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Lind, Johan

2026

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Lind, J. (2026). *Exploring the energy-flexibility potential in the thermal mass of residential buildings*. [Licentiate Thesis, Department of Energy Sciences]. Department of Energy Sciences, Faculty of Engineering, Lund university.

Total number of authors:
1

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Printed by Media-Tryck, Lund 2026 NORDIC SWAN ECOLABEL 3041 0903

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Faculty of Engineering
Department of Energy Sciences

ISRN LUTMMDN/TMHP-26/7112-SE
ISSN 0282-1990

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Lund University

Thesis for the degree of Licentiate in Engineering
Thesis advisors: Dr. Fredric Ottermo, Dr. Helge Averfalk, Dr. Erik Möllerström
Faculty opponent: Prof. Jan-Olof Dalenbäck

To be presented, with the permission of the Faculty of Engineering of Lund University, for public criticism in the M:B lecture hall at the Department of Energy Sciences on Friday, the 13th of March 2026 at 10:15.

DOKUMENTDATABLAD enl SIS 61 41 21

Organization **LUND UNIVERSITY**	Document name **LICENTIATE DISSERTATION**
Department of Energy Sciences Box 118 SE–221 00 LUND Sweden	Date of disputation 2026-03-13
	Sponsoring organization
Author(s) Johan Lind	

Title and subtitle

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Abstract

The striving for a sustainable energy system entails an increasing use of renewable energy. Since several renewable energy sources are non-dispatchable (e.g., wind and solar), this development brings challenges in terms of the balance between energy supply and demand. As a result, there is a growing need for demand-side flexibility.

The building stock has been highlighted as a promising resource of such flexibility; flexibility can be provided by storing heat in the thermal mass of the buildings and using it for load shifting. The heat-storage potential in Building Thermal Mass (BTM) depends on several building properties, including the insulation level of the building envelope, the heat capacity of building structures and indoor content, and the type of heating system. Regarding heating system type, previous studies have shown that floor-heating systems are beneficial compared to radiator systems since they better activate the thermal mass of the building structures.

This work has contributed to a better understanding of the heating system's influence on the energy-flexibility potential of residential buildings using heat storage in BTM. An existing low-energy multi-family house was used as a case building, heated by a Thermally Activated Building System (TABS). The TABS was compared to two other heating systems: an embedded surface system and a radiator system. It was found that the TABS performed best in every studied respect: it had the longest response time, the shortest recovery time, the greatest heat-storage capacity, and the smallest impact on thermal comfort. Furthermore, significant differences in heat-power capacity were observed.

Based on the same case building, the economic potential of load shifting using BTM storage was also investigated, including its impact on thermal comfort. The heat supply was provided by a modelled ground-source heat pump, and the heating system was controlled in response to historical day-ahead electricity prices. Also, the dependence of the economic potential on various limits of maximum allowable heat power was evaluated. The results showed that significant electricity cost savings for heat-pump operation were obtained, with a limited impact on thermal comfort. Furthermore, it was found that the temperature fluctuation caused by load shifting was counteracted by the natural temperature fluctuation resulting from varying internal heat gains.

Finally, the work includes a review of previous studies on the energy-flexibility potential of residential buildings using BTM storage, focusing on heat-storage potential, influencing factors, and associated benefits and challenges.

Key words

Building Thermal Mass (BTM), Energy flexibility, Load shifting, Residential buildings, Thermally Activated Building System (TABS)

Classification system and/or index terms (if any)			
Supplementary bibliographical information			Language English
ISSN and key title			ISBN
Recipient's notes	Number of pages 63		Price
	Security classification		

Signature ____________________ Date 2026-02-13

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LUND
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Funding information: The thesis work was financially supported by Halmstad University, Sweden (internal founding).

Faculty of Engineering, Department of Energy Sciences

ISRN: LUTMMDN/TMHP-26/7112-SE
ISSN: 0282-1990

Printed in Sweden by Media-Tryck, Lund University, Lund 2026

Dedicated to my family
Annika – Olle – Elsa – Majken

Contents

List of publications

This thesis is based on the following publications, referred to by their Roman numerals:

I **Energy flexibility using the thermal mass of residential buildings**

J. Lind, E. Möllerström, H. Averfalk, F. Ottermo
Energy & Buildings 301 (2023), 113698

II **Energy flexibility in multi-family houses heated by thermally activated building systems**
J. Lind, F. Ottermo
Energy & Buildings 330 (2025), 115345

III **The economic potential of load shifting and its impact on thermal comfort, combining a thermally activated building system with a ground-source heat pump**
J. Lind, F. Ottermo
Submitted to Energy

Papers I and II are reproduced with permission from their publisher.

Publications not included in this thesis:

I State-of-the-art
P.A. Sørensen et al.
IEA DHC Annex TS5 RES in DHC Report (2022)

Acknowledgement

First and foremost, I would like to thank Fredric Ottermo, my main supervisor. I am very grateful that you agreed to be my supervisor, for all your helpful support through the first half of my doctoral studies, and for always being available for questions and discussions. Moreover, I would like to thank co-supervisor Helge Averfalk for all the interesting conversations and valuable comments on my research and manuscripts. I would also like to thank co-supervisor Erik Möllerström for valuable comments and advice, and for your contribution in making it possible for me to begin doctoral studies. I would also like to thank Kerstin Sernhed, my co-supervisor at Lund University, and Sven Werner for valuable guidance at the beginning of my PhD journey. Furthermore, I would like to thank the former dean of the School of Business, Innovation and Sustainability at Halmstad University for giving me the opportunity to begin doctoral studies.

Finally, I would like to thank Henrik Jorbrant and Tobias Heikkinen at ÖrebroBostäder AB, and Jacob Thor and Lars Thunström at Thermotech Scandinavia AB, for their valuable assistance related to the case building in Örebro.

Popular summary in English

The energy supply of the energy system is increasingly comprised of renewable energy sources, since these sources cause less environmental impact than many non-renewable sources (e.g., fossil fuels). The energy supply from many renewable sources (e.g., wind and solar) cannot be fully controlled on demand as it depends on factors such as wind speed and solar radiation. This brings challenges for the operation of the energy system, as there must always be balance between energy supply and demand. One way to facilitate maintaining balance is to utilize energy users' ability to be flexible with their energy use.

The energy use of buildings constitutes a promising resource of such flexibility. Flexibility can be provided by storing heat in the mass of the buildings, which can be utilized for short-term time shifting of the energy use for space heating. The heat-storage potential in the mass of buildings depends on several building properties, including the insulation level of the building envelope, the amount of mass and the type of materials in the building, and the type of heating system. Regarding heating system type, previous studies have shown that floor-heating systems are more beneficial than radiator systems, as they better activate the mass of the building.

In the Swedish residential building stock, there are many multi-family houses with a large amount of mass, often due to a heavy structural frame of concrete. Considering this large mass, these buildings constitute a significant flexibility resource. However, these buildings are typically heated by radiators, which is not the most favourable heating system from a flexibility point of view.

This work has contributed to a better understanding of the heating system's influence on the flexibility potential of residential buildings through heat storage in their mass. An existing well-insulated multi-family house was used as a case, heated by a heating system called Thermally Activated Building System (TABS). The TABS is a heating system that is similar to conventional floor-heating systems, but with the difference that the heating pipes are embedded in the structural frame of the building, for instance, in intermediate floors of multi-storey buildings. The fact that the heating pipes are embedded in the structural frame, which is often made of thick layers of massive concrete, contributes to a great heat-storage capacity that can be used for time shifting of the energy use.

Based on a representative apartment of the case building, a simulation model was created, and its reliability was ensured by comparing simulation results with operational data from the actual building. The simulation model was used to compare the TABS with two other heating systems: a floor-heating system and a radiator system. It was found that the TABS performed better than the other two systems in every studied respect: it had the greatest heat-storage capacity, the best ability to shift energy use in time, with the smallest impact on the indoor climate of the building.

Using the same simulation model, the economic potential of energy-use shifting was also investigated, including its impact on the indoor climate. The heat was supplied by a modelled ground-source heat pump, and the heating system was controlled in response to time-varying electricity prices. Moreover, the dependence on various limits of maximum allowed heat power was evaluated. The results showed that significant electricity cost savings for heat-pump operation were obtained, with a limited impact on the indoor climate. Furthermore, it was found that the temperature fluctuation caused by the energy-use shifting was counteracted by a natural temperature fluctuation already present in the actual building, resulting from varying internal heat gains from occupants, lighting, and equipment.

Finally, the work includes a review of previous studies on the energy-flexibility potential of heat storage in the mass of residential buildings, focusing on storage potential, the factors influencing it, and its associated benefits and challenges.

Populärvetenskaplig sammanfattning

Energisystemets energitillförsel utgörs i allt högre grad av förnybara energikällor, eftersom dessa källor orsakar mindre klimatpåverkan än många icke-förnybara källor (t.ex. fossila bränslen). Energitillförseln från flera förnybara källor (t.ex. vind och sol) kan inte fullt ut kontrolleras efter behov, eftersom den beror på faktorer såsom vindhastighet och solstrålning. Detta medför utmaningar för driften av energisystemet eftersom det alltid måste råda balans mellan energitillförseln och energianvändningen. Ett sätt att underlätta upprätthållandet av denna balans är att utnyttja energianvändarnas förmåga att vara flexibla i deras energianvändning.

Byggnaders energianvändning utgör en lovande resurs av sådan flexibilitet. Byggnader kan bidra med flexibilitet genom att värme lagras i byggnadernas massa, vilket kan användas för kortsiktig tidsförflyttning av energianvändningen för uppvärmning. Hur mycket värme som kan lagras i en byggnads massa beror på flera faktorer, bland annat byggnadens isoleringsgrad, mängden massa och typ av material som finns i byggnaden, samt typen av uppvärmningssystem. När det gäller uppvärmningssystemet har tidigare studier visat att golvvärmesystem är mer gynnsamma än radiatorsystem eftersom de är bättre på att aktivera byggnadens massa.

I det svenska bostadsbeståndet finns många flerbostadshus med en stor mängd massa, ofta på grund av en tung betongstomme. Med tanke på den stora massan utgör dessa byggnader en betydande flexibilitetsresurs. Dock värms de ofta med hjälp av radiatorer, vilket inte är det mest gynnsamma uppvärmningssystemet utifrån ett flexibilitetsperspektiv.

Detta arbete har bidragit till en bättre förståelse för uppvärmningssystemets påverkan på bostäders möjligheter till flexibilitet genom värmelagring i byggnadernas massa. Ett befintligt välisolerat flerbostadshus användes som utgångspunkt för studierna, uppvärmt med uppvärmningssystemet stomvärme. Stomvärme är ett uppvärmningssystem som påminner om det konventionella golvvärmesystemet, men med skillnaden att värmeslingorna är ingjutna i byggnadens bärande stomme, t.ex. i mellanbjälklag i flervåningshus. Det faktum att värmeslingorna är ingjutna i stommen, som ofta består av tjocka skikt av massiv betong, bidrar till en stor värmelagringskapacitet som kan användas för att tidsförflytta energianvändningen.

En simuleringsmodell skapades, baserad på en representativ lägenhet i den studerade byggnaden, och modellens tillförlitlighet säkerställdes genom att simuleringsresultat jämfördes med driftsdata från den verkliga byggnaden. Simuleringsmodellen användes sedan för att jämföra stomvärmesystemet med två andra uppvärmningssystem: ett golvvärmesystem och ett radiatorsystem. Resultaten visade att stomvärmesystemet presterade bättre än de två andra systemen i samtliga avseenden som studerades; det hade störst värmelagringskapacitet, bäst förmåga att tidsförflytta energianvändningen, med minst påverkan på inomhusklimatet i byggnaden.

Med hjälp av samma simuleringsmodell undersöktes även den ekonomiska potentialen i att tidsförflytta energianvändningen, inklusive dess påverkan på inomhusklimatet. Värmetillförseln ombesörjdes av en modellerad bergvärmepump, och värmesystemet styrdes mot ett tidsvariabelt elpris. Dessutom undersöktes hur den ekonomiska potentialen beror på olika gränser för maximalt tillåten värmeeffekt. Resultaten visade att betydande elkostnadsbesparingar för värmepumpens drift kunde uppnås, med begränsad påverkan på inomhusklimatet. Dessutom visade det sig att den temperaturfluktuation som tidsförflyttningen av energianvändningen orsakade motverkades av den naturliga temperaturfluktuation som redan förekommer i den befintliga byggnaden, orsakad av variationer i gratisvärme från boende, belysning och apparater.

Slutligen innehåller arbetet även en översikt över tidigare studier kring flexibilitetspotentialen hos bostäder genom värmelagring i byggnadernas massa, med fokus på värmelagringskapaciteten, de faktorer som påverkar denna, samt de nyttor och utmaningar som användandet av denna lagringsresurs kan medföra.

Chapter 1

Introduction

1.1 Background

As part of the transition to a sustainable, decarbonized energy system, the share of renewable energy in the energy supply is continuously increasing. Figure 1.1 (left) presents the share of renewable energy in the EU's energy consumption, rising from 9.6 % in 2004 to 24.6 % in 2023. A significant part of the renewable energy comes from the sources wind and solar (percentages of various renewable sources in the EU's net electricity generation are presented in Figure 1.1 (right)). The fact that these sources are non-dispatchable — i.e., cannot be controlled by the grid operator due to their dependence on uncontrollable factors such as wind speed and solar radiation — poses challenges for maintaining balance between energy supply and demand [1]. Historically, it has primarily been the supply side that has managed this balance [2], but if the share of non-dispatchable renewable energy is to increase further, the demand side will need to be more involved [3]. As a consequence, there is a growing interest in demand-side flexibility [4], i.e., end users' ability to flexibly adjust their energy demand.

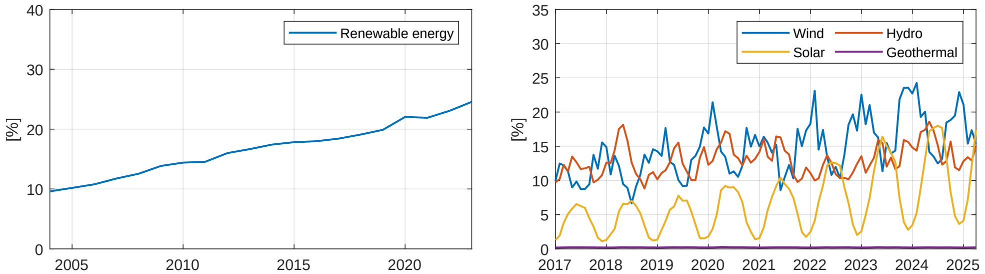

Figure 1.1: Share of renewable energy in the EU's energy consumption (left), and percentages of various renewable sources in the EU's net electricity generation (right). Source: Eurostat [5, 6].

The building stock has been proposed as a promising resource of demand-side flexibility that could facilitate the continued integration of renewable energy sources [3, 7]. The buildings constitute a significant part of the demand side of the energy system — approximately 40 % of the energy use in the EU can be attributed to buildings [8] — implying that a more flexible energy demand from the buildings could substantially influence the energy system. In fact, buildings have long been used for balancing purposes, but it has often been focused on large commercial and industrial customers [2]. As the share of non-dispatchable renewable energy increases, it would be beneficial if other building types — e.g., residential buildings — could also participate by providing flexibility [9]. Within this context, the concept of energy flexibility of buildings has been introduced, defined as a building's "*ability to manage its demand and generation according to local climate conditions, user needs, and energy network requirements*" [7].

Buildings can provide flexibility in several ways: through various thermal-energy-storage technologies, adjustable Heating, Ventilation, and Air Conditioning (HVAC) systems, electrical storage, electric-vehicle charging, and shifting of plug loads [7]. Focusing on residential buildings, thermal-energy storage in Building Thermal Mass (BTM) has been identified as a cost-effective storage solution with great potential [10–13]. This heat-storage technology exploits the high thermal inertia of the buildings, resulting from the substantial heat capacity of building structures and indoor content. Heat storage in the thermal mass of buildings is an inexpensive storage solution, as the thermal mass is readily available and can be utilized only by adjusting the control of the heating system [1]. An important condition for using this storage technology is that the indoor air temperature must be allowed to vary [14], implying that the occupants' requirements for thermal comfort constitute an important boundary condition.

The demand-side flexibility of buildings is of interest to both electric-power and district-heating systems. In district-heating systems, heat is typically supplied by a mix of heat sources that differ significantly in terms of cost and environmental impact, with fossil fuels still used to cover peak loads [15, 16]. As an example, Figure 1.2 presents the heat supply of a Swedish district-heating system during a winter month in 2024. Due to the mix of heat sources, it would be both economically and environmentally beneficial if buildings' heat demand could be adjusted to fit the heat supply. In addition to the conditions on supply side, the heat demand of district-heating systems often has considerable daily variations [17], partly due to a varying demand for domestic hot-water preparation. Reducing or eliminating these variations would bring several benefits, including decreased use of expensive peak-load power, reduced need for peak-load power capacity, and improved heat-supply efficiency, resulting in a more cost-effective and competitive operation of district-heating systems [17].

The heat-storage potential in the thermal mass of residential buildings, and its corresponding load-shifting potential, can be used for several purposes. For example, it can provide cost

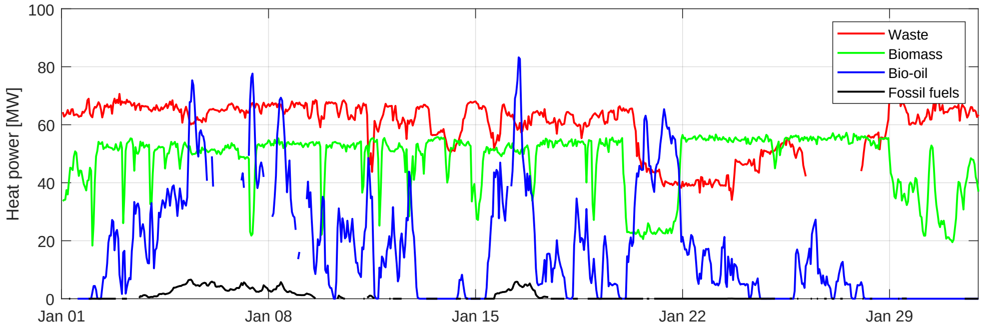

Figure 1.2: Heat supply of a Swedish district-heating system (Halmstad) during January, 2024. The gaps are caused by missing data. Source: Halmstads Energi och Miljö AB.

savings for end users [18] and energy providers [19], as well as reduced environmental impact from space-heating energy use [20]. Regarding cost savings for end users, the economic benefit depends on the heat source of the building. In heat-pump-heated buildings, load shifting can be used to purchase electricity at low prices on the day-ahead market. Moreover, by January 2027, all power-grid operators in Sweden are required to introduce a power tariff in their price models, with the purpose of achieving a more efficient use of the power grid [21]. The power tariff constitutes an additional economic incentive for load shifting in heat-pump-heated buildings. In buildings heated by district heating, the economic benefit of load shifting depends on the heat price model used by the district-heating company, which varies between companies.

1.2 Problem description

As outlined in Section 1.1, the growing integration of non-dispatchable renewable energy sources on the supply side of the energy system has increased the need for demand-side flexibility, and heat storage in the thermal mass of residential buildings has been identified as a promising source of flexibility that could facilitate the transition to a more sustainable energy system.

When using BTM for heat storage, a large available thermal mass in the building is favourable, as it increases the heat-storage capacity and provides a damping effect on temperature variations during load shifting [22–26]. In the residential building stock, the magnitude of the thermal mass varies across building types, partly due to differences in the heat capacity of building structures. Multi-family houses are typically characterized by a larger heat capacity than single-family houses [27], since the requirements for multi-family houses — e.g., regarding fire protection, acoustic performance, and load-bearing capacity — often result in the use of a heavy structural frame of concrete. The substantial heat capacity of concrete frames contributes to a high heat-storage capacity that makes multi-family houses particularly interesting from a flexibility perspective. Despite this, previous research on the energy flexibility of residential buildings using BTM storage has mostly focused on single-family houses [28]. This suggests that heat storage in the BTM of multi-family houses may constitute a valuable flexibility resource that is not yet fully utilized.

The heat-storage potential in BTM also depends on the installed type of heating system [22, 29]. Radiant heating systems, such as floor heating, are more advantageous than convective systems, such as radiators, since radiant systems are able to directly activate the thermal mass of building structures while having a smaller impact on indoor air temperature and thermal comfort [22]. In addition, radiant heating systems offer additional benefits for the energy supply: they are characterized by a low heat supply temperature which improves heat-pump efficiency [30], allows for lower system temperatures in district-heating networks [31], and facilitates the use of renewable and recyclable low-grade energy sources [32]. Despite this, the radiator system is frequently used in the residential building stock; it is the most common system in Swedish multi-family houses [33] and is also widely used in many other countries [34, 35].

The Thermally Activated Building System (TABS) is a radiant heating system that has recently been installed in several newly-built Swedish multi-family houses [36]. The TABS has a particularly large heat-storage capacity since the heating pipes are embedded in the structural frame of the building [37, 38], making it especially promising from a flexibility point of view. However, despite its potential, the TABS has not received much attention in previous studies on the energy flexibility of residential buildings using BTM [28]. Therefore, it is important to examine in more detail how the use of TABSs influences the heat-storage potential in the BTM of residential buildings, compared to other heating systems.

1.3 Objectives

The overall purpose of the research is to explore the energy-flexibility potential in the thermal mass of residential buildings, with a special focus on multi-family houses and the influence of different heating system types. Based on the problem description and the potential described in Section 1.2, the research aims to answer the following questions:

1. How large is the heat-storage potential in the thermal mass of residential buildings, and how is it affected by the building's properties?

2. Which benefits can the use of this heat-storage potential bring, and which challenges is it associated with?

3. In the case of a low-energy multi-family house, how does the use of a TABS affect the flexibility performance compared to other heating systems?
4. Based on the same case building, what is the economic potential of load shifting using TABS supplied by a ground-source heat pump, and how is the potential affected by limitations in available heat-power capacity?
5. How does the load shifting impact thermal comfort in the building?

1.4 Limitations

The work is limited to residential buildings located in geographic areas where heating (not cooling) demand dominates. Furthermore, it is limited to heat storage in the thermal mass of the buildings and to the energy demand for space heating. Hence, heat storage in water tanks in buildings and the energy demand for domestic hot-water preparation are not included.

1.5 Outline of the thesis

In Chapter 2, the basic principles of heat storage in the thermal mass of buildings are described, including an account of how various building properties influence the heat-storage potential and how it depends on thermal-comfort requirements.

In Chapter 3, radiant heating systems are introduced, including an account of two common types of radiant systems: the floor-heating system and the TABS. In this chapter, it is also described how the heating system influences the heat-storage potential in the thermal mass of buildings, based on previous studies.

In Chapter 4, the methods used in the papers are presented, including a description of the case building, and the main results can be found in Chapter 5. Finally, Chapter 6 contains a concluding discussion on the conducted research, including thoughts on future work.

The papers are appended at the end of the thesis.

Chapter 2

Heat storage in building thermal mass

The way in which Building Thermal Mass (BTM) can be used for heat storage and provide demand-side flexibility is by controlling the heating system of the building, thereby controlling the energy use for space heating. The purpose of the heating system is to provide sufficient heat to indoor spaces to fulfil the occupants' thermal comfort requirements. To satisfy these requirements, the operative temperature — i.e., the temperature experienced by the occupants, taking into account both the indoor air temperature and the radiation exchange with surrounding surfaces [39] — must be kept within an acceptable range. When the thermal mass is not used for heat storage, the heating system is typically controlled to maintain the operative temperature as stable as possible. Thus, the heat power of the heating system is controlled to meet the instantaneous heat-power demand at each point in time. In contrast, when the thermal mass functions as heat storage, the heat power is controlled not only to satisfy thermal comfort but also to enable short-term load shifting, i.e., temporal shifting of the space-heating energy use. This is possible thanks to the thermal inertia of the building, which allows the heat power at a given point in time to deviate from the actual heat-power demand.

As a simple example of a control strategy that uses the thermal mass of buildings for heat storage, intermittent operation can be used [40]. With this strategy, the heating system is turned off during periods when it is unfavourable to use energy, for instance, when it is expensive or has a large environmental impact, and turned on during other, more favourable, periods. The energy use is thereby shifted from off- to on-periods, and it is enabled by the thermal inertia of the building, which prevents the temperature from dropping too quickly during the off-periods.

Heat-storage technologies in buildings can be divided into two main categories: passive and active storage [14]. The thermal mass of buildings often acts as passive storage, which means

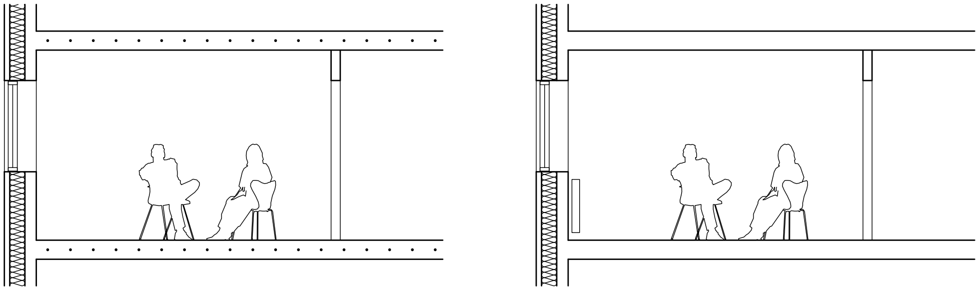

Figure 2.1: Part of a residential building, heated by a radiant heating system (left) and a radiator system (right).

that it is the temperature difference between the thermal-mass object and its surroundings that is the driving force for charging and discharging. However, the thermal mass can also serve as active storage, meaning that charging or discharging is done actively by using pumps or fans. For example, in the case of a floor-heating system with hydronic heating pipes embedded in a building structure, the storage is active during charging, as the heat is supplied by water circulated by a pump, and passive during discharging.

2.1 Properties influencing the heat-storage potential

The heat-storage potential in BTM, and thereby its potential for load shifting, depends on several building properties. In this section, an account of the most important building properties is provided. An illustration of a residential building, including some of the influencing building properties, is shown in Figure 2.1.

Firstly, the heat-storage potential in BTM depends on the insulation level of the building envelope [41]. The envelope's insulation level is represented by the U-value, i.e., the thermal transmittance, of the building elements of the envelope. The U-values affect the heat-transmission losses $\dot{Q}_{\text{trans}}$ of the building,

$$\dot{Q}_{\text{trans}} = \sum_k U_k A_k (T_i - T_a), \tag{2.1}$$

where U_k and A_k are the thermal transmittance and area of building element k, T_i the indoor air temperature, and T_a the ambient temperature [42]. The heat-transmission losses, in turn, affect the rate at which the indoor air temperature drops when the heating system is switched off during load shifting (for a mathematical account, see below). A higher insulation level (i.e., lower U-values), resulting in lower heat-transmission losses, leads to a slower temperature drop, which enables longer off-periods. In this sense, a higher insulation level is beneficial at load shifting. It can be compared to heat storage in a water tank: insulation around the tank is needed to retain the stored heat and to minimize the storage losses.

However, a high insulation level is not favourable in every respect. A lower insulation level brings an increased heat-storage capacity, in the sense that a larger amount of heat can be supplied to the building during a charging session [29]. Furthermore, the heating season is shorter for well-insulated buildings than for less-insulated ones [43], meaning that the storage resource in the thermal mass is available for a shorter portion of the year. Moreover, well-insulated buildings are at greater risk of overheating [43], i.e., that the load shifting causes too high temperatures in indoor spaces.

Secondly, the storage potential in BTM depends, as already mentioned in Section 1.2, on the available amount of thermal mass in the building, which, in turn, depends on the heat capacity C of building structures and indoor content [43]. The heat Q_{stor} that is stored in the thermal mass inside the building at the temperature change ΔT_i can be expressed as:

$$Q_{\text{stor}} = C\Delta T_i = \sum_j m_j c_{p,j} \Delta T_i, \tag{2.2}$$

where m_j is the mass of element j, and $c_{p,j}$ the specific heat capacity of its material. If it is heating season, i.e., there is a heat demand, and if the heating system is turned off due to load shifting, the mass of the building will cool down. An energy balance gives:

$$\dot{Q}_{\text{trans}} + \dot{Q}_{\text{vent}} + \dot{Q}_{\text{stor}} = 0, \tag{2.3}$$

which, in addition to the heat-transmission losses $\dot{Q}_{\text{trans}}$ and the storage heat flow $\dot{Q}_{\text{stor}}$ also includes the ventilation losses $\dot{Q}_{\text{vent}}$ due to air exchange and infiltration. Neglecting any heat recovery of the air exchange, the ventilation losses $\dot{Q}_{\text{vent}}$ can be expressed as [42]:

$$\dot{Q}_{\text{vent}} = \rho c_p \dot{V}(T_i - T_a), \tag{2.4}$$

where ρ and c_p are the density and specific heat capacity of air, and $\dot{V}$ the air exchange rate. Solving Eq. (2.3) gives the indoor air temperature T_i during cool down as a function of time t:

$$T_i(t) = T_i(0) + (e^{-t/\tau} - 1)(T_i(0) - T_a), \tag{2.5}$$

where τ is the time constant, defined as:

$$\tau = \frac{\sum m_j c_{p,j}}{K_{\text{tot}}}, \tag{2.6}$$

where K_{tot} is the total heat-transfer coefficient [42]:

$$K_{\text{tot}} = \sum_k U_k A_k + \rho c_p \dot{V}. \tag{2.7}$$

Eq. (2.5-2.6) imply that a large thermal mass inside the building, due to a large heat capacity of building structures and indoor content, is beneficial as it results in a longer time constant τ, and thus a slower temperature drop during off-periods at load shifting. Low total heat losses, for instance, due to a high insulation level of the building envelope, are beneficial for the same reason, as they bring a lower total heat-transfer coefficient K_{tot} and thus a longer time constant.

Even though the mathematical account above captures the fundamental principles of heat storage in BTM, additional aspects need to be added. Actually, there are several factors impacting the thermal mass's influence on the heat-storage potential. One important factor is whether the thermal mass functions as passive or active storage. Active storage is advantageous as it facilitates the activation of the thermal mass, resulting in improved heat-storage potential (see more about active storage below). In passive storage, it is the temperature difference between the thermal-mass object and the surrounding indoor air that is the driving force for charging/discharging. Consequently, it is the material located closest to the air that primarily contributes to heat storage. Within this context, it is reasonable to talk about a penetration depth of the heat [44], since sufficiently deep into the material, a passive charging/discharging cycle will have a very small impact on the temperature. The penetration depth is dependent on the thermal properties of the material and the time scale of the cycle. The fact that it is the material closest to the air that mainly contributes to heat storage implies, for example, that internal walls contribute more to the storage capacity than external walls, since internal walls are in contact with the indoor air on both sides, whereas external walls are exposed on only one side [11]. Moreover, it means that the storage capacity of a building structure is reduced if its surface is covered, for example, by carpets, acoustic panels, or bookshelves [44], since adding such isolating layers decreases the penetration depth. For thick indoor structures, it also has the implication that not the entire thickness of the structure is involved in the heat storage; it is limited by the penetration depth of the heat. Therefore, it is not always beneficial to increase the thickness of building structures [11].

Thirdly, the heat-storage potential in BTM depends (as also mentioned in Section 1.2) on the type of heating system installed in the building [22, 29]. Radiant heating systems, such as floor heating, are more beneficial than convective systems as they enable active, instead of passive, storage (at least during charging). Active storage entails a more direct activation of the thermal mass of the building structures in which the heating pipes are embedded [22], resulting in a smaller impact on indoor air temperature and, consequently, on thermal comfort. In contrast, convective systems, such as radiator systems, primarily heat the space through the air, resulting in a larger impact on the indoor air temperature and the thermal comfort at load shifting [22]. As a result, convective systems bring a lower heat-storage potential, since the occupants' requirements for thermal comfort must always be fulfilled.

Fourthly, the heat-storage potential is highly dependent on the occupants' requirements for thermal comfort in the indoor spaces. The presence of people inside the storage distinguishes BTM from many other heat-storage technologies (e.g., water tanks). Thermal-comfort requirements are often expressed as an acceptable range of the operative temperature [45]. A wider acceptable range increases the storage potential, as it allows the operative temperature to drop (and rise) to lower (and higher) levels during load shifting. A detailed account of how thermal-comfort requirements impact the storage potential of BTM is provided in Section 2.2.

Fifthly, the heat-storage potential depends on various boundary conditions, such as ambient temperature and solar radiation [11, 23]. This means that the storage potential varies over time, for example, between the heating and transition seasons [41]. The storage potential also depends on another boundary condition, namely the internal heat gains in the building, caused by occupants, lighting, and equipment [11]. The intensity and the variation of the internal heat gains affect the heat demand and the indoor air temperature of the building, and, consequently, the storage potential in BTM.

The extent to which the heat-storage potential in BTM can be unlocked depends on how the heating system is controlled. Regarding the design of control strategies, three main types have been identified: manual control by end users, automated rule-based control (RBC), and advanced optimization techniques [3]. RBC uses simple heuristic methods that generally operate by following logic statements (e.g., if-then statements), usually based on monitoring a specific trigger parameter such as the indoor air temperature [46]. Among advanced optimization techniques, model-predictive control (MPC) is frequently used. MPC is a more complex control strategy than RBC, relying on a model of the building that predicts its future behaviour [46]. Since MPC is an optimization technique, it seeks the optimal solution for the operation, within a given time horizon and specified constraints. For a review of control strategies for improved energy flexibility of buildings equipped with heat pumps, see [46].

2.2 Thermal comfort

As mentioned in Section 2.1, the occupants' requirements on thermal comfort constitute an important boundary condition for BTM storage. Occupants' experience of a thermal environment can be described by six parameters: clothing insulation, activity level, air temperature, surrounding surfaces' temperatures, air velocity, and air humidity [47]. The first two parameters are person-dependent, while the remaining four depend on the surroundings. Clothing insulation can be specified using the clothing unit clo, where 1 clo corresponds to typical indoor clothing, and the activity level can be specified with the metabolic unit met, where 1 met corresponds to the activity level of a seated, relaxed person [47].

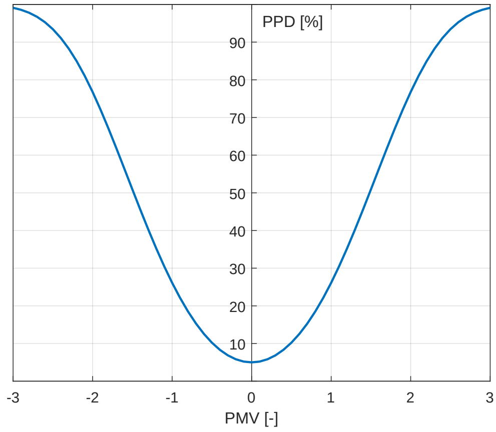

Figure 2.2: Relationship between the PMV and the PPD indices [39].

The operative temperature, defined as the "*uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment*" [39], accounts for the influence of two of the parameters mentioned above: the air temperature and the temperature of surrounding surfaces. The operative temperature is useful for evaluating thermal comfort as it better describes how occupants experience the thermal environment than the air temperature alone.

To evaluate thermal comfort in buildings, the SS-EN ISO 7730 standard [39] is frequently used. This standard includes the PMV (Predicted Mean Vote) index, representing the predicted mean value of the votes of a large group of people using a 7-point thermal sensation scale. The scale ranges from -3 (cold) to $+3$ (hot), where the value of 0 corresponds to a neutral thermal sensation (on average). The standard also includes the PPD (Predicted Percentage Dissatisfied) index, representing the percentage of a large group of people that is predicted to be dissatisfied with a given thermal environment. The PPD index is especially useful for evaluating thermal comfort as it explicitly indicates the proportion of people likely to feel uncomfortably warm or cool in a given environment. The relationship between the PMV and PPD indices is presented in Figure 2.2. The figure shows that the predicted percentage of dissatisfied (PPD) people is always 5 % or more.

For a given thermal environment, there is an optimum operative temperature $T_{\mathrm{op}}^{\mathrm{opt}}$, corresponding to PMV $= 0$, which can be determined using the SS-EN ISO 7730 standard [39]. The optimum operative temperature depends on clothing insulation, activity level, air humidity, and air velocity (compare with the six parameters mentioned above). However, in moderate environments, the air humidity has only a minor impact on the thermal sensation [39].

Table 2.1: Categories of thermal environment [39]. The table also includes the permissible operative temperature range T_{op}^{perm}, based on the clothing insulation of 1 clo and the activity level of 1 met.

Category	PPD	PMV	T_{op}^{perm}
A	< 6%	±0.2	T_{op}^{opt} ± 1 °C
B	< 10%	±0.5	T_{op}^{opt} ± 2 °C
C	< 15%	±0.7	T_{op}^{opt} ± 2.5 °C

The SS-EN ISO 7730 standard includes three categories of thermal environment (A, B, and C) that can be used to set requirements on thermal comfort. The definition of these categories, related to the PMV and PPD indices, is presented in Table 2.1. The standard also provides the permissible range in operative temperature for each category, as a function of clothing insulation, activity level, air humidity, and air velocity. In Table 2.1, the permissible range T_{op}^{perm} is presented, given the clothing insulation of 1 clo, the activity level of 1 met, 50 % relative humidity, and the air velocity of <0.1 m/s.

In Sweden, the thermal-environment categories (A-C) from the standard have been adopted by sector organisations and are, with some modifications, applied by the authorities [47]. Often, it is required that at least 90 % of the occupants should be thermally satisfied, which corresponds to category B. Based on the permissible temperature range belonging to this category (see Table 2.1), the operative temperature can be allowed to vary to some extent, while still fulfilling the requirements. This is favourable from a BTM-storage perspective, since this storage technology is dependent on a temperature fluctuation in the indoor space.

Chapter 3

Radiant heating systems

As outlined in Section 2.1, radiant heating systems are beneficial from a flexibility perspective due to their ability to activate the thermal mass of building structures with limited impact on the thermal comfort. In this chapter, a more detailed account of radiant heating systems is provided.

Heating systems can provide conditioned spaces with heat through two different modes of heat transfer: convection and radiation. A radiant heating system is defined as *"a system in which radiant heat transfer covers more than* 50 % *of heat exchange with a conditioned space"* [48]. For comparison, the convective/radiative fraction of a conventional radiator system is approximately 65 %/35 % [47]. The basic principle of radiant heating systems is to heat the mass of the building rather than the indoor air [49]. The indoor air is then heated indirectly through heat exchange between the building's structures and the indoor air.

The use of radiant systems in buildings has a very long history, and the systems have been used for both heating and cooling purposes. In archaeological remains of a 9000-year-old Kurdish settlement, evidence has been found of an intermediate space below the building floor, supplied with water from a nearby creek for summer cooling [49]. As historical examples of radiant heating systems, the Korean Ondol, the Chinese Kang, and the Roman Hypocaust can be mentioned [50]. For a historical account of radiant heating and cooling systems, see [51, 52].

Radiant heating systems can be divided into three categories [40]: embedded surface systems, Thermally Activated Building Systems (TABSs), and radiant panel systems (see Figure 3.1). Common to all these systems is that they are provided with heating pipes with water as heat carrier, but the position of the pipes and the design of the building structure in which they are embedded differ. In embedded surface systems, the pipes are insulated from the structural frame of the building, directing the heat transfer primarily in one

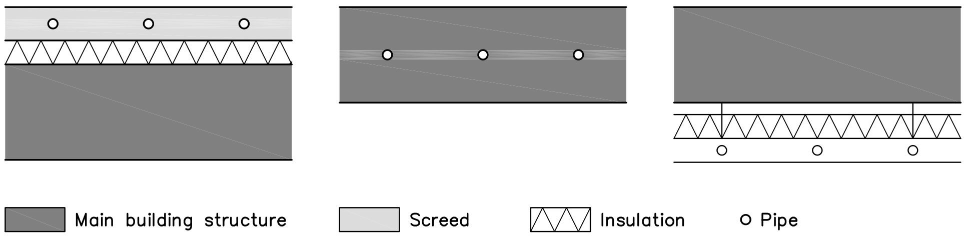

Figure 3.1: Schematic representation of an embedded surface system (left), a TABS (middle), and a radiant panel system (right).

direction, whereas in TABSs, the pipes are embedded in, and thermally coupled to the structural frame [40]. Since there is no insulation layer in TABSs, the heat is allowed to transfer both upwards (through the floor) and downwards (through the ceiling). In radiant panel systems, the pipes are integrated in panels suspended below the ceiling.

The embedded surface system is frequently used in floor surfaces (as shown in Figure 3.1), and is in that case often referred to as floor heating, but it can also be installed in ceiling and wall surfaces [40]. The TABS is often used in intermediate floor structures, but occurs also in wall structures [53].

Several advantages can be attributed to radiant heating systems: they can provide a high level of thermal comfort, are quiet in operation, require no cleaning, and allow an efficient use of space since the heating pipes are embedded within the building structures [48, 54]. Another benefit, compared to convective systems, is that the higher surface temperatures of the heated building structures enable the same level of thermal comfort at a lower indoor air temperature, resulting in reduced ventilation heat losses [54]. Moreover, radiant heating systems with high thermal inertia — such as TABSs — offer a great potential for load shifting, due to their large heat-storage capacity [38].

However, radiant systems with high thermal inertia also pose challenges when it comes to control [38]: the thermal inertia causes a long response time — i.e., a delay between changes in heating input and the thermal response in the conditioned space — making these systems more slow-reacting than, for example, radiator systems. For instance, when a high-inertia radiant heating system is turned on/off, it takes considerable time before it starts/stops heating the space, since the thermal mass must first be warmed up/cooled down. Another disadvantage, specifically for TABSs, is that individual room control is not reasonable [40], which limits the occupants' ability for individual temperature adjustments. For more about control of radiant systems, see Section 3.3.

Radiant heating systems are characterized by a low heat supply temperature, as their large surface area entails a relatively small temperature difference between the heating surface and the air in the conditioned space. Low-temperature heating systems bring several benefits, partly depending on the type of heat source used in the building. When district heating is used as heat source, low-temperature heating allows for lower system temperatures in the district heating network [31]. This is favourable for several reasons: it enables the use of renewable and recyclable low-grade energy sources such as geothermal heat, solar heat, and industrial excess heat, it improves the efficiency of the heat supply, and it reduces distribution losses in the piping network [32, 55]. When a heat pump is used as heat source, low-temperature heating significantly improves the thermal efficiency of the heat pump [30], resulting in reduced electricity use and CO_2 emissions [56]. If the heat pump is combined with photovoltaics, low-temperature heating can also contribute to an improved self-consumption [57]. A consequence of the improved heat-supply efficiency, both within a district-heating and a heat-pump context, is that low-temperature heating reduces the primary energy use [48]. Finally, low-temperature heating also has the advantage of reduced heat losses from heat-supply units and distribution pipes within the building [56].

The popularity of radiant heating and cooling systems has increased in recent decades [50], and today, they are widely implemented in both residential and non-residential buildings [48]. Guidance on radiant heating and cooling systems is provided in an international series of standards (SS-EN ISO 11855 [58]), covering comfort criteria, determination of design heating and cooling capacity, as well as system design, dimensioning, installation, and control. Moreover, the REHVA Guidebook [40] provides technical guidelines on radiant heating and cooling systems.

3.1 Floor-heating systems

Floor heating is a radiant heating system belonging to the embedded-surface-system category (see examples in Figure 3.2). The floor-heating system was introduced in the United States by the architect Frank Lloyd Wright in the 1930s, using steel pipes for heat distribution [54]. In the 1950s and 60s, floor-heating systems with pipes of steel or copper were installed in Central Europe. At that time, the system developed a poor reputation, as the low insulation levels of the building envelopes required very high floor-surface temperatures. In the late 1970s, the plastic pipe was introduced, contributing to a renewed interest in the system, and after a while, the floor-heating system became a standard solution, particularly in Germany, Switzerland, Austria, and the Nordic countries [54].

Floor heating is primarily used in residential buildings, although it is also widely implemented in commercial buildings in Europe [54]. As examples of its popularity in residential buildings, a significant proportion of new residential buildings in Germany, Austria, and Denmark are provided with floor heating [54], and it is also commonly used in other parts of the world, such as Korea [59] and China [60].

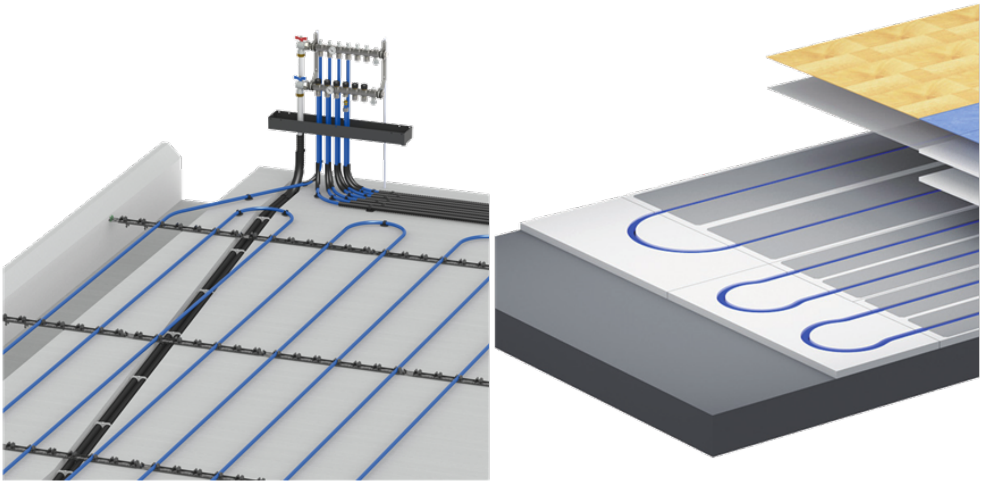

Figure 3.2: Examples of floor-heating systems. Source: Thermotech Scandinavia AB (pictures used with permission).

3.2 Thermally activated building systems

In the 1930s, a radiant heating and cooling system with hydronic pipes embedded in intermediate concrete slabs between storeys in multi-storey buildings was introduced, using pipes of welded steel [40]. Unfortunately, many of the early installations failed, often due to condensation problems during operation in cooling mode. In the 1990s, the interest in this type of radiant system was revived. The Swiss engineer Robert Meierhans introduced a ceiling slab cooling system in an office building [49], using plastic PE-X pipes instead of steel [40]. This solution combined the advantages of radiant cooling with the heat-storage capacity of the concrete slab, which was utilized to shift the building's cooling load to night hours [49]. Based on comfort measurements and operational data from the building, the solution was found to performed well, and subsequently, additional successful projects were implemented. The system became known as a Thermally Activated Building System (TABS), and its use spread across Europe, especially in Switzerland and Germany [49].

In Sweden, an interest in TABSs applied in multi-family houses has grown in recent years, and the system is now installed in many newly built multi-family houses [36]. The intermediate floor structure of Swedish multi-family houses commonly consist of a thin prefabricated concrete element at the bottom and a thicker in-situ concrete layer on top (see Figure 3.3). When using TABS in this type of floor structure, the heating pipes are typically installed on top of the prefabricated concrete element, before the in-situ concrete is cast. Pictures of various TABS installations are shown in Figure 3.4.

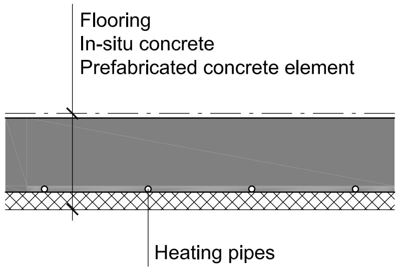

Figure 3.3: Position of the heating pipes of TABS in an intermediate concrete floor structure.

3.3 Control of radiant heating systems

The following section is entirely based on [40]:

The control of floor-heating systems consists typically of two parts: a central control and an individual room control. The central control regulates the system's water temperature based on the ambient temperature, using the building's heating curve, whereas the room control adjusts the water flow rate for each room according to the set-point selected by the occupants. Allowing occupants to individually adjust the temperature is beneficial, as it improves the thermal comfort and provides potential for energy savings. The valve regulating the heat flow rate in the room control is connected to a room sensor that measures the air temperature in the space.

Regarding the central control of floor-heating systems, it is recommended that it controls the average water temperature of the supply and the return, rather than only the supply temperature, as the average temperature is more directly related to the heat flow transferred to the space. Controlling the average temperature results in faster and more precise control, as well as improved energy performance.

For TABSs, individual room control is not reasonable, as the heat flows through both sides of the intermediate floor structure and is not directed toward a specific room. Instead, a zone control (e.g., south/north zones) is recommended, in which the water temperature or the flow rate can be controlled separately for each zone. A negative consequence of the lack of room control in the case of TABSs is that the occupants cannot adjust the temperature individually.

An important feature of radiant heating systems is their capacity for self-regulation, which helps stabilize the indoor air temperature under varying heat gains. The heat flow transferred to the space depends on the temperature difference between the heating surface and the air. If the air temperature rises — e.g., due to increased internal heat gains from solar radiation — the temperature difference between the surface and the air decreases, resulting in reduced heat exchange. This effect occurs instantaneously, and it is larger in

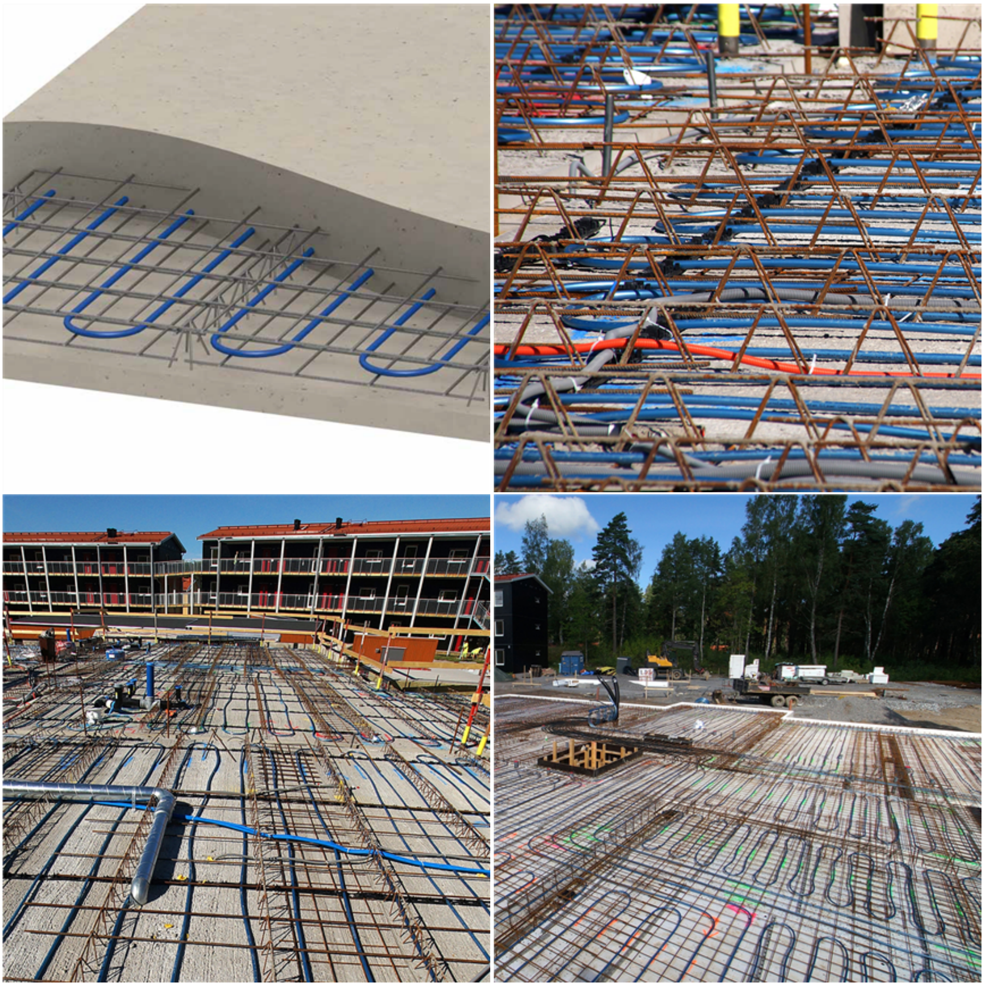

Figure 3.4: TABS installations. Source: Thermotech Scandinavia AB (pictures used with permission).

low-temperature systems than in high-temperature systems, due to a greater relative impact on the temperature difference. Since the water temperature of TABSs is exceptionally low — lower even than in floor-heating systems — the self-regulating effect of TABSs becomes even greater than in floor-heating systems.

In addition to water-temperature control and flow-rate control of TABSs, pump-operation control can also be applied. The pump-operation control can be either continuous, using modulated power, or intermittent.

3.4 Heating systems and the heat-storage potential of building thermal mass

The influence of the heating system on the heat-storage potential of BTM has been examined in several previous studies, some of which are summarized below.

Reynders et al. [22] studied a single-family house equipped with an air-water heat pump and photovoltaics with varying envelope insulation levels, heat capacities, and control strategies. They found that floor heating showed better peak-shaving potential than radiators; the heat pump's electricity use during peak demand periods was reduced by up to 94 % with floor heating, compared to up to 75 % with radiators.

Johra et al. [43] investigated how various parameters, including the type of heating system, influenced the energy flexibility of a single-family house, defining energy flexibility as "*the ability for the building to minimize the heating energy usage during high price periods and maximize it during low price periods*". They found that the use of floor heating instead of convective radiators led to an energy flexibility improvement by up to 44 % for low-insulation dwellings and 8 % for high-insulation dwellings.

Reynders et al. [29] quantified the energy-flexibility potential in the BTM of different types of single-family houses within the Belgian residential building stock. They found that the available heat-storage capacity was larger in floor-heated than in radiator-heated dwellings, ranging from 16–66 kWh for floor-heated cases and 12–30 kWh for radiator-heated cases, assuming a thermal comfort range of 2 °C. They also reported higher storage efficiencies for floor-heated dwellings, where storage efficiency was defined as "*the fraction of the heat that is stored during the ADR* [active demand response] *event that can be used subsequently to reduce the heating power needed to maintain thermal comfort*" [29].

Leerbeck et al. [61] studied how CO_2 emissions associated with the electricity use of heat pumps in single-family houses could be reduced by using model predictive control. They found that floor heating was beneficial compared to radiators; in well-insulated buildings with floor heating, CO_2-emission savings of up to 17 % could be reached, compared to up to 12 % with radiators. In older buildings with lower insulation levels, the corresponding CO_2-emission savings were significantly smaller, with a maximum of 3 %.

Chapter 4

Method

A significant part of the work presented in this thesis is based on an existing low-energy multi-family house located in the city of Örebro, Sweden. This building was constructed in 2017 and includes 70 apartments distributed on five floors, with an underground garage floor. The structural frame of the building consists of massive intermediate floors of concrete, supported by internal concrete walls. The building is equipped with a TABS as heating system, with the heating pipes embedded in the intermediate concrete floors (in accordance with Figure 3.3). Furthermore, it is provided with a central mechanical supply-and-exhaust ventilation system with heat recovery. This building served as a case building in Papers II and III. Further details about the building are provided in Paper II.

In Paper I, a review of previous studies on the energy flexibility of residential buildings using BTM was conducted. The review was based on a literature search in Scopus, using a well-defined query set presented in the paper. In total, 104 articles were found. Out of these, 42 articles were reviewed, as the remaining ones were outside the scope. Key findings from the reviewed articles were compiled, divided into four areas: the heat-storage potential in the thermal mass, the benefits of using this storage potential, the challenges associated with it, and the factors influencing it. In addition, general information about the reviewed studies was summarized, including building type (single- or multi-family house), heat source, heating system, and floor structure (in the case of floor heating).

In Paper II, one representative apartment of the case building (see Figure 4.1) was modelled using the simulation software TRNSYS 18 [62]. The apartment was modelled as a single zone using the Type 56 component in TRNSYS, with the TABS modelled as an active layer. Information about the case building was obtained from building documentation (e.g., drawings), the heating-system supplier, and the operation management system of the building. The simulation model was validated against operational data from the management system of the case building, using indoor air temperature and the heating system's supply and return temperatures for comparison. Regarding model input during validation,

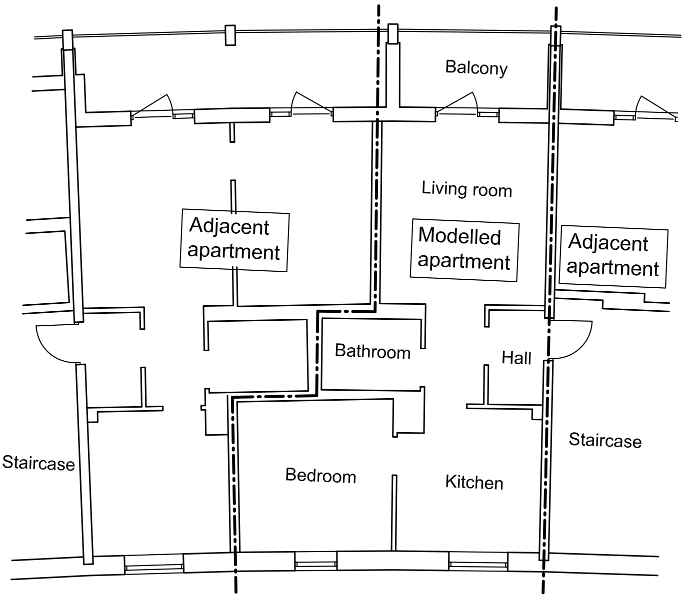

Figure 4.1: Plan view of the modelled apartment in Paper II.

the ambient temperature and the ventilation supply-air temperature were taken from the operational data, whereas solar radiation and cloudiness data were taken from Sveby [63] for the location of the building, as these data were not included in the operational data. During the validation process, the infiltration rate, the internal heat gains, the magnitude of thermal bridges, and the external shading factor were chosen to achieve compliance between the model and the actual building, guided by values found in the literature. A comparison of the indoor air temperature between the simulation model and the operational data from the case building is presented in Figure 4.2.

The indoor air temperature in the operational data varied significantly between apartments. As a basis for the validation, the mean temperature from 65 apartments was used, excluding the five apartments with the most extreme data series. Regarding the temperatures of the heating system, the operational data included the heat supply temperature at the substation and the overall heat return temperature for all apartments in each staircase; i.e., not the supply and return temperatures for individual apartments. The pipe losses between the modelled apartment and the locations for which the temperatures were known from the operational data were estimated by applying a simple general expression found in the literature, and by calibrating its coefficients to achieve model compliance with the operational data.

The validated simulation model was used to compare the TABS with two other heating systems: an embedded surface system and a radiator system. The embedded surface system

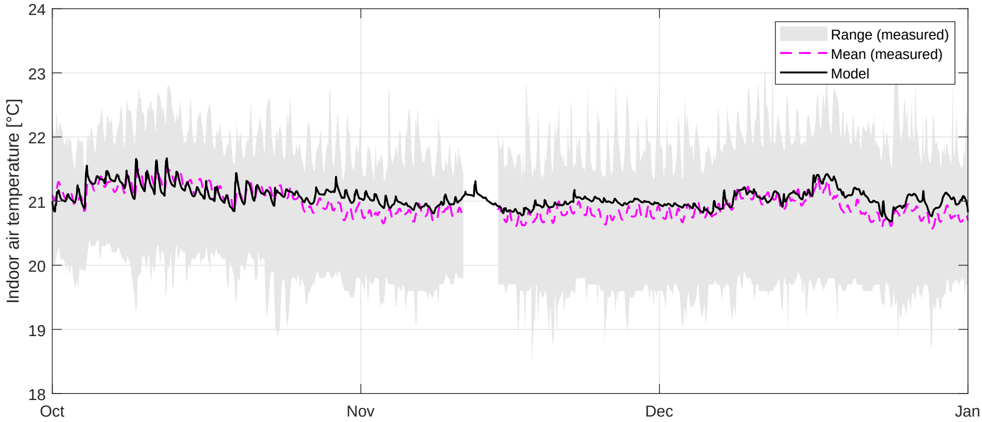

Figure 4.2: Comparison of the indoor air temperature between the simulation model and the operational (measured) data from the case building. The gap in the operational data is caused by missing data.

was modelled similarly to the TABS, using an active layer in Type 56 in TRNSYS, and the radiator system was modelled using the Type 1231 component, with TRNSYS default values for the convective/radiative fraction. To facilitate the comparison between the three systems, all simulations were conducted with constant boundary conditions (with respect to ambient climate and internal heat gains). The systems were compared based on three different flexibility scenarios, partly inspired by [37], chosen to highlight different ways in which buildings can provide flexibility. The simulation results were evaluated based on response time, recovery time, heat-storage capacity, and operative temperature fluctuation. Furthermore, the Flexibility Time Ratio (FTR) was introduced as a flexibility indicator:

$$\mathrm{FTR} = \frac{t_{\mathrm{res}}}{t_{\mathrm{res}} + t_{\mathrm{rec}}}, \tag{4.1}$$

capturing the combined impact of the response time t_{res} and the recovery time t_{rec}.

In Paper III, the validated simulation model established in Paper II was used as a starting point. However, to investigate the economic potential of load shifting by controlling the heating system in response to day-ahead electricity prices, a ground-source heat pump was added to the simulation model. The coefficient of performance of the heat pump was estimated using a regression model from [64], and the electricity cost of heat-pump operation was calculated based on the day-ahead electricity price, excluding fixed electricity costs and cost surcharges on the variable part. The heating system was controlled using a simple rule-based strategy applying intermittent operation, operating during hours with the lowest prices. Thermal comfort was evaluated according to the SS-EN ISO 7730 standard [39] using thermal environment category A (PPD <6 %), and the simulation results were evaluated based on the heat-pump electricity cost and the operative temperature in the apartment.

In Paper II, the internal heat gains in the simulation model were assumed to be constant, as the model was used only with constant boundary conditions. Since the model in Paper III, in contrast, was used with dynamic boundary conditions, its compliance with the actual building was improved by providing the internal heat gains with a diurnal variation, resulting in an indoor air temperature fluctuation similar to the corresponding temperature in the operational data. This measure contributed to an improved reliability of the simulation results in Paper III, regarding the operative temperature in the apartment.

4.1 TRNSYS

As mentioned in the previous section, the TRNSYS software was used for the simulations. TRNSYS is a simulation environment used for transient simulations of various systems, including buildings [65]. A TRNSYS simulation model consists of different components (referred to as Types) that are connected to each other with links. TRNSYS contains an extensive library of pre-defined Types that can be used in simulation models. Among these is the Type 56 component, which can be used to model the thermal behaviour of multi-zone buildings [66].

To solve a system of Types and connections at each time step, TRNSYS uses an iterative method called successive substitution. At each new time step, the Types are called with inputs from the previous time step, and the returned outputs are recorded. These outputs are then used as new inputs to the Types, which are called again to return new outputs. At each iteration, the new outputs are compared with the previous outputs. This procedure is repeated until it converges, i.e., when the difference between the previous and new outputs is smaller than a given tolerance specified by the user. After convergence, it proceeds to the next time step.

Chapter 5

Main results

The main results from the papers included in this thesis are summarized below. For further details, see the appended papers.

5.1 Paper I

The research conducted in Paper I aimed at addressing the first and second research questions. By reviewing previous research articles, it was found that the heat-storage capacity of Building Thermal Mass (BTM) was up to approximately 70 kWh in single-family houses [29] and 100 Wh/m^2 in multi-family houses [10], depending on various properties of the buildings. Moreover, BTM storage showed a great ability to reduce energy demand during peak periods, by up to 94 % [22] in the reviewed studies. Regarding building properties influencing the heat-storage potential, it was found that the insulation level of the building envelope had the largest impact [43]; more insulation resulted in improved storage efficiency and prolonged thermal autonomy, but also an increased risk of overheating. Furthermore, it was found that a large available thermal mass was beneficial [43], that floor-heating systems were more favourable than radiator systems since they could better activate the thermal mass [22, 29], and that the heat-storage potential was also influenced by ambient climate conditions [11] and applied control strategy [18].

There are several ways to benefit from the heat-storage potential of BTM, largely depending on the type of heat source used in the building. In reviewed studies on buildings heated by heat pumps/electricity, the heat-storage potential was used to reduce electricity use during peak hours [22, 67], reduce electricity costs for end users [18, 68], reduce system costs for local energy systems [69], reduce procurement costs for electricity suppliers [70], and reduce operational costs [19] and total system costs [71] for electric-power systems. The heat-storage potential of BTM was also used to reduce energy-related CO_2 emissions

[20, 72], increase the utilization and the self-consumption of renewable energy from local photovoltaic generation [73], and to lower primary energy demand [45, 74]. Furthermore, it was used to improve the coefficient of performance of heat pumps [75], reduce the peak power at the building level [13, 76], provide peak-load reductions at both aggregated [69] and system levels [71], and prevent overloading of highly utilized power grids [77].

In reviewed studies conducted in a district-heating context, the heat-storage potential of BTM was used to reduce daily peaks in heat demand [1, 10, 78, 79], reduce heat costs for end users [80, 81], reduce heat-supply costs and running costs for district-heating systems [1, 12, 27, 79], increase profits from combined heat and power plants [82], and reduce primary energy demand at the neighbourhood level [83].

Finally, the reviewed studies showed that heat storage in BTM is associated with some challenges: load shifting may increase the total energy use [70], due to deviations from optimal operation of the heating system, and it may lead to new, undesired peak loads [84]. Another challenge concerns the interaction between the supply and demand sides of the energy system; if load shifting is implemented on a large scale, it may influence the energy prices [85], which complicates the estimation of economic benefits for end users.

5.2 Paper II

The work in Paper II sought to answer the third research question by comparing the flexibility performance of a TABS with an Embedded Surface System (ESS) and a Radiator System (RS). It was found that the TABS outperformed the other two systems in every respect studied, that the radiator system performed worst, whereas the performance of the embedded surface system was in between the TABS and the radiator system. Based on the first flexibility scenario in which the heating system was switched off until the operative temperature reached the lower thermal-comfort limit, then switched on with maximum heat power, it was found that the TABS had the longest response time (i.e., the duration of the off-period) and the shortest recovery time (i.e., the duration of the recovery period), resulting in the largest Flexibility Time Ratio (see Eq. (4.1)). A comparison of the heat power, the indoor air temperature, and the operative temperature for the three heating systems is presented in Figure 5.1.

The short response time of the radiator system in the first scenario was caused by a rapid air-temperature drop immediately after the heating system was switched off (see Figure 5.1). This temperature drop can be explained by the fact that the surface temperatures of the building structures surrounding the zone were initially lower than the air temperature. When the radiator system was switched off, the radiative fraction of the heat supply (as well as the convective fraction) was removed, resulting in even lower surface temperatures. The air was then cooled down by the surrounding surfaces. For the TABS and the embedded

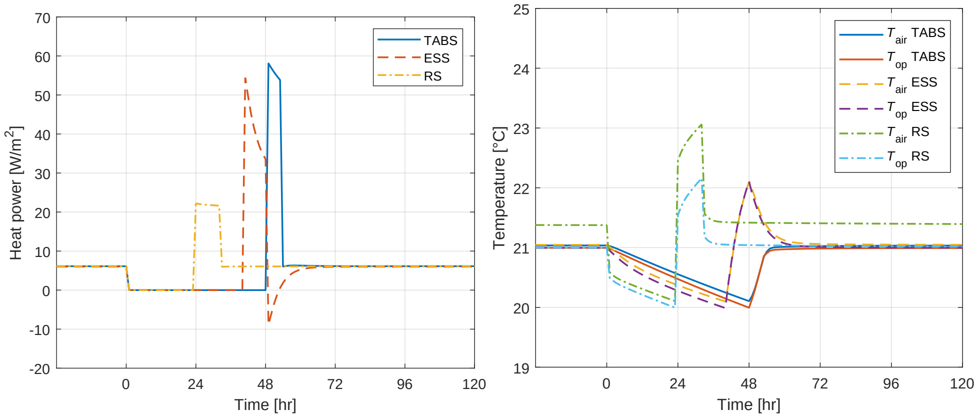

Figure 5.1: Comparison of heat power (left) and temperatures (right) between the three heating systems (TABS/ESS/RS), based on the first flexibility scenario in Paper II.

surface system, a similar effect did not occur; for these systems, the initial surface temperatures of the surrounding building structures were generally higher, and the air temperature dropped more slowly due to the high heat capacity of the intermediate floor structures.

Based on the second flexibility scenario, it was found that the heat-storage capacity of the TABS was almost twice as large as that of the embedded surface system and nearly four times as large as that of the radiator system (see Figure 5.2). The TABS was also beneficial in terms of impact on thermal comfort; in the third flexibility scenario, in which intermittent operation was applied with heating only during the night, the operative temperature fluctuated by only 0.4 °C for the TABS, compared to 1.0 °C for the embedded surface system and 2.0 °C for the radiator system (see Figure 5.3).

Finally, differences between the three systems in terms of heat-power capacity were noted. For low-temperature systems such as TABSs and embedded surface systems, the heat power can be increased significantly by increasing the heat supply temperature. However, for radiator systems, it is harder to achieve a corresponding increase in heat power due to higher system temperatures and smaller heat-emission areas. This is significant since load shifting increases the need for heat-power capacity.

5.3 Paper III

The research conducted in Paper III aimed to answer the fourth and fifth research questions by simulating various load-shifting scenarios during a heating season (2022/2023). It was found that time shifting of electricity use to periods with low day-ahead electricity prices resulted in significant reductions of the variable electricity cost of heat-pump operation,

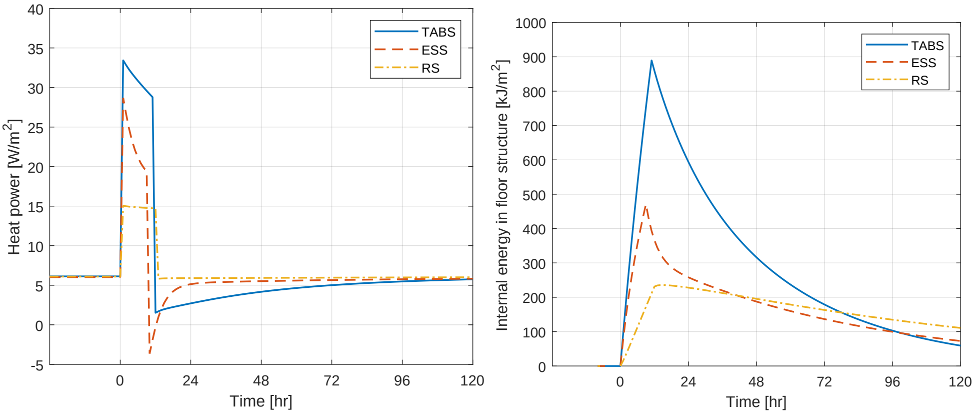

Figure 5.2: Comparison of heat power (left) and energy stored internally in the floor structure (right), based on the second flexibility scenario in Paper II. The peak value of the right plot represents the heat-storage capacity.

by up to 27 % during the studied period. The maximum savings were obtained when the upper heat-power limit was twice the design heat-power demand. However, already at an upper heat-power limit equal to the design heat-power demand, the electricity cost was reduced by almost 20 %, and already at a limit 50 % higher than the design heat-power demand, the vast majority of the maximum cost reduction was achieved. Furthermore, it was noted that similar relative cost reductions could be expected for adjacent bidding areas and the subsequent heating season.

Regarding thermal comfort, the load shifting had only a limited impact on the operative temperature in the apartment. Assuming a daily variation of the internal heat gains based on operational data from the case building, the average diurnal range in operative temperature was smaller for all load-shifting scenarios compared to the reference case. Thus, the temperature fluctuation caused by the load shifting was counteracted by the already existing temperature fluctuation in the actual building, resulting from varying internal heat gains. In Figure 5.4, the operative temperature during two weeks of the studied period is presented, for various load-shifting scenarios and the reference case.

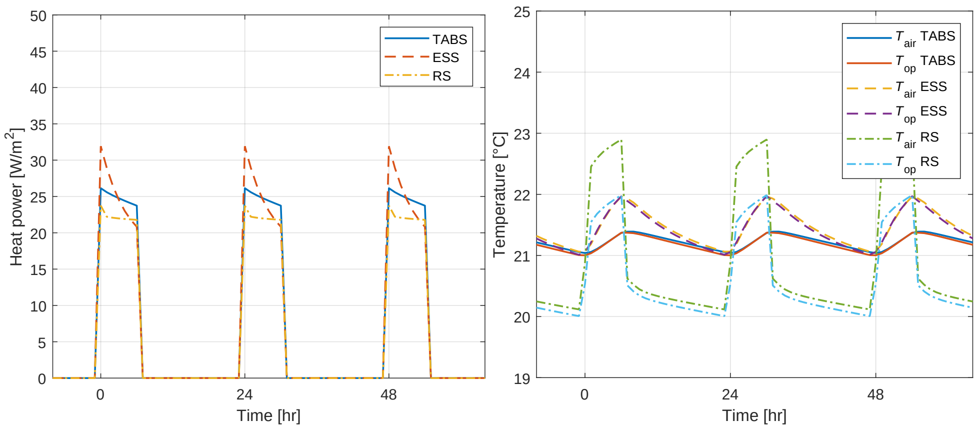

Figure 5.3: Comparison of heat power (left) and temperatures (right), based on the third flexibility scenario in Paper II.

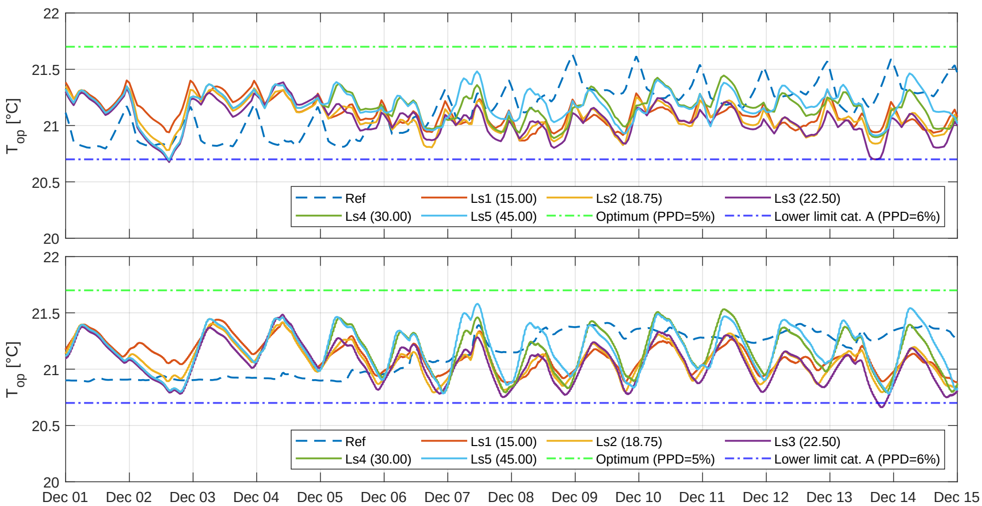

Figure 5.4: Operative temperature T_{op} during two weeks of the studied heating season for various load-shifting (ls) scenarios and the reference (ref) case in Paper III, based on varying (top) and constant (bottom) internal heat gains. The numbers within () in the legend correspond to different heat-power limits in $\mathrm{W/m^2}$.

Chapter 6

Concluding discussion and future work

The results of the papers are discussed within each paper. In this chapter, a general discussion on the conducted research is provided:

The topic of the research — the energy flexibility of residential buildings using heat storage in Building Thermal Mass (BTM) — can be approached from several perspectives, including the energy-system perspective and the building-owner perspective. The starting point is the energy system; it is the energy system that is in need of demand-side flexibility, and building owners possess a flexibility resource in BTM that the energy system could benefit from. However, as long as heating systems of buildings are operated solely to maintain an even indoor air temperature, for example, by controlling the heat power in response to the ambient temperature, the flexibility potential in BTM remains unused.

Paper II has a clear focus on the building owner's perspective. In this paper, the influence of the chosen heating system on the flexibility potential of BTM in residential buildings is investigated. The results can be used during the design phase of new buildings, supporting building owners and designers in making informed decisions about the choice of heating systems concerning flexibility. From the building owner's perspective, flexibility is one factor that may influence this choice, but several other factors also play a role, such as construction costs, energy costs, thermal comfort, possibilities for individual control etc.

To encourage building owners to use their flexibility resources, energy providers can offer economic incentives for load shifting. Within an electric-power context, this is done by the offering of time-varying electricity prices and the introduction of power tariffs. For building owners of heat-pump-heated buildings, this represents an obvious way to utilize their flexibility resource in BTM, a possibility explored in Paper III.

In the context of District Heating (DH), it has been argued that the DH sector is not as mature for load shifting as the electric-power sector, due to a less developed and less transparent market structure, without time-varying tariffs [1]. As mentioned in Section 1.1, the economic benefit for building owners of district-heated buildings to shift their heat use depends on the price model used by the DH company. In a survey of price models used by Swedish DH companies [86], published in 2017, four price components were identified: a fixed component, an energy-demand component, a load-demand component, and a flow-demand component. Of these components, the energy-demand component and the load-demand component generally had by far the largest impact on users' total cost. The energy-demand component is used to cover the heat-supply costs of DH companies, mainly fuel costs, and is typically constant (in SEK/kWh), either over the entire year or the season. Since this component is constant, it cannot be affected by short-term load shifting. The load-demand component is usually used to cover DH companies' costs for maintaining a certain level of peak-load capacity, including investment costs of new facilities. The user's cost of this component depends on the capacity reserved for the user's building, often by pricing a unit of load demand (usually in SEK/kW) based on measured or estimated peak-load demand. Depending on how the load-demand component is designed, it could be affected by the user's load shifting. For example, in the DH company of Gothenburg, the load-demand component is based on the mean value of the three highest daily average load demands during the latest twelve months [87]. If the building owner utilizes load shifting to reduce these highest daily average loads, its heat cost would be reduced.

An additional potential reason for building owners to utilize their flexibility resources and engage in load shifting is related to the environmental impact of the energy supply associated with space heating of buildings. Given that building owners have a general interest in having sustainable buildings with a small environmental impact, and given that the buildings' energy-related CO_2 emissions vary with time, environmental impact could constitute an additional incentive for load shifting. However, if building owners are to be able to control their energy use in response to the environmental impact of the energy supply, information about that impact is needed. This may be challenging due to the complexity of the energy system. One possible solution, though, in the context of electricity markets with a high share of renewable energy, is to utilize the fact that there is a strong correlation between the available power from renewable sources and the electricity price [68]. Hence, by shifting the energy use towards periods with low electricity prices, the use of renewable energy would increase, resulting in a reduced environmental impact.

Regarding load shifting using BTM storage in residential buildings, there is an important difference between multi-family and single-family houses worth mentioning. In single-family houses, the building owner is often also an occupant in the building, implying that the person benefiting from load shifting is also affected by any impact on thermal comfort. In multi-family houses, on the other hand, this is often not the case, meaning that the occupants that may be affected in terms of thermal comfort do not directly gain from the load shifting. This difference may influence the possibilities for load shifting in multi-family houses. However, this challenge can be handled by ensuring that the impact on thermal comfort remains within limits that are acceptable to, or even unnoticed by, the occupants.

In future studies, an advanced adaptive control for heating systems in buildings connected to district heating will be developed and evaluated, aiming to minimize the heat-return temperature on the primary side of the heat exchanger in the substation. In addition, it would be interesting to study how load shifting using BTM storage can be employed to achieve more sustainable residential buildings by reducing the environmental impact associated with the energy supply for space heating. Such a study could include investigating to which extent the flexibility of buildings contributes to the possibilities for achieving net/nearly-zero energy buildings. Finally, a general evaluation of TABS could be conducted, considering other aspects than just flexibility, based on the experiences of Swedish building owners who recently have implemented this heating system.

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Scientific publications

Author's contribution to the papers

Paper I

I was responsible for the literature search, compiling reviewed articles, and writing the manuscript. The work was supervised by Fredric Ottermo, Helge Averfalk, and Erik Möllerström, who provided feedback and ideas for the paper, and comments for improvement of the manuscript.

Paper II

I was responsible for collecting operational data, creating the simulation model, performing simulations, analyzing simulation results, and writing the manuscript. The work was supervised by Fredric Ottermo, who provided feedback and ideas for the paper and participated in the analysis of the results. Fredric Ottermo and Helge Averfalk reviewed the manuscript and provided valuable comments for improvement.

Paper III

I was responsible for further development of the simulation model, performing simulations, analyzing simulation results, and writing the manuscript. The work was supervised by Fredric Ottermo, who provided feedback and ideas for the paper and participated in the analysis of the results. Fredric Ottermo and Helge Averfalk reviewed the manuscript and provided valuable comments for improvement.