Social and technical potential of single family houses in increasing the resilience of the power grid during severe disturbances

Citation for the original published paper (version of record):
Nalini Ramakrishna, S., Björner Brauer, H., Thiringer, T. et al (2024). Social and technical potential of single family houses in increasing the resilience of the power grid during severe disturbances. Energy Conversion and Management, 321.
http://dx.doi.org/10.1016/j.enconman.2024.119077

Energy Conversion and Management 321 (2024) 119077

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Social and technical potential of single family houses in increasing the resilience of the power grid during severe disturbances

Sindhu Kanya Nalini Ramakrishna [a,*], Hanna Björner Brauer [b,c], Torbjörn Thiringer [a], Maria Håkansson [b]

[a] Division of Electric Power Engineering, Chalmers University of Technology, Sweden
[b] Division of Built Environment, RISE Research Institutes of Sweden, Sweden
[c] Department of Social and Behavioural Studies, University West, Sweden

ARTICLE INFO

Keywords:
Flexibility quantification
Space heating
Interviews
Heat pumps
Renewable energy resources
Electric energy reduction

ABSTRACT

Flexible resources aids in enhancing the resilience of a renewable dominated power system. Space heating systems equipped with heat pumps is one such flexible resource. With this background, the current study deals with the quantification of flexibility potential of space heating systems in houses equipped with various heat pump types. A heat pump model is represented using a vapour compression heat pump cycle. This model is integrated with a thermal model of a house to estimate electricity consumption, for maintaining the indoor temperature at a set value, as flexibility quantification depends on electricity consumption. In addition to this, flexibility potential is quantified by, analysing and incorporating the results on minimum acceptable indoor temperature from twelve interviews with households owning heat pumps, into the integrated model. The results from interviews reveal that, there is an uncertainty in minimum acceptable indoor temperature, as it is dependant on a number of factors such as frequency and duration of interruption, access to additional heating and motivation to be flexible. Hence, to quantify flexibility using thermal simulations, the indoor temperature is reduced from 20 °C to values between 18 °C and 15 °C, based on minimum acceptable temperatures stated in the interviews. The flexibility potential is quantified in terms of an instantaneous reduction in electric power and reduction in electric energy. By reducing the indoor temperature from 20 °C to the aforementioned values at an outdoor ambient temperature of -5 °C, in about a million single family houses in southern half of Sweden, an instantaneous reduction in electric power is estimated to be 1.6 GW, for the power system with 23 GW plannable power. Additionally, considering the recovery of the indoor temperature to 20 °C in 24 h, electric energy reduction is found to be between 4.06 GWh and 7.4 GWh, when the reference indoor temperature is reduced to values between 18 °C and 15 °C respectively, over 17.25 h. Furthermore, with time the amount of flexibility offered reduces, becomes negative during the recovery period and finally reaches zero, when the indoor temperature is restored. The results reveal that space heating systems in houses equipped with heat pumps have the potential to enhance the resilience of the power grid during severe grid disturbances.

1. Introduction

Currently, there is a transition of conventional power systems towards fossil free power systems. This implies an increase in the share of electricity production from intermittent energy resources, such as wind and solar. At the same time, electrification of industries and the transport system will likely lead to an increase in power demand in the years ahead. In addition, the International Energy Agency foresees several threats to power systems, for example in terms of climate change and extreme weather events, cyber attacks, variability in supply and growing demand [1]. Hence, one of the main challenges is to ensure the balance between electricity production and consumption, especially during severe disturbances leading to power deficit conditions. An example of a severe disturbance could be a loss of a major power plant, especially when a power system is operating with narrow margins. One possible way to address this challenge, from a load perspective is to be able to quickly reduce the electricity consumption.

For example, in Sweden, the residential and service sector accounts for the highest total energy use and electric energy consumption [2].

* Corresponding author.
E-mail address: kanya@chalmers.se (S.K. Nalini Ramakrishna).

https://doi.org/10.1016/j.enconman.2024.119077
Received 16 March 2024; Received in revised form 5 August 2024; Accepted 16 September 2024
Available online 24 September 2024

In this sector, the total electric energy consumption in single-family houses is around 4.5 times higher compared to multi-family buildings [3]. Furthermore, a majority of single family houses are equipped with heat pumps [4] and in these houses about 50% of the total electricity use is attributed to space and water heating [5].

Thus, a possible way of ensuring the balance in a power system, during severe power deficit conditions is by reducing the electricity consumption for space heating in single family houses, utilising the thermal inertia to avoid an instantaneous temperature drop. In this way, space heating systems equipped with heat pumps can be viewed as a flexibility resource. In line with this, [6] also suggests a high flexibility potential in space heating systems of single family houses in Sweden. With this background, the main aim of this study is, to quantify the flexibility potential of space heating systems equipped with different types of heat pumps, in single family houses for enhancing the resilience of a power system during severe disturbances. The flexibility is quantified in terms of an instantaneous reduction in electric power and reduction in electric energy.

Co-efficient of performance (COP), is the term used for indicating the performance of a heat pump. It is defined as the ratio of heat delivered to the electricity consumed in a heat pump. This plays a significant role in estimating the electricity consumption and quantifying the flexibility potential.

There are a number of articles in the scientific literature on flexibility studies using heat pumps. For example, future flexibility potential from photovoltaic, battery storage, electric vehicles and heat pumps connected to single-family and twin homes is investigated in [7]. [8] deals with estimations of flexibility potential from heat pumps using a decentralised model. [9] also involves an investigation of flexibility potential in a heating system. Flexibility assessment of a heat pump pool is explored in [10]. Techno-economic investigation of demand side flexibility from heat pumps is dealt with in [11]. [12] deals with demand side management of residential heat pumps. [13] involve flexibility evaluation of heat pumps with thermal storage in the German intraday market. The potential for economic savings through an operational optimisation of a variable speed air source heat pump is shown in [14]. [15] deals with the utilisation of variable speed air-source heat pumps to reduce the power peak in the electricity grid.

Articles [7,9,12] do not present how COP is obtained and the value considered for the study is also not stated. Thus the results are not reproducible. Refs. [8,10,11] assume fixed speed heat pumps. Furthermore, the estimation of COP, is based on empirical formulas and is not the same in these articles. Additionally, considering energy efficiency measures being taken, fixed speed heat pumps will be replaced with variable speed heat pumps. Despite considering new variable speed heat pumps, COP estimation is using empirical formulas and the speed limitations of heat pumps are not taken into account in articles [13,15]. Furthermore in Ref. [14], the COP of a variable speed air source heat pump is obtained using a performance map based on the operational data only at specific compressor speeds. Thus, the models used for COP estimation fail to represent a universal model, which can be used for different heat pump types. Also, most of the technical studies dealt with in the literature mainly focus on normal demand side management and not in increasing the resilience of a power system during severe disturbances, to avoid blackouts by compromising thermal comfort.

From a social science perspective, there are valuable articles related to the households' needs for different resilient behaviours and resources to deal with power disruptions and power peaks. For instance, article [16] discusses the use of back-up technologies, time-shifting of activities and reduction in electricity use as a way of achieving household energy resilience. Also, there is a body of work concerning households' resilience during blackouts in Nordic and European countries, for example how households engage in preparedness and adapt to blackouts is addressed in [17], and how households are able to uphold everyday routines during longer blackouts is discussed in [18]. How households' different experiences, technical resources and vulnerabilities affect their capacity for resilience in the face of longer blackouts is also investigated in [19]. These studies typically either lean towards normal demand side management, or adaptive behaviours during longer blackouts, rather than increasing resilience of a power system during severe disturbances to avoid blackouts. One exception is Watt's ethnographic research on the Orkney Islands [20], which deals with inhabitants' resilience towards changes in power supply and weather. However, such studies, examining everyday energy resilience in households in affluent contexts, are scarce.

Previous research reveal that thermal comfort perception is dependent on a range of factors such as residents' thermal comfort experiences [21], gender [22], age, time spent at home and even education level [23]. This indicates that, the tolerance against variations in temperature will vary from household to household [24]. The social science studies on flexibility interventions in heating systems show that user acceptance and involvement in flexibility are dependent on many different parameters. For example, in article [25] it is observed that the residents need to be sufficiently informed on how the heating system and demand response interventions work. Article [26] found that user acceptance is dependent on having sufficient control over the system as well as timing and magnitude of load shifts. The importance of control and information is further confirmed by [27], in addition to other factors such as familiarity and trust in the system or stakeholders responsible, as well as complexity and perceived risk associated with participating in demand response.

Articles [16–19] in social sciences overlooks studies that focus on how households' resilience can enhance the resilience of a power system, aiming to prevent blackouts. Thermal comfort is dependent on several factors as indicated in [21–27]. Furthermore, as thermal comfort is closely related to the flexibility potential, it is important to know about the willingness and the measures taken by the households, in the light of increasing resilience of a power system during severe grid disturbances which otherwise can lead to blackouts.

To sum up, previous studies on utilising heat pumps as a flexible load show improvement potential regarding some aspects. For example, the COP estimation in the literature is limited to specific heat pump types. Also, in some articles modern variable speed heat pumps are not accounted for. Even if new variable speed heat pumps are considered in the study, the limitations in terms of the compressor's operating envelope and maximum electrical input to compressor is not accounted for. Additionally, they are also limited to specific heat pump types as empirical formulas are used for COP estimation. Furthermore, the assumptions behind the thermal comfort compromise, is not based on discussions with residents. Additionally, the studies from both social and engineering sciences, focus on flexibility for normal demand side management and not for enhancing the resilience of a power system during severe power deficit conditions. Considering these aspects, the main contributions of this study are as follows:

- A white box model for COP estimation of different types of variable speed heat pumps is presented considering, the limitations of a compressor in terms of its maximum electrical rating and operating envelope. This generic model aids in estimating the performance of any heat pump at various operating points as opposed to performance data which is obtained only at standard conditions. Furthermore, the speed limitations are taken into account as opposed to the assumption that a variable speed heat pump can modulate its speed between zero and a maximum value stated.
- An accurate estimate of electricity consumption for space heating in a heat pump is obtained by integrating a heat pump model with a detailed thermal model of a house, for maintaining the indoor temperature at a set value. This thermal model includes, the heat losses due to infiltration, sanitary ventilation and recovery of ventilation losses by a heat recovery unit. Additionally, heat input to a house from a specific type of heat pump via heat

emitters such as radiators or floor heaters is taken into account. Furthermore, heat losses to outdoor ambient air based on the thermal and physical properties of a house is also considered.
- The range of thermal threshold for quantifying the flexibility by reducing the indoor temperature, is based on the interviews with the household residents as opposed to an assumption of a random value.
- Representation of thermal thresholds and households' resilience potential in a social context, by obtaining the perspectives on being flexible with reduced indoor temperature through interviews.
- Quantification of performance comparison among fixed, variable speed heat pumps available in the literature and a variable speed heat pump under study.
- Quantification of flexibility in terms of an instantaneous reduction in electric power and reduction in electric energy, considering the recovery of the indoor temperature to 20 °C. Also, the significance of slow recovery in electric energy reduction is demonstrated.
- Finally, the study adopts a multidisciplinary approach, allowing both technical and social perspectives to be included, as it is essential to achieve sustainability [28].

2. Method

This section deals with the description of methods, scenarios and case study adopted in this article.

2.1. Qualitative interviews and thematic analysis

Twelve semi-structured qualitative interviews were conducted with twelve people from seven different households. The interviews were conducted during the winter of 2021/2022. The participating households were recruited based on the fact that, they all had heat pumps that could be remotely steered. The qualitative data collection was done in the context of an interview study with households, connected to a heat pump study conducted at Research Institutes of Sweden. Two households consisted of two adults and children, and the remaining five households consisted of two adults. The two adults in households were always invited and encouraged to participate in the interview. In two households, both adults were interviewed separately. In the other two, only one of the adults was interviewed. In the remaining three households, both the adults were interviewed. The interviews were recorded and transcribed with the consent of the participating respondents.

In the interviews, the respondents were first asked to describe the energy practices of their everyday lives, and then to reflect on how different potential power deficit situations would affect them. For the purpose of this study, there were certain questions specifically surrounding thermal comfort. For example, households were asked to describe their experience with the current heating system. The respondents were then asked to reflect on, what temperature they would be willing to accept for a shorter time (such as two days), during a power deficit condition, where power would be temporarily limited. They were encouraged to reason around a 'thermal threshold' that is, a limit to what temperature they would be comfortable with, during a shorter period of time.

The data from the interviews were analysed using thematic analysis [29], a process where descriptive codes and themes are generated bottom-up from multiple readings of the data. In other words, the transcribed material was categorised into different themes and sub-themes, depending on what they were interpreted to be about. For example, the statements on temperature and temperature-related practices were especially significant for the purpose of the thermal simulations and was thus categorised as one theme. The analysis was guided by the concept of resilience, with a specific focus on how the participating households anticipated that they would adapt and respond in a power deficit scenario in terms of changes in thermal comfort.

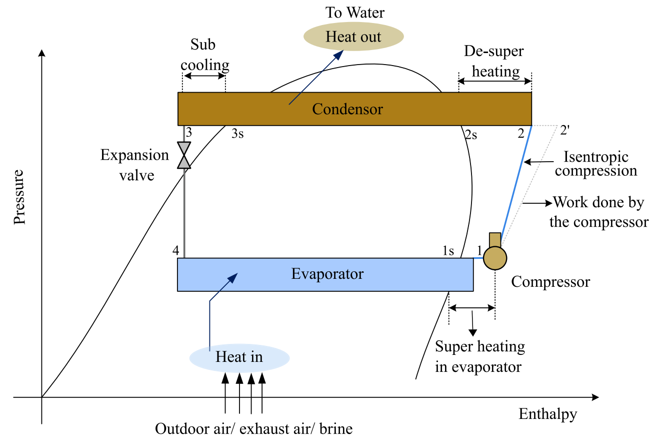


Fig. 1. Heat pump model [31].

The purpose of qualitative interviews in this study is not to obtain quantifiable or statistical generalisations, but rather to: (1) collect respondents' own estimations on what reduction in indoor temperature they would temporarily accept, and (2) get a deep understanding of the social context of households, through rich descriptions from the respondents about their life experiences with regard to space heating [30]. Qualitative interviews helps in capturing nuanced data instead of alternative methods to gather user perspectives such as quantitative surveys.

2.2. Heat pump model

As the objective is to investigate the usage of heat pumps as a flexible resource, it is of prime importance to determine the COP at various operating conditions. A vapour compression heat pump cycle with associated components together with the states on a pressure-enthalpy diagram is shown in Fig. 1. The procedure for estimating the power consumed by the compressor and COP is as follows:

- The mass flow rate of the refrigerant '$\dot{m}$' is computed using

$$\dot{m} = \frac{V_{dis}\rho_s f \eta_{vol}}{10^6} \tag{1}$$

where, V_{dis} is the compressor displacement volume in $\left(\frac{\mathrm{cc}}{\mathrm{rev}}\right)$, ρ_s is the density at suction $\left(\frac{\mathrm{kg}}{\mathrm{m}^3}\right)$, f is the frequency (Hz) and η_{vol} is the volumetric efficiency of the compressor.
- Based on efficiencies associated with energy flows to a compressor [32], the electric power input to the compressor is given by

$$P_{comp} = \frac{\dot{m}(h_2 - h_1)}{\eta_{isent,speed}} \tag{2}$$

here, h represents the enthalpy at a state indicated in the subscript. $\eta_{isent,speed}$ is an overall isentropic efficiency at different compressor speeds corresponding to a given compression ratio and is estimated as described in [31].
- The COP of a heat pump is given by

$$COP = \frac{\dot{m}(h_2 - h_3)}{P_{comp}} \tag{3}$$

2.3. Thermal model of a house

The indoor temperature is estimated by accounting for the heat losses due to infiltration, sanitary ventilation and recovery of ventilation heat loss through a heat recovery unit. Additionally, heat input to a house from a specific type of heat pump via heat emitters such as radiators or floor heaters is taken into account. Furthermore, heat losses

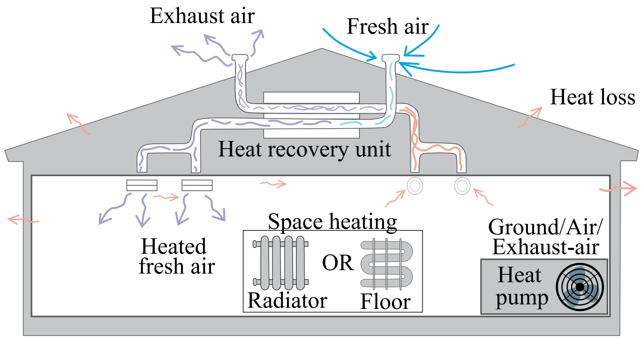


Fig. 2. Representation of a house considered for thermal modelling [33].

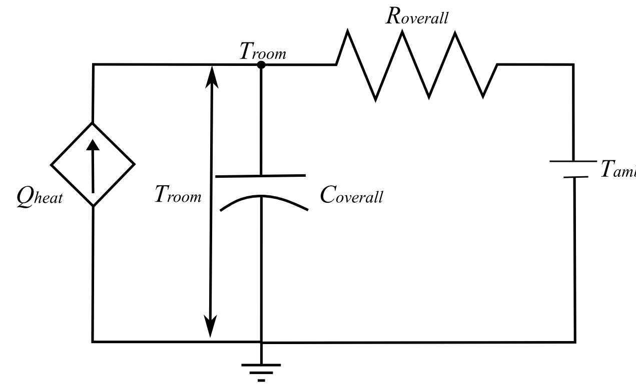


Fig. 3. Thermal model of a building.

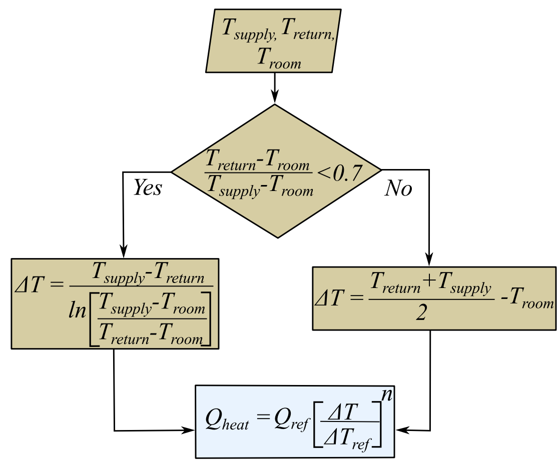


Fig. 4. Space heating model.

to outdoor ambient air based on the thermal and physical properties of a house is also considered. The representation of a house considered for modelling is shown in Fig. 2.

- The heat loss due to sanitary ventilation accounting for, heat recovery from a heat recovery unit and infiltration, '$U_{vent,infil}$' in $\left(\frac{\mathrm{W}}{\mathrm{K}}\right)$ is estimated as

$$U_{vent,infil} = \frac{\rho C_{in}}{1000}\left((1-\eta_{vent})V_{vent}A_{floor} + V_{infil}A_{ext}\right) \tag{4}$$

  where, ρ is the density of air in $\left(\frac{\mathrm{kg}}{\mathrm{m}^3}\right)$ and C_{in} is the specific heat capacity of air in $\left(\frac{\mathrm{J}}{\mathrm{kg\ K}}\right)$, η_{vent} is the efficiency of the heat recovery unit, V_{vent} and V_{infil} are ventilation rates for sanitary ventilation and infiltration respectively in $\left(\frac{\mathrm{l}}{\mathrm{s\ m}^2}\right)$. A_{floor} is the heated floor area and A_{ext} is the external surface area of the building envelope in m^2. η_{vent} is zero, in the absence of a heat recovery unit.
- The overall heat transfer co-efficient of a house '$U_{overall}$' is given by

$$U_{overall} = U_{value}A_{floor} + U_{vent,infil} \tag{5}$$

  here U_{value} represents the average heat transfer coefficient of a house's envelope per heated floor area, considering all construction materials. The total thermal resistance '$R_{overall}$' is the reciprocal of $U_{overall}$.
- Based on the time constant 'τ' in hours and $R_{overall}$ of a house, the thermal capacitance, '$C_{overall}$' is obtained as

$$C_{overall} = \frac{\tau}{R_{overall}}3600 \tag{6}$$

- After obtaining $R_{overall}$ and $C_{overall}$, accounting for the heat from the heat pump 'Q_{heat}' via heat emitters, the thermal model is represented as a series resistance-capacitance network as shown in Fig. 3.
- The outdoor ambient temperature 'T_{amb}' is represented as a voltage source. The voltage across the capacitor represents the indoor temperature 'T_{room}'. 'Q_{heat}' is modelled as a dependant current source as its value changes based on the outdoor ambient temperature and a set value of indoor temperature.
- Based on the circuit in Fig. 3, the indoor temperature is estimated as

$$\frac{dT_{room}}{dt} = \frac{1}{C_{overall}}\left(Q_{heat}(t) - \frac{T_{room}(t) - T_{amb}(t)}{R_{overall}}\right) \tag{7}$$

This model is chosen based on the data availability. Nevertheless, it provides a good estimate of indoor temperature based on the input values provided [34,35]. Furthermore, [36] states that if an entire house is heated to the same temperature, with relatively small heat gains (internal and solar heat gains), an entire house can be treated as one thermal zone as described above.

2.4. Modelling of heat emitters

The thermal output from heat emitters is modelled as shown in Fig. 4 [37]. The terms 'T_{supply}' and 'T_{return}' represents the water supply temperature and return temperature in heat emitters respectively. 'Q_{ref}' and 'ΔT_{ref}' represents the total heat output from heat emitters and reference temperature at standard conditions (i.e., at 55 °C supply temperature, 45 °C return temperature and 20 °C room temperature) respectively. The term 'n' refers to the exponent characteristic of a heat emitter.

The heat output from heat emitters, for a given set of indoor temperature, water supply and return temperatures are formulated into a look-up table. Furthermore, this look-up table is utilised to provide water supply and return temperatures, to obtain a given value of heat at a specific indoor temperature.

For a given value of supply and return temperature of water in a hydronic space heating system, the quantity of heat delivered by heat emitters are further regulated using mass flow rate.

2.5. Scenario

The power system of Sweden is chosen as an example in this study. Currently, Sweden's power system is dominated by the hydro power generation in the north. The electricity production in the southern regions is dominated by nuclear followed by thermal and wind power plants [38]. The southern transmission network is connected to Norway, Finland, Denmark, Germany, Poland and Lithuania. Due to growing environmental concerns, the thermal power plants will gradually be replaced by wind power plants. In this power system, the

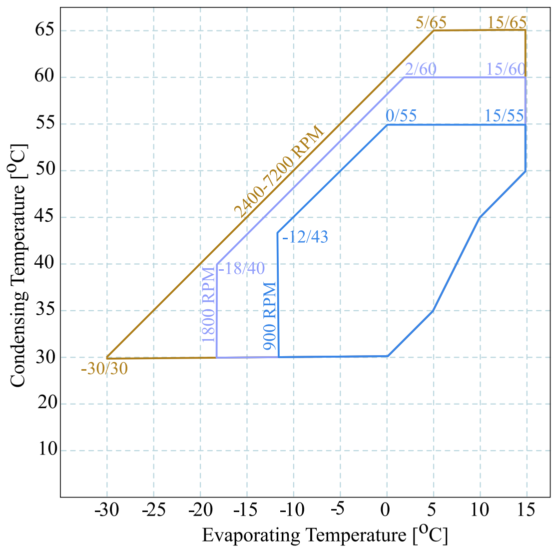


Fig. 5. Operating envelope considered for study [42].

scenario to quantify and investigate the flexibility potential is adopted based on the information provided in 'Nordic and Baltic Sea Winter Power Balance 2022–2023' [39]. The details of this scenario are as follows:

- Low hydro reservoir levels due to a dry season
- Restrictions on fossil fuel based energy import from the surrounding countries i.e., from Denmark, Germany, Poland and Lithuania
- Outage of a major nuclear power plant

2.6. Case study

The electricity market in Sweden, is divided into four electricity price areas, where area 1 is in the most northern part of the country and area 4 is in the southern most part. Generally, area 1 and 2 have a surplus of electricity production, while areas 3 and 4 have a deficit [40]. Thus, areas 3 and 4, have higher electricity prices. Even though there is a transmission of power from the north to the south, the differences in electricity production in combination with the demand, sometimes result in significantly higher electricity prices in areas 3 and 4 (south), in comparison with areas 1 and 2 (north). Furthermore, 9 out of 10 million people live in areas 3 and 4. Areas 3 and 4 are chosen as geographical boundaries for the case, because of high electricity demand in these regions.

2.6.1. Parameters considered for heat pump model

Air source heat pumps (ASHP), ground source heat pumps (GSHP) and exhaust air heat pumps (EASHP) are assumed to be equipped with an Emerson Copeland ZPV030 scroll compressor. This compressor is assumed to have a maximum electrical rating of 3 kW and the refrigerant is 'R410a' [41]. The source temperature for the GSHP is chosen to be 10 °C. The temperature drop between the source and evaporator for GSHPs, ASHPs and EASHPs are assumed to be 10 °C, 8 °C and 20 °C respectively. The operating envelope adapted for the study is shown in Fig. 5. The reasons for this selection is explained in [31].

2.6.2. Parameters for the thermal model of houses

The classification of single family houses in Sweden, based on the year of construction and thermal properties is dealt with in [43]. Based on this classification, the parameters considered for thermal modelling of the houses are shown in Table 1. The time constants are considered based on a study in example Swedish single family houses (including furniture and interior walls) [44]. A ventilation rate of 0.35 $\left(\frac{l}{s\ m^2}\right)$ is used in this study. The houses constructed before 1961 are excluded from the analysis, following a conservative approach as the heating source for these buildings are mixed.

An outdoor ambient temperature of −5 °C is considered in southern Sweden i.e., electricity price area 3 and 4, as this is below the average temperature during winter. An average indoor temperature of 20 °C is assumed [46] and a uniform temperature is maintained throughout a house in most of the Swedish residential houses [36]. The average size of Swedish single family houses is 122 m^2 [47] and the same is considered for the analysis.

The heat emitters in houses considered for the analysis is assumed to be equipped with Purmo radiators of type PURMO C 33 400 × 1000 [37]. Due to lack of data availability, houses with floor heating system are also assumed to be equipped with the same radiator type indicated above. However, the number of radiators considered is high in this case, so that it can mimic a floor heating system by producing desired heat at a low supply temperature of 30 °C. This value of supply temperature is experimentally verified for an under floor heating system in [48]. Furthermore, based on the type and number of radiators considered in the current study, at a water supply temperature of 30 °C and return temperature of 25 °C, a desired value of heat is provided by the radiators, thus mimicking a typical floor heating system. This is verified using 'Purmo heat output calculator' [49].

2.7. Delimitations

The following are delimitations of the current study:

- Qualitative interviews are chosen to obtain deep insights regarding households' thermal comfort and their perspectives on offering flexibility. Consequently, statistical generalisations are not possible using a quantitative method like survey.
- The electricity consumption by auxiliary units in a heat pump such as by fans in case of ASHPs and EASHPs, followed by circulation pumps in case of GSHPs and in the heating circuit are not included. The electricity consumption by these units are relatively lower in comparison to the compressor [50]. Following a conservative approach, the electricity consumption by these units are excluded in the flexibility quantification due to uncertainty in data availability during different operating conditions.
- The indoor temperature is dependent on several factors such as solar irradiation, wind speed and activities of residents. These aspects are excluded from the thermal model of a house to eliminate uncertainty. Moreover, the internal and solar heat gains are relatively smaller in Swedish residential houses [36].
- Indeed detailed floor plans and indoor wall construction materials impact the results. However, in order to keep the result derivation 'clear and easily reproducible', in the light of detailed knowledge, an entire house is modelled as a one mass model as shown in Fig. 2. Nevertheless, if an entire house is heated to the same temperature, with relatively small internal and solar heat gains (which is typical in Sweden), an entire house can be treated as one thermal zone as described in Section 2.3 [36] and this model is believed to provide a good estimate of indoor temperature based on the input values provided [34,35].
- Experimental validation of the models developed is not included.

Undoubtedly, with a detailed knowledge of the house including floor plans and interior walls, wind speed, solar irradiation, a designated number of persons in the house and their activity, usage of other electrical heat-producing equipment (due to losses in the electrical conversion and usage), and thereby considering a further detailed model of the house, more detailed results could be obtained. However, with the study at hand, involving a large number of houses and the uncertainties of their individual floor plans, only very solid Ref. [43] is used as a basis for the investigation, so the work is easily traceable and reproducible.

Table 1
Parameters considered for thermal modelling of houses [43–45].

Year of construction	U_{value} $\left(\frac{W}{m^2\ K}\right)$	Time constant τ (h)	Infiltration $\left(\frac{l}{s\ m^2}\right)$	Efficiency of heat recovery	Heat emitter	Type of heat pump	Number of radiators	Number of houses
1961–1975	1.2	34	0.00	0.00	Radiators	GSHP	12	445 500
1976–1985	0.9	38[a]	0.60	0.60	Radiators	ASHP	15	274 322
1986–1995	0.8	42[a]	0.00	0.60	Radiators	ASHP	10	147 400
1996–2009	0.8	48[a]	0.00	0.00	Floor heating	EASHP	28	105 636
2010-beyond	0.6	53	0.80	0.00	Floor heating	EASHP	46	112 229

[a] Interpolated. The estimates of time constants includes furniture.

Table 2
Fictive names of respondents.

Household	Name
1	John Maria
2 3	Claes Robin
4	Tor Stina
5	Gustav Karina
6	Harry Helene
7	Christopher Vera

3. Results and discussion

The results are presented as follows. First, the households and results from the interviews are described. In the next step, the results from thermal simulations considering thermal boundaries from the interviews is presented.

3.1. Households

The purpose of the interview study for this article, is to identify levels of acceptable reduction in indoor temperature for the households' residents. Additionally, the purpose is also to understand, residents' perspective on these boundaries and how such boundaries might affect the resilience offered through temporary shutting off of space heating systems during power deficit conditions. When analysing the interview data, besides a basic understanding of the structure and everyday lives of these different households, some relevant themes were created. These themes are 'Estimations of acceptable reduction in indoor temperature', 'Frequency and duration of disturbances', 'Motivation', 'Room preference', 'Additional heating', 'Personal experience' and 'Family needs'. These themes represent important parameters that came up through analysis of the interviews that have an impact on social resilience potential, meaning the capacity and willingness for households to contribute to a resilient grid. All respondents have been given fictive names in this paper and the names are tabulated in Table 2.

3.2. Estimations of acceptable reduction in indoor temperature

When asked what reduction in indoor temperature would be acceptable during power deficit conditions, respondents gave different answers, and their estimations of acceptable minimum temperatures ranged between a minimum of 15 °C to no accepted change, meaning no drop from their normal temperature of around 19 °C to 20 °C. For example, Christopher, Vera, Robin suggested 15 °C to 16 °C as their accepted minimum, while others like Stina, Harry, John and Maria reasoned that 17 °C to 18 °C was what they would be able to accept. Others still like Claes and Tor did not want to reduce temperatures below 19 °C. Some respondents had difficulty stating an acceptable reduction, as they felt that this is depended on the situation, the reason for the disturbance, the length and frequency of disturbances, as well as other factors, which are described in the following subsections. Furthermore, respondents within the same households did not always agree on what temperature reduction would be acceptable, indicating that the variation in thermal comfort needs between different household members needs to be taken into account when estimating the resilience potential.

3.2.1. Frequency and duration of disturbances

The envisioned capacity and willingness to cope with temporary lower indoor temperatures is dependent on the duration and frequency of power disturbance, according to the interviews. Some respondents like Vera and Gustav reasoned that depending on if the disturbance is for hours, days or weeks their willingness to accept such a deviation would differ. Stina stated that she thought two days was the maximum duration she would be willing to deal with. Gustav also reasoned that the maximum reduction in indoor temperature was related to duration, and that a higher reduction in temperature will be acceptable for a short amount of time and vice versa. How often such disturbances happen was also relevant for the resilience potential. For example, John stated that rare occasions such as once per year would be no problem for his household to handle. All in all, the uncertainty around duration and frequency of disturbances makes it hard for householders to know to what degree they could contribute to power grid resilience.

3.2.2. Motivation

Knowing why a disturbance has occurred and why it would be beneficial or helpful to temporarily reduce electricity use, with a consequential reduced indoor temperature was also raised as an important factor. For example, while Tor initially stated it would not feel good to reduce indoor temperature, he reasoned that "*(...) Is it because of an energy crisis than it's an energy crisis. Then you'll have to adapt to that. (...) if there's no more juice in the power line then you'll just have to endure one way or another*". Others like Stina reasoned that knowing in advance what will or may happen could also help them prepare and would also help them accept the reduction in indoor comfort. This indicates the importance of clear and transparent communication around the need for households' contribution to power grid resilience.

3.2.3. Room preference

When discussing reduction in indoor temperature, it was clear that respondents' feelings and thoughts around reducing temperature had a lot to do with what room that was in question. As different rooms are used for different activities, respondents had different temperature needs associated with each room. For example, most respondents were very positive towards lowering temperature in the bedroom, while they were more concerned about having a very cold living room. Respondents also reasoned that most activities except sleeping could be moved into the living room. For example, Vera mentioned that cooking could be done in the kitchen while the eating could be moved to the living room, and Robin mentioned even moving mattresses to the living room to sleep there if there was an emergency. Others like John and Karina mentioned that "shutting off" other rooms such as storage rooms, garages, bedrooms and other areas would be a viable option during power deficit times. The perceived acceptable temperature reduction was thus not the same for the entire house but depends on the rooms and activities of the household. However, it should also be noted that several respondents had open-plan kitchen and living rooms, meaning that their preferred heated room may be a big space to heat in comparison to other, smaller rooms.

3.2.4. Additional heating

Additional sources of heating such as fireplaces and wood stoves came up in the interviews as helpful resources in power deficit scenarios. Households with fireplaces seemed to feel more confident knowing that they could deal with a temperature reduction if such a situation would occur. For example, Harry and Helene already used the fireplace every week and often had the radiators in the living room turned down, which meant that they were already accustomed to big variation in temperature in the living room, depending on if they had a fire going or not. In contrast, Claes and his family did not own a fireplace and had an old house with bad windows. He stated that they were not willing to reduce temperature because they were already vulnerable to feeling cold at home. Although fireplaces were the most common additional source for heating, some households such as John also mentioned that they considered getting back-up energy systems such as diesel generators to be able to run their heating, as well as bigger water boilers or batteries to be able to store energy.

3.2.5. Personal experience

Some respondents referred to their previous experiences to estimate how well they would deal with temporary reductions in indoor temperature, anchoring their perception to specific memories. For example, Maria recalled having a temperature of 16 °C in the laundry room before they renovated it, and therefore she had a point of reference to what she estimated was her minimum acceptable temperature. Similarly, Stina had a memory of malfunctioning heating in an apartment where the temperature dropped to 14 °C, and so she knew she was not comfortable with such a low temperature. Gustav remembered getting by during an extensive power outage caused by a big storm by using a gas-stove to heat the kitchen and living room. Christopher was also accustomed to lower temperatures indoors due to his previous years in the UK. For those respondents who had previous memories and experiences of having lower indoor temperatures for some amount of time, the estimation of what they would be able to deal with seemed to be more assertive. They seemed more sure of where their limits were and what they would do when such a situation emerge. For those who did not have any such specific experiences to draw on, the question of what they would be willing to deal with during a power deficit condition was more difficult to answer. It is therefore important to note that, the temperature levels stated to be acceptable, are not always anchored in real experience but rather an estimation on their part, and need to be treated with respect for that subjective uncertainty.

3.2.6. Family needs

For parents participating in the study, the concern for their children seemed to be a significant factor when discussing a reduced indoor temperature. Robin argued that it would be easier to deal with a reduction if they had no children, but that in this situation they would maybe go to live with his parents, if the house was to become too cold. Robin also mentioned that when the ground source heat pump broke at one point when the outside temperature was −10 °C, he became very worried during those hours where they had no heating even though the house did not become so cold. His concern for his children was illustrated by: *"I've noticed you can do a lot of crazy things when you are a parent that has to do with making sure your children are all right"*. Households with children expressed a concern for vulnerability regarding reduction in indoor temperature and an uncertainty if they would be able to deal with it, while having small children.

Table 3
Comparison of result obtained with data provided in [31,42].

Compressor model	ZPV030	
	Given	Obtained
Speed (RPM)	3600	3600
Rated capacity (kW) @ ARI 3600 RPM	9.7	9.85
Electric power input (kW)	2.98	2.96
COP (W/W)	3.25	3.33

3.3. Indoor temperature range for flexibility quantification

The minimum acceptable temperatures stated in the interviews is used as an input for quantifying flexibility. Based on the results from the interviews, it is evident that there is no consensus on minimum acceptable indoor temperature as it depends on a number of factors. It was also difficult for some of the respondents to state a temperature drop that they would accept in a power deficit scenario. Hence for the thermal simulations, minimum acceptable temperatures varying between 15 °C and 18 °C is chosen for quantifying flexibility, based on the values stated in interviews. Furthermore, additional heating units are excluded in the thermal simulations due to a large uncertainty in the data availability in the number of houses having access to fireplaces/fire stoves and the size of these units.

An advantage of using a range of minimum acceptable indoor temperature is that a range of flexibility levels are obtained as opposed to a single value.

3.4. Performance comparison of the heat pump under study

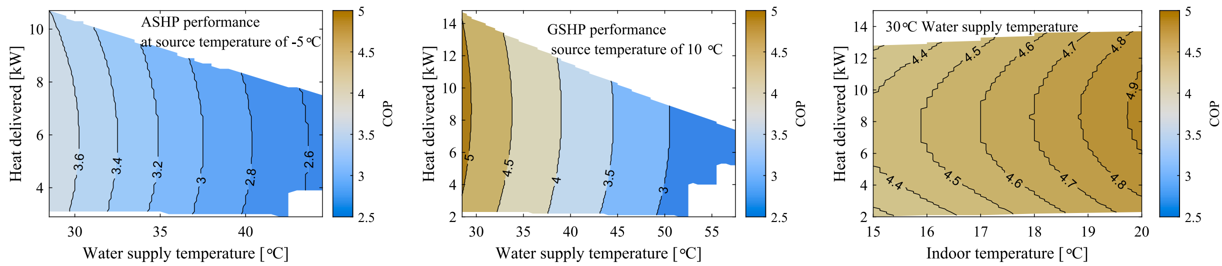
The heat pump model presented in Section 2.2 is validated by comparing the results obtained at standard air conditioning and refrigeration institute (ARI) conditions i.e., 7 °C evaporator temperature and 55 °C condenser temperature at a compressor speed of 3600 RPM, with the data given in [42].

The results are tabulated in Table 3 and it is seen that the results from the model presented matches well with the data provided in [42].

3.5. Performance comparison of heat pumps under study with empirical heat pump models

The COP estimated from empirical models of heat pumps in the literature at standard ARI conditions is tabulated in Table 4. As the temperature drop between the source and evaporator for GSHPs and ASHPs are assumed to be 10 °C and 8 °C, the corresponding source temperature is chosen to be 17 °C and 15 °C respectively to obtain an evaporator temperature of 7 °C. However, it should be noted that the information regarding the refrigerant and compressor speed are missing in empirical models available in the literature.

In Table 4, it is observed that the COP and quantity of heat delivered for fixed speed heat pumps is different from the heat pump models under study, except in case of Ref. [8], where the values are relatively close to the model under study. In case of variable speed heat pumps, the maximum and minimum values of heat delivered are not mentioned except in Ref. [14]. In this case, the maximum value of heat delivered is presented as it is nearer to the heat value to be compared with the heat pump under study. From the comparison of variable speed heat pumps with the heat pump models under study, it is observed that there are discrepancies with respect to COP and the value of heat delivered. Furthermore, the maximum electrical input to compressors are missing for variable speed heat pumps in the literature. Consequently, using empirical models without the knowledge of heat pumps in terms of maximum electrical input to a compressor and speed limitations might lead to an error in thermal simulations and mask the usage of additional electric heating elements in heat pumps. Thus, leading to errors while quantifying flexibility.



(a) Air source heat pump performance (b) Ground source heat pump performance (c) Exhaust air heat pump performance

Fig. 6. Performance of ground source, air to water and exhaust air heat pumps based on source and sink temperatures.

Table 4
Performance of empirical models of heat pumps in literature at standard ARI conditions.

Reference	Type of heat pump	COP	Heat [kW]	Speed
[8]	GSHP	3.24	09.66	
[10]	ASHP	3.11	08.00	Fixed
	GSHP	4.38	13.00	
[13]	GSHP	3.00	–	
	ASHP	2.40	–	
[14]	ASHP	2.90	9.20	Variable
[15]	ASHP	2.91	–	

3.6. Performance comparison of different heat pump types under study

The performance of three types of heat pumps considered in this study, based on the source temperature is shown in Fig. 6. The source temperature would be outdoor ambient air, ground temperature and indoor temperature for ASHP, GSHP and EASHP respectively. For EASHPs, a water supply temperature of 30 °C is chosen as it is mainly used for floor heating in this study. Furthermore an indoor temperature varying between 15 °C and 20 °C is chosen, due to the reason explained in Section 3.3.

As the source temperature for the three different heat pumps is different, COP as a function of heat delivered and water supply temperature is used as the basis of comparison between ASHPs and GSHPs. The COP and heat delivering capability for supplying water at 30 °C will be used as the basis for comparing ASHPs and GSHPs with EASHPs.

From Fig. 6, it is observed that the heat delivering capability and COP is higher in EASHPs in comparison with ASHPs, as the evaporator temperature is higher in the former case, even after considering the temperature drop between the source and the evaporator. On the other hand, while comparing EASHPs with GSHPs, the COP and heat delivering capability are relatively closer as the evaporator temperatures are similar considering the temperature drop between the source and the evaporator.

On comparing GSHPs and ASHPs, it is noticed that, the heat delivering capability and COP is higher in GSHPs due to a higher source temperature. Consequently, the capability to supply high water temperature is greater in GSHPs compared to ASHPs.

3.7. Flexibility analysis of a house constructed in 1961–1975

The thermodynamics in the house constructed during 1961–1975, while reducing the indoor temperature to 17 °C and during the recovery of the same to 20 °C is shown in Fig. 7. The thermal and physical properties of this house are as indicated in Table 1.

From Figs. 7(a)–7(c), it is observed that around 5.1 kW of heat is required to maintain an indoor temperature of 20 °C. The supply and return temperature of water for delivering this amount of heat are 43 °C and 33 °C respectively. The electric power consumption by the GSHP during this condition is 1.4 kW. The corresponding COP and speed of the heat pump is shown in Fig. 7(d).

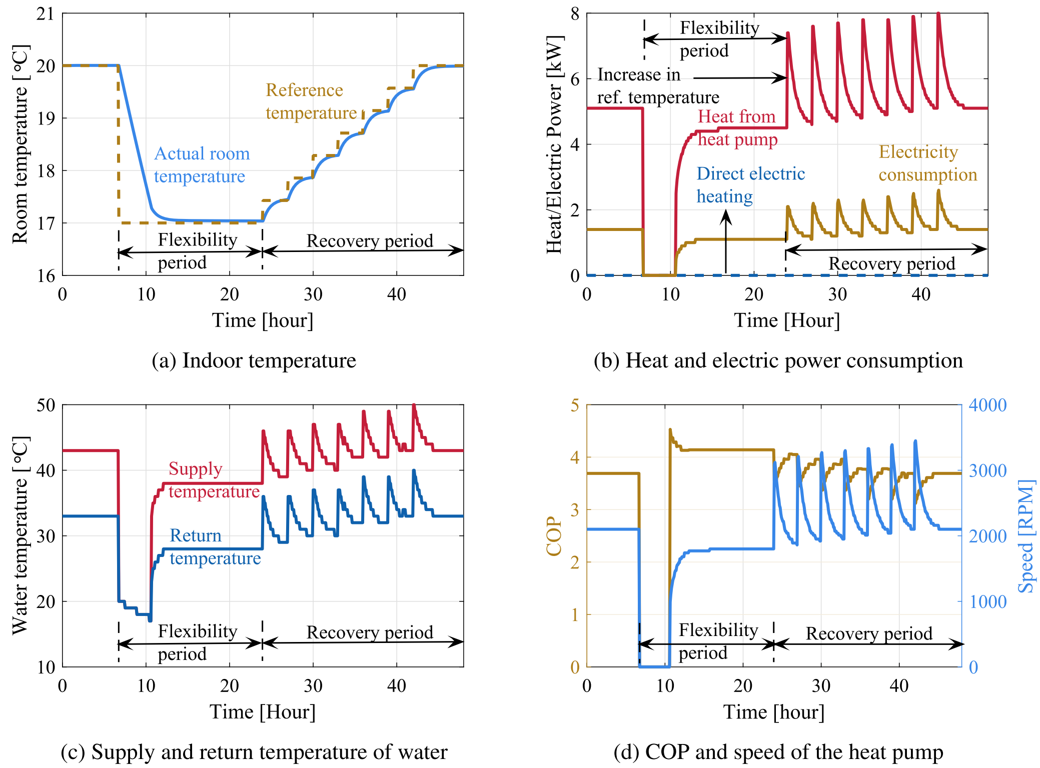
When the indoor reference temperature is changed to 17 °C at 6.75 h, it is observed in Fig. 7(b) that the heat and electric power consumption goes to zero for nearly 3.83 h. This is because the indoor temperature is greater than the reference temperature and hence the heating requirements goes to zero. This can also be witnessed in Fig. 7(c), where the temperature of the water in radiators eventually decrease and become equal to the indoor temperature. Furthermore, in Fig. 7(d), COP and speed of the heat pump is zero indicating that the heat pump is turned off. Thus during this period an instantaneous reduction in electric power of 1.4 kW is offered for a duration of 3.83 h. Thus, the flexibility in terms of an instantaneous reduction in electric power is 1.4 kW and in terms of electric energy reduction is 5.36 kWh.

When the indoor temperature reaches near to the reference temperature at about 10.6 h, the indoor temperature controller provides an appropriate signal to the heat pump to produce a desired heat to maintain the indoor temperature at 17 °C. During this period, it is observed in Figs. 7(c) and 7(d) that the COP is initially high and then reduces, since the supply temperature of the water is initially low and then it gradually increases until it reaches a steady state value of 38 °C. Furthermore, the speed increases gradually and reaches a steady state value of 1800 RPM. Thus during this period between 10.6 h and 24 h, the electricity consumption is lower compared to the condition during which indoor temperature is maintained at 20 °C. Thus, the total electric energy reduction is 4.54 kWh compared to normal condition. Thus, the total reduction in electric energy consumption during the flexibility period between 6.75 h and 24 h is 9.9 kWh.

During the period after providing flexibility, it is assumed that all the reserves in the power system are restored. The period during which the temperature is gradually brought to 20 °C is referred to as recovery period. This is an important aspect to consider, because too high electric energy consumption during this period may strain the grid. During this period, the reference temperature is gradually increased in steps. It is noticed that when the reference temperature is increased, there is an increase in the electricity consumption, heat delivered, supply temperature of water and the speed of the heat pump. As the indoor temperature reaches the reference value, the aforementioned quantities reduces and reaches a steady state value.

With respect to electric energy consumption while maintaining the indoor temperature at 20 °C, the electric energy reduction until the recovery period, while offering flexibility is 9.9 kWh. During the recovery period, the electric energy consumption is 3.55 kWh higher than the electric energy consumption while maintaining the indoor temperature at 20 °C. Thus the net reduction in electric energy consumption is around 6.35 kWh. Thus, the flexibility offered in terms of an instantaneous reduction in electric power is 1.4 kW and flexibility in terms of electric energy reduction is 6.35 kWh in comparison with the condition where no flexibility is offered by maintaining the indoor temperature at 20 °C.

If the indoor temperature is directly increased to 20 °C at 24 h by blocking the direct electric heater, the net saving in electric energy would be 1.15 kWh only. This is because, the compressor runs at its maximum rating for about 4.67 h and also that the supply temperature



(a) Indoor temperature

(b) Heat and electric power consumption

(c) Supply and return temperature of water

(d) COP and speed of the heat pump

Fig. 7. Thermodynamics in a typical house constructed during 1961–1975, equipped with a variable speed ground source heat pump while offering flexibility and considering slow recovery.

of water is maximum during this condition. This is shown in Fig. 8. However, it should be noted that, the indoor temperature recovers earlier in comparison to resetting the indoor temperature slowly.

An important message is that, there is a trade off between energy saving and compromising thermal comfort. Rapid recovery helps in recovering the indoor temperature rapidly. However, the reduction in electric energy is lower in comparison with a slow recovery.

3.8. Validation of an integrated model of a house with a heat pump and heat emitters

The results obtained from thermal simulations in Section 3.7 will be used as the basis of comparison for the model validation.

The total heat required to maintain an indoor temperature at a given outdoor ambient temperature, during a steady state condition can be calculated using

$$Q_{heat} = \frac{T_{room}(t) - T_{amb}(t)}{R_{overall}} \tag{8}$$

The value of '$R_{overall}$' is 0.0049 $\frac{\mathrm{K}}{\mathrm{W}}$, for the house considered for analysis in Section 3.7. It is observed that to maintain an indoor temperature of 20 °C and 17 °C, at an outdoor ambient temperature of −5 °C, a heat of 5.1 kW and 4.5 kW is required respectively. These values obtained using (8) matches well with simulation results. Thus, the model works reasonably well.

The water supply temperature in radiators obtained in Section 3.7, to maintain an indoor temperature of 20 °C in steady state, is compared with empirical models defined in [10] and a heating curve defined in [51] to obtain a reasonability check. However, it should be noted that the corresponding information of indoor temperature is missing in the references used for comparison. The comparison results are tabulated in Table 5.

The comparison shows that there can be a certain degree of uncertainty in the water supply temperature in radiators based on the number of radiators considered for the analysis. Discrepancies of 6% and 8% are obtained when compared with the empirical models presented in [10]. However, the supply temperature obtained from simulations in this study matches perfectly with the heating curve having a slope of 0.6 presented in [51].

Table 5
Comparison of the water supply temperature in radiators at an outdoor ambient temperature of −5 °C available in literature with the current study.

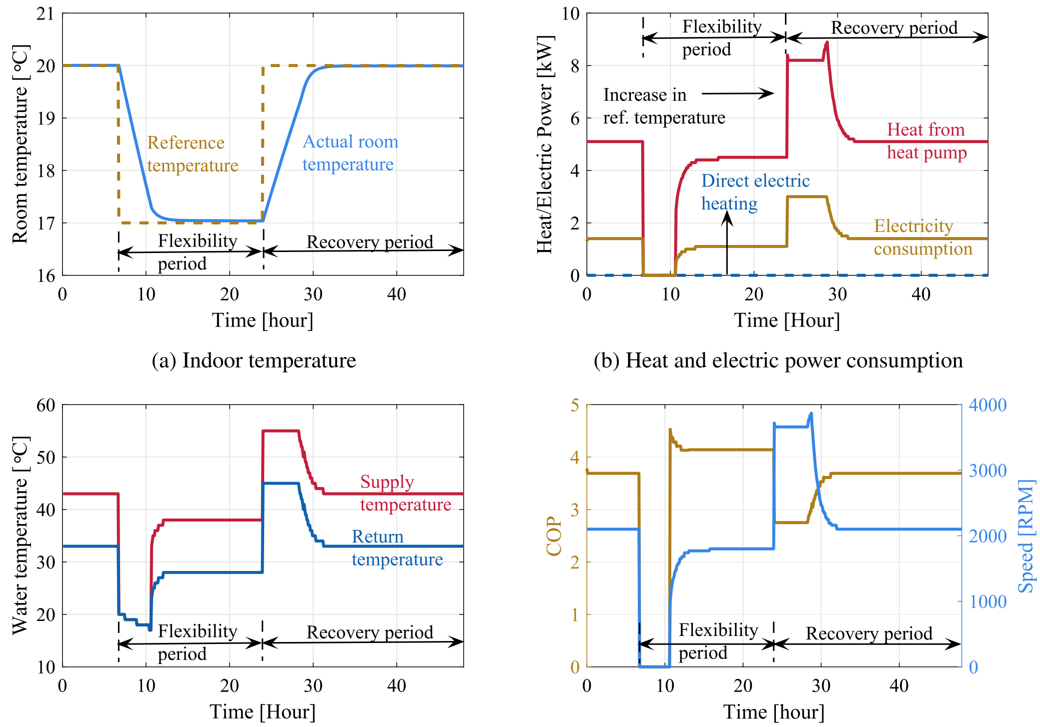
Reference	Heat emitter type	T_{supply} [°C]	Discrepancy
[10]	A-10/W51	46.8	8%
	A-10/W44	40.5	6%
[51]	Radiator	43.0	0%

The heat emitted by radiators based on the water supply and return temperature, to maintain an indoor temperature of 20 °C and 17 °C, can be calculated using equations represented in Section 2.4. By regulating the mass flow rate at the stated water supply and return temperatures, the heat delivered by radiators matches with the value of 5.1 kW and 4.5 kW respectively. Thus the integrated model of the house works reasonably well.

3.9. Performance comparison of a fixed speed ground source heat pump in [8] with the variable speed ground source heat pump dealt in Section 3.7

The house considered for analysis has the same properties as dealt in Section 3.7. This house is assumed to be equipped with a fixed speed GSHP used in article [8]. The thermodynamics in the house, while reducing the indoor temperature to 17 °C is shown in Fig. 9. It is observed that the room temperature cannot be controlled exactly at the reference temperature, as in case of a variable speed heat pump. This is because the heat produced is higher than the desired value. As a result, the heat pump switches between on and off state. This can be seen in Figs. 9(a)–9(c).

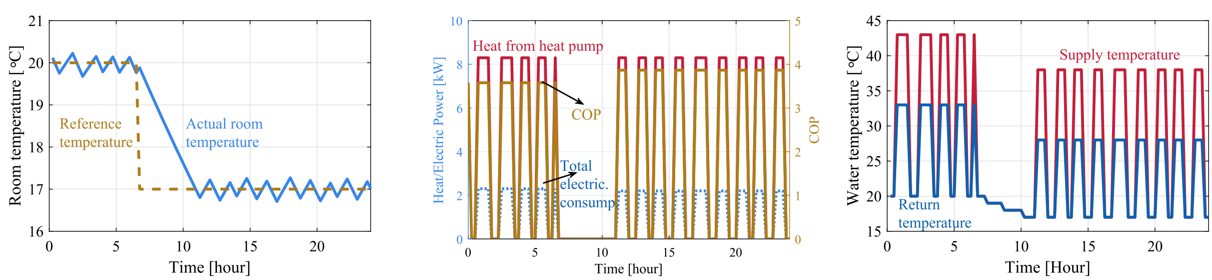
The electric power consumption by the fixed speed GSHP, when maintaining the indoor temperature around 20 °C is 2.3 kW. This is



(a) Indoor temperature (b) Heat and electric power consumption

(c) Supply and return temperature of water (d) COP and speed of the heat pump

Fig. 8. Thermodynamics in a typical house constructed during 1961–1975, equipped with a variable speed ground source heat pump while offering flexibility and considering rapid recovery.



(a) Indoor temperature (b) Heat and electric power consumption (c) Supply and return temperature of water

Fig. 9. Thermodynamics in a typical house constructed during 1961–1975, equipped with a fixed speed ground source heat pump dealt in [8].

0.9 kW higher when compared with that of the variable speed heat pump dealt in Section 3.7. Also, to maintain an indoor temperature of 17 °C, the electric power consumption is 1.1 kW and 2.2 kW for the variable and fixed speed heat pumps under study respectively.

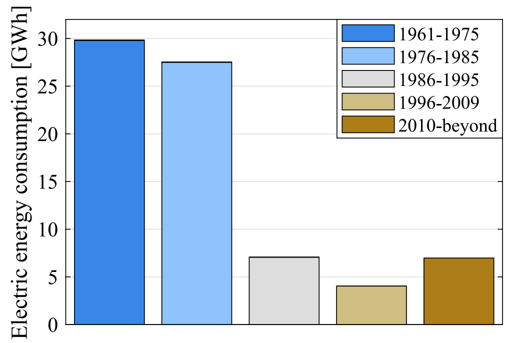
Thus, it is inferred that electric power consumption from fixed speed heat pumps are generally higher than that of variable speed heat pumps. Hence, inclusion of such elderly heat pumps in the study, leads to an overestimation of the flexibility potential.

3.10. Quantification of flexibility from space heating systems in different houses

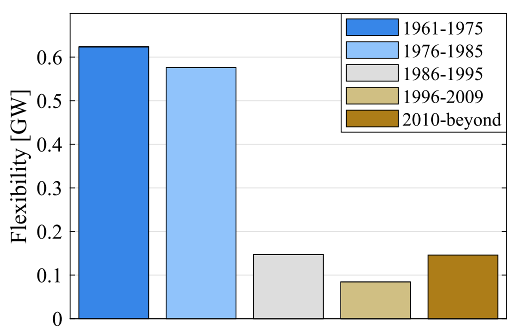
The total electric energy consumption in the houses dealt in Table 1, when maintaining an indoor temperature at 20 °C, is shown in Fig. 10(a). The corresponding flexibility in terms of an instantaneous reduction in electric power is shown in Fig. 10(b). This figure indicates the possible instantaneous reduction in electric power by space heating systems in all houses equipped with heat pumps under study. It should be noted here that, the electric energy consumption and flexibility (GW) is dependant on the number of houses as well. For instance, the number of houses constructed during 1961–1975, is the highest compared to other houses. If these plots are seen on an individual house level, the electricity consumption and thereby flexibility potential is the highest in the house belonging to the category 1976–1985.

The trend of flexibility in terms of an instantaneous reduction in electric power is similar to Fig. 10(a), as it is dependent on the electric energy consumption. The higher the consumption, the greater the flexibility potential. On the other hand, low flexibility potential indicates, higher energy efficiency.

The reduction in electric energy during flexibility period and considering the recovery period with slow as well as fast recovery, are shown in Figs. 11 and 12. As discussed above, the electric energy reduction is higher in less energy efficient houses. The potential of electric energy reduction decreases, as the insulation and performance of a heat pump in a house increases. Furthermore, it is observed that, a higher electric energy reduction is possible with an increase in the reduction of indoor temperature, for the time when offering flexibility as well as during the recovery period. It is observed that the reduction in electric energy is lower in the case of rapid recovery compared to the slow recovery. However, the indoor temperature is recovered earlier with a rapid recovery.



(a) Electric energy consumption during normal condition



(b) Flexibility in terms of an instantaneous reduction in electric power

Fig. 10. Total electric energy consumption and flexibility potential of different buildings considered in the study.

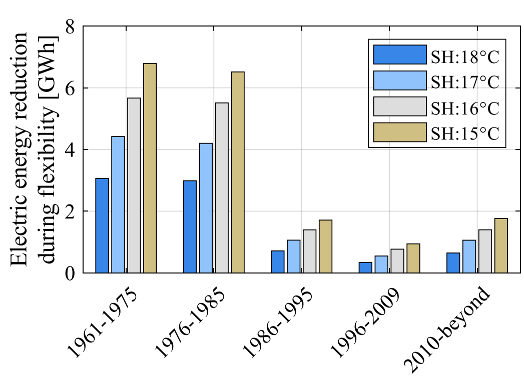
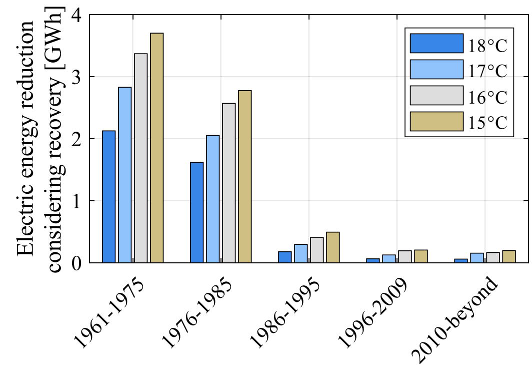
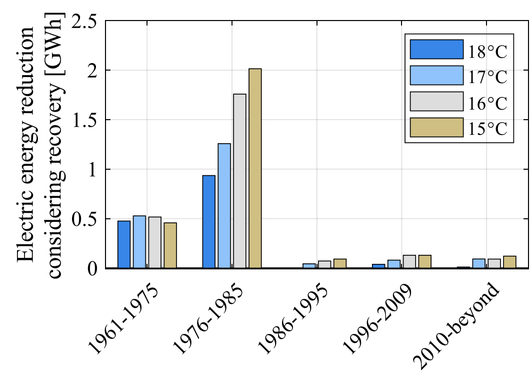


Fig. 11. Electric energy reduction during flexibility.



(a) Electric energy reduction with slow recovery



(b) Electric energy reduction with rapid recovery

Fig. 12. Electric energy reduction considering slow and rapid recovery.

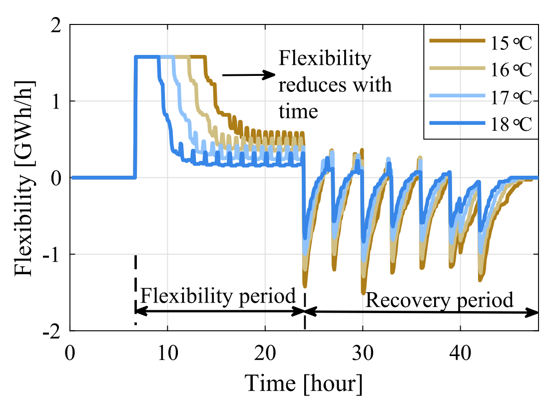


Fig. 13. Estimated flexibility potential considering slow recovery.

3.11. Quantification of flexibility potential as a function of time

The electricity consumption characteristics during the reduction of the indoor temperature to a value between 15 °C and 18 °C for a million single family houses, considering slow and rapid recovery of the indoor temperature, are shown in Figs. 13 and 14. From Figs. 13 and 14, it is observed that the flexibility potential from space heating is a function of time and with time the amount of flexibility reduces. The higher the temperature drop, the greater the flexibility in terms of energy. If all the houses considered under study, accept to have an indoor temperature of 18 °C, flexibility in terms of an instantaneous reduction in electric power of 1.6 GW can be offered for 2.33 h. If the indoor temperature is reduced to 17 °C, 16 °C and 15 °C, the same flexibility can be offered for 3.83 h, 5.42 h and 7.1 h respectively. The value of 1.6 GW represents around 7% of the total plannable power in Sweden [2]. Thus, the Swedish power system has the potential to be resilient towards a power deficit condition of almost 1.6 GW by temporarily compromising the indoor temperature, as well as with fairly moderate reductions.

During recovery period, it is observed that, flexibility becomes negative, indicating that more electricity is consumed. However, towards the end of the recovery period, flexibility level again goes back to zero. It is important to note that the trend in flexibility changes for a slow and a rapid recovery. During a slow recovery, the duration of time for which flexibility is negative is lower compared to that of a fast recovery. Thus, the savings in electric energy is higher considering a slow recovery. These plots of flexibility quantification can serve as a valuable information for the power system planning and operation to take informed decisions during severe power deficit conditions. However, it should be noted that these plots are obtained by an aggregation of one million

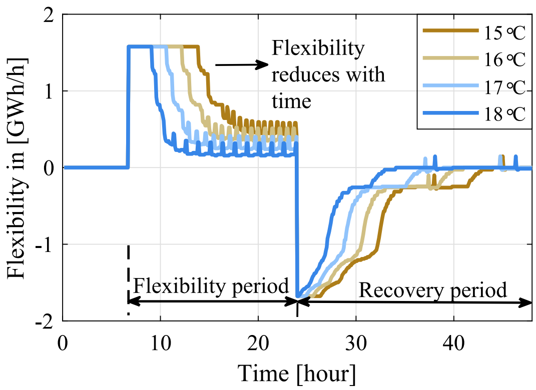


Fig. 14. Estimated flexibility potential considering rapid recovery.

houses. The recovery in these houses should be coordinated in such a way that there are no additional disturbances in the grid because of power peaks.

It is important to mention that a lack of a good market structure or lack of incentives for the consumers offering flexibility can lead to hampering the utilisation of such flexible resources.

3.12. Future work

A very valuable work effort in the future would be to conduct experimental comparisons on a real house. It should be acknowledged that this involves a substantial effort, to collect data related to solar irradiation, wind speed, detailed information about the interior walls of the house, the heading system used as well as the conduction of the heating system, in addition to equipping the house with sensors and a measurement system.

4. Conclusion

With an objective of enhancing the resilience of a power system with a high share of renewable energy resources, this study quantifies the flexibility potential of space heating systems in about a million single family houses equipped with heat pumps by adopting a multidisciplinary approach. This approach comprises of qualitative interviews with single family households' owning heat pumps and thermal models of houses with a heat input from heat pumps via heat emitters such as radiators or floor heating.

Qualitative interviews provide deep insights into the social potential of offering flexibility, by reducing the indoor temperature. This potential to compromise the thermal comfort is dependant on a number of factors such as the frequency and duration of disturbances, motivation, family needs and access to additional heating. However, it should be noted that a few respondents had difficulty in stating the minimum acceptable indoor temperature due to lack of specific experiences of such low indoor temperatures. The interviews further revealed that there is no consensus on the minimum acceptable indoor temperature among the residents. The minimum acceptable indoor temperatures stated were between 15 °C and 18 °C.

A generic model of a variable speed heat pump using a vapour compression heat pump cycle is presented considering the limitations posed by a compressor's operating envelope and the maximum electrical input to the compressor. The electricity consumption by the compressor of a heat pump is estimated for maintaining an indoor temperature at a set value. This is realised by integrating a thermal model of a house with a heat pump model and a heat emitter model. The true potential for flexibility is quantified based on minimum acceptable indoor temperatures stated in interviews. As a range of minimum acceptable indoor temperature is used for thermal simulations, a flexibility range is obtained as opposed to a single value.

It is demonstrated that the flexibility quantification is overestimated if fixed speed heat pumps are used as they are less energy efficient compared to variable speed heat pumps. Furthermore, empirical models of variable speed heat pumps with lack of information on speed limitations at various operating conditions and compressor's maximum electrical rating can lead to errors while quantifying flexibility.

By reducing the indoor temperature from 20 °C to a value between 18 °C and 15 °C over 17.25 h, in about a million single family houses in southern half of Sweden at an outdoor ambient temperature of −5 °C, the flexibility in terms of reduction in electric energy is found to be between 4.06 GWh and 7.4 GWh, considering a recovery period (slow recovery) of 24 h. The flexibility in terms of an instantaneous reduction in electric power is estimated to be 1.6 GW and is independent of the minimum acceptable indoor temperature. This value represents around 7% of the total plannable power in Sweden. Furthermore, the flexibility offered is a function of time. With time the amount of flexibility offered reduces, becomes negative during the recovery period and finally reaches zero, when the indoor temperature reaches 20 °C. Thus, the Swedish power system has the potential to be resilient towards a power deficit condition of almost 1.6 GW for a duration between 2.33 h and 7.1 h by temporarily compromising the indoor temperature between 18 °C and 15 °C respectively, at an outdoor ambient temperature of −5 °C.

CRediT authorship contribution statement

Sindhu Kanya Nalini Ramakrishna: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hanna Björner Brauer:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Torbjörn Thiringer:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Maria Håkansson:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to thank Huijuan Chen at RISE (Research Institutes of Sweden) for sharing the data on the thermal properties of the houses.

The financial support given by the Swedish Energy Agency through grant No. 50343-1 is gratefully acknowledged.

References

[1] IEA. Power Systems in Transition. [Online]. Available: https://www.iea.org/reports/power-systems-in-transition.
[2] Swedish Energy Agency. Energy in Sweden- An overview. Energimyndigheten 2021.
[3] statista. Final electricity consumption in households in Sweden from 2013 to 2019, by type. 2021, https://www.statista.com/statistics/1027100/final-consumption-of-electricity-in-households-in-sweden-by-type/.

[4] Savvidou G, Nykvist B. Heat demand in the Swedish residential building stock - pathways on demand reduction potential based on socio-technical analysis. Energy Policy 2020;144:111679. http://dx.doi.org/10.1016/j.enpol.2020.111679, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301421520304080.
[5] Walfridson T, Lindahl M, Ericsson N, Bergentz T, Willis M, Gustafsson O, Haglund Stignor C. Large scale demand response of heat pumps to support the national power system. In: 14^{th} IEA, heat pump conference. 2023.
[6] Nyholm E, Puranik S, Mata É, Odenberger M, Johnsson F. Demand response potential of electrical space heating in Swedish single-family dwellings. Build Environ 2016;96:270–82. http://dx.doi.org/10.1016/j.buildenv.2015.11.019, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360132315301815.
[7] Dörre E, Pfaffel S, Dreher A, Girón P, Heising S, Wiedemann K. Flexibility reserve of self-consumption optimized energy systems in the household sector. Energies 2021;14(11):3017.
[8] You Z, Zade M, Kumaran Nalini B, Tzscheutschler P. Flexibility estimation of residential heat pumps under heat demand uncertainty. Energies 2021;14(18):5709.
[9] Golmohamadi H, Larsen KG, Jensen PG, Hasrat IR. Hierarchical flexibility potentials of residential buildings with responsive heat pumps: A case study of Denmark. J Build Eng 2021;41:102425.
[10] Fischer D, Wolf T, Wapler J, Hollinger R, Madani H. Model-based flexibility assessment of a residential heat pump pool. Energy 2017;118:853–64.
[11] Arnaudo M, Topel M, Laumert B. Techno-economic analysis of demand side flexibility to enable the integration of distributed heat pumps within a Swedish neighborhood. Energy 2020;195:117012.
[12] Golmohamadi H. Stochastic energy optimization of residential heat pumps in uncertain electricity markets. Appl Energy 2021;303:117629.
[13] Marijanovic Z, Theile P, Czock BH. Value of short-term heating system flexibility–A case study for residential heat pumps on the German intraday market. Energy 2022;249:123664.
[14] Olympios AV, Sapin P, Freeman J, Olkis C, Markides CN. Operational optimisation of an air-source heat pump system with thermal energy storage for domestic applications. Energy Convers Manage 2022;273:116426. http://dx.doi.org/10.1016/j.enconman.2022.116426, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0196890422012043.
[15] Vivian J, Prataviera E, Cunsolo F, Pau M. Demand side management of a pool of air source heat pumps for space heating and domestic hot water production in a residential district. Energy Convers Manage 2020;225:113457. http://dx.doi.org/10.1016/j.enconman.2020.113457, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0196890420309912.
[16] Hasselqvist H, Renström S, Håkansson M, Strömberg H. Exploring renewable energy futures through household energy resilience. In: Proceedings of the 2022 CHI conference on human factors in computing systems. 2022, p. 1–18.
[17] Heidenstrøm N, Throne-Holst H. "Someone will take care of it". Households' understanding of their responsibility to prepare for and cope with electricity and ICT infrastructure breakdowns. Energy Policy 2020;144:111676.
[18] Wethal U. Practices, provision and protest: Power outages in rural norwegian households. In: Consumption, sustainability and everyday life. Springer; 2023, p. 135–70.
[19] Abi Ghanem D, Mander S, Gough C. "I think we need to get a better generator": Household resilience to disruption to power supply during storm events. Energy Policy 2016;92:171–80.
[20] Watts L. Energy at the end of the world: An Orkney Islands saga. MIT Press; 2019.
[21] Luo M, Wang Z, Brager G, Cao B, Zhu Y. Indoor climate experience, migration, and thermal comfort expectation in buildings. Build Environ 2018;141:262–72.
[22] Indraganti M, Humphreys MA. A comparative study of gender differences in thermal comfort and environmental satisfaction in air-conditioned offices in Qatar, India, and Japan. Build Environ 2021;206:108297.
[23] Hansen AR, Gram-Hanssen K, Knudsen HN. How building design and technologies influence heat-related habits. Build Res Inf 2018;46(1):83–98.
[24] Mallaband B, Lipson M. From health to harmony: Uncovering the range of heating needs in British households. Energy Res Soc Sci 2020;69:101590.
[25] Calver P, Mander S, Abi Ghanem D. Low carbon system innovation through an energy justice lens: exploring domestic heat pump adoption with direct load control in the United Kingdom. Energy Res Soc Sci 2022;83:102299.
[26] Hagejärd S, Dokter G, Rahe U, Femenías P. My apartment is cold! household perceptions of indoor climate and demand-side management in Sweden. Energy Res Soc Sci 2021;73:101948.
[27] Parrish B, Heptonstall P, Gross R, Sovacool BK. A systematic review of motivations, enablers and barriers for consumer engagement with residential demand response. Energy Policy 2020;138:111221.
[28] Hernandez-Aguilera JN, Anderson W, Bridges AL, Fernandez MP, Hansen WD, Maurer ML, Ilboudo Nébié EK, Stock A. Supporting interdisciplinary careers for sustainability. Nat Sustain 2021;4(5):374–5.
[29] Braun V, Clarke V. Using thematic analysis in psychology. Qual Res Psychol 2006;3(2):77–101.
[30] Clark T, Foster L, Bryman A, Sloan L. Bryman's social research methods. Oxford University Press; 2021.
[31] Nalini Ramakrishna SK, Thiringer T, Markusson C. Quantification of electrical load flexibility offered by an air to water heat pump equipped single-family residential building in Sweden. In: 14^{th} IEA, heat pump conference. 2023.
[32] Air Squared Articles. Scroll compressor and vaccum pump efficiency, [Online]. Available: https://airsquared.com/scroll-articles/scroll-compressor-and-scroll-vacuum-pump-efficiency-explained/.
[33] Swedish Energy agency. Exhaust and supply air ventilation with heat recovery, [Online]. Available: https://www.energimyndigheten.se/en/sustainability/households/other-energy-consumption-in-your-home/ventilation/exhaust-and-supply-air-ventilation-with-heat-recovery-ftx-system/.
[34] Fux SF, Ashouri A, Benz MJ, Guzzella L. EKF based self-adaptive thermal model for a passive house. Energy Build 2014;68:811–7. http://dx.doi.org/10.1016/j.enbuild.2012.06.016, [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378778812003039.
[35] Amara F, Agbossou K, Cardenas A, Dubé Y, Kelouwani S, et al. Comparison and simulation of building thermal models for effective energy management. Smart Grid Renew Energy 2015;6(04):95.
[36] Mata E, Kalagasidis AS. Calculation of energy use in the Swedish housing, Vol. 2009, Gothenburg, Sweden: Chalmers Univeristy of Technology; 2009, p. 4.
[37] Purmo. Technical catalogue, panel radiators, [Online]. Available: https://www.purmo.com/docs/Purmo-technical-catalogue-full-panel-radiators-10_2021_EN.pdf.
[38] Müller S. Development of Nordic 32 system model and performance analysis based on real operation statistics (Thesis), KTH royal institute of technology; 2019.
[39] Ling J. Nordic and Baltic Sea winter power balance 2022–2023, [Online]. Available: https://www.svk.se/en/national-grid/the-control-room/.
[40] Svenska kraftnät. The control room, [Online]. Available: https://www.svk.se/en/national-grid/the-control-room/.
[41] Emerson Climate Technologies. Variable speed compressors for residential air conditioning applications, [Online]. Available: https://climate.emerson.com/documents/product-brochure-copeland-scroll-variable-speed-compressors-for-residential-air-conditioning-applications-en-sg-7237218.pdf.
[42] Copeland™. Emerson climate technologies. In: *copeland*™ scroll variable speed compressors for residential air conditioning applications. Emerson Electric Co.; 2020, [Online]. Available: https://climate.emerson.com/documents/product-brochure-copeland-scroll-variable-speed-compressors-for-residential-air-conditioning-applications-en-sg-7237218.pdf. [Accessed 04 March 2022].
[43] Boverket. Energi i bebyggelsen – tekniska egenskaper och beräkningar–resultat från projektet BETSI, [Online]. Available: https://www.boverket.se/sv/om-boverket/publicerat-av-boverket/publikationer/2011/energi-i-bebyggelsen---tekniska-egenskaper-och-berakningar/.
[44] Hedbrant J. On the thermal inertia and time constant of single-family houses (Licentiate dissertation), linköping: linköpings universitet; 2001, 2001.
[45] SCB statistics Sweden. Households by housing type and region. 2021, [Online]. Available: https://www.scb.se/en/finding-statistics/statistics-by-subject-area/household-finances/income-and-income-distribution/households-housing/.
[46] Blom N. Folkhälsomyndighetens allmänna råd om temperatur inomhus. 2014.
[47] Statistics Sweden, SCB. Just over 4.9 million dwellings in Sweden. 2023, (Accessed 20 December 2023).
[48] Hesaraki A, Bourdakis E, Ploskić A, Holmberg S. Experimental study of energy performance in low-temperature hydronic heating systems. Energy Build 2015;109:108–14. http://dx.doi.org/10.1016/j.enbuild.2015.09.064.
[49] PURMO. Heat output calculator, [Online]. Available: https://global.purmo.com/en/tools-and-services/item-selector.
[50] Infineon. Advanced semiconductor solutions for a hot future in heat pumps.
[51] Bash, Cli Tools and Cheat-Sheets. Heating curve, [Online]. Available: https://www.bashpi.org/?page_id=225.