

Energy flexibility using thermal mass for Swedish single-family houses

Huijuan Chen^{1*}, Svein Ruud¹, and Caroline Markusson¹

¹RISE Research institutes of Sweden, Energy and Resource Department, 50115 Borås, Sweden

Abstract. This paper characterised the potential of energy flexibility in relation to building envelop properties, heat emitters and ventilation for the Swedish context. Simulation results indicated that the potential was higher for newer houses with floor heating and lower for older houses with radiators in winter. Older houses with different levels of insulation showed a similar ability of conserving heat due to different extents of heat losses from ventilation. A house with balanced ventilation tended to be over-ventilated especially if the house was not airtight. The flexibility was decreased with increasing outdoor temperatures, and it was higher in winter and lower in spring/autumn.

1 Introduction

There is a growing demand for increasing the share of renewable energy in the energy system. According to European renewable energy directive, at least 42.5 % of the total energy needs in EU must derive from renewables by the year 2030 [1]. In some countries, the climate and energy framework are even stricter. In Sweden, for example, the electricity production should be 100% fossil-free by 2045 [2]. Integration of renewable energy into existing electricity systems results in great challenges, strategies for balancing the electrical grid availability and energy use have attracted great attention. Among others, flexible energy systems are regarded as a cost-effective solution to facilitate the management of the electrical grid with integration of large share of renewables.

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 [3]. In many countries, buildings share a significant part of the total energy use. Taking Sweden as an example, about 29 % of the total electricity consumption is used by residential buildings, and 75% of the energy is dedicated for space heating [4]. Buildings consume lots of energy, meanwhile, they also provide lots of resources for contributing to energy flexibility. Thermal mass is a readily available energy storage medium which can be used directly to reduce the impact on indoor temperatures while modulating heating power for increasing energy flexibility. For buildings with a high thermal mass (i.e., well-insulated buildings), the load shifting can be done with small variations of

* Corresponding author: huijuan.chen@ri.se

indoor temperature and allows decreasing the heating need compared to a building always at 19 °C [5].

There are two million single-family houses in Sweden, out of which 1.3 million have some form of electrical heating system [4]. The potential of energy flexibility of thermal loads for Swedish single-family houses is large. Buildings and their users can adjust their energy consumption to decrease energy use in case of energy shortage or increase energy use in case of excess production. By modulating the indoor temperature setpoint, thermal loads can be shifted from peak to off-peak hours. The energy flexible operation should be performed without severely affecting occupant's thermal comfort, and the indoor temperature should be maintained within certain comfort limits. It is worth mentioning that load management operations, i.e., load shift and peak shaving, do not necessarily decrease energy consumption but are utilized to stabilize the energy grids and allow for a larger integration of renewables [6]. To quantify energy flexibility of building thermal loads, different approaches and indicators have been proposed. In this paper, energy flexibility is defined as the deviation of energy demand against normal operation of building mechanical systems during a certain period, for instance, during grid peak hours [7-8].

The flexibility potential of thermal loads with use of building's thermal mass has been investigated by many studies, impacts of building thermal performance (e.g., insulation level, air tightness), its technical system, and control strategies are highlighted. Building insulation level has a great influence on the capacity and ability of load shifting [9]. For low-insulation buildings, a large amount of thermal energy can be shifted over a short period of time, while the well-insulated ones can shift a smaller quantity of energy over a long period of time [10]. A similar finding is reported by [6, 11]. Regarding the effect of heat distribution systems, according to [10-11], flexibility is slightly higher with floor heating than radiators, but overconsumption due to load shifting is larger for floor heating. The temperature variation is always smaller with the floor heating, but it is related to the risk of overheating. [10] suggest that for a well-insulated house (e.g., passive house) with a floor heating system, a short and small increase of the setpoint could be tested; for a poorly insulated house with a water radiator system, the setpoint can be decreased within a time frame of 2 to 6 h to limit the influence on indoor climate while maximum the flexibility.

Although similar research has been done for other countries, a few publications are available for the Swedish context regarding the use of thermal mass of buildings to move heating loads. There was one study [12] found for the Swedish case, which investigated the load shifting potential of electrical space heating by optimizing the pre-heating time and duration and provided overall assessment of the flexibility potential for the electricity grid. As the focus in [12] was towards evaluation the impacts of large-scale implementation of demand response on the Swedish electricity system, the dynamic behaviour of charging and discharging building thermal mass was not clearly characterized. Finally, further research is still needed to examine the effect of building parameters and its systems, especially including the type of ventilation (i.e., natural ventilation, exhaust ventilation, and balanced ventilation with heat recovery). The project aimed to address this research gap and provide an overview of the thermal flexibility of Swedish single-family houses built from 1940s and onwards. Outputs from this study can be used as a basis for e.g., assessing the potential of flexible loads for aggregation, or for development of control strategies to ease the implementation of demand response.

2 Methods

2.1 Description of the single-family houses and physical building model

A set of representative Swedish single-family houses were studied, and the main parameters were listed in Table 1.

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} ($W/K \cdot m^2$)	0.65	0.49	0.38	0.33	0.34	0.26
U-value external wall ($W/K \cdot m^2$)	0.52	0.31	0.21	0.17	0.2	0.17
U-value ceiling ($W/K \cdot m^2$)	0.33	0.23	0.17	0.14	0.13	0.11
U-value floor ($W/K \cdot m^2$)	0.16	0.18	0.16	0.15	0.12	0.15
U-value window ($W/K \cdot m^2$)	1.9	1.6	1.6	1.4	1.4	1.2
Building envelop losses $\sum UA/A$ ($W/K \cdot m^2$)	1.5	1.06	0.82	0.72	0.72	0.56
Air infiltration q_{50} ($l/s \cdot m^2$ external surface)	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 ($l/s \cdot m^2$)	/	/	0.35	0.35	0.35	0.35
Heat emitter	Water radiator	Water radiator	Electrical heating panel	Water radiator	Floor heating and radiator	Floor heating and radiator
IDA-ICE calculated heating demand ($kWh/m^2/year$)	155	116	109	90	101	84

The Swedish single-family houses were classified into different groups based on the BETSI program (i.e., a national survey of the residential stock initiated in 2005) [13] while including the latest building category: 1940-1960, 1961-1975, 1976-1985, 1986-1995, 1996-2009, 2010-; the input to Table 1 was mainly based on the BETSI report [13] and together with our own assumptions. This study did not only focus on the prototype houses, but also considered typical renovations of the houses that were built at different time periods. The insulation level and air tightness were improved by the building regulations. The ventilation

system was changed from natural ventilation to mechanical ventilation such as exhaust ventilation or balanced ventilation with heat recovery for improving indoor air quality. For two-story houses built from 90s and onwards, it was commonly to have two types of heating systems, i.e., floor heating on the first floor and water-radiator on the second floor, whereas for older houses, radiators were most commonly used. Most of the Swedish houses were built by wood, while some old houses were built by bricks in combination with wood panel.

The flexibility of space heating for different buildings was investigated by means of simulations based on a validated IDA-ICE model [14]. The house model can be seen from Figure 1. This model corresponded to a prototype house situated in Borås, located at the south-west part of Sweden. IDA-ICE [15] was a building and energy simulation program, which was used to provide heating demand for various boundary conditions and perform modulations of the heating power in this study.

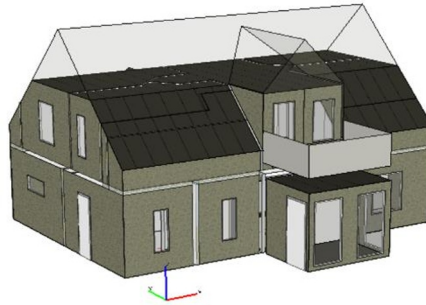


Fig. 1. The IDA-ICE model.

The house had a total heated floor area of 151 m², assumed to be occupied by two adults and two children. The total heat load from people and equipment was assumed to 30 kWh/m² year [16], distributed to different rooms and followed by different time schedules. The first floor was the space mainly for living and the family's different activities, and the second floor was for sleeping which had four bedrooms. The same house model had been used in this study to represent different types of single-family houses; however, this was done with a special care that the overall transmission losses $\sum UA/A$ (listed in Table 1) was ensured to be reasonable when comparing to BETSI. $\sum UA/A$ is the overall heat loss coefficient which is the parameter determines the total heat transmission losses through the building envelop.

Floor heating was simulated in the form of a tempered layer (without height) at a given depth in the floor construction in IDA-ICE, and water radiator was simulated as radiant and convective baseboard. They were sized based on the actual dimensioned winter outdoor temperature for Borås and oversized to 125% [10]. The water supply temperature for floor heating and radiator varied with outdoor temperatures, which had the maximum temperature of 55 °C with the assumption of the house was connected to heat pumps. The weather profile was for the design of a reference year for Borås, which was a kind of averaged weather profile over 30 years (1991-2020) [17]. The calculated heating demand for the reference year by IDA-ICE was in the range of 84 - 155 kWh/m²_{floor} between the latest and oldest house.

2.2 Flexibility case studies

The conceptional flexibility was investigated by modulating heating power through a direct change of the heating setpoint, with the purpose of reducing heating demand during grid peak hours. Different control strategies were defined by decreasing or increasing the reference setpoint by 2 °C, and the reference temperature was kept at 21 °C which was the typical

desired indoor temperature during the heating season in Swedish household. The schemes of the temperature setpoint for different controls were illustrated in Figure 2.

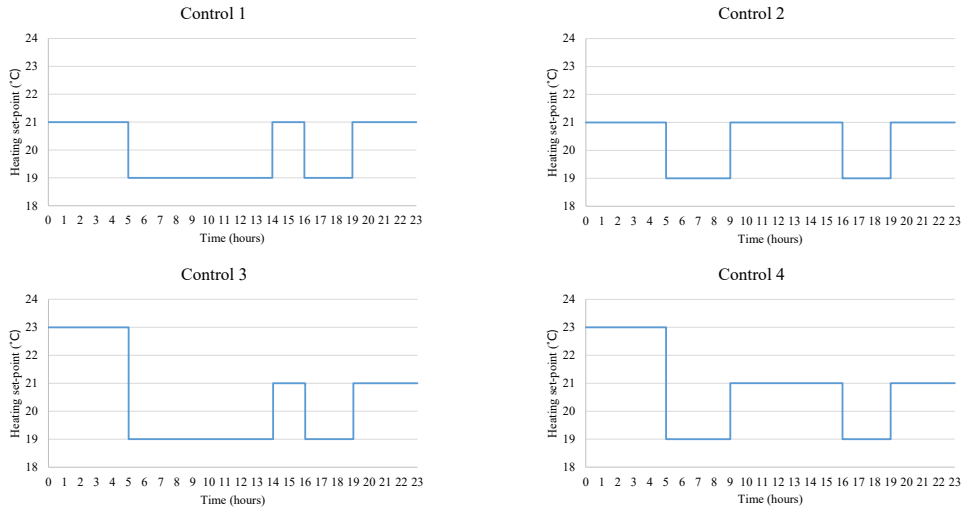


Fig. 2. Temperature setpoints for different controls.

In this study, peak hours were assumed to occur in the same time period every day, i.e., from 5:00 to 9:00 and 16:00 to 19:00, and the temperature during the peak hours was set to be 19 °C. The main difference between different controls was the temperature setpoint during the non-occupied hours (9:00-14:00) and night (0:00-05:00). In control 1 and 3, the room temperature was allowed to decrease to 19 °C during the non-occupied hours while it was remained at 21 °C in control 2 and 4. Control 3 and 4 was actually the same as control 1 and 2, except for that there was overheating during the night that the temperature on the first floor was increased from 21 to 23 °C. To gain more flexibility during the second peak (i.e., evening peak), it was attempted to recover the interior temperature from 19 to 21 °C between 14:00 and 16:00 for control 1 and 3 where the setpoint was remained at 19 °C after the morning peak.

The four control strategies were tested for each house category, and the results were compared with each respective reference case. Besides that, the effect of weather conditions was also examined by studying the flexibility for a very cold and cold day with a little solar radiation, and a spring/autumn day with some solar radiation. The average outdoor temperature for these three selected days was -13 and -6 °C and 5 °C.

To better understand the effect of building thermal properties and its technical systems, an extra case was performed to study the response of indoor temperatures after turning off the heating system at 05:00. As it was seldom to have many very cold days in winter, a cold day was more relevant and therefore chosen for this temperature decay study.

3 Results and discussion

3.1 Temperature decay

Figure 3 presented temperature decay for different houses after turning off the heating system at 05:00 for a cold day. The temperature was for living room and kitchen on the first floor. These houses seemed to be divided into three different groups depending on how fast the indoor temperature decayed. The first group was for the houses decayed most slowly, i.e.,

2010-'s and 1996-2009's house, which had the maximum decrease of 1 °C within the first 4 hours after turning off the heating system. The second group, i.e., 1986-1995's, 1976-1985's and 1961-1975's house, it decayed faster than the first group and the temperature dropped by about 3 °C within 4 hours. The last group was for the 1940-1960's house that the temperature dropped immediately after turning off heating.

This trend was mainly attributed to the level of insulation; the more insulated house it was, the slower response it would be. Another parameter affecting the thermal behaviour was the type of heat emitter. As floor heating had much larger thermal masses than radiator, it provided larger thermal inertia against temperature fluctuations, and thus for houses with floor heating (i.e., 2010-'s house), the temperature reacted much slower than the house with radiator. If all houses were heated by radiator, a smaller temperature difference would be expected.

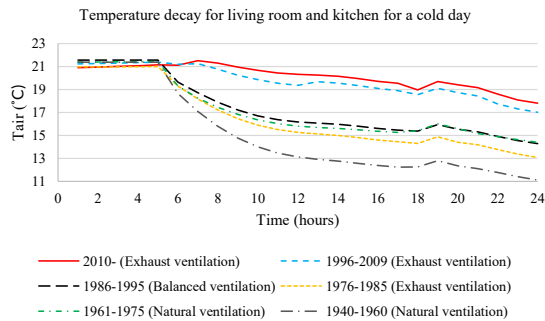


Fig. 3. Temperature decay for different houses after turning off the heating system at 05:00 for a cold day.

Within the second group, it was also interesting to notice that the temperature profiles for the 1961-1975's and 1986-1995's house were similar though these two houses were insulated at different levels. The possible explanation could be due to the effect of ventilation. For the 1961-1975's house, it had natural ventilation, and the heat losses were much smaller than the 1986-1995's house with mechanical ventilation. The average calculated ventilation flow rate (from IDA-ICE) for the 1961-1975's house was about 0.25 l/s·m², which was below the threshold of 0.35 l/s·m² based on Swedish building regulation. Although the 1961-1975's house had larger envelop transmission losses, it was compensated by lower heat losses through natural ventilation; while for the 1986-1995's house, it had lower transmission losses, however this benefit was counteracted by larger ventilation losses. Thus, these two houses showed a similar ability of conserving heat after turning off the heating system.

From Figure 3, the effect with/without heat recovery of ventilation on heat conservation could be also observed by comparing the results between the 1986-1995's house and the 1996-2009's house. Both houses had a similar U-value of about 0.33 W/K m² (see Table 1), the former had balanced ventilation with heat recovery, and the heat recovery efficiency was 60% which was typical for the 80's houses, while the latter had exhaust ventilation. Based on IDA-ICE simulation, the calculated ventilation flow rate for the 1986-1995's house was about 29 % higher than the 1996-2009's house with exhaust ventilation, as a result, the effect of heat recovery was reduced due to the additional ventilation losses.

Based on the results discussed above, it could be concluded that, newer buildings with floor heating were able to conserve heat for a longer period than the older buildings with radiator; a less-insulated building with natural ventilation could have a similar ability of maintaining heat as better-insulated buildings with mechanical ventilation. For houses with balanced ventilation, they could get over-ventilated due to additional flowrate caused by

ventilation and infiltration, the benefit of having heat recovery could be reduced particularly if the houses were not properly sealed.

3.2 Temperature and heating power profiles with flexibility control

To illustrate how temperature and heating power profile changed with different flexibility controls, some of the results were presented and discussed here as examples. Figure 4 showed the results for 2010-'s and 1961-1975's house, with control 1 and 3 for a cold day. Control 1 was without overheating and control 3 was with overheating (only on the first floor), otherwise they were the same. The results included the profile for the temperature setpoint, air temperature for the living room and kitchen (on the first floor) and sleeping room (on the second floor), total heating power demand for the reference case, and the power demand for the controlled case.

The setpoint was shown by the back solid curve which varied between 19 and 23 °C, and the reference heating power was indicated by the back solid curve with the unit of kW. As seen, the temperature for the living room and kitchen and the sleeping room was increased/decreased with the setpoint. The temperature dropped when the setpoint was reduced for saving energy (i.e., downward modulation), and the minimum heating power was required for maintaining the temperature at the setpoint; it was increased when the setpoint was elevated for storing or regaining heat (i.e., upward modulation), which happened during the night when overheating the first floor in control 3, or recovering the temperature during 14:00-16:00 after the setpoint being decreased which was also known as rebound effect. When looked at the total heating power demand for the controlled case (indicated by the dash green curve), it changed positively with the setpoint temperature, i.e., it was below or above the reference power demand curve when the setpoint was reduced or increased.

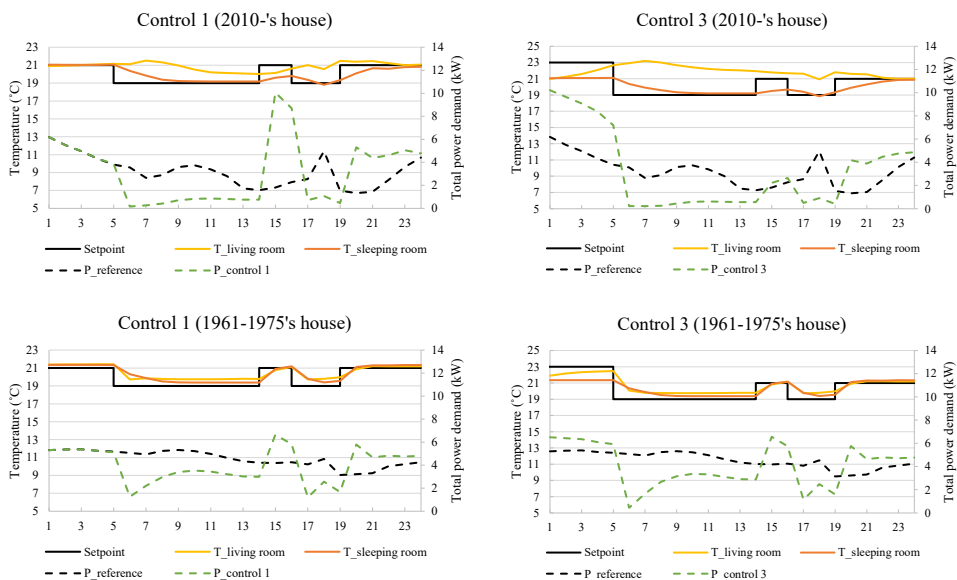


Fig. 4. Temperature and total heating power profiles for the 2010-'s and 1961-1975's house for a cold day.

Comparing the results between these two houses, the 2010-'s house showed a slower reaction of the temperature change for the living room and kitchen and presented a larger extent of power variation than the 1961-1975's house. For example, for the case with control

3, a much larger extra heating power demand was needed for the 2010-'s house than the 1961-1975's house when increasing the room temperature from 21 to 23 °C during the night. This was because that floor heating had much larger thermal inertia than radiator, the temperature reacted slower and thus it was easier for floor heating to reach to its maximum power when increasing the setpoint temperature. Measures were needed to avoid the peak power when recovering heat with floor heating, for instance, the setpoint could be increased linearly over several steps.

Comparisons of the heating power profiles between different controls for the 2010-'s and 1961-1975's house for a cold day were shown in Figure 5. The reference heating power demand was indicated by the black dash curve. As seen, the 2010-'s house showed quite different profiles with different controls compared to the 1961-1975's house when increasing the setpoint (i.e., the curves above the reference curve), this was mainly due to different thermal inertial of floor heating and radiator. When reducing the setpoint, the curves below the reference curve for different controls aligned to each other for both houses.

The difference between the sum of the power use for the controlled case and the reference case during the modulation event was the flexible energy (i.e., upward or downward), and the downward flexible energy was the amount of energy could be shifted during the peak hours. More results of the downward flexible energy were presented in the coming part.

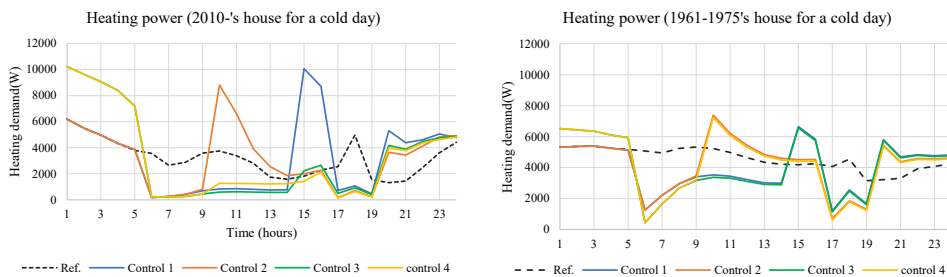


Fig. 5. Heating power profiles for the 2010-'s and 1961-1975's house for a cold day.

3.3 Energy flexibility for different houses

Energy flexibility contributed by building's thermal mass for different houses and weather conditions were shown in Figure 6, where the reference heating demand for each house category was also presented. As seen from Figure 6(a), the reference heating demand was decreased as the outdoor temperature was increased, and it was much higher for the older houses than the newer ones. For a very cold day, the reference heating demand varied from about 120 to 180 kWh/day (see the blue bars) between the latest and oldest house, which was decreased to the range of about 80 – 140 kWh/day for a cold day (see the yellow bars) and 40 – 80 kWh/day for a spring/autumn day (see the green bars).

The amount of flexible energy for different houses with different controls can be seen from Figure 6 (b-d). As seen, the potential was much higher in winter than in spring/autumn. For a very cold day (Figure 6b), about 30 – 35 kWh/day flexible energy could be achieved with the tested controls which was the maximum, provided by the 1996-2009's house (indicated by the orange bars); this was followed by the 2010-'s house with the potential of about 25 – 30 kWh/day (shown by the blue bars), and rest of the houses with the potential of about 15 – 20 kWh/day. For a cold day (Figure 6c), the highest potential was still provided by the 1996-2009's house, i.e., 25 kWh/day, followed by the 2010-'s house and rest of the houses which had a similar maximum potential of about 20 kWh/day. For a spring/autumn day (Figure 6d), the older houses provided a slightly higher potential than the newer ones,

which was about 15 kWh/day (i.e., provided by the last three house categories) and 10 kWh/day by the 2010- 's house, respectively.

Regarding the effect of different controls, the impact was larger in winter than in spring/autumn. Control 1, i.e., without overheating and with a lower temperature setpoint (i.e., 19 °C) during the peak hours, provided slightly lower flexible energy than the other controls (control 2, 3 and 4) which had overheating and/or a higher setpoint (i.e., 21 °C) during the day. As this study only looked at heating demand, the effect of different control strategies for charging/discharging the house could have a significant impact on the electricity use and cost if the houses were connected to heat pumps. This needs to be investigated by future studies including different types and sizes of heat pumps.

It could be concluded that, the potential was higher in winter than in spring/autumn as more heating was needed to maintain the setpoint of 21 °C for the reference case when outside was colder. For a very cold and cold day, newer houses provided a larger potential than the older houses due to better envelop insulation and larger thermal masses from floor heating. While for a spring/autumn day, the older houses showed a slightly higher potential as they were more sensitive to the changes of the heating power than the newer houses for maintaining the setpoint. To gain more flexibility, newer buildings with better insulation could be focused on in winter, while in spring/autumn the older houses could be targeted for modulating the heating power.

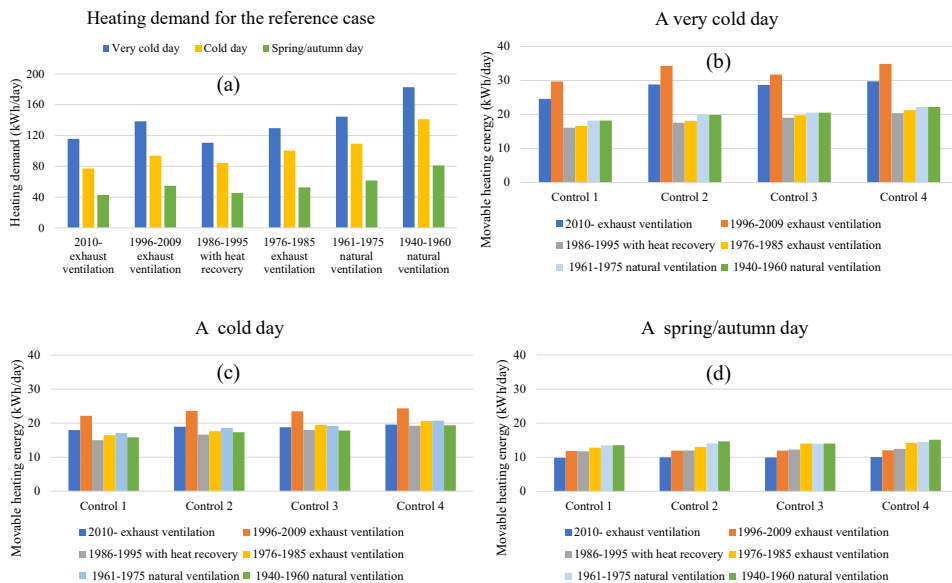


Fig. 6. (a): the reference heating demand for different houses for a very cold, cold and spring/autumn day; (b-d): the corresponding shiftable heating demand during the peak hours with different controls.

4 Conclusion

This study investigated energy flexibility for a wide range of Swedish single-family houses, covering different building envelop properties (i.e., the level of insulation, air tightness), heat emitters (i.e., floor heating and radiators), and ventilation. Simple temperature setpoint modulation was implemented, and the flexibility was studied by means of IDA-ICE simulation.

The flexibility was strongly related to building envelop properties, technical systems, and weather conditions. Newer buildings with floor heating, i.e., the 1996-2009's and 2010's

house, were able to conserve the heat for a longer time period after turning off the heating system. These two houses also showed a higher flexibility than the older houses for a very cold and cold day. Although the older houses were insulated at different levels, they showed a similar flexibility potential due to different extents of ventilation and infiltration losses. Houses with balanced ventilation could be over-ventilated compared to the house with exhaust ventilation. The flexibility was reduced with increasing the outdoor temperature, it was higher in winter and lower in spring/autumn.

Although small impacts of different controls were found in this study, the influence on electricity use could be significant as this study mainly looked at the heating demand. Future studies were needed to explore the impact of charging, discharging, and rebound on the electricity use and cost for different controls and for different types and sizes of heat pumps.

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