Energy flexibility using the thermal inertia of Swedish single-family houses

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E2B2

Förord

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Bebyggelsesektorn svarar för cirka en tredjedel av Sveriges totala energianvändning och en effektivare energianvändning är en viktig del av utvecklingen av energisystemet. Hållbarhet, effektivitet och robusthet i bebyggelsen behöver stärkas och utvecklas. Lösningarna behöver samspela för att fungera och utnyttjas. Forskning, utveckling, innovation och kommersialisering spelar en avgörande roll.

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Stockholm, 21 december 2022

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Sammanfattning

Detta projekt syftar till att utforska potentialen i att använda termisk tröghet hos småhus för att öka deras energiflexibilitet. Det har funnits begränsad kunskap om i vilken utsträckning och under vilka förhållanden denna flexibilitet kan realiseras utan att kompromissa med termisk komfort. Detta projekt har adresserat denna kunskapslucka genom att undersöka den termiska energiflexibiliteten hos svenska småhus byggda från 1940-talet och framåt. Energiflexibiliteten har studerats genom att i IDA-ICE-modeller simulera vad som händer när man förändrar börvärdet för temperaturen inomhus under vissa av dygnets timmar och därigenom sänker eller höjer värmeeffektbehovet.

Nyare, välisolerade hus med golvvärme behåller värmen bättre och kan stänga av värmen under längre perioder utan betydande temperaturfall jämfört med äldre, dåligt isolerade hus med radiatorer. När temperaturen sänks visar nyare hus liknande effektminskningar (3-4 kW) som äldre hus med radiatorer, främst på grund av golvvärmen. Mängden flyttbar energi är större för nyare hus, särskilt i mycket kallt väder, och kan nå upp till cirka 20 kWh på en mycket kall dag och 15 kWh på en kall vinterdag, under en 4-timmarsmodulering från 05:00 till 09:00. För äldre hus är den flyttbara energin cirka 10-12 kWh. Skillnaden minskar när utomhustemperaturen ökar, med cirka 10 kWh tillgängligt för alla hus på en vår- eller höstdag.

Effektåterhämtning, den extra effekt som behövs för att återgå till den ursprungliga temperaturen efter en minskning, är en viktig aspekt att beakta vid lastförskjutning. Den varierar med typen av distributionssystem och kontrollstrategier och kan vara avsevärt högre än referenstoppeffekten utan någon temperaturmodulering. Ekonomiska analyser av hus från 2010-talet visar att sänkning av temperaturen inte minskar de totala elkostnaderna på kalla vinterdagar på grund av de högre elkostnaderna som är förknippade med temperaturåterhämtning. Orsaken är att nyare småhus oftast har frånluftsvärmepumpar med relativt låg kapacitet vilket innebär mycket användning av elpatron för att höja temperaturen igen efter en sänkning.

Genom energiflexibilitet finns i befintliga småhus en betydande potential att under dygnet flytta värmeanvändningen från höglastperioder till perioder med lägre belastning och därigenom avlasta både det lokal och det nationella elnätet. Men för att detta ska vara lönsamt för småhusägarna krävs dels att man har timdebitering, dels att såväl styrningen av värmesystemen som utformningen av kommande effekttaxor i de lokala elnäten görs på ett genomtänkt sätt. De toppar i värmeeffektbehov som enligt simuleringarna kan uppstå när börvärdet efter en sänkning höjs igen, framför allt med de tröga golvvärmesystemen, kan med de nya eleffekttarifferna annars leda till höga elnätsavgifter.

Nyckelord: energiflexibilitet, termisk tröghet, IDA ICE-simulering, småhus, golvvärme, elkostnad

Summary

This project aims to explore the potential of using thermal inertia to increase their energy flexibility. There has been limited knowledge about the extent and conditions under which this flexibility can be realized without compromising thermal comfort. This project has addressed this knowledge gap by investigating the thermal energy flexibility of Swedish small houses built from the 1940s onwards. The energy flexibility has been studied by using IDA-ICE models to simulate what happens when the setpoint for indoor temperature is changed during certain hours of the day, thereby lowering or raising the heating power demand.

Newer, well-insulated houses with floor heating retain heat better and can turn off the heating for longer periods without significant temperature drops compared to older, poorly insulated houses with radiators. When the temperature is reduced, newer houses show similar power reductions (3-4 kW) as older houses with radiators, mainly due to the floor heating. The amount of movable energy is greater for newer houses, especially in very cold weather, and can reach up to about 20 kWh on a very cold day and 15 kWh on a cold winter day, during a 4-hour modulation from 05:00 to 09:00. For older houses, the movable energy is about 10-12 kWh. The difference decreases as the outdoor temperature increases, with about 10 kWh available for all houses on a spring or autumn day.

Power recovery, the extra power needed to return to the original temperature after a reduction, is an important aspect to consider in load shifting. It varies with the type of distribution system and control strategies and can be significantly higher than the reference peak power without any temperature modulation. Economic analyses of houses from the 2010s show that lowering the temperature does not reduce the total electricity costs on cold winter days due to the higher electricity costs associated with temperature recovery. The reason is that newer small houses often have exhaust air heat pumps with relatively low capacity, which means a lot of use of electric heaters to raise the temperature again after a reduction.

Through energy flexibility, there is significant potential in existing single-family houses to shift heating usage from peak load periods to periods with lower load during the day, thereby relieving both the local and national power grids. However, for this to be profitable for small house owners, it is necessary to have hourly billing, and both the control of heating systems and the design of upcoming power tariffs in the local grids must be done thoughtfully. The peaks in heating power demand that, according to simulations, can occur when the setpoint is raised again after a reduction, especially with the slow response floor heating systems, can otherwise lead to high grid fees with the new power tariffs.

Key words: energy flexibility, thermal inertia, IDA-ICE simulation, single-family houses, floor heating, energy cost.

INNEHÅLL

1 INTRODUCTION AND BACKGROUND 7
1.1 BACKGROUND 7
1.2 PURPOSE AND OBJECTIVES 8
1.3 SCOPE AND LIMITATION 9

2 IMPLEMENTATION 10
2.1 DATA AND INFORMATION COLLECTION 10
2.2 IDA-ICE SIMULATION 10
2.3 CONCEPTUAL FLEXIBILITY: CONTROL STRATEGIES AND CASE STUDIES 11
2.4 ADDITIONAL ANALYSIS ON THE ECONOMICS OF ENERGY FLEXIBILITY 12

3 RESULT 13
3.1 OVERVIEW OF THE SWEDISH SINGLE-FAMILY HOUSES 13
3.2 TEMPERATURE DECAY AT A CONSTANT OUTDOOR TEMPERATURE 14
3.3 ENERGY FLEXIBILITY 15
3.3.1 TEMPERATURE AND HEATING POWER PROFILE 15
3.3.2 FLEXIBLE POWER 17
3.3.3 FLEXIBLE ENERGY 18
3.4 ENERGY FLEXIBILITY VERSUS ELECTRICITY FLEXIBILITY 20
3.4.1 ELECTRICITY PRICES IN SWEDEN 20
3.4.2 LOCAL ELECTRICITY NETWORK FEES AND ELECTRICITY TAX 21
3.4.3 THE INFLUENCE OF HEAT PUMPS ON THE ECONOMICS OF ENERGY FLEXIBILITY 22

4 DISCUSSION AND CONCLUSION 24

5 PUBLICATION LIST 26

6 REFERENCES 27

APPENDIX 29

1 Introduction and background

1.1 Background

There is a growing demand for increasing energy flexibility to relive strains on the power grid and to facilitate integration of renewable energy sources [1]. As countries like Sweden strive to achieve 100% fossil-free electricity production by 2045, prioritizing the integration of renewable energy sources becomes essential [2]. Given the unpredictable nature of these sources, a flexible energy system is crucial for effectively managing these fluctuations. Energy storage solutions, demand response systems, and other technologies enable better distribution and utilization of existing energy resources, thereby significantly improving grid stability [3].

Energy flexibility in buildings is broadly referred to as the ability to manage its energy demand and energy production according to its local climate conditions, user needs and energy net work requirements [4]. Building and their users can adjust their energy consumption to have a flexible energy demand, i.e., decrease energy use in case of shortage (energy conservation) or increase the energy use in case of excess production (energy storage) [5]. In many countries, buildings account for a significant portion of total energy use. In Sweden, approximately 32% of total electricity consumption in 2022 is attributed to residential buildings, with 48% of this energy dedicated to space heating [6]. According to 2023 statistics, electricity use for heating and hot water in single-family houses was 16.1 TWh, while it was 2.6 TWh for multi-family dwellings [7]. Based on the analysis in [8], up to 5.5 GW of electrical space heating loads can be shifted in Swedish single-family houses, which is substantial.

How much flexibility available depends on several factors: [9]: (1) physical characteristics such as thermal mass, insulation, and architectural layout, (2) technical systems including ventilation, heating, and storage equipment, (3) control systems that enable user interactions and the ability to respond to external signals like electricity prices or CO_2 factors, and (4) occupants' behavior and comfort requirements.

Insulation levels are one of the most important parameters affecting energy flexibility, as pointed out by [10-11]. In poorly insulated buildings, a large amount of thermal energy can be shifted over a short period, whereas well-insulated buildings can shift smaller quantities of energy over longer periods [5, 12-13]. In older buildings, temperatures drop quickly when heating systems are turned off, while in newer buildings, load shifting can be done with small variations of indoor temperature, allowing for decreased heating needs compared to a building always at 19°C [14]. Additionally, the type of heat emitter has a considerable impact [5]. Studies indicate that flexibility potential is slightly higher with floor heating systems compared to radiators, but the risk of overheating or overconsumption can be higher with floor heating. This is because that, floor heating requires a large amount of energy to activate the building's thermal mass before the temperature can start increasing, and it operates on its maximum capacity to reach the desired setpoint though the operative temperature is not too low [15]. Therefore, it is suggested that [5] for well-insulated houses (e.g., passive houses) with floor heating systems, a short and small increase in the setpoint could be tested. For poorly insulated houses with water radiator systems, the setpoint can be decreased within a 2 to 6-hour timeframe to limit the impact on indoor climate while maximizing flexibility.

Research in Denmark [5] and Belgium [9] evaluated the potential of using building thermal mass to modulate the energy use (thermal or electrical) of heating systems. They found that the flexibility potential for residential buildings ranged from 50 to 140 Wh/m^2 of floor area for a 4-hour modulation period. A Canadian study [16] estimated that reducing the heating setpoint by 2°C in a single-family house built in 1998 could achieve a maximum power reduction of around 3-4 kW. A recent study in Finland [17] assessed the flexibility potential of energy storage and conservation in both new and old residential buildings with ideal heaters. It showed that decreasing the setpoint by 1.5°C resulted in energy discharge of 6.2 to 38.5 kWh over 2 to 18 hours in the new building, and 4.5 to 21.3 kWh in the old buildings. This indicated that the new building could store energy more efficiently than the old building due to lower heat losses to the ambient surroundings.

While these studies provide valuable insights, they are often based on one or two building typologies and specific technical and control systems. There is still a lack of comprehensive knowledge about the extent and conditions under which flexibility can be realized without compromising thermal comfort for different types of buildings, especially in the Swedish context. One study [8] investigated the load-shifting potential of electrical space heating in Swedish single-family houses by optimizing pre-heating times and durations, providing an overall assessment of the flexibility potential for the electricity grid. However, this study mainly focused on evaluating the impacts of large-scale demand response implementation on the Swedish electricity system, the dynamic behavior of charging and discharging building was not clearly characterized. This project is therefore proposed to address these research gaps by providing an overview of the energy flexibility potential for Swedish single-family houses.

The aim of this project is to explore the potential of using thermal inertia to increase energy flexibility, considering energy, power, and thermal comfort. By studying a diverse range of buildings representing the Swedish residential building stock, the impact of building standards/techniques, types of technical systems, and location/climate on thermal dynamic behavior can be addressed. This approach allows for the assessment of the potential for shifting power and energy. Additionally, the recovery process in terms of power and time is investigated. The simulation program IDA-ICE is used to provide quantitative data. This work provides a basis for various applications, such as developing control strategies to facilitate the implementation of demand response.

1.2 Purpose and objectives

The overall goal of this project is to explore the potential of utilizing thermal inertia to increase energy flexibility across various Swedish building typologies without violating thermal comfort.

The project goals are:

- Evaluate energy flexibility for typical Swedish single-family houses while considering thermal comfort, including the level of insulation, the type of window, heat emitters and ventilation, as well as weather conditions.
- Evaluate the flexibility potential for charging and discharging the building, and impact of different activation durations.
- Provide quantitative data of shiftable energy, peak reduction, and indoor temperature.
- Provide an overview of energy flexibility potential for Swedish single-family houses.

Output from the project can help in understanding and optimizing flexibility controls of buildings while maintaining an acceptable indoor environment.

1.3 Scope and limitation

This project evaluates the potential of buildings to shift heating power and energy and defines simple control strategies to exploit the flexibility potential for different types of houses and weather scenarios. The study mainly focuses on thermal energy, with limited consideration of the impact on electrical power and energy, as addressing these aspects would require more time and effort than the scope of this project allows. Nevertheless, some analyses are conducted to determine the effects of different charging and discharging strategies on electrical power and energy cost.

2 Implementation

2.1 Data and information collection

Data and information for representative building typologies of Swedish single-family houses are collected, covering buildings from the 1940's onwards. The focus is not only on prototype houses but also on typical renovations for houses built in different periods. This information is gathered from previous studies, such as Boverket surveys/reports, statistical data, and in-house interviews. The results are summarized in Table 1 in the "Results" section.

2.2 IDA-ICE simulation

The flexibility of space heating for different buildings was investigated through simulations using a validated IDA-ICE model [18]. IDA ICE models the building, its systems and controllers, which provides detailed and dynamic multi-zone simulation for thermal indoor climate as well as the energy consumption of the entire building [19]. In this study, it was employed to determine heating demand for various boundary conditions and to perform modulations of heating power.

A model of a typical Swedish single-family house was created in IDA-ICE (see Figure 1), corresponding to a prototype house called Research Villa located at the RISE premises in Borås. The house had a total heated floor area of 151 m^2 and was assumed to be occupied by two adults and two children. The first floor was primarily for living and family activities, including a living room and kitchen, while the second floor was mainly for sleeping, with four bedrooms. The total heat load from household appliances was assumed to be 30 kWh/m^2 per year [20], distributed across different rooms and following various time schedules.

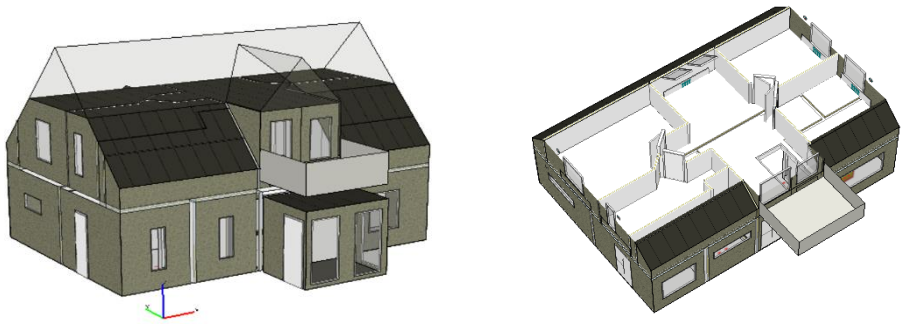


Figure 1 IDA-ICE model (left) and zone layout (right).

The same house model was used in this study to represent different types of single-family houses. Special care was taken to ensure that the overall transmission loss, i.e., ∑UA/A, was reasonable for each house by comparing the value with the BETSI report [21]. ∑UA/A is the overall heat loss coefficient, which is the sum of all the U-values of the individual elements of the external walls, ceiling, floor, windows, and doors, multiplied by their respective areas, and divided by the total heated floor area. This parameter determines the total heat losses through the building envelope.

Floor heating was simulated as a tempered layer (without height) at a given depth in the floor construction in IDA-ICE, while water radiators were simulated as radiant and convective baseboards. They were sized based on the actual dimensioned winter outdoor temperature for Borås and oversized to 125% [5]. The water supply temperature for floor heating and radiators varied with outdoor temperatures, with a maximum temperature of 55°C, assuming the house was connected to heat pumps. The weather profile used was for the design of a reference year for Borås, which averaged weather data over 30 years (1991-2020). The calculated heating demand for the reference year by IDA-ICE ranged from 84 to 155 kWh/m^2 between the newest and oldest houses. Additionally, the yearly heating demand from the IDA simulation was compared with TMF Energi, showing a good agreement with a maximum discrepancy of 8%.

2.3 Conceptual flexibility: control strategies and case studies

The conceptual flexibility is investigated by modulating heating power through direct changes to the heating setpoint. Various scenarios are studied to evaluate the impact of activation duration and overheating on flexible power and energy:

- **Scenario 1**: Reduce the temperature setpoint from 21°C to 19°C between 5:00 and 9:00, and between 16:00 and 19:00
- **Scenario 2**: Reduce the temperature setpoint from 21°C to 19°C between 5:00 and 14:00, and between 16:00 and 19:00
- **Scenario 3 and 4**: Consider overheating for scenarios 1 and 2 by increasing the temperature setpoint from 21°C to 23°C from midnight to 5:00 for the first floor only[1]

The temperature setpoint schemes for different scenarios are illustrated in Figure 2, maintaining a range of 21 ± 2°C. Peak hours are assumed to occur daily from 5:00 to 9:00 (morning peak) and 16:00 to 19:00 (evening peak), with a setpoint of 19°C. In all scenarios, the setpoint is increased back to the original 21°C after the reduction period.

The four scenarios are evaluated for each house category, and the results are compared with their respective reference cases with a constant setpoint of 21°C. Three weather conditions are considered: a very cold winter day, a cold winter day with very little solar radiation, and a spring/autumn day with some solar radiation. The average outdoor temperatures for these days are -13°C, -6°C, and 5°C, respectively. Additionally, extra cases are simulated to study how quickly the indoor temperature of different houses decreases after turning off the heating system for a cold day with a constant outdoor temperature of -10°C.

[1] Not always easy to implement overheating for the first floor only in existing heating systems.

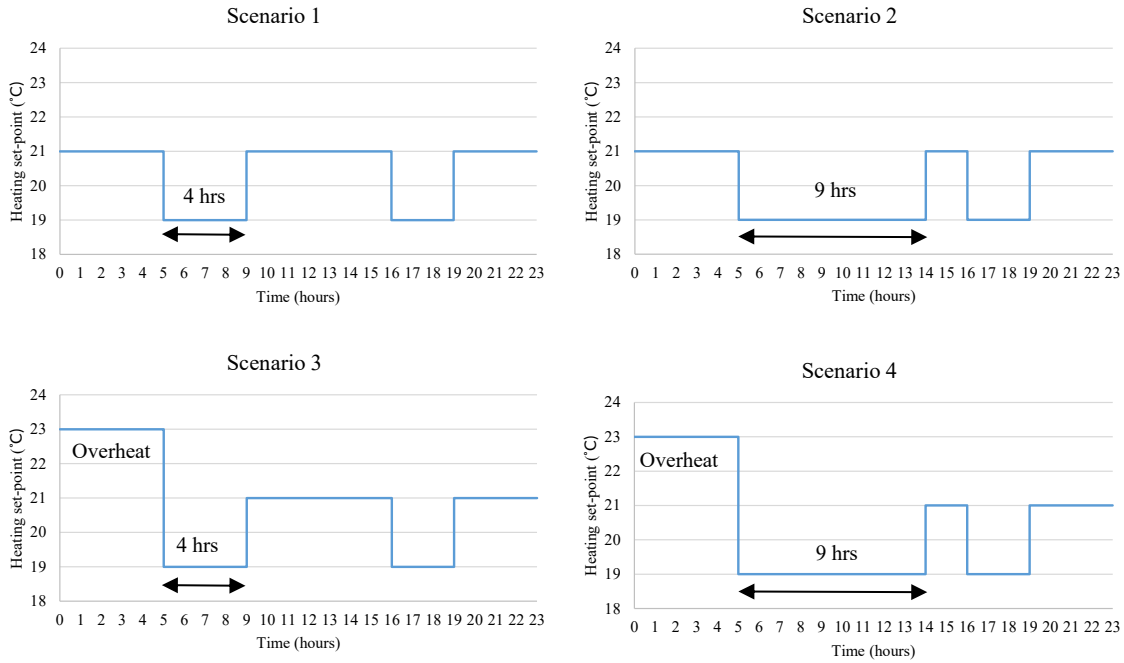


Figure 2 setpoint of heating temperatures for different scenarios.

2.4 Additional analysis on the economics of energy flexibility

An additional analysis was conducted for a house built in the 2010 – 's to illustrate the influence of heat pumps on the economics of energy flexibility. This analysis considered the Coefficient of Performance (COP) of the heat pump, hourly electricity prices, and data on hourly heating power demand from IDA-ICE simulations.

3 Result

3.1 Overview of the Swedish single-family houses

Swedish single-family houses are classified into different groups based on the BETSI program (a national survey of the residential stock initiated in 2005) [21], including the latest building categories: 1940-1960, 1961-1975, 1976-1985, 1986-1995, 1996-2009, and 2010 onwards. Information for these houses is listed in Table 1, with inputs based on the BETSI report [21] and our own assumptions.

As shown, building insulation levels and air tightness has been improved over time, and ventilation systems have changed from natural ventilation to mechanical ventilation (exhaust ventilation or balanced ventilation with heat recovery) to improve indoor air quality. Many older houses with natural ventilation are under-ventilated, and the flow rate is strongly influenced by outdoor conditions such as air temperature and wind speed. In houses with mechanical ventilation, the flow rate could be maintained at 0.35 l/s m^2. For two-story houses built from the 1990's onwards, it is common to have two types of heating systems: floor heating on the first floor and water radiators on the second floor. In older houses, radiators are mostly used. Many Swedish houses are built with wood, while some older houses are constructed with bricks combined with wood panels.

Table 1 list of the main building parameters

	1940-1960	1961-1975	1976-1985	1986-1995	1996-2009	2010-
Building envelop heat losses U_{ave} (W/K·m^2 internal envelop area)	0.65	0.49	0.38	0.33	0.34	0.26
U-value external wall (W/K·m^2)	0.52	0.31	0.21	0.17	0.2	0.17
U-value ceiling (W/K·m^2)	0.33	0.23	0.17	0.14	0.13	0.11
U-value floor (W/K·m^2)	0.16	0.18	0.16	0.15	0.12	0.12
U-value window (W/K·m^2)	1.9	1.6	1.6	1.4	1.4	1.2
Air infiltration q50 (l/s·m^2 internal envelop area)	0.8	0.8	0.8	0.8	0.6	0.4
Ventilation	Natural ventilation	Natural ventilation	Exhaust ventilation	Balanced ventilation with heat recovery of 60%	Exhaust ventilation	Exhaust ventilation
Ventilation flow rate (l/s·m^2 heated floor)	/	/	0.35	0.35	0.35	0.35

Internal heat load (kWh/m² heated floor per year)	30	30	30	30	30	30
Heat distribution system	Water radiator	Water radiator	Electrical heating panel	Water radiator	Floor heating (1st floor), and radiator (2nd floor)	Floor heating (1st floor), and radiator (2nd floor)
Space heating demand from IDA (kWh/m² heated floor are per year)	155	116	109	90	101	84

3.2 Temperature decay at a constant outdoor temperature

Figure 3 illustrates the temperature decay for three houses with varying insulation levels at a constant outdoor temperature of -10°C. Initially, all houses are heated to approximately 21°C. The house built in the 2010 – 's retains heat significantly better than the others, taking around 4-5 hours to cool down to 19°C. In contrast, the temperature in the house from the 1940-1960 drops to 19°C in less than 1 hour, while the house from the 1961-1975 period takes slightly more than 1 hour to reach 19°C.

The slower temperature decline in the 2010 – 's house is largely attributed to its better insulation and the extra-large thermal mass provided by floor heating. In comparison, the older houses, which are less insulated and heated by radiators, lose heat more quickly. These simulation results indicate that heating can be turned off for longer periods in newer buildings. However, this is not suitable for older houses which are normally poorly insulated and have high transmission losses.

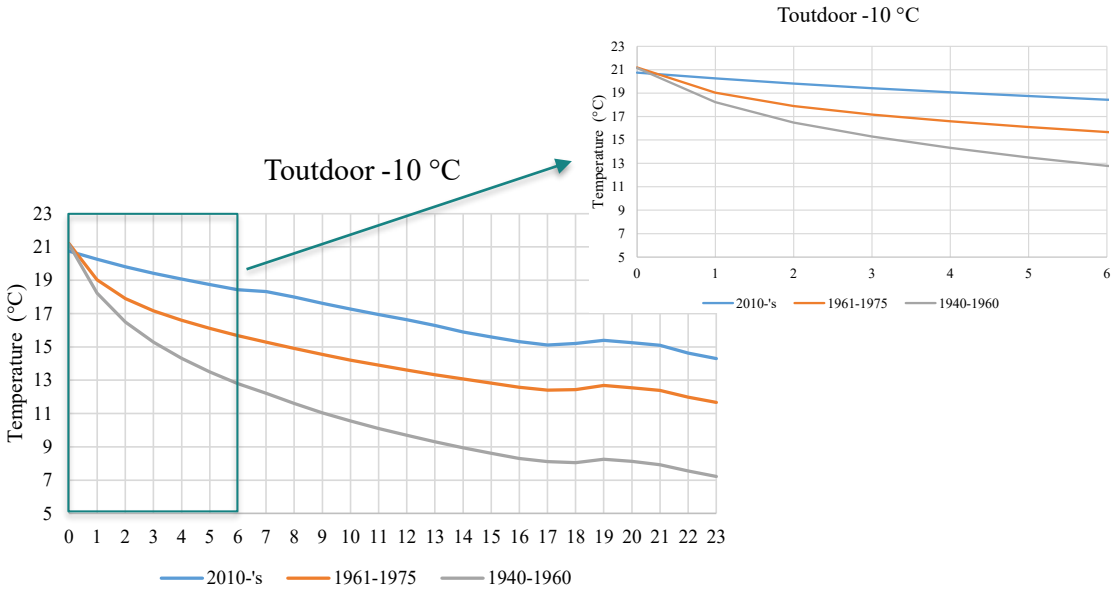


Figure 3 the average indoor temperature decay at the constant outdoor temperature of -10°C.

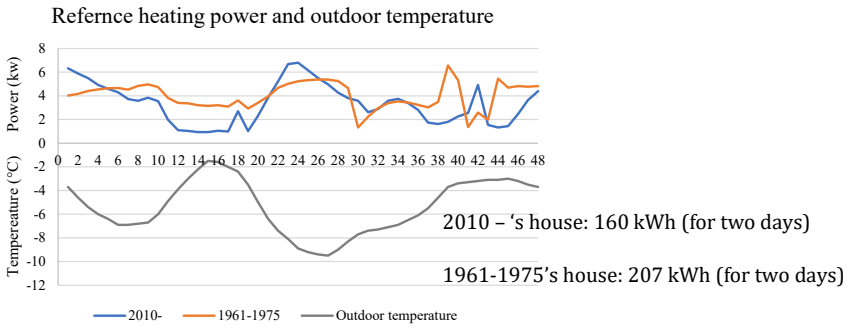
3.3 Energy flexibility

3.3.1 Temperature and heating power profile

This section illustrates changes in indoor temperature and heating power following different heating setpoint schemes. Results from a well-insulated 2010 – 's house and a poorly insulated 1961-1975's house on a cold day are shown in Figure 4. The figure presents data over a two-day period: the first day without modulation (reference case) and the second day with modulation. It also shows the variation of reference heating power with outdoor temperature for these houses. The reference heating power is for maintaining a constant setpoint of 21°C.

The reference heating power increases as the outdoor temperature decreases, requiring more heating to maintain the house at 21°C. The 2010 – 's house shows a higher peak power than the 1961-1975 house during the coldest hours (around midnight), but otherwise has a lower power demand. This is due to the slow reaction of floor heating and imperfect control of the regulator, causing a short-term power peak. Over a two-day period, the reference heating demand is 160 kWh for the 2010 – 's house and 207 kWh for the 1961-1975's house. If the 2010 house used radiators, a lower heating demand would be expected due to the absence of overshoot issues associated with floor heating.

Figure 4 shows temperature profiles for the heating setpoint, living room and kitchen air temperature (first floor), and sleeping room air temperature (second floor) with solid curves. The heating power demand for the reference case (P_reference) and modulation case (P_M) is shown in kW with black and green dashed curves, respectively. All data are hourly values.



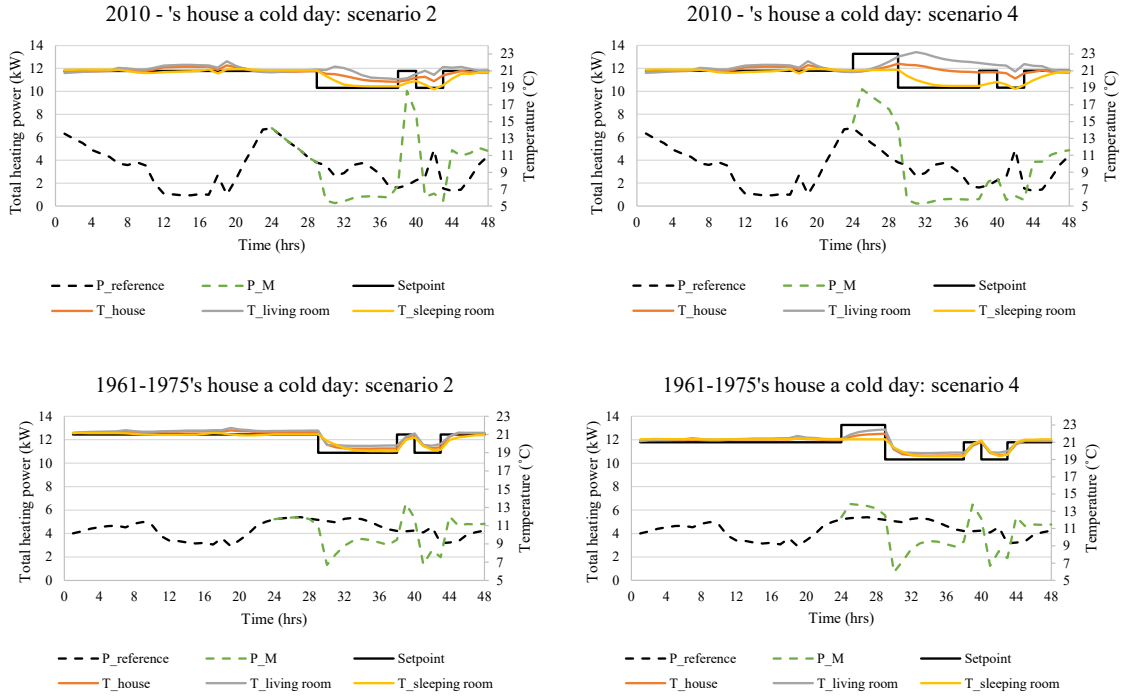


Figure 4 hourly temperature and power profiles for a cold day. Scenario 2 is without overheating, while scenario 4 is with overheating. Both scenarios have a downward modulation period of 9 hours from 29th to 38th hour (corresponding to 05:00 to 14:00). P_refernce represents the reference heating power, and P_M represents the modulation heating power, both shown on the left axis. The temperature is read from the right axis.

During the first day, the temperature for both houses is maintained at about 21°C, with heating power closely related to outdoor temperatures. On the second day, temperature and heating power change with the setpoint settings. For example, in scenario 2, the temperature drops when the setpoint is reduced between 05:00 and 14:00, requiring minimal heating power. In scenario 4, the temperature increases when the setpoint is raised from 21°C to 23°C at night to store energy, necessitating

additional power. Extra heating power is also needed to recover the temperature after a setpoint decrease, such as from 14:00 to 16:00 in both scenarios.

The total heating power demand is lower than the reference case when the setpoint is decreased and higher when it is increased. The variation in heating power is larger with floor heating (2010 – 's house) and smaller with radiators (1961-1975's house). The 2010 house reacts more slowly to setpoint changes due to the large thermal mass of floor heating, resulting in greater flexibility but higher peaks when recovering temperature. Therefore, floor heating needs careful control to avoid activating maximum power, such as by gradually increasing the setpoint to smooth out power demand.

3.3.2 Flexible power

The difference in power demand between the reference and modulation cases represents the flexible power. Figure 5 shows the deviation in power demand (ΔP) for the 2010 and 1961-1975 houses on a cold day. Results for other weather conditions are in the Appendix. Figure 5 includes a 4-hour downward modulation from 5:00 to 9:00 (scenarios 1 and 3) and a 9-hour modulation from 5:00 to 14:00 (scenarios 2 and 4). Scenarios 1 and 2 are without overheating, while scenarios 3 and 4 include overheating on the first floor. Data are hourly values.

In Figure 5, ΔP = 0 indicates no change in heating power compared to the reference case (setpoint at 21°C). A positive ΔP means increased heating power when raising the setpoint, and a negative ΔP indicates decreased heating power when lowering the temperature.

When reducing the setpoint, the maximum flexible power for the 2010 and 1961-1975 houses is about 3 kW and 4 kW, respectively, between 5:00 and 9:00 (see Figure 5 a, c). The small difference is mainly due to improper control of floor heating and overshooting, as a larger reduction is expected for the 1961-1975 house due to higher heating demand in the reference case.

Overheating does not significantly contribute to power reduction but impacts rebound power, which is the power needed to return the temperature to its original value. For the 2010 – 's house (Figure 5a, b), rebound power is negative after the 4-hour downward modulation, indicating no additional heating is needed. After the 9-hour modulation, the peak of ΔP is close to 0, meaning power remains unchanged compared to the reference case. In contrast, rebound power is much higher without overheating, approximately 4 kW and 8 kW for the 4-hour and 9-hour periods, respectively. The longer the discharging period, the more heat needs to be recovered.

This effect is not observed in the 1961-1975 house, Figure 5 (c, d), where rebound power remains the same with or without overheating due to large heat losses. Overheating is less effective for storing energy in poorly insulated buildings compared to well-insulated ones, especially if the latter also have floor heating.

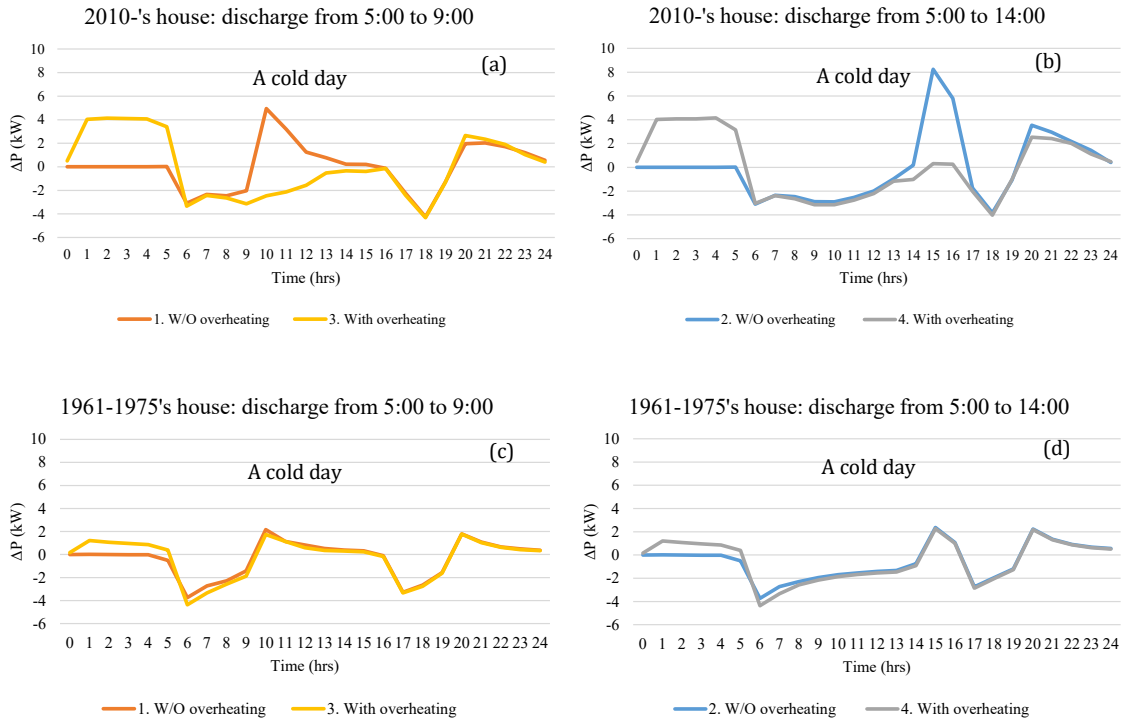


Figure 5 deviation of the heating power from the reference case for different scenarios with the downward modulation from 5:00 to 9:00 and 5:00 to 14:00, with and without overheating during the night. W/O means without overheating, different number in the legend means scenario 1, 2, 3 and 4. The data is based on hourly value.

3.3.3 Flexible energy

The difference in power demand between the modulation and reference cases during the activation period is called flexible or movable energy (in kWh). Figure 6 shows the among of movable energy during the 4-hour (5:00-9:00) and 9-hour (5:00-14:00) modulation periods for all houses on very cold, cold, and spring/autumn days. The results are presented daily.

Better-insulated houses generally provide higher flexible energy, especially in winter. On very cold days, houses built between 1996 and 2009 offer the highest flexible energy (around 20 kWh for a 4-hour period), followed by houses built from 2010 onwards (about 15 kWh), and older houses (10-12 kWh); see Figure 6a. As outdoor temperatures rise, these differences decrease. On spring/autumn days, all houses provide similar flexible energy, close to 10 kWh; see Figure 6e. Overheating does not significantly impact the 4-hour downward modulation period.

Extending the modulation period to 9 hours increases flexible energy and the effect of overheating becomes noticeable (Figure 6b, d, f), especially for well-insulated houses with floor heating. On very cold days, the highest flexible energy is about 27 kWh without overheating and 40 kWh with

overheating (1996-2009 houses). On spring/autumn days, flexible energy decreases to about 15-17 kWh for all houses.

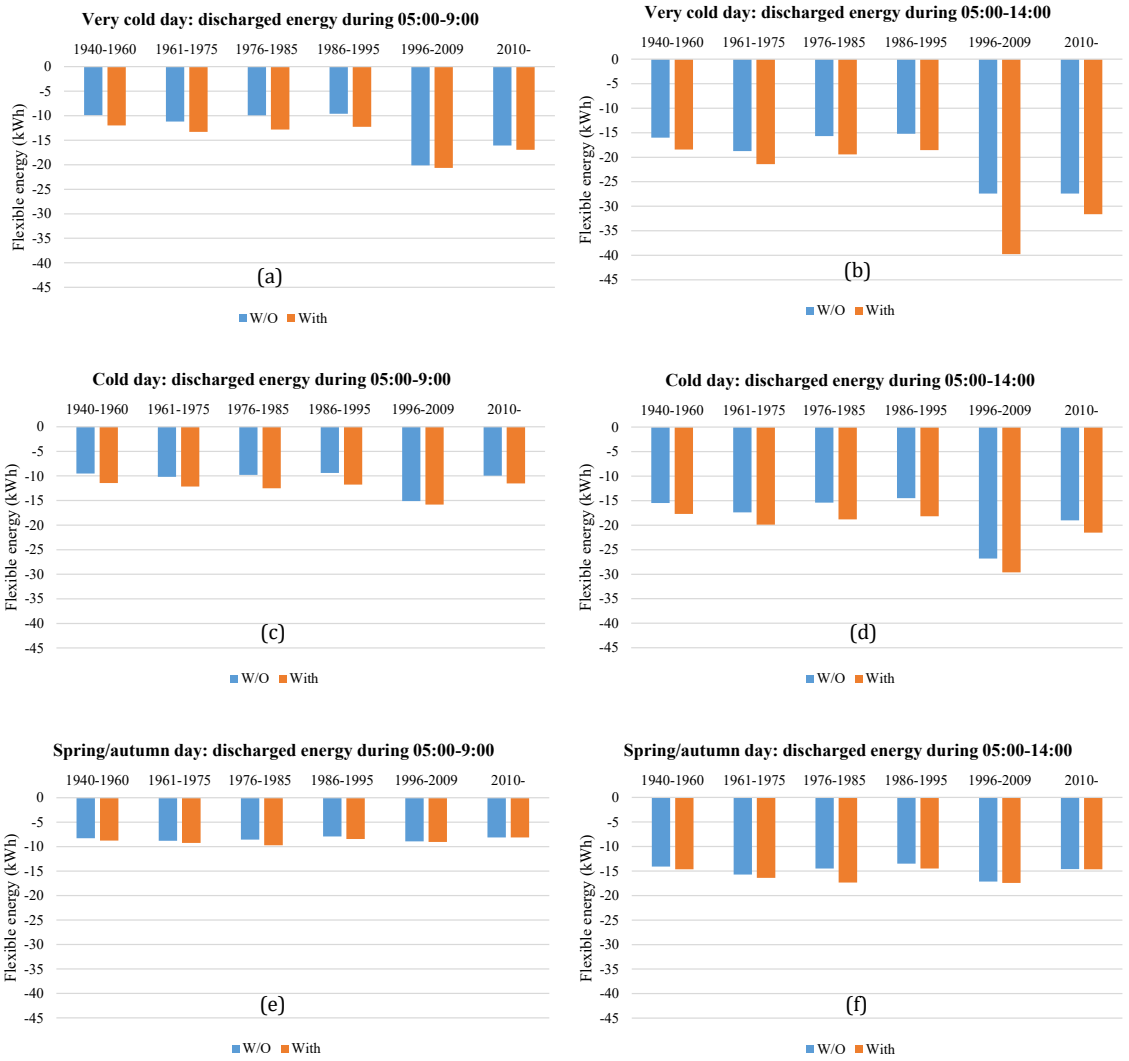


Figure 6 flexible energy for 4-h (5:00-9:00) and 9-h (5:00-14:00) downward modulation with and without overheating. "W/O "means without overheating, and "With" means with overheating. Overheating only occurs on the first floor during the night.

3.4 Energy flexibility versus electricity flexibility

3.4.1 Electricity prices in Sweden

Sweden is divided into four bidding areas from bidding area SE1 in the north to bidding area SE4 in the south. The price of electricity in each bidding area is determined by supply and demand of electricity and transmission capacity between bidding areas. In northern Sweden more electricity is produced than is needed, in southern Sweden it is the opposite. Therefore, a large amount of electricity is transported from the north to the south of Sweden, and hence the electricity price is normally higher in bidding area SE4 than in bidding area SE1, see figure 7 below. Bidding area SE4 is also more liked to other parts of the European electricity net and hence more influenced by the electricity prices in the rest of Europe.

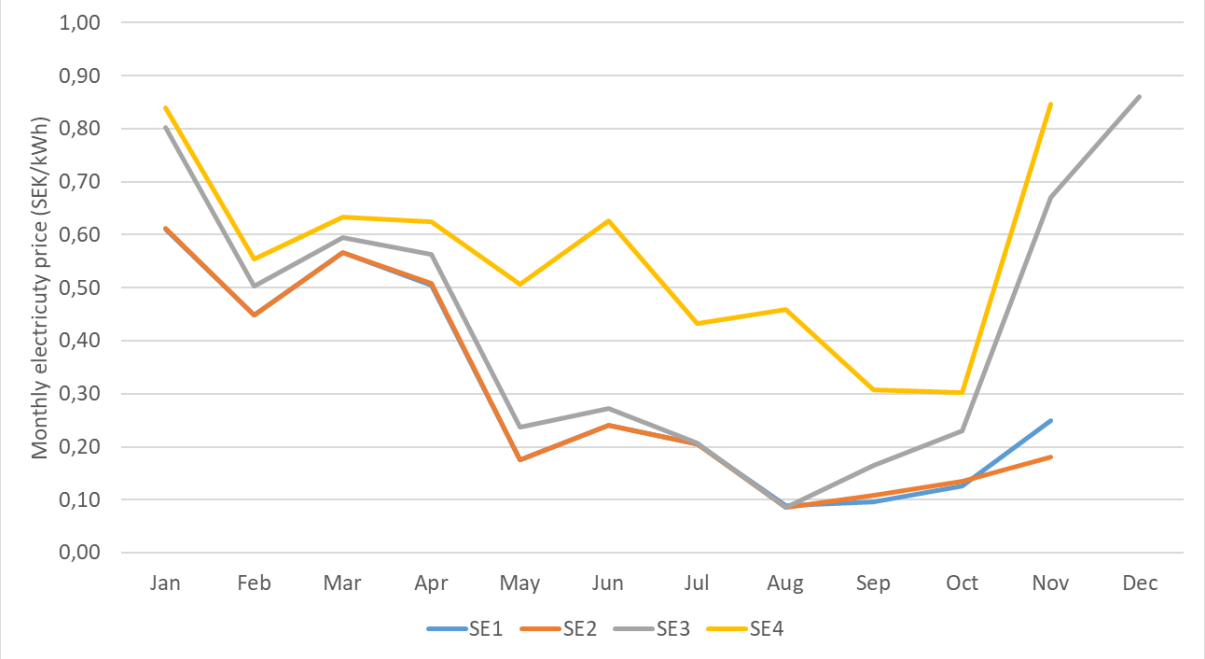


Figure 7 monthly mean spot prices for the different bidding areas during 2024.

In figure 7 one can also see that on an average, the electricity price is higher during colder winter days when the need for heating is higher.

As an electricity consumer in Sweden, you can have different types of electricity price subscriptions. Either you have a fixed electricity price per kilowatt-hour regardless of when the electricity is used during the day, or you have a variable spot price where the electricity price varies hour by hour. There are also different fixed electricity price subscriptions. Either you have a semi-fixed electricity price per kWh that varies per month as the mean value of the spot price for that month, see figure 7 above, or you have a negotiated fixed electricity price regardless of when during the day or during the year the electricity is used. In the latter case the price is normally fixed for 1-5 years.

The spot price of electricity that is of most interest in this study is usually low at night, medium high in the middle of the day, and as high in the morning and high in the afternoon/evening, see figure 8. The values in figure 8 have been modified to reflect a typical monthly day with an average electricity price of 0.86 SEK/kWh.

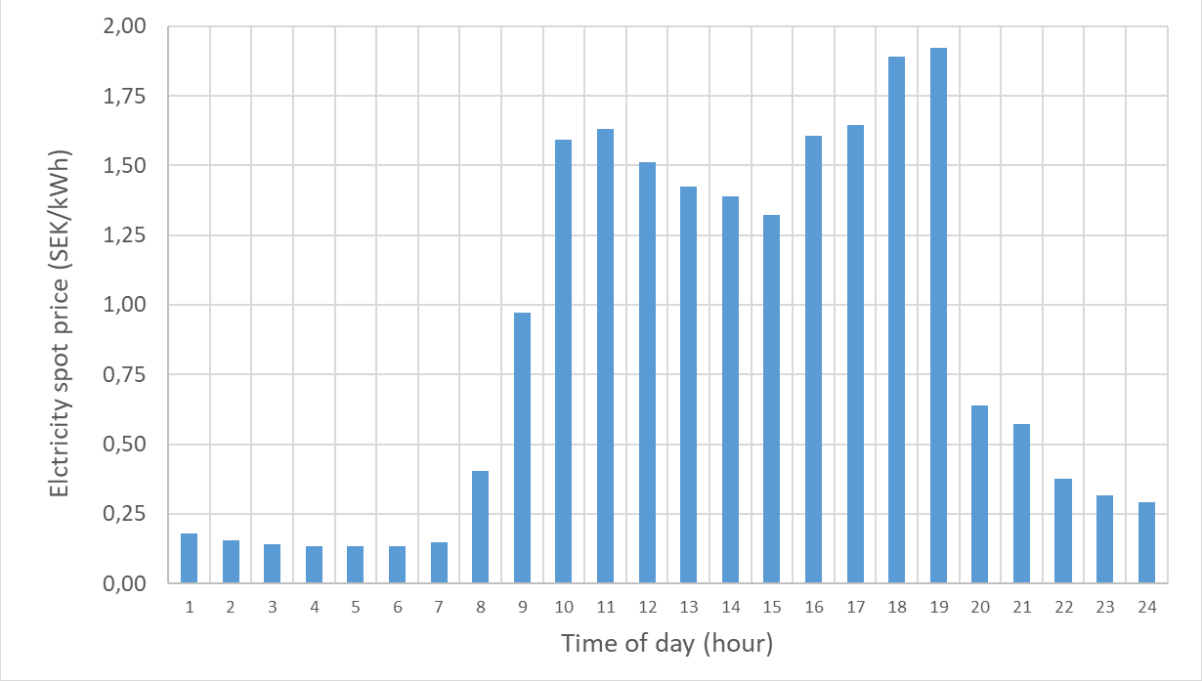


Figure 8 Example of hourly spot prices including VAT during a cold winter day in bidding area SE3.

The only financial incentive to shift energy use to another time of the day is that the energy price is then lower. Therefore, when moving loads, you should choose an electricity subscription where you pay according to a spot price that varies hour by hour.

In addition to the spot price, all electricity trading companies charge a surcharge on the spot price of approximately SEK 0.1/kWh including VAT. The surcharge compensates the electricity trading companies for their costs of buying in electricity certificates and any guarantees of origin, their fees to Nord Pool and Svenska Kraftnät, as well as costs for balancing power.

3.4.2 Local electricity network fees and electricity tax

In addition to the electricity spot price and surcharge, network fees and electricity tax is added to the electricity bill. The network fees are charged by the local network owner to manage the maintenance of the electricity network. The network fees vary considerably between different network owners but depends also on the size of the main fuse and the total electricity consumption.

Today most network owners have flat rate for the electricity used within the network, i.e. the same price per kWh used regardless of when it is used. However, by the1th of January 2027 at the latest, all

electricity network companies must have introduced a new pricing model that includes a power tariff. With power-based pricing, electricity users will be given incentives to spread out their electricity use to avoid power peaks that can lead to problems in the electricity network. The power tariff shall hence be time-differentiated, which means that it should be different at different times to reflect how the load on the electricity grid varies over time. A more even load on the electricity network has several advantages, including that more people can use the existing electricity grid and that it can generally contribute to lower electricity grid costs and a lower electricity price.

The electricity tax is the same per used kWh regardless of when it is used. The electricity tax is 0.535 SEK/kWh for year 2024 and will in 2025 be increased to 0.549 SEK/kWh, including VAT. For households in certain municipalities in northern Sweden there is a deduction of 0.12 SEK/kWh including VAT.

3.4.3 The influence of heat pumps on the economics of energy flexibility

Most Swedish single-family houses are heated by heat pumps driven by electricity from the electricity grid. Depending on the actual heat demand, type of heat pump and the size/capacity of the compressor there is not always a direct correlation between the movable amount of heat and heat power reduction, as presented in paragraph 3.3, and the movable amount of electricity and electric power reduction in a house heated by a heat pump.

As an example, calculations have been made for the 2010 – 's house equipped with an exhaust air heat pump with a variable speed compressor, which is the most common heating and ventilation system for these houses. Calculations have been made for a cold day and control strategies according to scenarios 1-4 as well as the reference case. The calculations considered the Coefficient of Performance (COP) of the heat pump, hourly and monthly electricity prices, and data on hourly heating power demand from IDA-ICE simulations. The COP varies with the heat power demand according to the heat pump manufacturers data. For the reference case a monthly average electricity price of 0.86 SEK/kWh has been used and for scenarios 1-4 the hourly price varies according to figure 8 has been used. Based on the electricity network fee of 0.157 SEK/kWh, used by the local electricity network owner in the City of Borås in 2024, a total fixed cost of 0.80 SEK/kWh has been used in the calculations for electricity tax, network fee and surcharges. The results of the calculations are summarized in table 2 below.

Table 2 Example of the influence of an exhaust air heat pump on the economics of flexibility

	Total heat kWh	Kompr. heat kWh	electr. kWk	Reheat. electr kWh	Total electr. kWh	Total power kW	Total price SEK
Reference	77.1	71.9	25.6	5.2	30.8	3.7	51.1
Scenario 1	76.6	64.0	24.0	12.6	36.5	6.3	58.3
Scenario 2	75.5	57.9	22.1	17.7	39.8	7.5	61.7
Scenario 3	78.0	53.3	19.7	24.7	44.4	7.7	49.0
Scenario 4	77.4	52.4	19.7	25.0	44.7	7.7	49.2

The results show that moving energy use from periods of high energy prices to periods of lower energy prices may not be economically beneficial when the house is heated with an exhaust air heat pump. The reason is that required rebound heat power is much higher than the maximum heat power output from the compressor. Additional heating power is therefore needed from a resistance electric reheater. The calculations show that for scenarios 1-2 the electricity costs would be considerably higher than for the reference case, even though the total heating energy demand is slightly lower. For scenarios 3-4 the electricity costs would be slightly lower than for the reference case, even though the total heating energy demand is slightly higher. In these calculations the influence of future electricity network power tariffs has not been included but must according to the calculation results be included in future studies. It should be emphasized that the presented results are only valid for the 2010 – 's house equipped with an exhaust air heat pump and for the chosen cold day and price scenario. Further studies should be done for different house types and different heat pumps, and for whole year simulations including different electricity price scenarios and control strategies.

4 Discussion and conclusion

This project characterizes the flexibility potential for a wide range of Swedish single-family houses and provides detailed insights into their dynamic thermal behavior. Various parameters affecting energy flexibility are assessed, including envelope properties (e.g., insulation level, air tightness), heat emitters (e.g., floor heating and radiators), ventilation, charging/discharging strategies, and weather conditions. Conceptual flexibility is investigated by modulating heating power through direct changes to the heating setpoint based on IDA-ICE simulations.

Although newer houses require less energy for heating than older houses, as shown in Table 1, the simulation results indicate that the potential to shift heating loads from peak periods to periods with lower demand, while maintaining acceptable thermal comfort, is just as great or even greater in newer houses. The main reason is that older houses have poorer thermal insulation, causing the temperature to drop more quickly when the heating system's setpoint is lowered. In contrast, newer houses with better insulation and airtightness experience a much slower temperature drop when the setpoint is lowered. For example, in newer houses, heating can be turned off for up to 5 hours without the temperature dropping below 19°C, whereas in older houses, this period is limited to about 1 hour. This effect is further accentuated in houses with heavy and slow-response floor heating systems, which are most common in single-family houses built in recent decades.

Energy flexibility is higher in winter and lower in spring and autumn because more heat is needed in the reference case during winter, and less is needed as the outdoor temperature warms up. Another important aspect of energy flexibility is power rebound. When the temperature needs to return to its initial level after being decreased, additional power is required to raise the temperature. Depending on the type of heat emitter, the activation time, and the duration (i.e., when the setpoint is decreased and for how long), the rebound power occurs at different times of the day and with varying peaks. Floor heating requires much higher power than radiators when recovering temperature, which could generate a new peak and needs to be controlled carefully. Gradually recovery the temperature in steps is necessary to avoid overshooting with floor heating.

Based on the analysis of cold winter days, the estimated potential for shifting heating loads is greatest for houses built between 1996 and 2009. This is because they have floor heating but are less well insulated than houses built from 2010 onwards. However, it may be difficult for owners of houses from 1996-2009 to make shifting heating loads profitable, as these houses often have simpler exhaust air heat pumps with relatively low capacity, which means a lot of use of electric heaters to raise the temperature again after a reduction. Even with the more powerful exhaust air heat pump that is most common in houses built from 2010 onwards, our calculations show a high risk that unconsidered reductions in the setpoint during peak periods with more expensive electricity will lead to higher overall electricity costs.

Through energy flexibility, there is significant potential in existing single-family houses to shift heating usage from peak periods to periods with lower demand during the day, thereby relieving both the local and national power grids. However, for this to be profitable for homeowners, it requires both hourly billing and that the control of heating systems and the design of upcoming power tariffs in local grids are done thoughtfully. The peaks in heating power demand that can occur when the setpoint is raised

again after a reduction, especially with sluggish underfloor heating systems, can otherwise lead to high grid fees with the new power tariffs.

The project has primarily focused on thermal energy, specifically the amount of heat delivered to maintain certain temperatures in the house, with limited analysis on the influence of heat pumps on the economics of energy flexibility. To better quantify the potential of flexibility in combination with heat pumps—especially since most single-family houses in Sweden use some type of heat pump—other parameters need to be considered. These include the type of heat pump, compressor size, locations, electricity price scenarios, and control strategies. These aspects are planned for investigation in a future continuation project.

5 Publication list

Huijuan Chen, Svein Ruud & Caroline Markusson (2024). Energy flexibility using thermal mass for Swedish single-family houses, BuildSim Nordic 2024, 9 – 11 June, Espoo, Finland.

Svein Ruud & Huijuan Chen (2025). Potentialen för att flytta värmebehovet under dygnet i befintliga svenska småhus. Teknik- och forskningsartikel i Energi&Miljö, submitted in January 2025.

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Appendix

Figure 1 shows the deviation of power from the reference case for the 2010 – 's house and the 1961-1975's house for different scenarios on very cold, cold, and spring/autumn days. For the 1996-2009's house with floor heating, the variation trend can be represented by the 2010 – 's house, while for the other houses, the results are similar to the 1961-1975's house.

Figure 1 deviation of power from the reference case for different scenarios and weather conditions. 'W/O' indicates scenarios without overheating during the night, while 'with' includes overheating. '4h' and '9h' represent downward modulation periods of 4 and 9 hours, respectively.

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