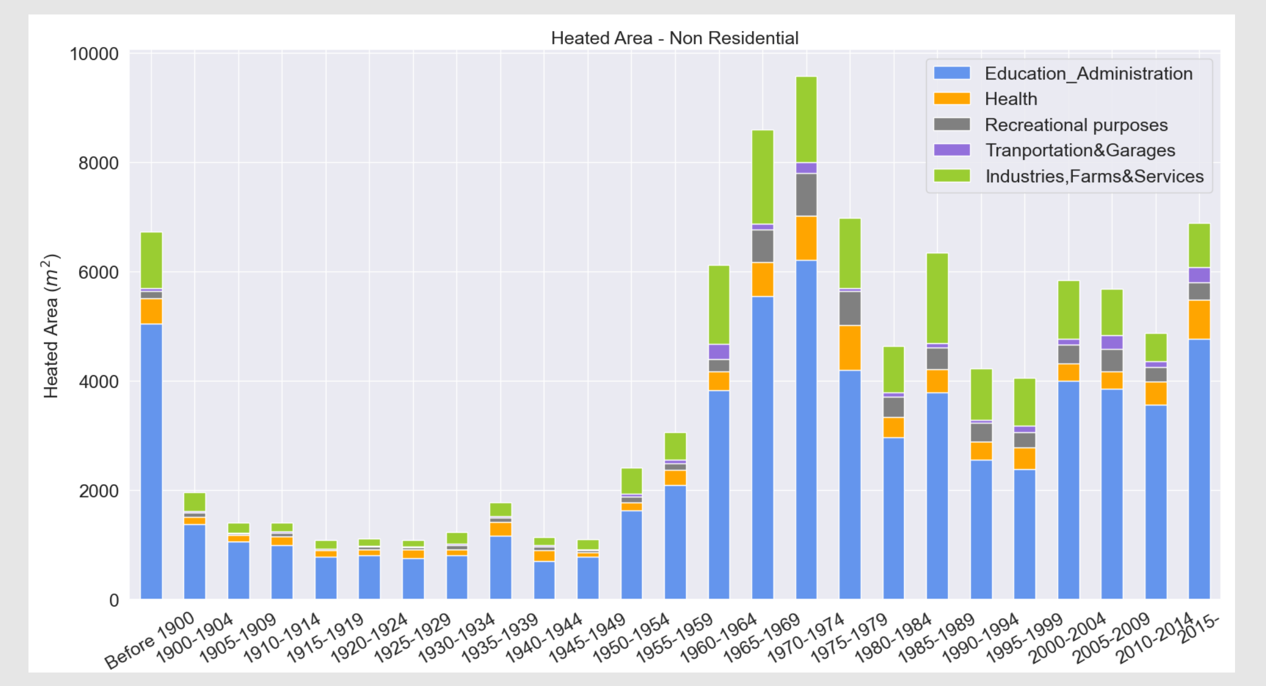


Figure 8: Non-residential buildings connected to district heating networks in Denmark – heated area (AEE INTEC, Data: Statistics Denmark [6])

Most demand-side management implementations to date have been carried out in residential buildings. However, non-residential buildings can also be suitable for demand response measures due to their larger thermal masses, which allow for greater heat and cold storage capacity. Nevertheless, non-residential buildings present unique challenges, in particular, require highly specific energy demand profiles, which are not flexible.

Aggregated Thermal Storage Capacity in the Entire Building Stock in Denmark

If the entire building stock of a country participates in demand response programs, the thermal storage capacity of the indoor environments across all buildings accumulates to significant figures. A recent study by Johra et al. (2024) estimated that the total effective heat capacity in the Danish building stock ranges from 13 GWh (for short-term heating/cooling temperature setpoint modulation) up to 130 GWh (for longer modulation periods of 24 hours). This thermal energy storage capacity is comparable to that of all industrial storage tanks across Danish district heating plants and similar to the storage capacity of an entire fleet of fully electrified cars (see Figure 9) [7].

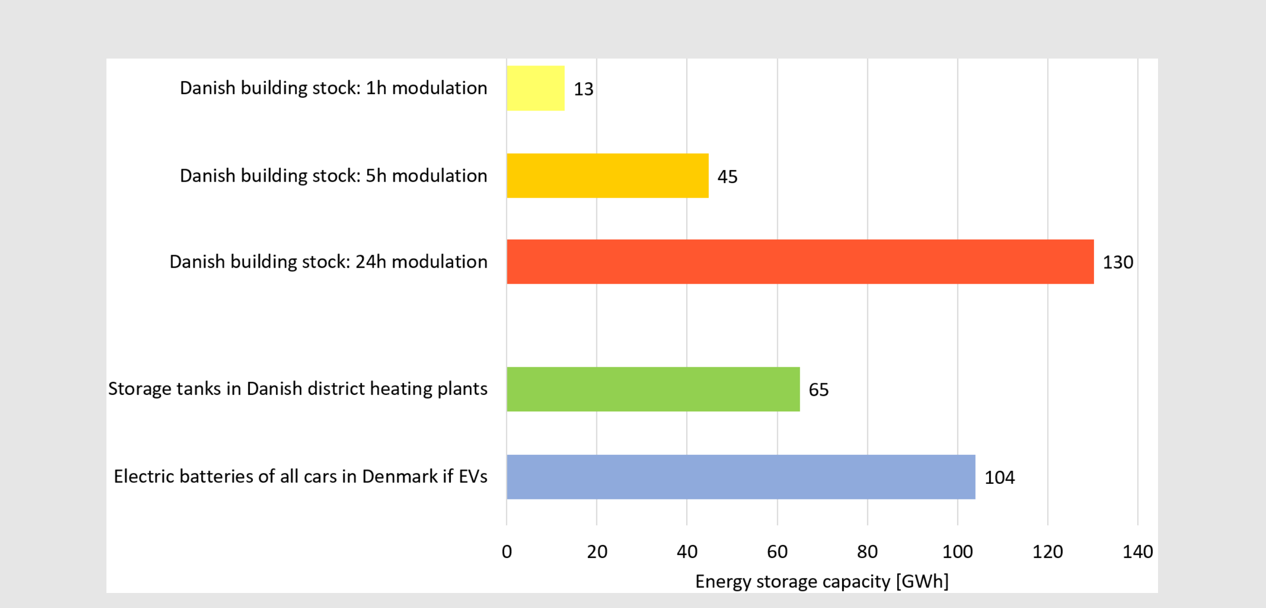


Figure 9: Estimates of the thermal storage capacity in the indoor environment of the entire Danish building stock compared with other key storage assets [7]

2.2.2 Germany

Information on the residential building stock in Germany was primarily adapted from the TABULA database [8] [8 Tabula] and filtered to include only statistics for the buildings connected to district heating networks. The database categorizes buildings into the following construction periods: *Pre-1948, 1949–1978, 1979–1990, 1991–2010, Post-2011.*

These periods largely correspond to the introduction of revised building standards regarding glazing and insulation, with buildings from the same period exhibiting similar U-values.

The residential building categories are defined as follows:

- Single Family Home
- Small Multi-family Home (2–10 dwellings)
- Large Multi-family Home (more than 10 dwellings)

Germany Residential Building Stock

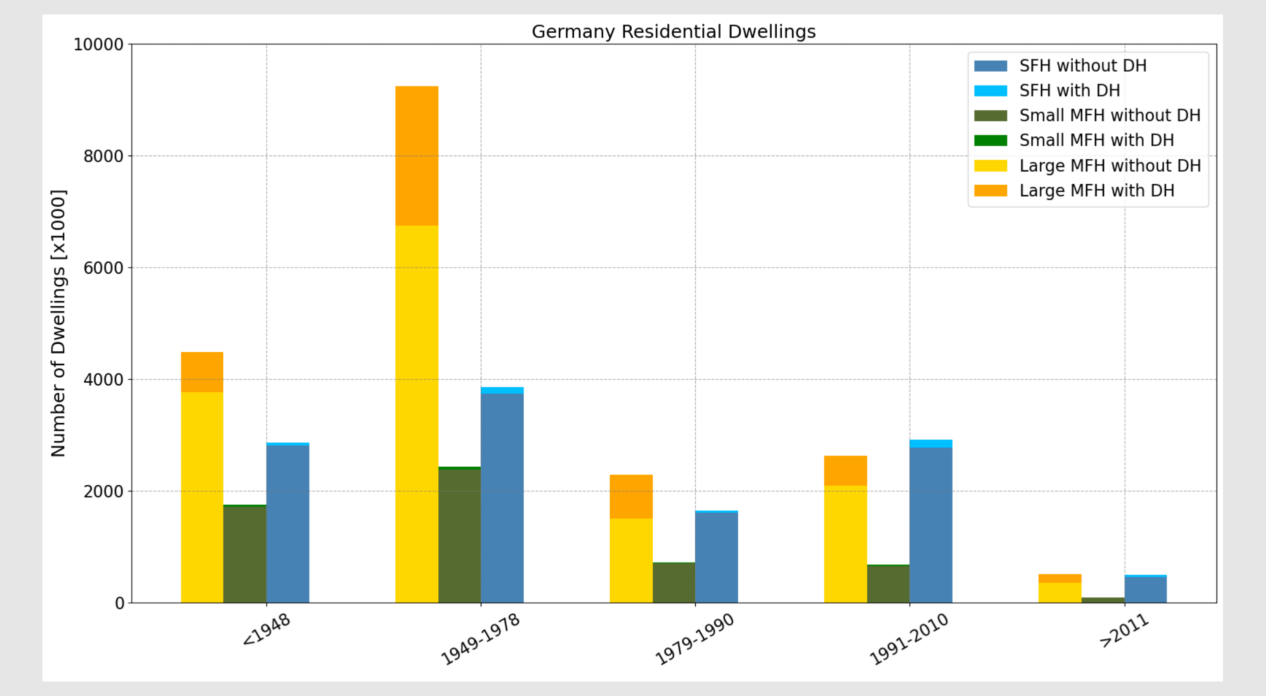


Figure 10: Breakdown of buildings with and without a connection to a district heating grid in Germany based on construction period and building use (AEE INTEC)

Figure 11 shows that the majority of residential buildings connected to district heating in Germany are large multi-family homes, i.e., apartment blocks, particularly from the post-war period (1949–1978).

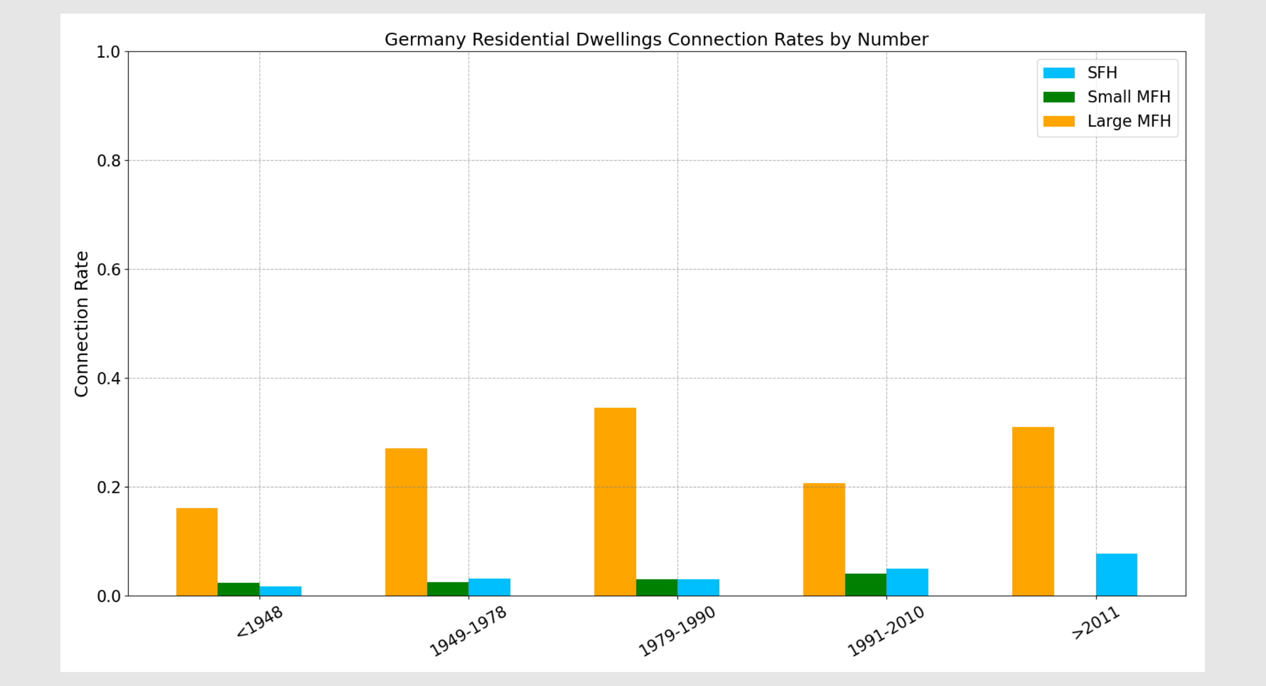


Figure 11: Connection rate of buildings in Germany based on construction period and building use (AEE INTEC)

Apartment blocks constructed between 1949 and the present have a connection rate of approximately 25–35%. Single family homes have a significantly lower connection rate of 2–3%, though newer SFH (post-2011) have a slightly higher connection rate of approximately 7%.

2.2.3 Czechia

For Czechia, statistical data was also collected from the TABULA data base [8] for [8 TABULA database] residential buildings. However, instead of providing data on the number of buildings connected to district heating networks, the database specifies the number of dwellings. As a result, for apartment blocks with many dwellings, the reported number of connected units will be significantly higher than for single-family homes, where each building typically contains one dwelling. In total, the connection rate of residential dwellings is relatively, ranging between 40–50% for buildings constructed between 1960 and 1990, as shown in Figure 12.

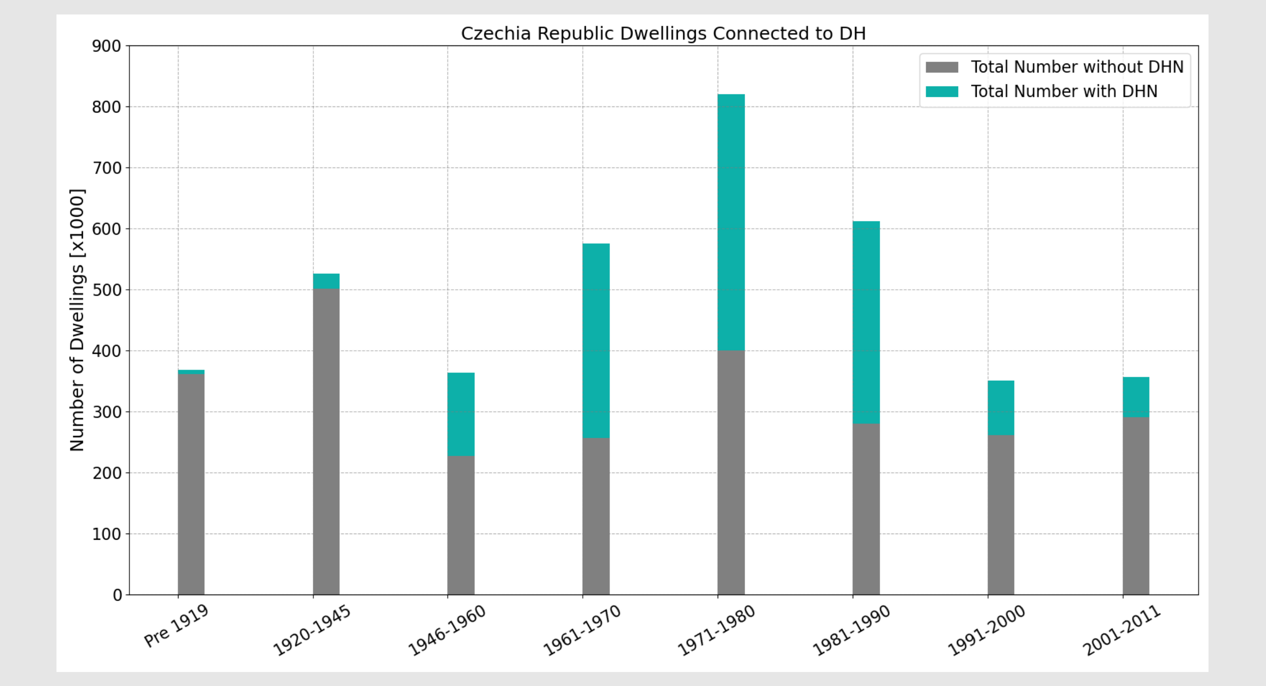


Figure 12: Breakdown of dwellings with and without a connection to a district heating grid in Czechia based on construction period (AEE INTEC)

Regardless of construction year, the majority of district heating connections are found in apartment blocks, as represented in Figure 13.

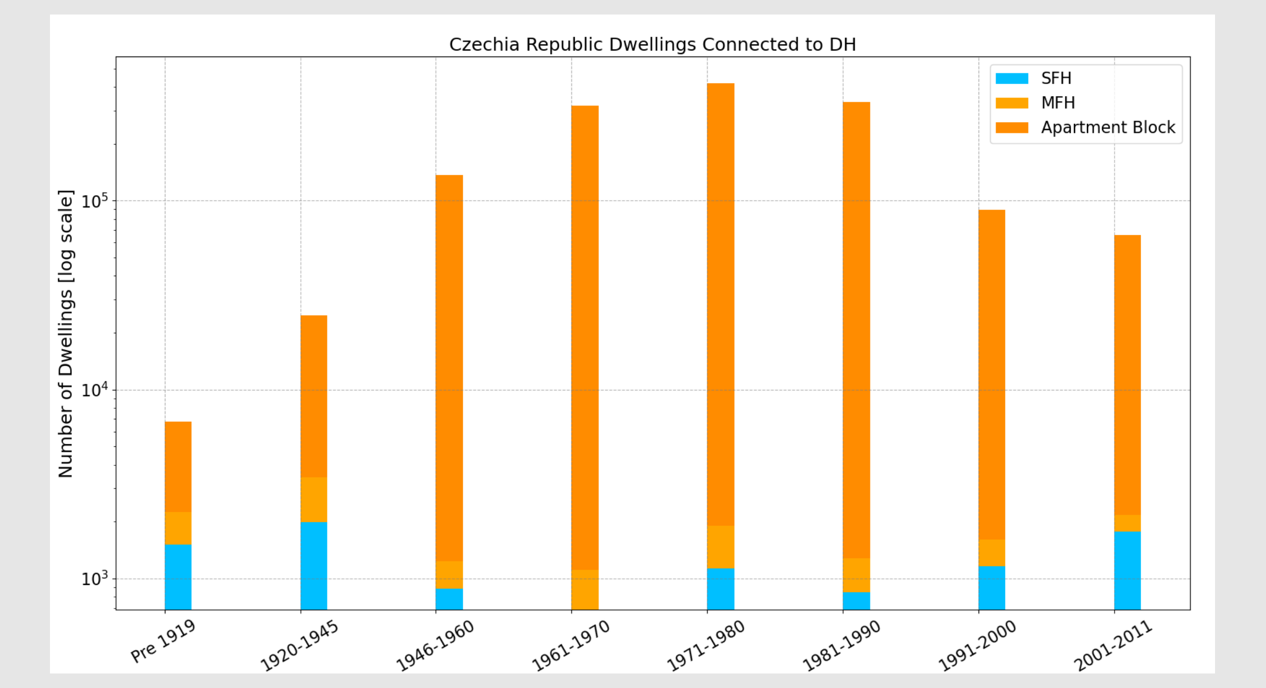


Figure 13: Breakdown of dwellings connected to a district heating grid in Czechia based on construction period and type of residential building (SFH, MFH, apartment block) (AEE INTEC)

2.2.4 Slovenia

Buildings in Slovenia are categorized into the following construction periods under the TABULA database [8]: *Pre 1945, 1946–1970, 1971–1980, 1981–2022, 2003–2008, Post-2008.*

The overall connection rate of residential buildings is relatively low, with only 1–2% of SFH (detached/terraced) connected, as shown in Figure 14. Larger buildings, including MFH and apartment blocks, have a higher connection rate with approximately 22–24% of MFH/apartment buildings constructed between 1971 and 2022 being connected. Newer SFH buildings (post-2008) show a slightly higher connection rate of approximately 4%.

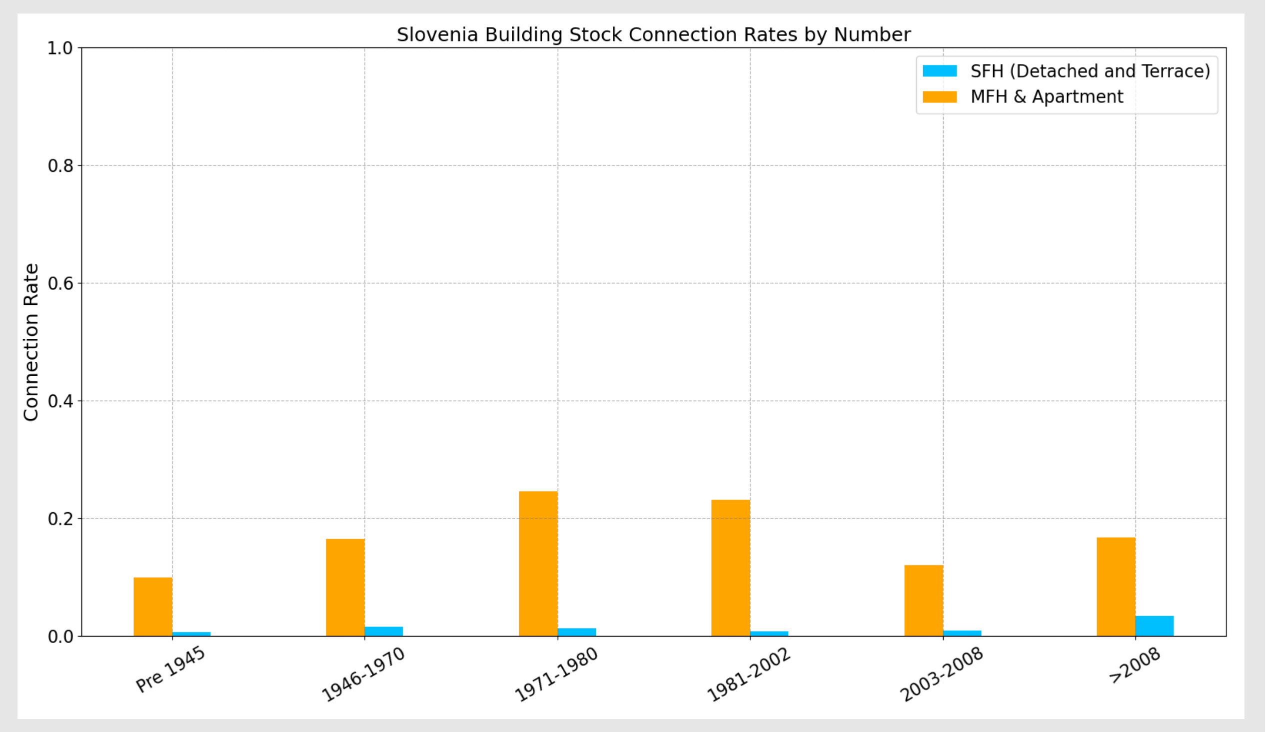


Figure 14: Connection rate of buildings to district heating networks in Slovenia based on construction year and building type – SFH (detached + terraced) or MFH/apartment (AEE INTEC)

The heated area of connected buildings is illustrated in Figure 15.

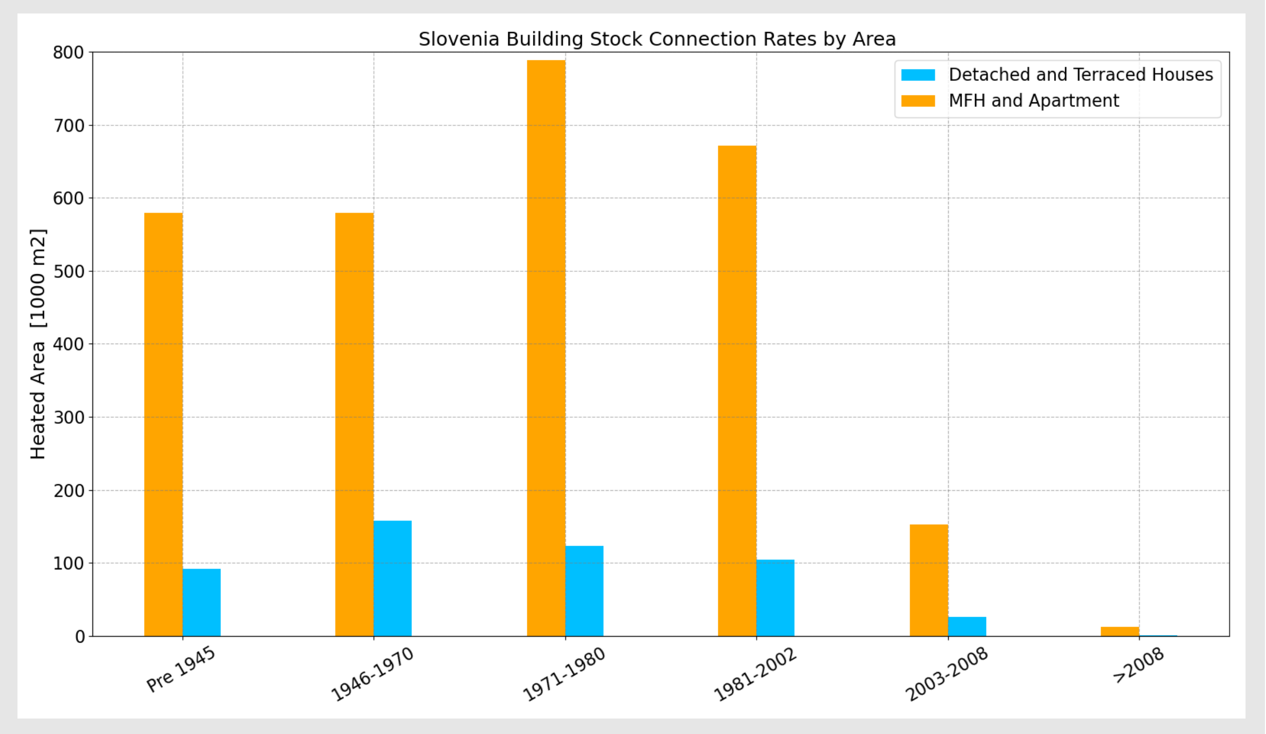


Figure 15: Total heated area of buildings connected to district heating networks in Slovenia based on construction year and building type – SFH (detached + terraced) or MFH/apartment (AEE INTEC)

Although the number of SFH in Slovenia is significantly higher than MFH/apartment blocks, the absolute number of SFH connected to DH networks is comparable to apartment blocks (see Figure 16).

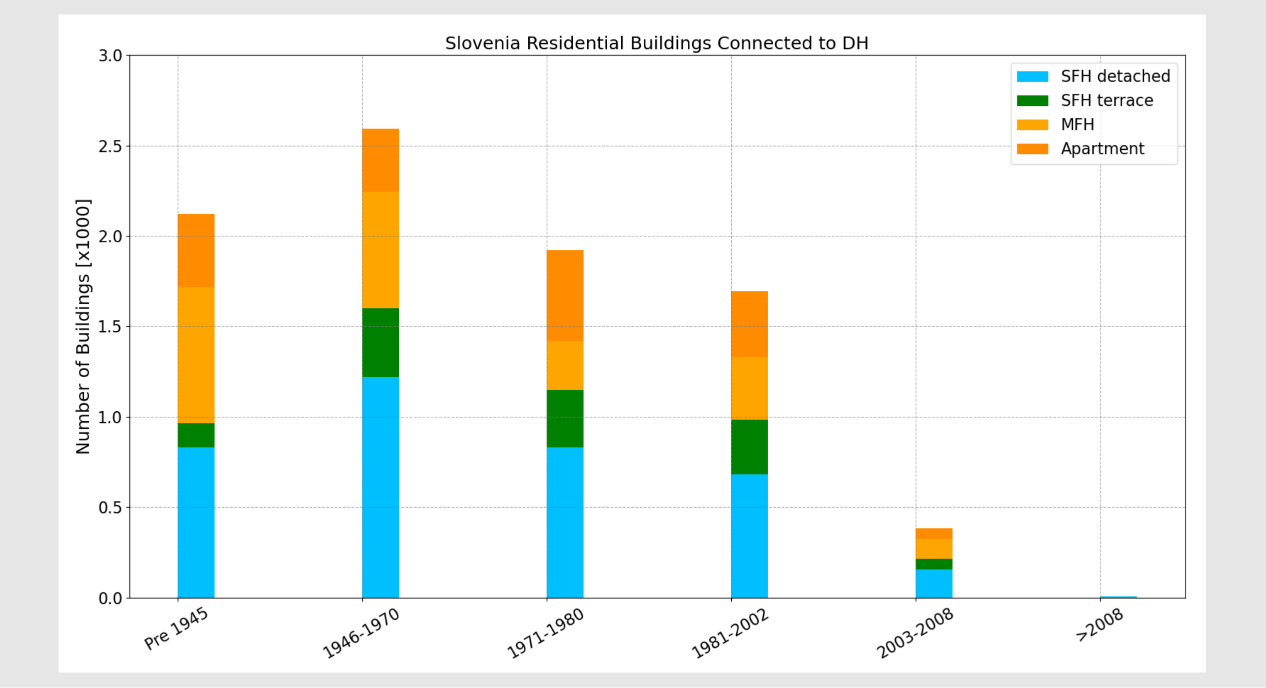


Figure 16: Breakdown of number of buildings connected to district heating networks in Slovenia based on construction year and building type (AEE INTEC)

2.2.5 Sweden

Buildings in Sweden are categorized into the following construction periods under the TABULA database [8]: *Pre 1940, 1941–1960, 1961–1970, 1971–1980, 1981–1990, 199–-2000, Post-2001.*

In Sweden, there is a high connection rate for buildings in the MFH category, which includes all residential buildings occupied by more than one family. MFH buildings have a connection rate of 70–80%, with the highest rate observed in buildings constructed between 1971 and 1980 (approximately 89%). SFH have a significantly lower connection rate, ranging between 5–18%.

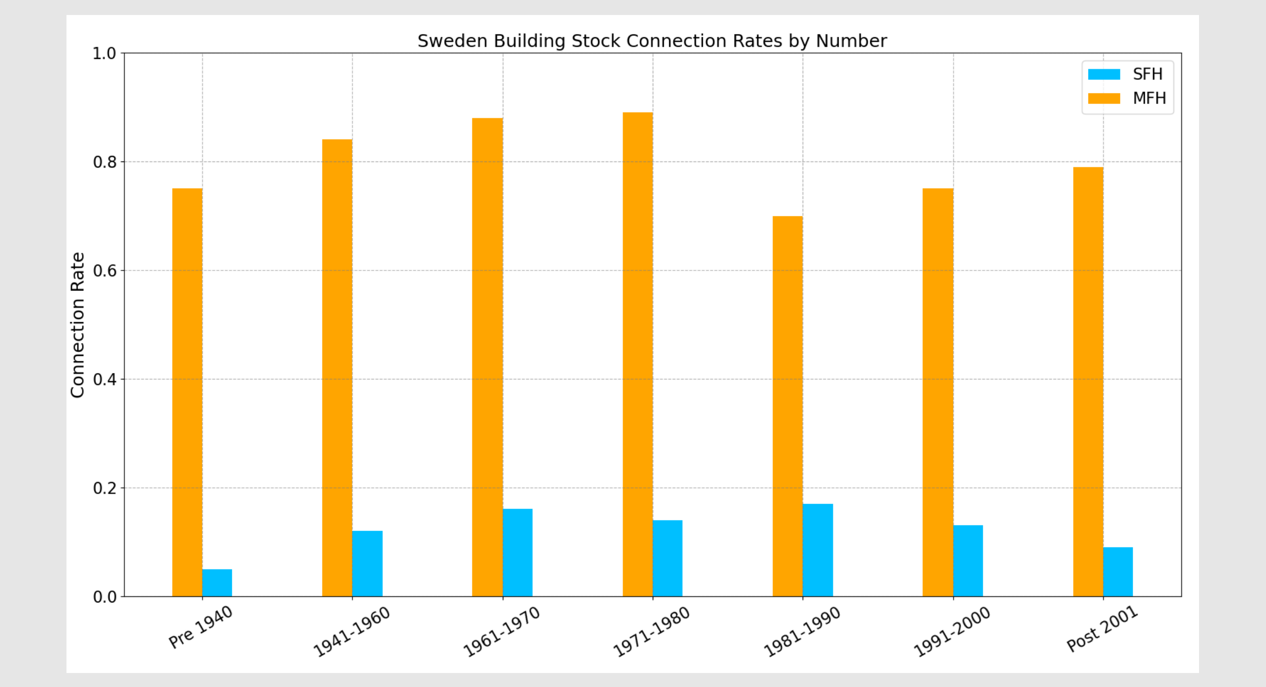


Figure 17: Connection rate of buildings to district heating networks in Sweden based on construction year and building type – SFH (detached + terraced) or MFH/apartment (AEE INTEC)

Figure 18 and Figure 19 show the breakdown of district-heated buildings in terms of heated area and total number of residential buildings connected. The highest total heated floor area for MFH connections is found in buildings constructed between 1961 and 1970, whereas for SFH, the peak occurs in buildings from 1971 to 1980.

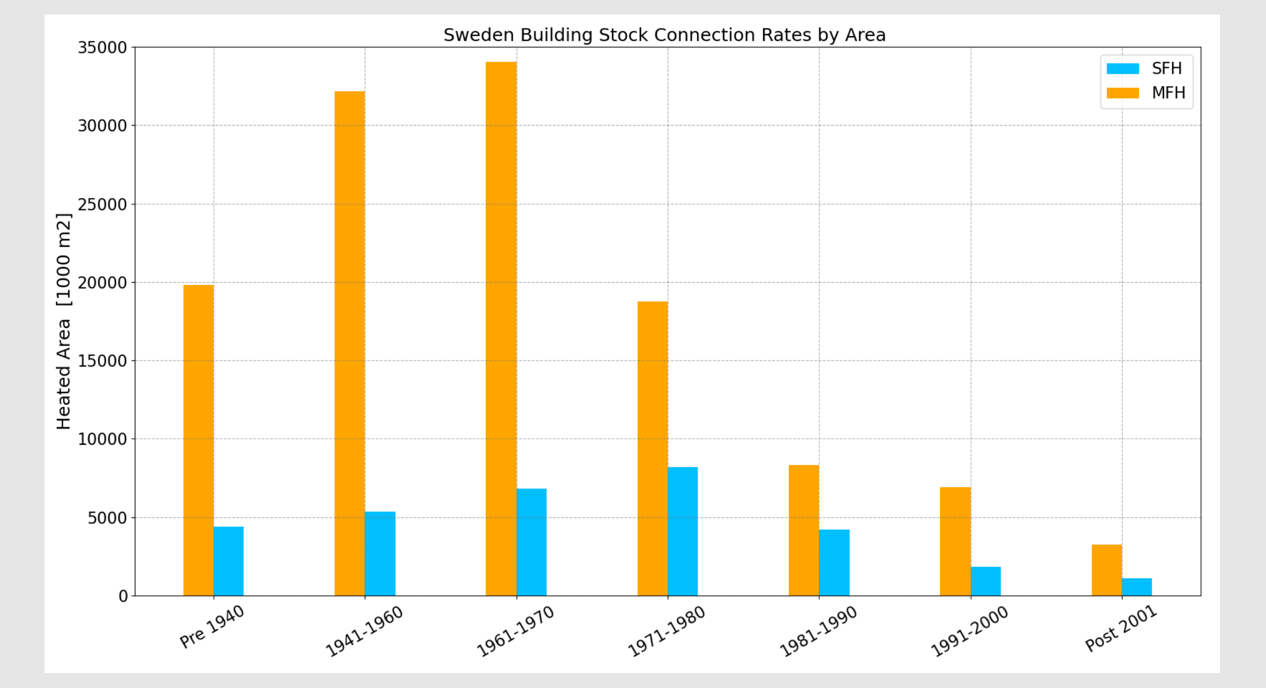


Figure 18: Total heated area of buildings connected to district heating networks in Sweden based on construction year and building type – SFH (detached + terraced) or MFH/apartment (AEE INTEC)

The absolute number of SFH connected to district heating networks is higher than that of MFH buildings. This reflects the larger share of SFH in Sweden’s total building stock compared to MFH and apartments. The total number of buildings and heated area connected to district heating networks is significantly lower for newer construction periods (1981–present). However, the connection rate for new buildings is comparable to older building, indicating that fewer residential buildings have been constructed post-1981 compared to the boom in the 1960s and 1970s.

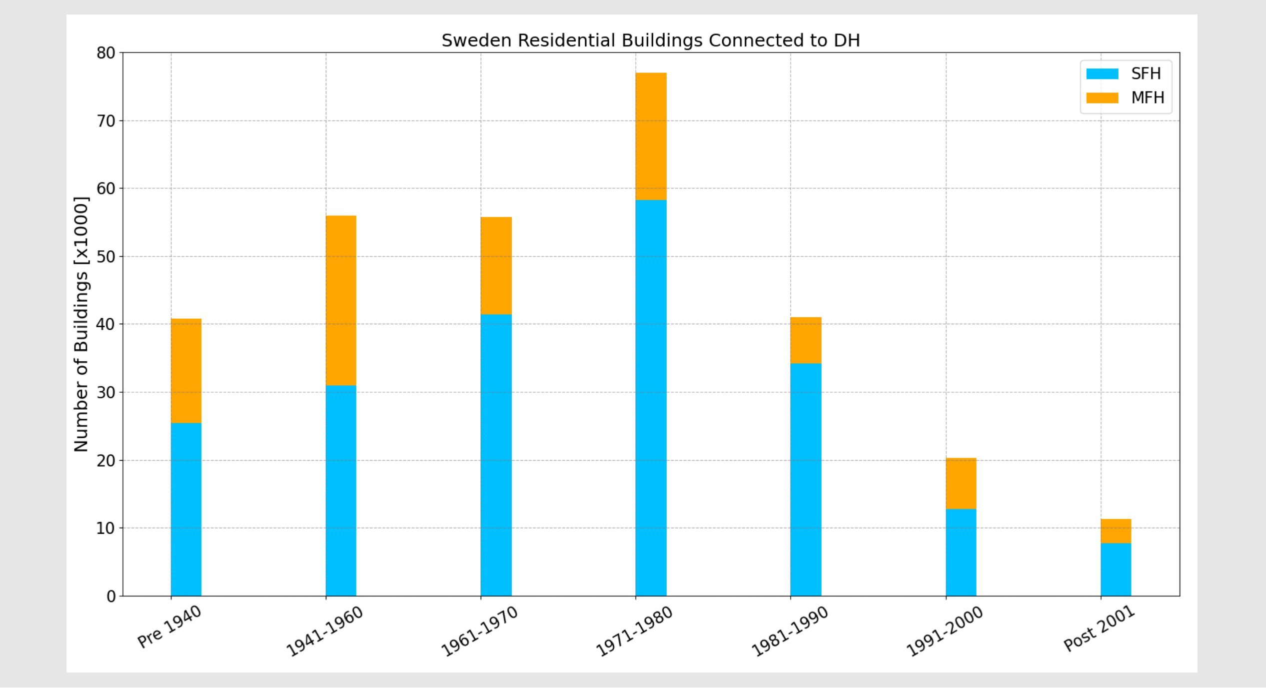


Figure 19: Breakdown of number of buildings connected to district heating networks in Sweden based on construction year and building type (AEE INTEC)

2.2.6 Norway

Buildings in Norway are categorized into following construction periods under the TABULA database [8]: *Pre 1955, 1956–1970, 1971–1990, 1991–2010, Post-2011.*

Compared to other Scandinavian countries such as Sweden and Denmark, Norway's district heating network is relatively small, with MFH connection rates ranging between 10–20% (see Figure 20). Older SFH buildings (pre-1970) have almost no connections to district heating networks, while only SFH buildings constructed after 1970 are registered with district heating connections. Among these, the connection rate is between 1–3%.

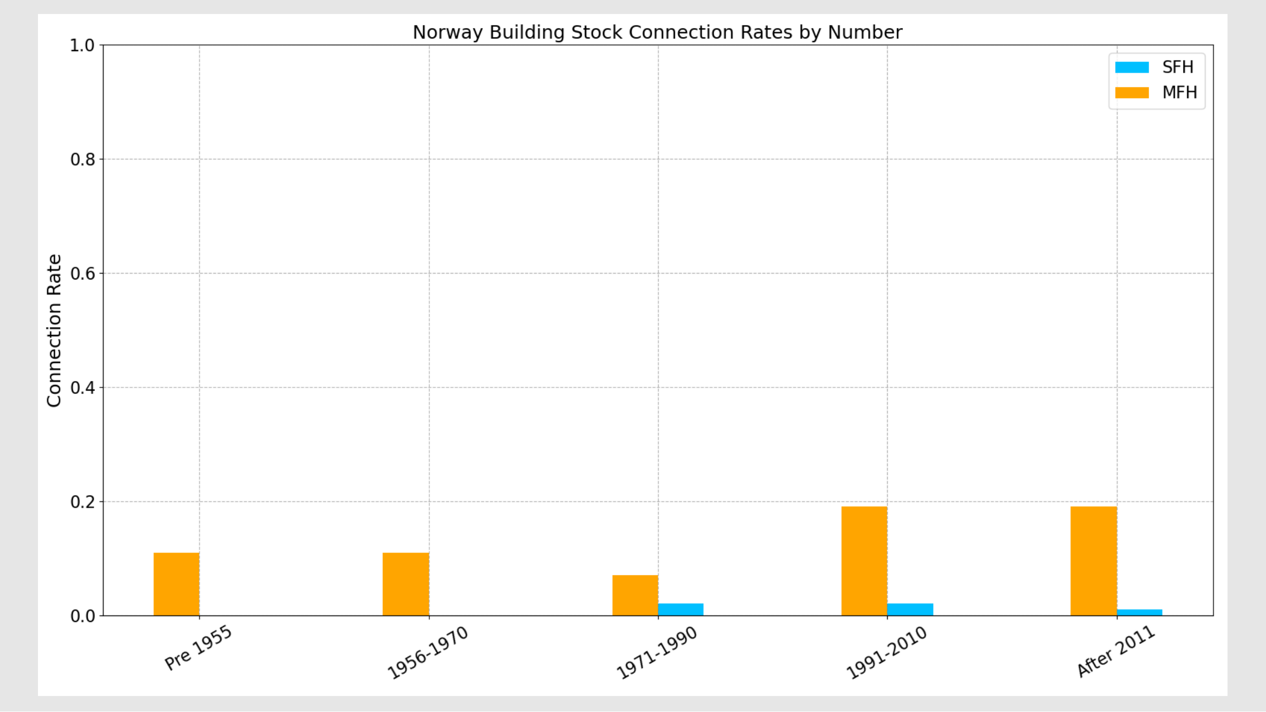


Figure 20: Connection rate of buildings to district heating networks in Norway based on construction year and building type – SFH (detached + terraced) or MFH/apartment (AEE INTEC)

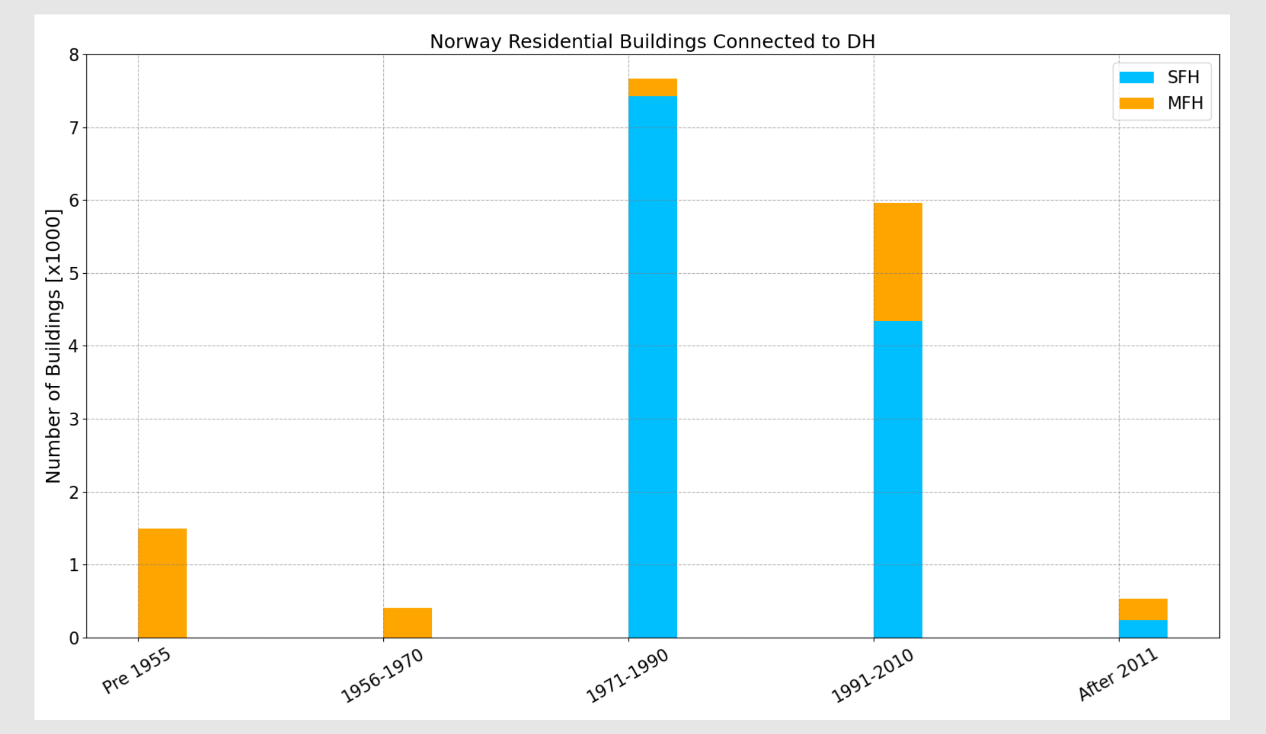


Figure 21: Breakdown of number of buildings connected to district heating networks in Norway based on construction year and building type (AEE INTEC)

Figure 21 provides a breakdown of SFH and MFH buildings in terms of total heated area and the number of connected buildings. The highest number of buildings connected to district heating networks are those constructed between 1971 and 1990, primarily SFH. However, in terms of total heated area, the largest share of heat demand comes from MFH built between 1991 and 2010, as illustrated in Figure 22.

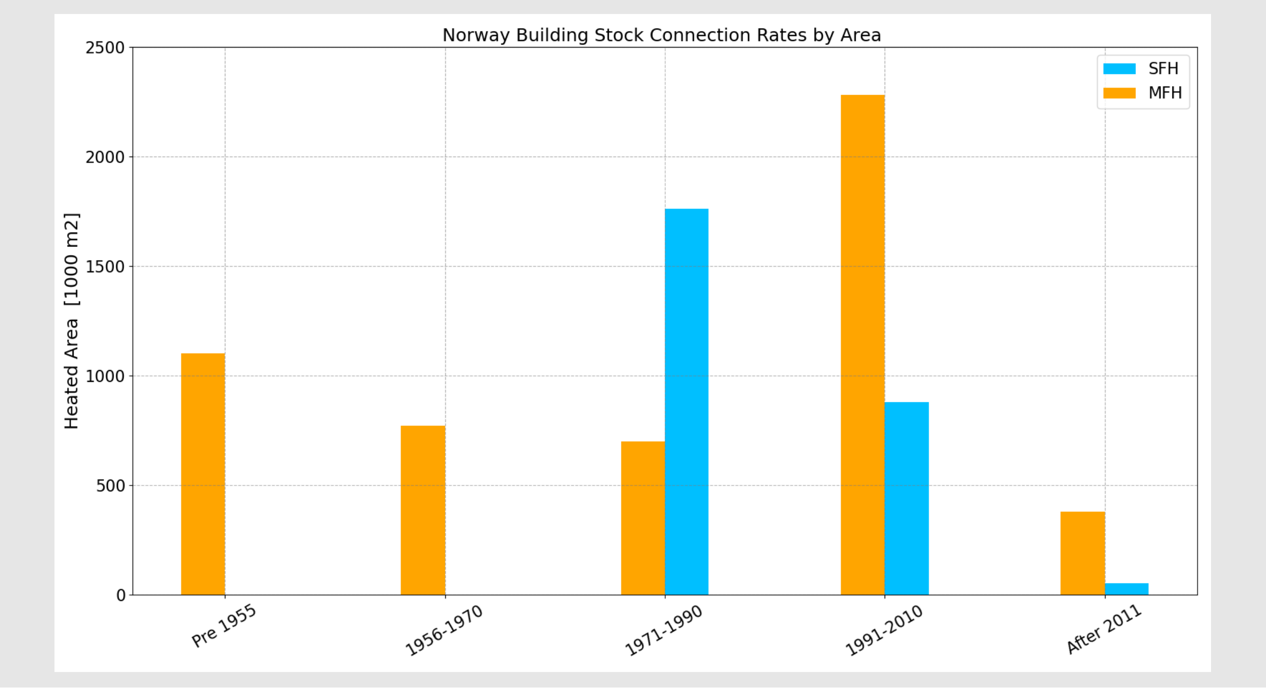


Figure 22: Total heated area of buildings connected to district heating networks in Norway based on construction year and building type – SFH (detached + terraced) or MFH/apartment (AEE INTEC)

2.2.7 Bosnia and Herzegovina

For Bosnia and Herzegovina, the TABULA database [8] [8 Tabula] categorizes residential buildings into the following construction periods: *Pre-1970, 1971–1980, 1981–1991, 1992–2014.*

For building typology there exists for categories on the database

- Single Family Home (detached) – denoted below as SFH
- Single Family Home (Terraced) – denoted below as TH
- Multi Family Home– denoted below as MFH
- Apartment Block – denoted below as AB

The connected rate for detached SFH buildings is the lowest, averaging below 1%. Terraced SFH, however, have a higher connection rate, with the highest percentages among older building stock (16% for pre-1970 and 19% for those from 1971–1980). MFH and apartment blocks have the highest connection rates, ranging from approximately 22–35% for MFH and 30–60% for apartment blocks, depending on construction period.

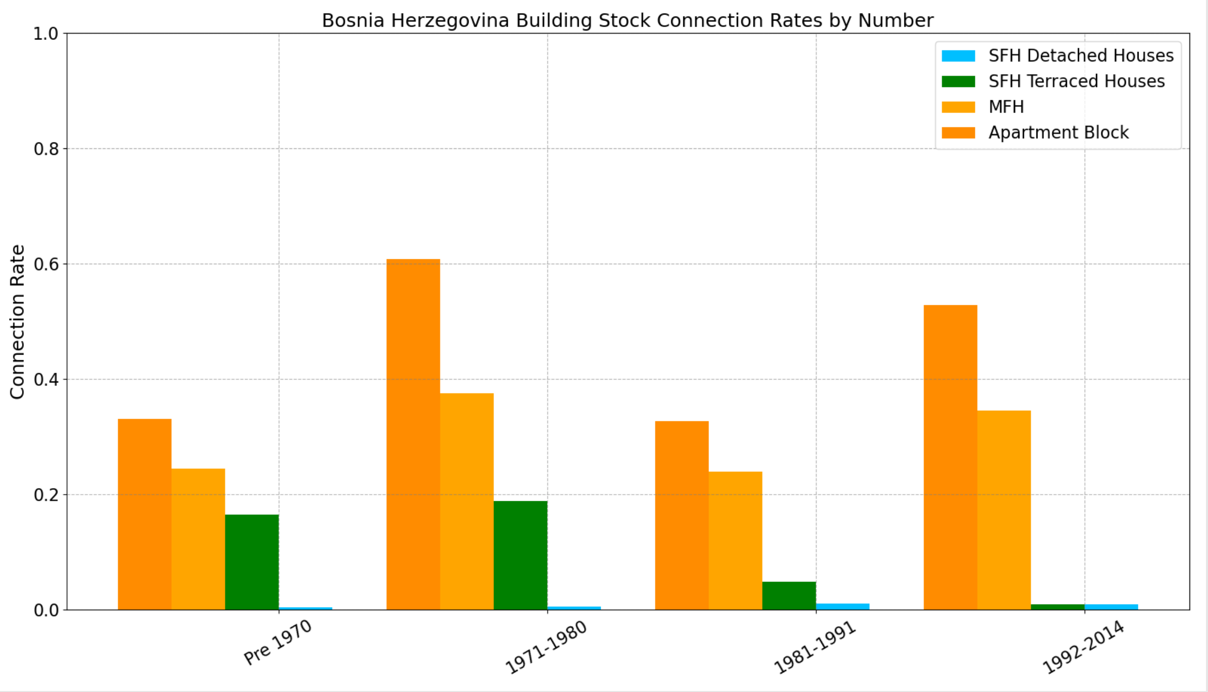


Figure 23: Connection rate of buildings to district heating networks in Bosnia and Herzegovina based on construction year and building type – SFH (detached + terraced) or MFH/apartment (AEE INTEC)

In terms of absolute number, the highest number of residential buildings connected to district heating networks are apartment blocks constructed between 1971 and 1980, as shown in Figure 24.

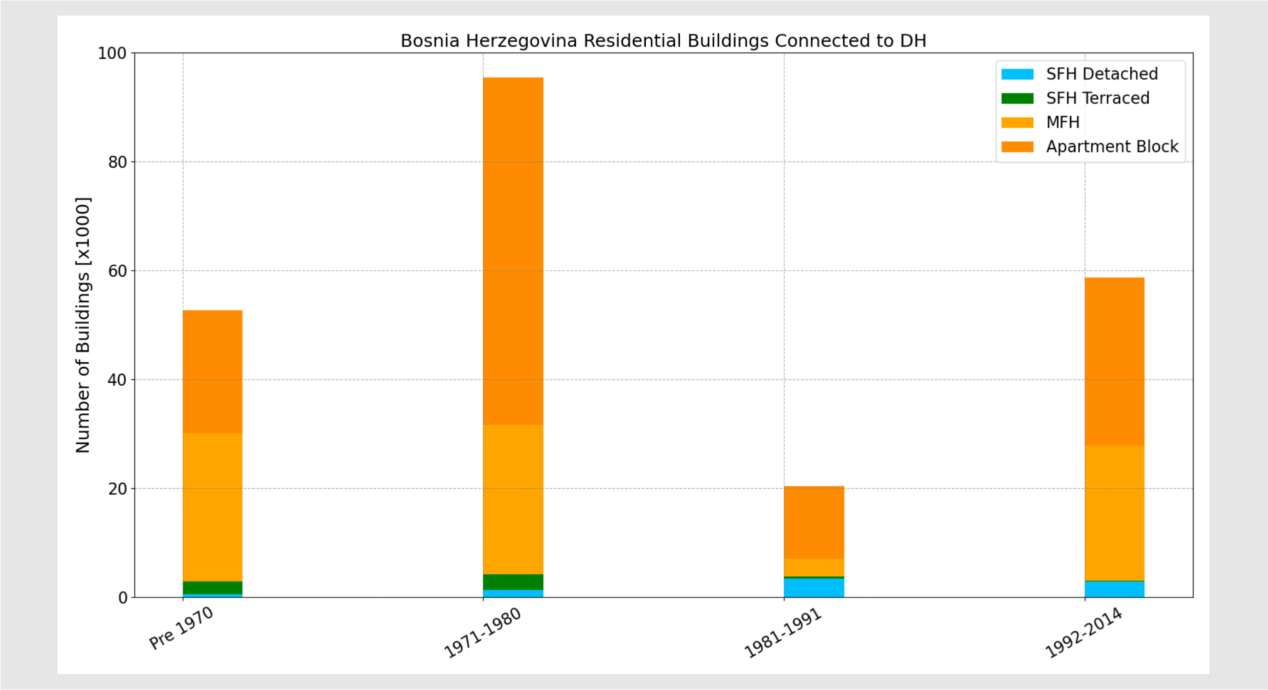


Figure 24: Breakdown of number of buildings connected to district heating networks in Bosnia and Herzegovina based on construction year and building type (AEE INTEC)

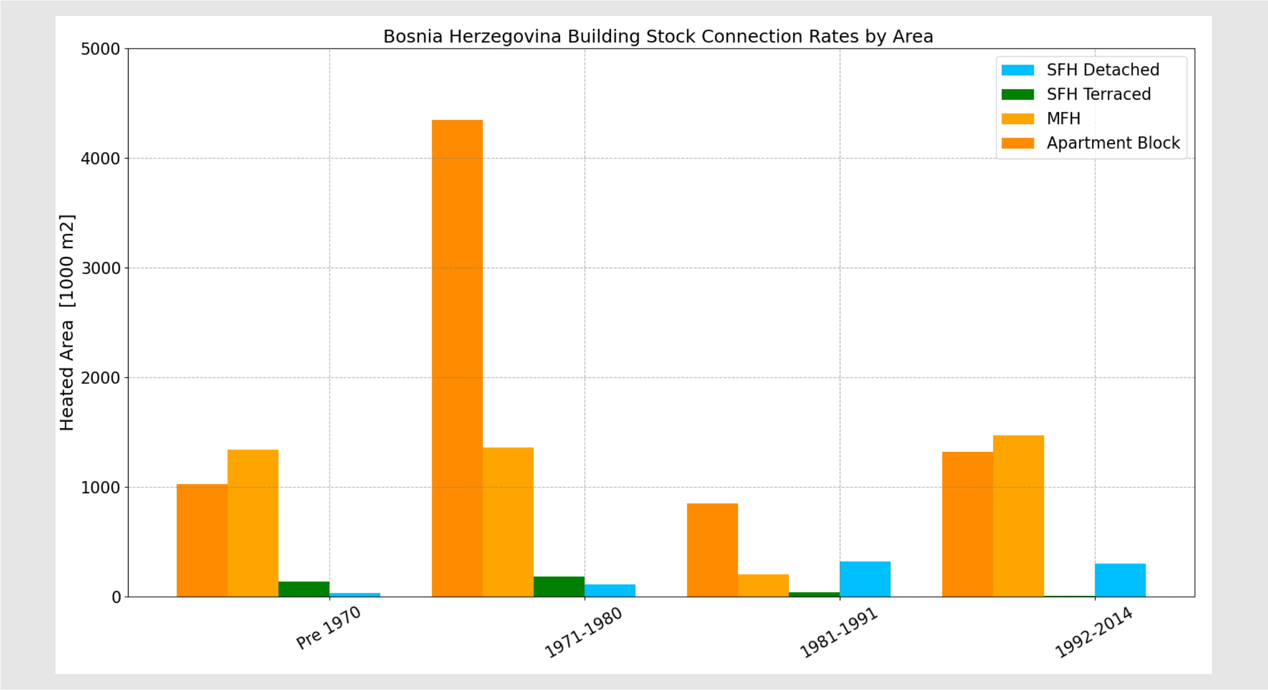


Figure 25: Total heated area of buildings connected to district heating networks in Bosnia and Herzegovina based on construction year and building type (AEE INTEC)

Figure 26 illustrates the district heating network connection rates for SFH and MFH buildings across seven countries. Denmark has the highest SFH connection rate, whereas Slovenia and Norway have the lowest connection rates.

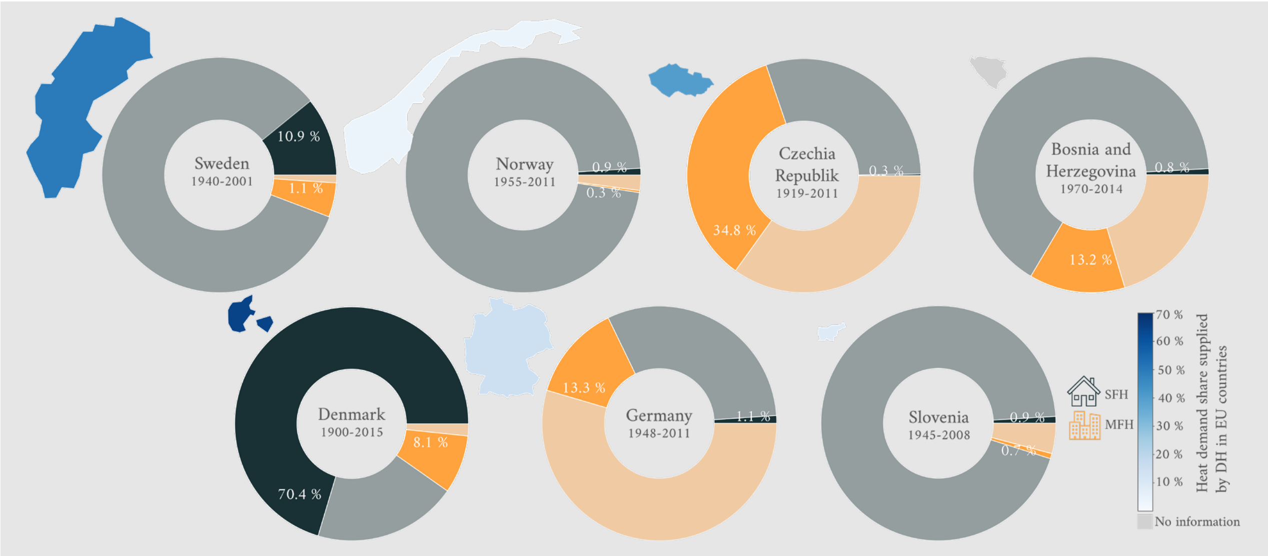


Figure 26: The total proportion of buildings in the seven countries that have SFH and MFH connections to district heating networks (AEE INTEC, Data: [8])

2.3 Building Classification

In district heating systems, several methods exist to balance energy demand and production. All of these methods involve storing a portion of the generated energy for later use when needed. One such approach is to utilize the building's structure as a heat storage medium. This is achieved by providing heat at a time different from when it is needed, thereby raising the indoor temperature when there is excess heat in the network and allowing the building to cool down slightly to conserve energy when heat supply is scarce (e.g., when renewable energy sources are unavailable). The thermal inertia of walls, ceilings, internal walls, and indoor items such as furniture can serve as a large-scale thermal storage system [9]. This allows buildings to maintain adequate indoor thermal comfort over time while adjusting heat use to provide demand response services to the grid.

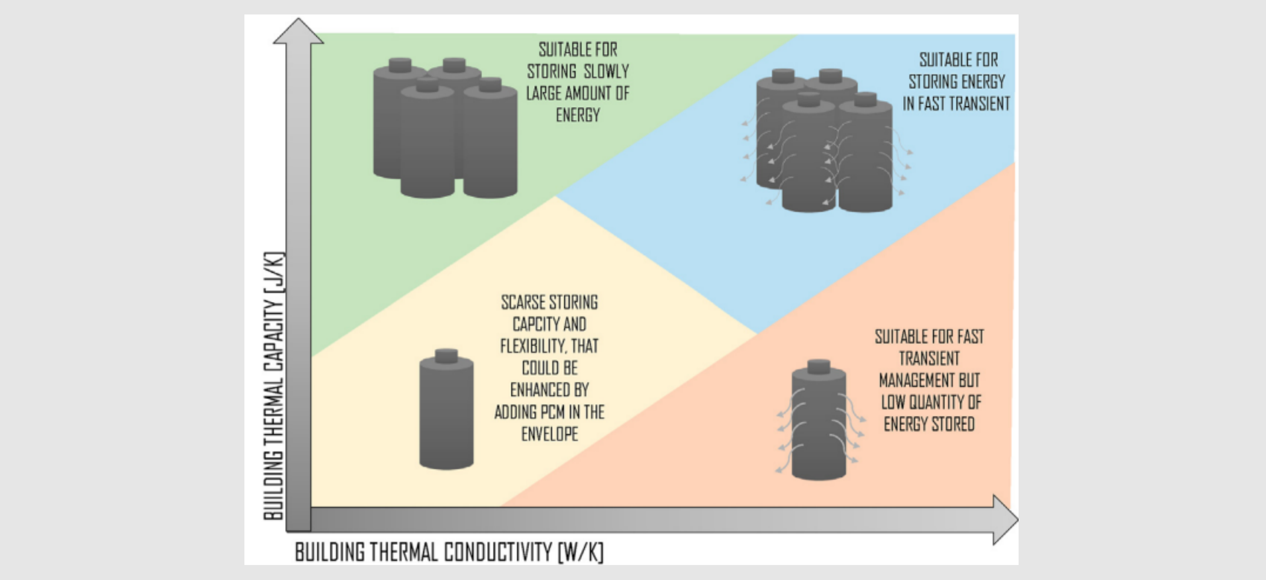


Figure 27: Building thermal conductivity and thermal capacities as indicators of a building envelope's ability to shift thermal loads [10]

A building with high thermal capacity offers greater heat storage potential, while high thermal conductivity leads to significant heat losses. **When the ratio between stored energy and thermal power needed for temperature control is large, thermal losses are minimal, making the building a viable heat storage option.** Conversely, a low ratio indicates unsuitability for DSM due to high thermal losses and limited storage capacity. Another crucial factor affecting DSM suitability is the interaction between DH water fluid and the building envelope, primarily through indoor air. Well-insulated buildings can quickly overheat indoor air when exposed to excess heat due to reduced heat transfer between the indoor air and the building envelope. In low thermal conductivity buildings, it is easier to store excess heat in the building envelope, even though some heat is inevitably lost. **This limitation can be addressed by incorporating phase change materials into the envelope, enhancing heat exchange between indoor air and the envelope.**

A research study investigated the potential use of thermal building mass for energy storage, employing a comprehensive approach combining detailed building simulations with a linear optimization model of the energy system [10]. Various building prototypes were analysed to assess their capacity for preheating and subsequent heat supply interruptions. The study's findings indicate that in cold and overcast weather conditions, heat losses have a greater impact than the building's heat capacity or thermal mass. For poorly insulated buildings, the ability to retain heat is limited, meaning they can operate without an active heating system for only a short period. In contrast, energy-efficient passive houses exhibit significantly longer thermal stability, allowing for extended periods without heating activation. This suggests that poorly insulated buildings can transfer significant amounts of heat over shorter time intervals, whereas airtight, well-insulated buildings inherently provide high thermal autonomy (approximately six hours), with minor improvements achievable through preheating.

These results align with other numerical studies on demand response potential of single-family houses in Denmark, particularly regarding heating setpoint modulation based on an energy price signal. Le Dréau & Heiselberg (2016) and Johra et al. (2019) demonstrated that the insulation level of the building envelope is the most important building factor affecting heating energy flexibility via setpoint modulation. Total thermal inertia also plays a significant role, to a lesser extent. If poorly insulated houses can only reduce heating for 30 minutes to a few hours, low-energy dwellings can significantly reduce their heating demand profile for 12 to 24 hours after preheating. Underfloor heating systems provide greater energy flexibility due to their enhanced activation of the thermal mass within the concrete screed in which they are embedded in. Furthermore, the additional thermal mass from indoor items and furniture can increase a building's thermal time constant and energy flexibility potential by 20–40% in homes with low structural thermal inertia. Integrating phase change materials into wallboards or in furnishing elements can also substantially enhance a building's heating and cooling energy flexibility [11], [12].

The calculation of heat loss in buildings relies on U-value determination. Figure 28 illustrates the average U-values for windows, roofs, floors, and walls across buildings in 20 European countries over different years. The countries highlighted in red (Czech Republic, Denmark, Germany, Belgium, Sweden, and Slovenia) were selected in Section 2.1.2. The figure shows a clear improvement in materials and regulatory standards over time, leading to reduced U-values. The Netherlands records the highest U-values, whereas Sweden has the lowest [8].

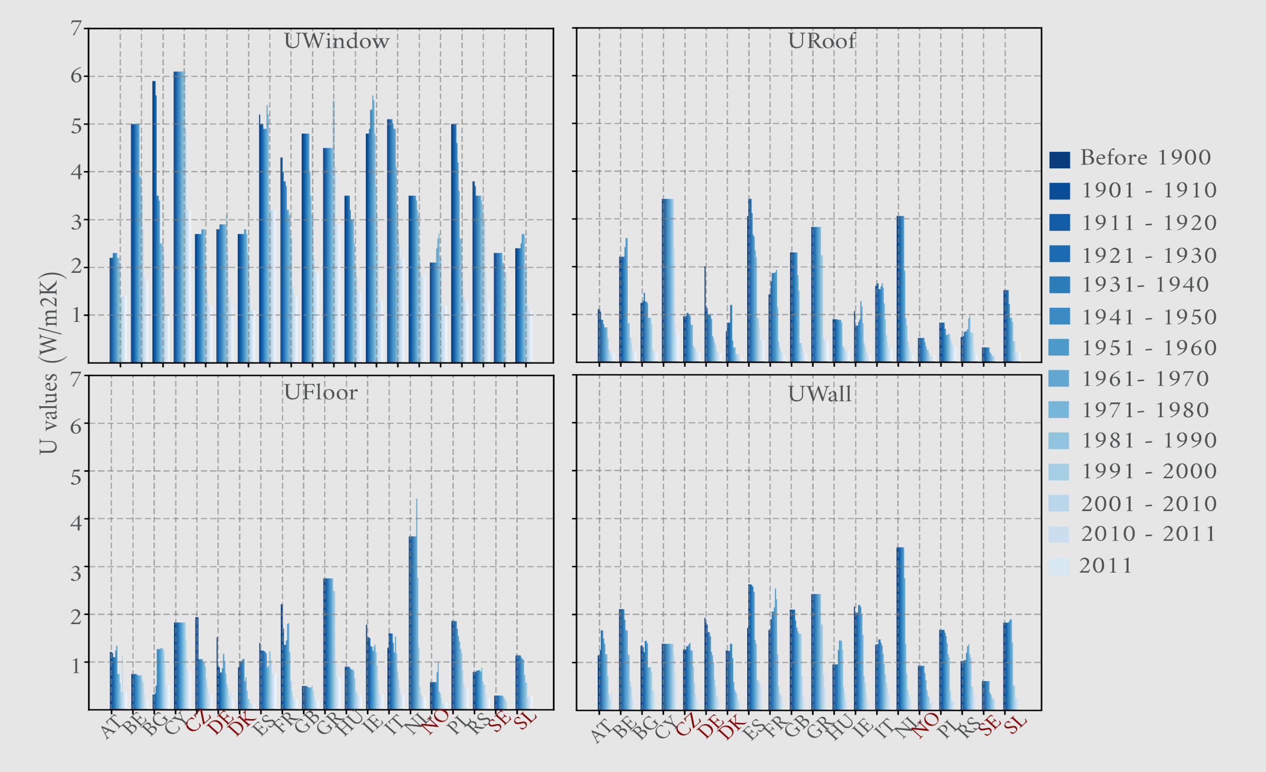


Figure 28: Extract from the "TABULA.xlsm" data analyses – comparison of features of exemplary buildings: U-values per country and decade (no refurbishment applied) (AEE INTEC, Data: [8])

The section aims to assess whether buildings constructed in different years across the selected seven countries are suitable for Demand-Side Management (DSM). Figure 26 serves as a reference point for Figure 29. The primary graph in Figure 29 illustrates the relationship between specific heat capacity and heat transfer coefficient for four distinct building types (SFH, TH - terraced houses, MFH, and apartments) constructed between 1850 and 2016 in these seven countries. Buildings constructed before 1980 typically exhibit limited heat storage capacity and rapid heat exchange. In contrast, buildings constructed after 1980 tend to store larger amounts of energy over time, making them more suitable for thermal mass utilization. SFH and TH generally show lower potential for DSM compared to MFH and apartments. However, the actual energy savings depend on factors such as the prevalence of these building types and their construction timelines within a city. Consequently, an example from Copenhagen district heating network in Denmark will be analysed.

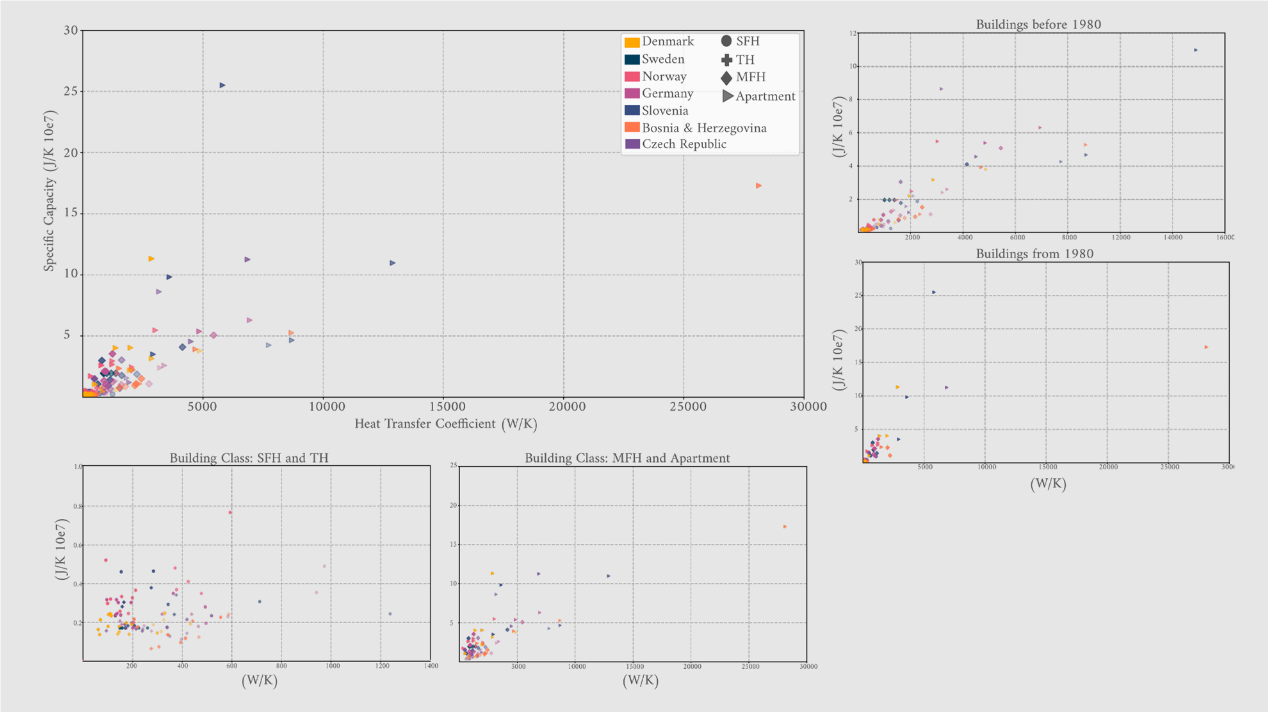


Figure 29: Specific heat capacity vs heat transfer coefficient across seven countries, categorized by building and construction year (AEE INTEC, Data: [8])

A recent study of Denmark’s building stock investigated the correlation between envelope performance characteristics and indoor thermal storage capacity for demand response via heating/cooling setpoint modulation [7]. Figure 30 and Figure 31 illustrate a strong correlation between the building's theoretical time constants and the space heating needs in Denmark’s residential sector. A higher building time constant is associated with greater energy flexibility for heating/cooling setpoint modulation. Once the indoor space is “charged” (pre-heated or pre-cooled), the heating or cooling system can be adjusted or turned off. The higher the building time constant, the longer it takes for indoor temperatures to change significantly, ensuring occupants thermal comfort. Thus, newer or renovated buildings with improved envelope performance (i.e., lower space heating needs) provide more efficient thermal storage capacity, enabling load shifting and peak shaving.

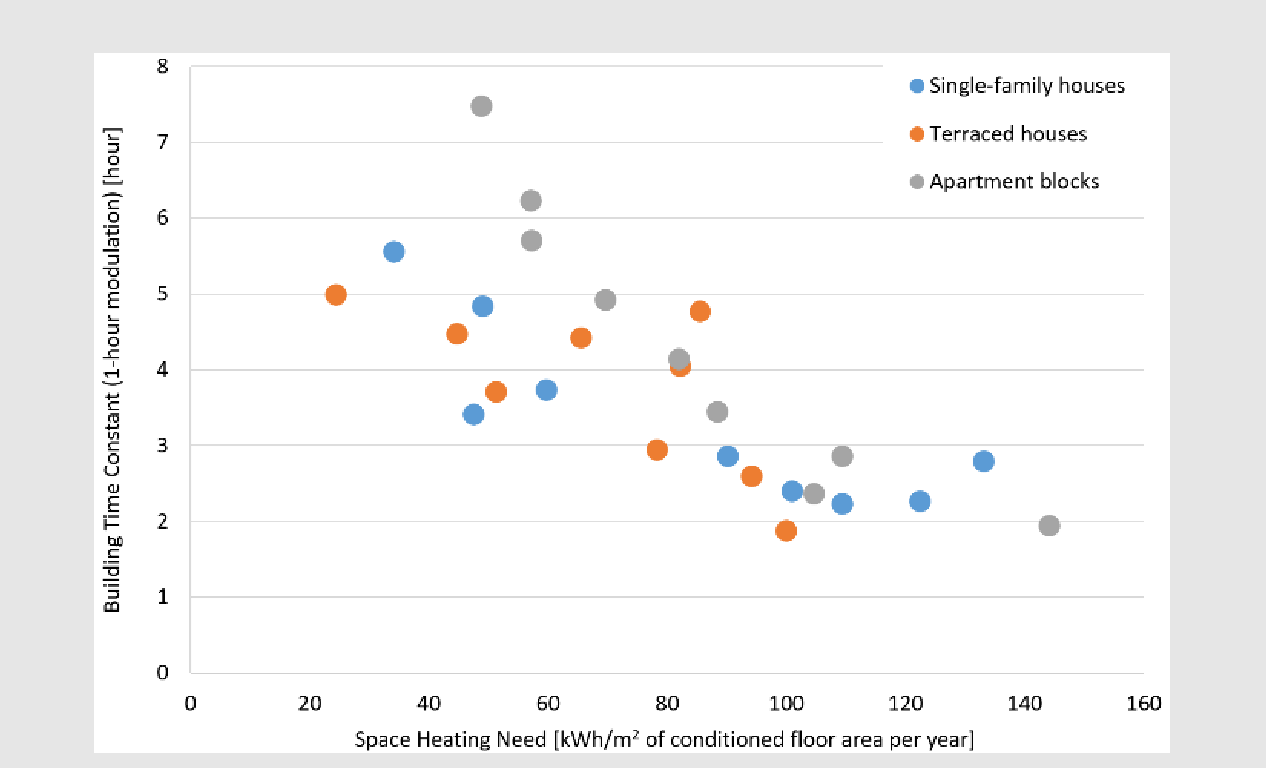


Figure 30: Theoretical time constant (indoor environment for a 1-hour modulation) vs. space heating need in the Danish building stock [7]

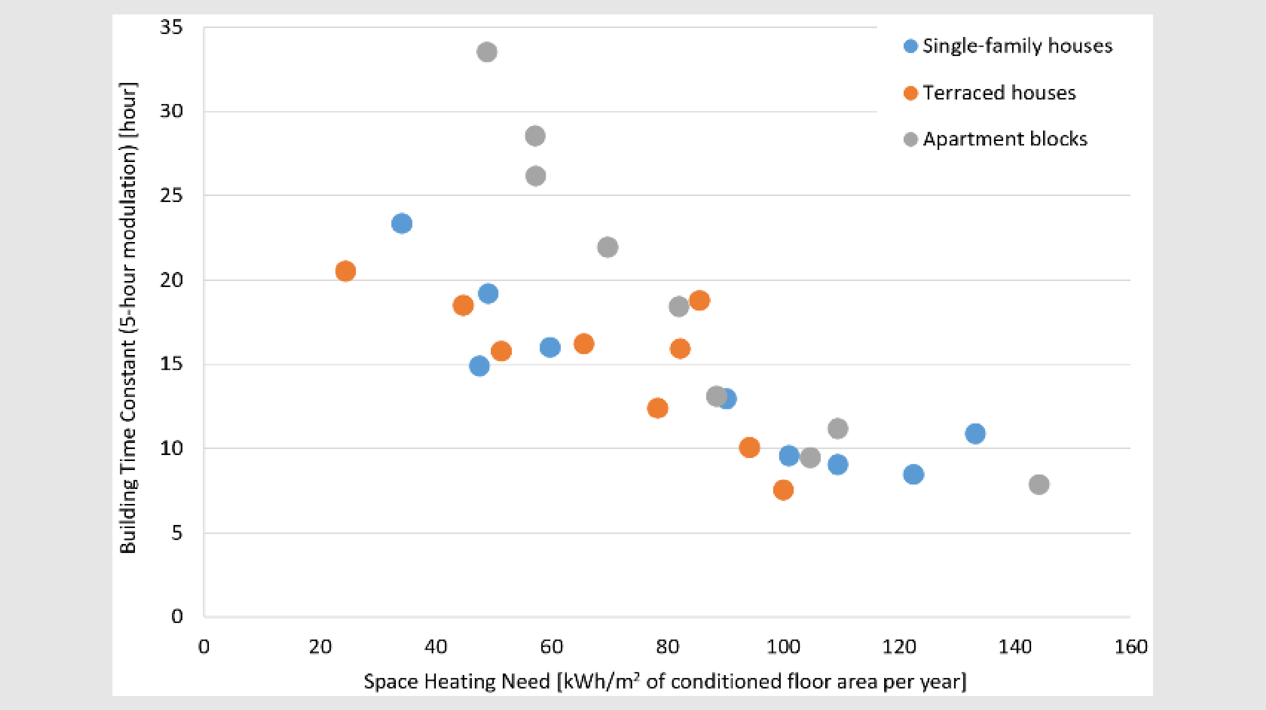


Figure 31: Theoretical time constant (indoor environment for a 5-hour modulation) as a function of the space heating need in the Danish building stock [7]

However, the correlation between the effective heat capacity of indoor environment in Danish buildings and their envelope thermal performance is much weaker (see Figure 32).

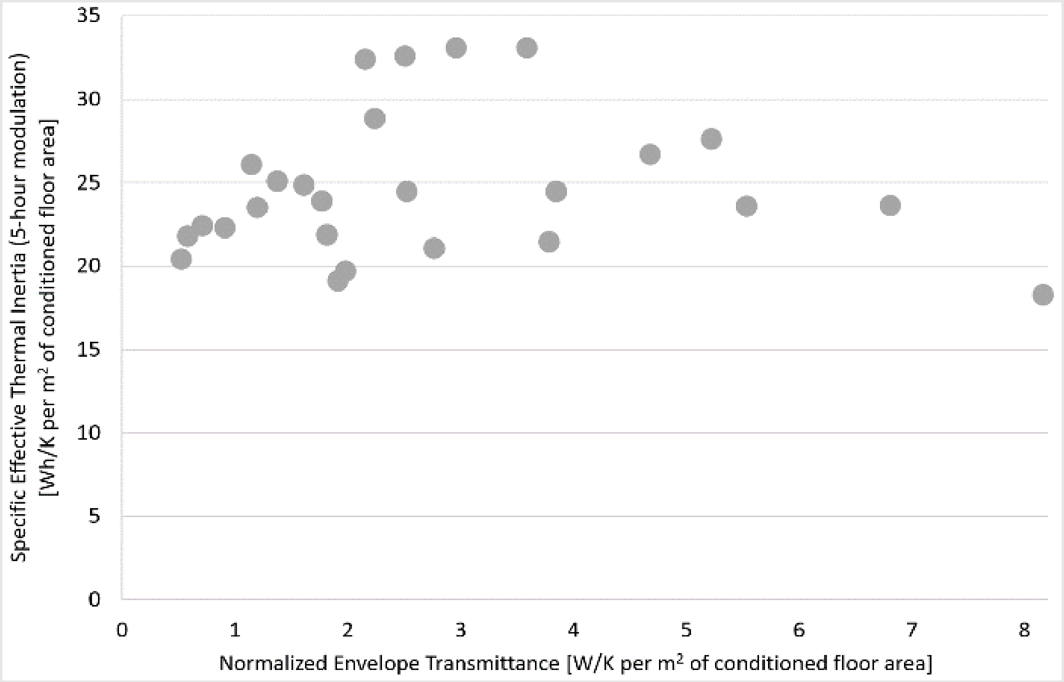


Figure 32: Effective thermal inertia (heat capacity for a 5-hour modulation) vs. as a function of the normalized envelope transmittance in the Danish building stock [7]

Copenhagen was selected due to the availability of a comprehensive and detailed dataset. Between 1900 and 2015, data on detached, terraced, linked or semi-detached, multi-dwelling and apartment blocks, including heated areas for these four building types, were extracted from the database. Using U-values for floors, windows, roofs, and walls of buildings constructed between during this period, the UA values per m^2/buildings were calculated (see Figure 33). In the Copenhagen, apartments and multi-dwellings have greater potential for energy savings. The construction period plays a crucial role; newer buildings (represented by green scatter points) exhibit lower heat transfer than older buildings, giving them a greater advantage for energy saving.

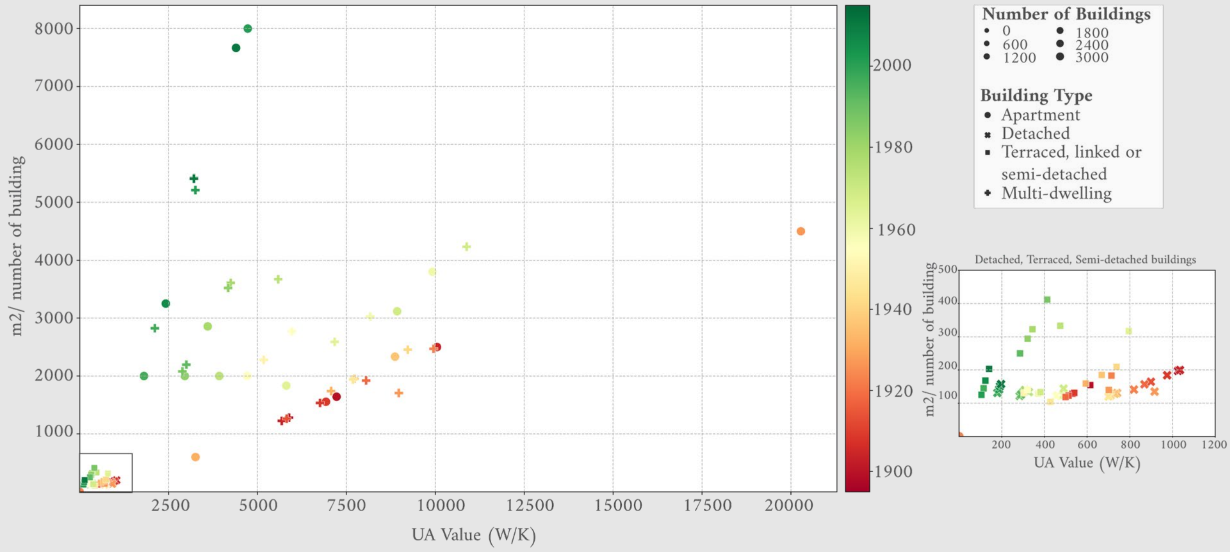


Figure 33: Average floor area per building (5-year step) in Copenhagen (AEE INTEC, Data: [8])

Case Study: Heat meter data analysis of 3,027 residential buildings connected to Aalborg city district heating grid.

High resolution (hourly) heat meter data is crucial for district heating and cooling operators to predict heat consumption patterns. Residential heat demand fluctuates with outdoor air temperature, peaking during the coldest months of the year. Seasonal variations in heat demand are influenced by climate (temperature fluctuations) and building envelope properties (insulation quality, thermal capacity). However, domestic hot water (DHW) demand is largely independent of outdoor temperature and instead depends on occupant behavior. DHW demand introduces peaks in thermal demand over a short period of time (one hour or less depending on whether there is a buffer tank present in the building or not) and has a pronounced impact on the daily variation in heat demand from the building.

A publicly available dataset contains hourly smart heat meter data from 3,027 residential buildings in Aalborg's district heating network (2019–2021). This dataset includes supply and return temperature as well as volume flow rates [13]. Heat flow rates were calculated based on a fixed specific heat capacity of the working fluid. To quantify short-term (daily) and long-term (seasonal) heat load fluctuations, several key performance indicators (KPIs) were applied [14].

One widely used KPI is the **Daily Annual Relative Load Variation (Ga)**, which measures the accumulated positive difference between the hourly average heat loads (P_h) and daily average heat load (P_d) over a year, divided by annual average heat load (P_a) and the number of hours in the year. It hereby provides a measure of how the heat load pattern in a building is offset from a flat average load profile. The division with the annual average heat load is introduced to get a normalized measure independent of building size:

$$G_a = \frac{\frac{1}{2}\sum_{i=1,j=1}^{8760,365} \left|P_{h,i} - P_{d,j}\right|}{P_a \cdot 8760} \cdot 100 \ [\%]$$

This parameter can serve as a key measure of the degree in which a buildings heat load fluctuates over the course of the day. Buildings with a high Ga value can be deemed more "problematic" in contributing to peak loads in the network particularly if they are a large consumer with a high average heat load to begin with.

Another common KPI is the **Annual Relative Seasonal Variation**, which quantifies how much a building's daily average heat load fluctuates throughout the year. This is calculated by summing the absolute difference between the daily average heat load (P_d) and the yearly average heat load (P_a) for each day, nominalized by the annual average load (P_a) over 8,760 hours. This metric reveals how much a building's heat demand deviates from a flat load profile on a daily basis, omitting intraday fluctuations.

$$W = \frac{24 \cdot \frac{1}{2}\sum_{j=1}^{365} \left|P_{d,j} - P_a\right|}{P_a \cdot 8760} \cdot 100 \ [\%]$$

To analyze the impact of building age, annual heat demand, and dwelling type on these two KPIs, both were calculated for each building in the dataset based on the heat meter data from 2018 and plotted in a scatter plot below to firstly observe the spread throughout the network. The scatter plot in Figure 34 illustrates the distribution of Ga and seasonal variation across buildings. The majority of buildings constructed before 1960 have relative daily variations between 5–20%, whereas newer buildings with higher degrees of insulation have a much higher spread in values for the annual relative daily variation, between 20–65%. As discussed, the specific space heating demand ($kWh_{th}/m^2/a$) for the newest buildings connected to the network is expected to be relatively low due to higher insulation standards, therefore the relative peaks introduced for DHW demand become more pronounced compared to the space heating demand. The Annual Relative Seasonal variation for all dwellings falls within 25–35%, with less pronounced dependency on building construction period. **Most buildings in the dataset are single-family homes, limiting the ability to generalize results across different building types**.

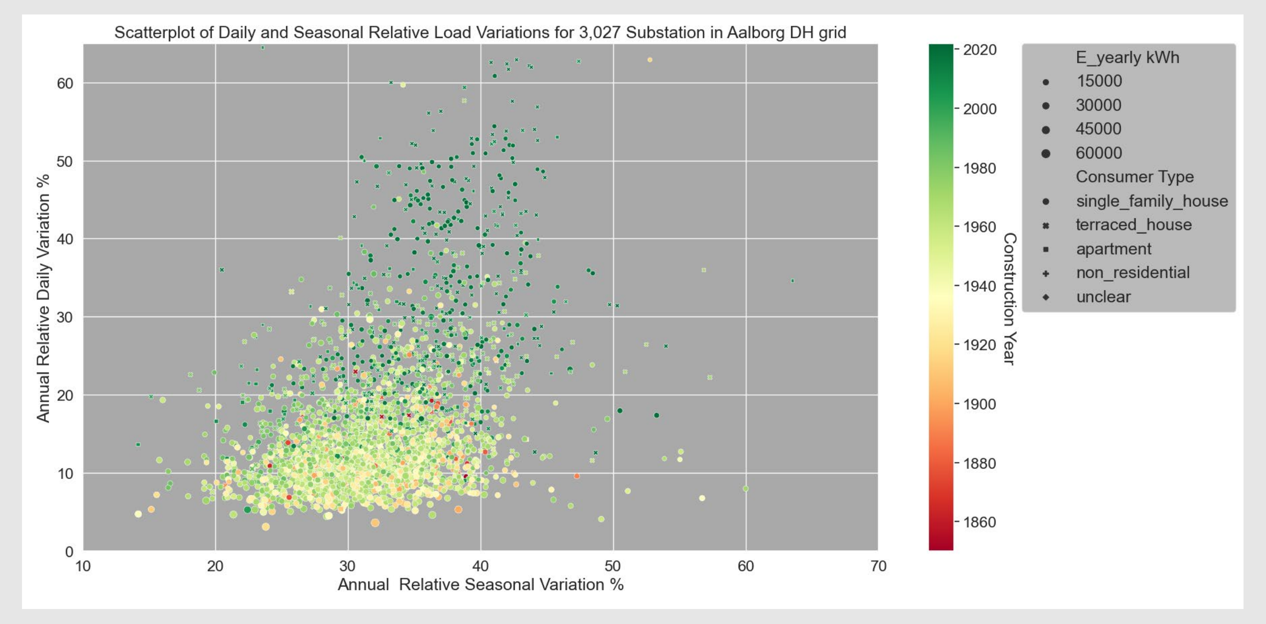


Figure 34: Scatter Plot showing the Annual Relative Daily Variation (left) against Annual Relative Seasonal Variation (right) for all dwellings in the dataset. The colour indicates construction year and the size of datapoint indicates the yearly heat demand (AEE INTEC)

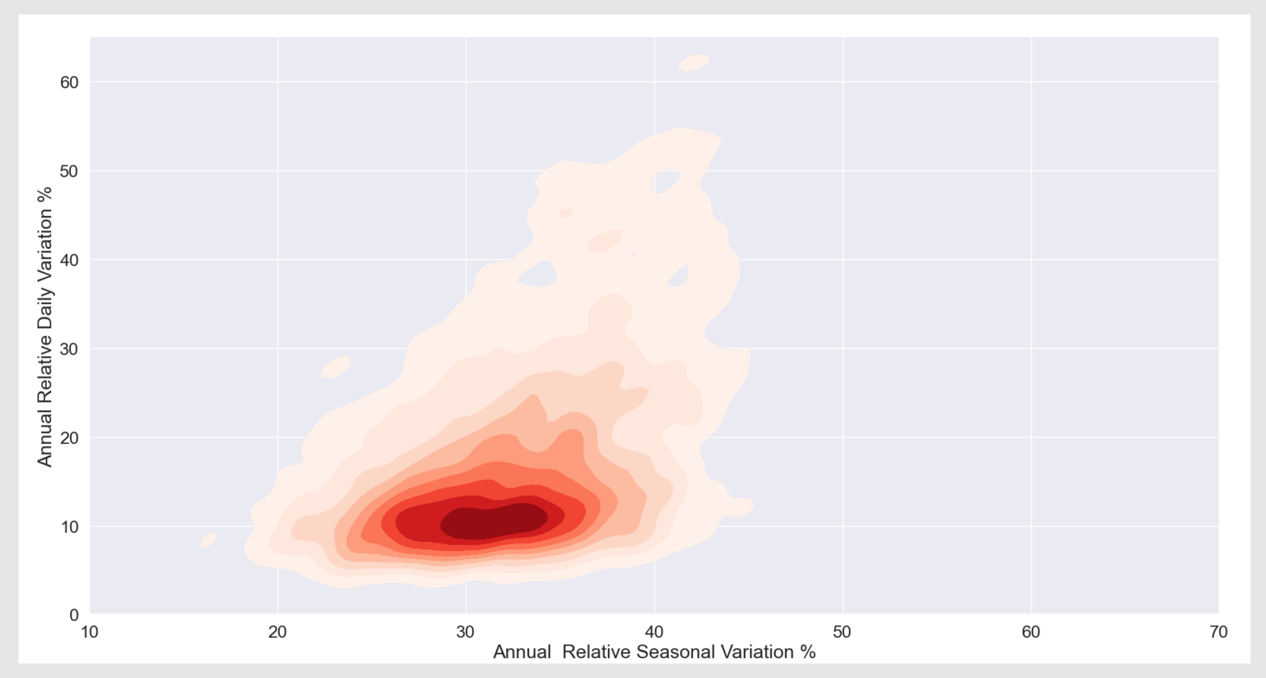


Figure 35: Contour Plot showing the Annual Relative Daily Variation (left) against Annual Relative Seasonal Variation (right) for all dwellings in the dataset (AEE INTEC)

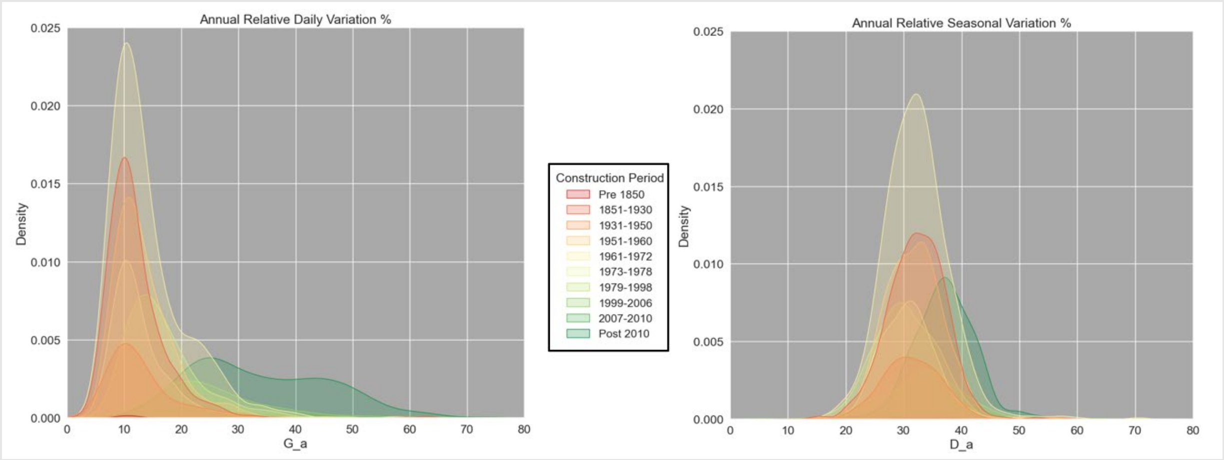
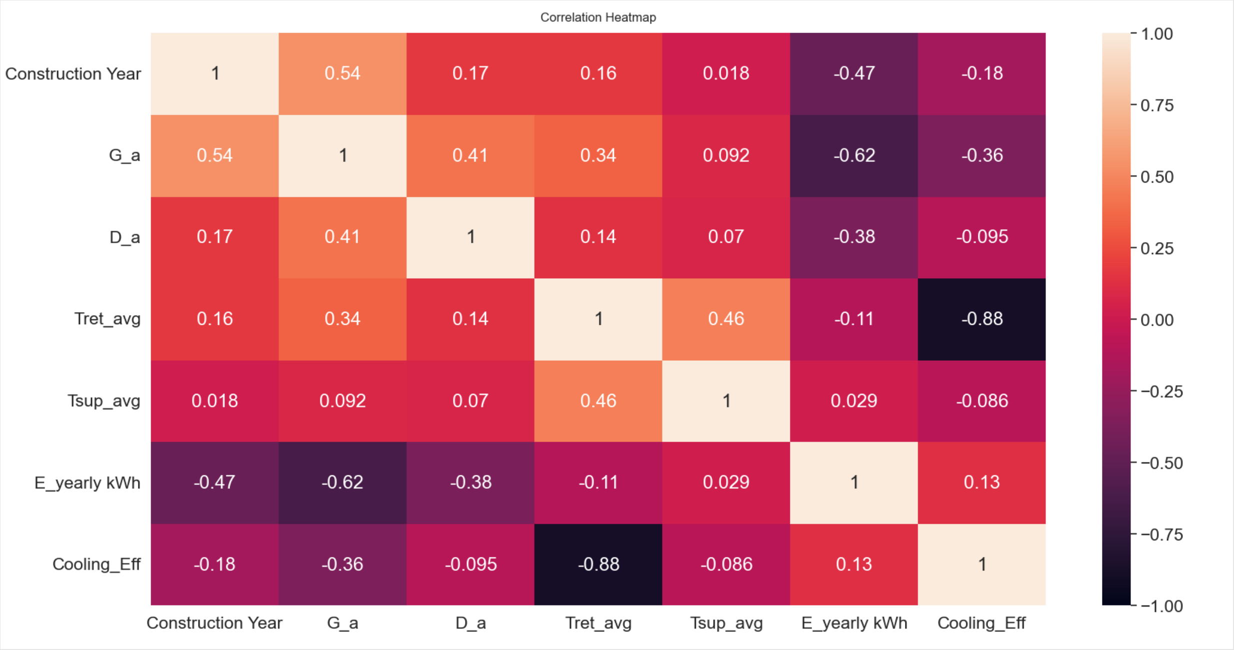


Figure 36: Density Plots showing the highest occurring Annual Relative Daily Variation (left) and the highest occurring Annual Relative Seasonal Variation (right) for all buildings categorised by their construction period (AEE INTEC)

Figure 37 displays density plots by building age, aligning with Danish regulation changes for insulation standards. Before 1972, the annual relative daily variation is centred around 10–11%, increasing for newer buildings constructed due to DHW demand peaks. Post-2010 buildings exhibit a wider spread due to these effects.


Correlation Heatmap

	Construction Year	G_a	D_a	Tret_avg	Tsup_avg	E_yearly kWh	Cooling_Eff
Construction Year	1	0.54	0.17	0.16	0.018	-0.47	-0.18
G_a	0.54	1	0.41	0.34	0.092	-0.62	-0.36
D_a	0.17	0.41	1	0.14	0.07	-0.38	-0.095
Tret_avg	0.16	0.34	0.14	1	0.46	-0.11	-0.88
Tsup_avg	0.018	0.092	0.07	0.46	1	0.029	-0.086
E_yearly kWh	-0.47	-0.62	-0.38	-0.11	0.029	1	0.13
Cooling_Eff	-0.18	-0.36	-0.095	-0.88	-0.086	0.13	1

Figure 37: Correlation matrix identifying key relationships between calculated building parameters (AEE INTEC)

This analysis highlights the potential smart heat meter data to identify building types suitable for demand response measures based on their heat demand profiles. However, it does not account for social factors such as occupant comfort preferences, night-time thermostat setback, or DHW usage patterns. A more comprehensive analysis, incorporating occupant behaviour data, would enhance the accuracy of heat load predictions for different building typologies.

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