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Demand response potential of electrical space heating in Swedish single-family dwellings

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Abstract

This paper investigates the potential and economics of electrical space heating in Swedish single-family dwellings (SFDs) to provide Demand Response (DR) for the electricity load in Sweden.

A dynamic and detailed building-stock model, is used to calculate the net energy demand by end-use of a set of sample buildings taken as representative of all Swedish SFDs with electrical heating. A new sub-model optimizes the dispatch of heating systems on an hourly basis, for each representative building, minimizing the cost of electricity purchased from the hourly spot market.

The analysis of the Swedish SFD buildings indicates a technical DR capacity potential of 7.3 GW, which is considerable and can be used for the management of intermittent electricity generation. This potential could also prove to be valuable in the operating reserve market. However, this requires that the DR, rather than being governed by a single hourly electricity price signal, would instead be subject to a more centralized control. The modeling shows that DR can be expected to result in up to 5.5 GW of decreased load and 4.4 GW of increased load, if applying current Swedish electricity prices. The modeling shows that DR shifts up to 1.46 TWh of electric heating, corresponding to 1% of total Swedish electricity demand. The potential savings from DR for individual SFDs is found to be low, 0.9 to 330 €/year, given current Swedish electricity prices.

Keywords: Building-stock modeling; Demand response; Electric space heating; Bottom-up model

1. Introduction

One way to facilitate large-scale integration of intermittent electricity generation is to match electricity supply and demand by applying Demand Side Management (DSM) measures. One such DSM measure is Demand Response (DR), whereby electricity consumers, in response to some incentive, alter their consumption patterns to in a more optimal way match the generation of electricity [1]. With the implementation of electricity smart meters in Sweden it has become possible for residential customers to have real time pricing and thereby take part in DR [2]. With the residential sector in Sweden accounting for 23% of total electricity consumption, residential loads could potentially have a significant role in balancing variations in the electricity supply system. The potential for dishwasher, laundry and water heating loads has previously been studied by Puranik [3]. Electrical space heating of single-family dwellings (SFDs) represents about 50% of the residential electricity demand and has a higher power capacity compared to other electrical household devices, such as white appliances [4]. Thus, electrical space heating offers a substantial contribution to variation management. This demand can be used for DR purposes through the storage of the heat produced by electric heating systems, e.g., heat pumps and electric radiators, in the building mass and in the indoor air [5, 6]. The present study aims at investigating the DR potential, in terms of time frame for load shifting as well as capacity and energy of the shifted load, for electric space heating in Swedish SFDs through using the thermal inertia of the building stock. From these results, we show the potential impact such DR could have on the load curve in the Swedish electricity system.

Three different options for heat storage in buildings were introduced by Arteconi et al. [7]: latent heat storage in the form of phase-changing materials; sensible heat storage through active storage, i.e., *via* the use of heat storage equipment; and sensible heat storage through passive storage that utilizes the thermal mass of the building by varying the indoor temperature. The present study focuses on the latter option, utilizing sensible heat storage. Several studies have investigated the possibility to utilize this type of storage to shift electricity consumption for heating or cooling loads temporally. The modeling approach in literature can be divided into two types of models, system level optimization models and simulation models, simulating an individual or a few individual buildings in order to analyze strategies for shifting load.

Studies that have investigated the use of thermal mass of buildings to move cooling loads [8-13], mainly target commercial buildings due to their high levels of electricity consumption for cooling. The analysis of the load shifting is usually based on the performance for days up to weeks. Yin et al. [11] identified the possibility to shift peak loads (on a single building level) to achieve a 10%–30% reduction in the maximum electricity load of the building. Furthermore, Morgan and Krarti [10] and Braun [12] have shown that the operating cost of cooling systems can be reduced by 10%–20% by shifting the load from peak demand hours. Published studies on the pre-heating of buildings mainly propose strategies to control the heating system to shift the load and optimize electricity consumption with respect to reduced peak demand [14-16]. Apart from reducing the peak load, Hughes [17] has concluded that load shifting facilitates the integration of more renewable energy sources into electricity systems, such as wind power. Reynders et al. [18] modeled the potential for thermal storage using space heating in a net zero-energy building in Belgium equipped with a PV system. They conclude that there is a mismatch between PV generation and space heating demand. Consequently, it is not obvious how to apply thermal storage in order to increase the use of PV electricity. Yet, DR through thermal storage was shown to reduce demand with up to 94% during peak demand hours [18].

Patteeuw et al. [19] investigated different optimization modeling approaches for DR of electric heating systems and their ability to describe the DR behavior. They conclude that in order to capture the characteristics of DR, models that include both supply and demand is preferable (which they denote integrated models).

A few studies have investigated the potential of DR residential heating loads on a system level with different geographic scope, i.e., Hedegaard and Balyk [20] and Hedegaard et al. [21] for the Danish heating system, Papaefthymiou et al. [22] for Germany, and Meibom et al. [23] for Northern Europe, all of which have focused on the integration of wind power into the electricity system. Papaefthymiou et al. [22] showed that for a case with renewable energy penetration of 47%, heat pumps reduce system costs to a greater degree than pumped hydro storage. This is because the losses incurred by the round-trip efficiency of the pumped hydro storage are higher than the losses that result from storing heat. Papaefthymiou et al. [22] concluded that taking into account the minimum load requirements and start-up costs for conventional power plants without allowing curtailment increases the system value of the DR measure. Hedegaard et al. [21] concluded that investments in heat pumps together with passive storage, i.e., using the thermal inertia of the buildings, could reduce fuel costs and CO_2 emissions to a break-even cost in the Danish energy system when there is 50% wind power (the possibility to export/import electricity is included). They also found that investments in heat storage in the form of accumulation tanks are not cost-effective. However, their study was limited to future investments in heat pumps and did not consider the currently existing heating technologies in the Danish building stock. As Hedegaard et al. [21] utilized a simplified modeling of the thermal behavior of the buildings, their results may overestimate shifting times. Papaefthymiou et al. [22] applied more in-depth modeling of the buildings, although the temperature dependency in the heat losses was not accounted for in their analysis. In the study of Hedegaard and Balyk [20], a modeling framework for the thermal behavior of the buildings was implemented, although it did not include solar radiation and lacked a detailed description of the building stock. They showed that the use of heat pumps for DR resulted in a reduced need for peak and reserve capacity investments.

Although the above works indicate that implementing DR may be favorable for the electricity system, none of the above papers assessed how building characteristics influence the use of electric heating for DR, in the form of passive storage, in the building stock. There is also a lack of studies on the effects of large-scale implementation of DR by electric heating in Sweden and its effects on the Swedish electricity system. Therefore, the present study investigates the potential of electrical space heating in Swedish SFDs to act as a DR and examines both how DR influences the electricity load curve and the magnitude of the economic benefit from the resulting reduction in the cost of electricity. More specifically, we address the following four research questions: (1) What is the DR potential available under the present price structure given an individual DR?; (2) What would the potential effect of such a shift be on the Swedish electricity load curve and on the final electricity demand for space heating?; (3) Which building characteristics influence load shifting the most?; and (4) What are the possible monetary savings for consumers who shift their electrical space heating load, assuming the current market structure?

2. Electricity demand in Swedish SFDs

The total amount of electricity consumed in Sweden during Year 2012[2] was 143 TWh: 42% by industry, 25% by the residential sector, 25% by the tertiary sector, and 8% attributed to distribution losses. In the residential sector, permanent SFDs use 25.6 TWh of electricity (56% for space heating and production of hot water, and 44% for household electricity), while multi-family dwellings (MFDs) use 6.4 TWh (23% for space heating and production of hot water, and 77% for household electricity) [24]. The low level of electric heating use in MFDs is due to the fact that 92% of the MFDs are connected to the district heating grid [4]. In all, space heating in SFDs accounts for 12% of the total electricity consumption in Sweden. These values are comparable with the most recent data for the year 2013 [25], although the overall electricity demand was slightly (3%) lower during 2013.

There are approximately two million SFDs in Sweden[3], out of which 1.3 million have some form of electrical heating system [24, 26]. Figure 1 shows the distribution of heating sources in Swedish SFDs. In the electricity category, electric radiators, electric boilers, and air-source heat pumps are included. It is clear that electric heating by itself or in combination with other heating systems constitutes a major proportion of the installed heating systems. The other electricity-consuming category is ground-source heat pumps, which includes heat pumps that draw energy from the ground or a body of water. Comparing the 2012 to data for 2013 the changes in distribution of heating sources and number of households are minor [27].

Swedish SFDs that are heated directly with electricity consume on average 15,000 kWh/year of electricity for space heating [24]. In contrast, households that are indirectly heated by electricity (both partially and using heat pumps) consume about 6,000 kWh/year of electricity for space heating [28].

In summary, there is substantial potential for space heating electricity in Swedish SFDs, which could provide DR. The purpose of this paper is to investigate to what extent and under which conditions this potential can be realized.

[2] One of the years modeled in this work

[3] Year 2012

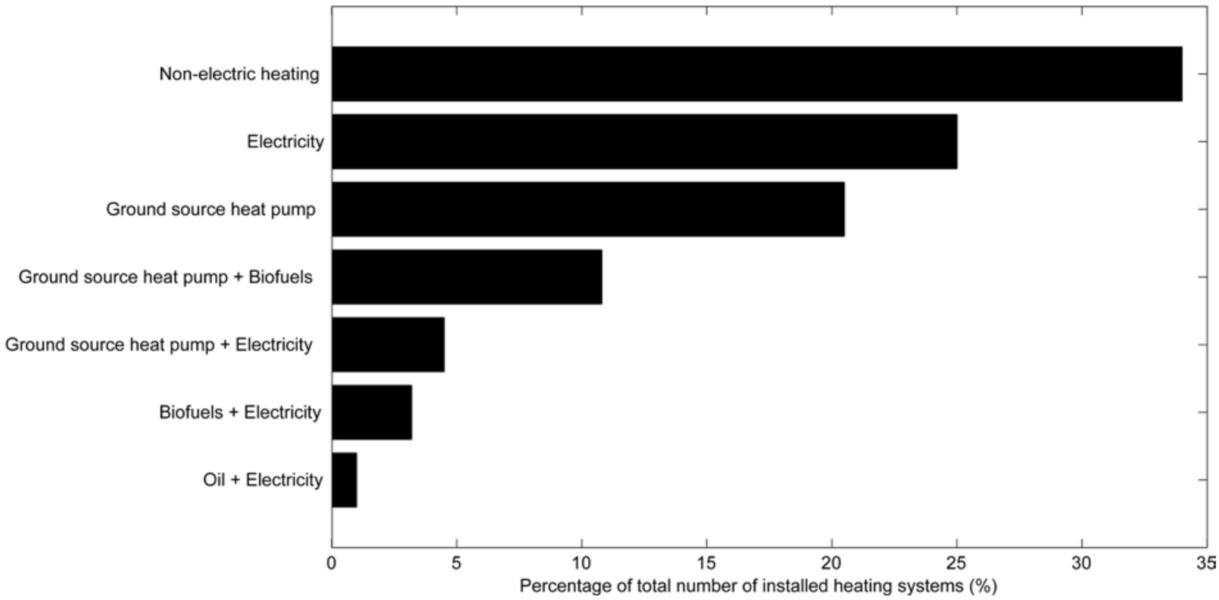


Figure 1. Distribution of space heating sources in Swedish SFDs, where 'Electricity' denotes electric boilers, electric radiators or air heat pumps and 'Non-electric heating' comprises mainly district heating and local boilers, such as those fueled by pellets or oil [24].

3. Method

The electricity demand for space heating is calculated with the building-stock model ECCABS (Energy Carbon and Cost Assessment of Building Stocks) [29], together with an additional sub-model developed for this work. This sub-model enables shifting of the electric space-heating load in time. The sub-model is allowed to shift the electric space-heating load as long as the indoor temperature stays within a predefined temperature range (21.2°–24.0°C).

3.1 Modeling of the building stock

The ECCABS model is a bottom-up engineering model [according to the classification of Swan and Ugursal [30]]. The model calculates net energy demand of individual representative buildings based on the physical properties of the buildings, a description of the heating and ventilation systems, the level of energy usage, and climatic conditions. The model treats each building as one thermal zone. According to the classification of calculation procedures in ISO 13790, the model is detailed, hourly specification of the input data and the results, and dynamic, takes into account the thermal mass of the building at each time step[31]. The energy balance is calculated every hour for each representative building, and the results are summed to give the annual net and final energy demands per end-use and building type. The results are extrapolated to represent the building stock of a country (in this case, Sweden) by means of weighting coefficients that are related to the frequency of each representative building in the building stock investigated. The energy model has been verified by inter-model comparisons and empirical validations [29]. The building-stock model has already been used to investigate the building stock of Sweden, see Mata et al. [32], Mata et al. [33] and Nik et al. [34] as well as of various European countries [35, 36].

To analyze the characteristics of DR requires a dynamic and detailed modeling approach. Thus, the modeling approach enables input of hourly patterns, the same resolution as real-time pricing, of heat gains (occupants, lighting and appliances), and accounts for the thermal inertia of the building, while also allowing calculation of the indoor temperature.

3.2 Optimization

The sub-model developed in the present work minimizes the annual electricity cost of each modeled SFD, based on the demand for electrical space heating obtained from the ECCABS model. This is done by dispatching the different electric heating systems installed in each SFD, i.e., the sub-model decides how the heating system should operate in each hourly time step. The dispatch of the heating system is governed by the hourly price of electricity, which for a consumer includes the spot price, surcharges, electricity tax, VAT, and a grid transfer fee. The model dispatches the heating system in order to pre-heat the building during low-price hours and maintain the heating off during high-price periods, provided that the indoor temperature is within limits that are defined as set values in the modeling (21.2°–24.0°C). This operation is restricted by an upper limit to the amount of energy that can be supplied during a single time step, which is determined by the installed heating capacity, i.e., the power rating of each heating system, and the maximum and minimum allowed indoor temperatures. For details of the sub-model, see the Appendix.

The potentials for DR are obtained by comparison to a reference electricity demand, for which no DR occurs. The baseline is created by assuming that only a minimum indoor temperature of 21.2°C has to be maintained, as this temperature corresponds to the measured average temperature in Swedish SFDs [37].

3.3 Input data for the building stock model

In the model, 571 sample buildings represent the Swedish SFDs with electrical heating. These sample buildings are extracted from a dataset of 1,400 buildings that are representative of the entire Swedish building stock that has already been presented [32], taken from a survey conducted by the Swedish National Board of Housing, Building and Planning for the Swedish residential building stock [37]. As summarized in Table 1, most of input parameters for the building-stock description can be found in Mata et al. [32], whereas modified or new data for this paper follow below. The buildings are located in 30 different municipalities, chosen to represent different climatic regions and sizes of municipalities. Years 2010 and 2012 are investigated with respect to outdoor temperature and irradiance input data [38], where Year 2010 represents a year with a low average temperature and high average electricity price and Year 2012 is a year with a normal average temperature and normal average electricity price.

Table 1. Summary of input data (with corresponding sources) for the two models used in this work.

Input data for the building stock model ECCABS	
Building geometry Properties of construction materials	Presented in [32], based on[39], and [40]
Effective heat capacity*	130,000 J/K m^2 [32, 41].
Use of lighting and appliances	Average values based on[37]. Profiles based on [28]
Type and efficiency of the electrical heating systems*	Presented in [32], based on [39] and [40]
Power rating of the heating equipment	Done in this paper, based on [41]
Temperature and solar irradiation data	Taken from [38]
Input data for the optimization sub-model	
Hourly day-ahead electricity spot prices	Taken from [42]

Electricity tax	0.0417 €/kWh [43]
VAT	25% [44]
Distribution fee	0.0345€/kWh [45]
Company surcharge	0.0046 €/kWh [45]

(*) These inputs have already been used in [32], but are described in detail in this paper for being key for studying DR.

The effective heat capacity of each building, which is used here and in the original dataset, is estimated by The Swedish National Board of Housing Building and Planning [46] as a fixed value per square meter of the buildings' heated floor area, i.e., 130,000 J/K m^2. This fixed value is approximately the average of the range for very light to very heavy buildings reported in the ISO13790 standard [31].

Six different types of electrical heating systems are used with different levels of efficiency and, for the heat pumps, different coefficient of performance (COP): electric boilers (with hydronic system); direct electric heating (without hydronic system); and four different types of heat pumps. The heat pumps are categorized based on their COPs, and the COP is assumed to be constant for each type of heat pump and is set to a yearly average, with the COPs being 3.5, 3, 2.5, and 1. The efficiency of the electric boilers and for direct electricity is set at 0.98. The classification and efficiency levels/COPs are taken from [39].

The definition of the values for the power rating of the heating equipment in the different buildings is based on the method recommended by the Swedish National Board of Housing, Building and Planning [41].

Variations in the hourly internal heat gains from lighting, appliances (not including heating), and occupancy are given as inputs to the energy balance in the modeling. The variations consist of a weekly variation (one value per week) for heat gains from lighting and cold appliance loads to capture seasonal variations (seasonal variations are not applicable to other appliance loads) (see Figure 2), and intraday variations (one value per hour) from lighting, appliances, and cold appliances (see Figure 3), both of which are based on the data from Zimmermann [28]. The same variations are applied to each sample building. The annual average internal heat gains per hour for the loads, which are used as the basis for calculating the variations, are assumed to be the same as in the original dataset, i.e., 0.72 W/m^2 for lighting, 0.78 W/m^2 for occupancy, and 2.15 W/m^2 for appliances [29]. Heat gains due to occupancy are assumed to follow the calculated average for the appliance and lighting patterns.

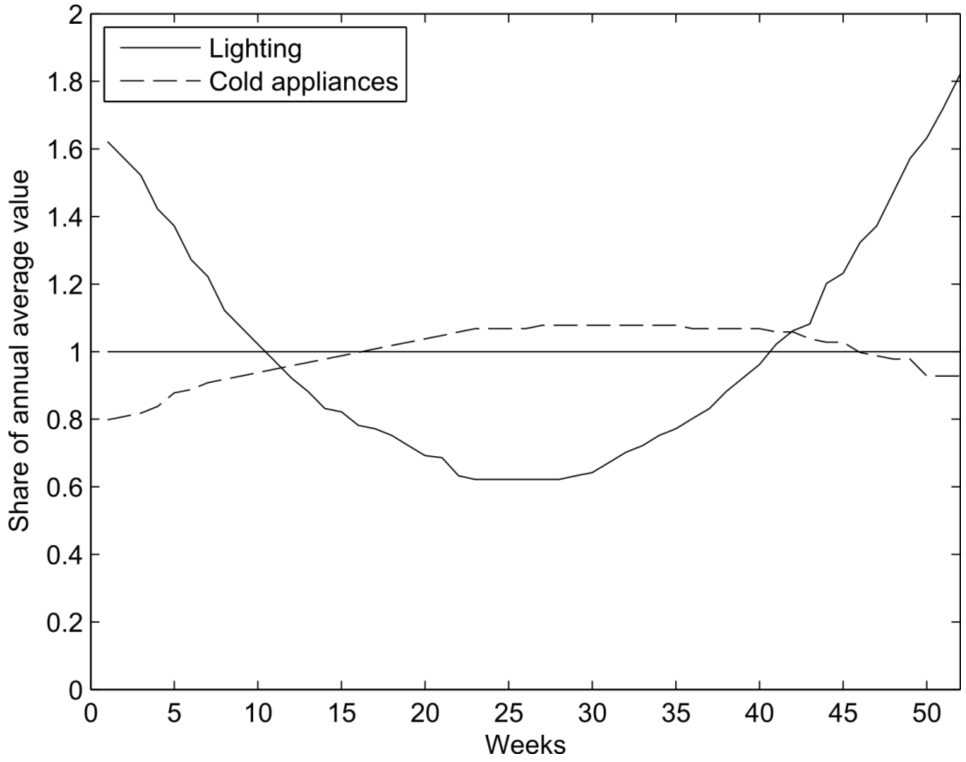


Figure 2: Average weekly variations in heat gains from lighting loads and cold appliances as a share of the average annual heat gain in Swedish SFDs[28].

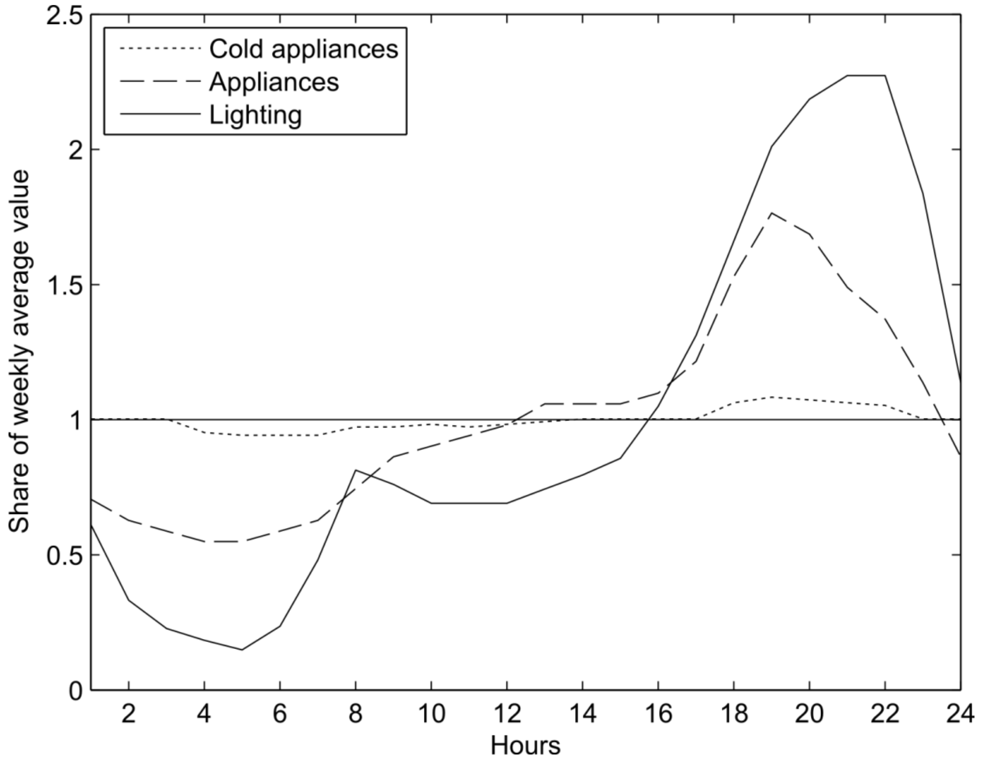


Figure 3: The average hourly (hour 1–24) variations in heat gains as shares of the weekly mean values from cold appliances, appliances, and lighting, obtained from measurements in Swedish SFDs[28].

3.4 Input data for the optimization sub-model

The hourly day-ahead electricity spot prices are obtained from Nordpool Spot for the years 2010 and 2012 [42]. In Year 2010, Sweden had a common electricity price, with an average annual electricity price of 0.062 €/kWh. However, since November 2011, Sweden has been divided into four pricing areas, SE1–SE4, and for Year 2012, the following average prices (in €/kWh) applied to the four pricing areas: 0.032 (SE1), 0.032 (SE2), 0.033 (SE3), and 0.034 (SE4). The electricity tax, VAT, distribution fee, and company surcharge were set at 0.0417 €/kWh [43], 25% [44], 0.0345€/kWh, and 0.0046 €/kWh, respectively [45]. All costs are given in $€_{2012}$.

3.5 Validation of the baseline

The description of all Swedish SFDs with electrical heating is validated for Year 2010 by comparing the electricity demand obtained from the modeling using the building description with the corresponding data in statistics from the Swedish Energy Agency. The resulting total demand for electricity for space heating and hot water from the model for Year 2010 is 19.9 TWh, which is 1.5% higher than the value derived from the statistics. According to the Swedish Energy Agency [47], the total electricity demand for space heating and hot water in Swedish SFDs in Year 2010 was 15.9 TWh. However, in dwellings that were partly or exclusively heated with electricity, the Swedish Energy Agency [24] indicates that an additional 2,900 kWh/dwelling should be treated as electricity for heating purposes, resulting in an additional demand of 3.73 TWh when applying this value to the 1.29 million SFDs that are partly or exclusively heated with electricity in the present work. Thus, the electricity demand for heating and hot water becomes 19.6 TWh. The electricity demand for space heating (only) from the model is 17.5 TWh. The hot water demand is not modeled. Instead, an average demand of 1,900 kWh/dwelling is assumed, which gives a total electric hot water demand of 2.44 TWh [48]. Thus, the total electricity demand for space heating and hot water is 19.9 TWh.

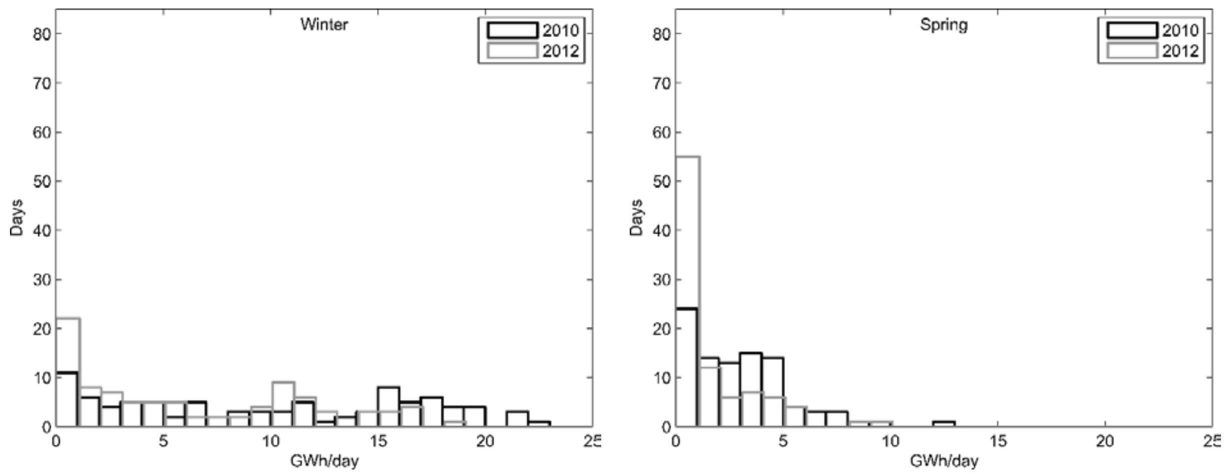
According to The Swedish Energy Agency [47], approximately 1.29 million SFDs are entirely or in part heated by electricity; the corresponding number for the input used in this work is 1.26 million, which is 2.3% lower than the value from the statistics. The heated floor area reported by The Swedish Energy Agency [47] is 185 million m^2 for dwellings that are partly or exclusively heated with electricity; the corresponding result for the input used in this work is 192 million m^2, i.e., 3.8% higher.

4. Results

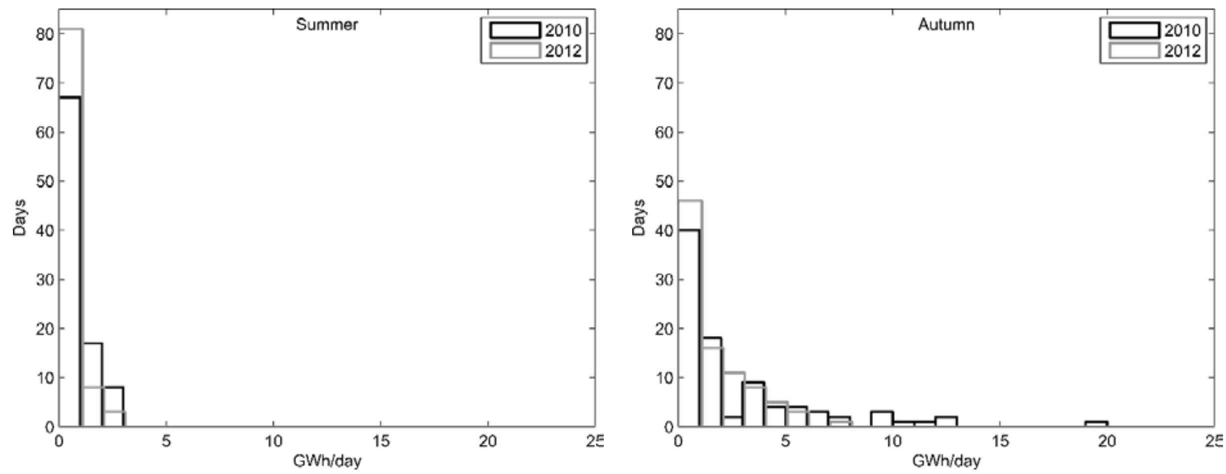
The shifting patterns in the modeling are dependent upon the electricity price structure, outside temperature and the internal and external heat gains. In the modeling three general shifting patterns can be observed, all of which are primarily driven by the electricity price structure. The first occurs when a fairly flat price curve is followed by an increase in electricity price. Such a curve will result in a large decrease in load for the hour with high electricity price, and a large increases in load on the hour or hours just prior to the decrease. The second pattern is seen when a lower-priced hour is surrounded in time by hours of higher and flat prices. This will lead to the load from several hours being concentrated into the low-price hour. The final pattern is seen for a continuously increasing price curve, which is usually seen during periods when system demand is increasing. Such a price curve will result in a decrease in load during one or a few hours with the load increase being spread out during several of the preceding hours to utilize the lower prices.

4.1 Potentials for demand response

Resulting from the input data presented in Section 2.3 the technical potential of the power available for DR from all electrical space heating systems in Swedish SFDs is 7.3 GW. In other words, this is the maximum load that can be used when shifting. The data also gives that the amount of energy storable in the SFD building stock is 6.9 GWh/°C. Given the current electricity prices the optimization sub-model shows that out of the 7.3 GW technical potential up to 5.5 GW of decreased load and 4.4 GW of increased load is observed during one hour. Furthermore, 1.46 TWh of the 17.5 TWh of total electric space heating demand are shifted in the case of the high-price year (2010), with 60% of the shifting taking place during the winter months, 18% each during the spring and autumn months, and 4% during the summer months. For the normal-price year (2012), 0.90 TWh of approximately 13.4 TWh of electric space heating demand are shifted, with 63% of the demand being shifted during the winter, 17% in the spring, 16% in the autumn, and 4% during the summer months. The shifting is not evenly spread between days and can vary substantially within a season, with some days having no shifting at all. Figure 4 shows the obtained number of days within steps that have a width of 1 GWh/day of electricity shifted for the four seasons for the years of high price (Year 2010) and normal price (Year 2012). It can be seen that during winter the days with shifting are fairly evenly spread over the range of electricity demand shifted, while for the three other seasons there is a concentration of days with low levels of shifted energy (<1 GWh/day). Furthermore, it can be seen that for the normal-price year (2012) case, the days with shifting are more concentrated towards days with a low level of energy shifted. Both these observations are primarily driven by intraday electricity price fluctuations, which are higher during winter and for the high-price year (2010). The maximum amount of electricity shifted during a day is 23 GWh, which is seen during the winter of the high-price year (2010). The amounts of shifted electricity are lower during the other seasons: around 12 GWh per day in the spring, 19 GWh in the autumn, and 2.5 GWh in the summer. For the normal-price year (2012) case, the maximum amount of energy shifted is less than that in the high-price year during the winter, autumn, and spring (18 GWh, 7 GWh, and 10 GWh, respectively), while both years give approximately the same levels of shifting during the summer.



a) b)



c) d)

Figure 4. Number of days with a specific number of GWh of electric heating demand shifted for Swedish SFDs, as obtained from the modeling for the high-price (2010) and normal-price (2012) years. a, winter; b, spring; c, summer; and d, autumn.

Figure 5 shows the modeled electricity shift on an hourly basis, separating the increases and decreases in load with a step width of 0.4 GWh/h. Only the high-price year is displayed, since the two years show similar shifting characteristics. During the winter, the number of hours with increased load exceeds the number of hours with decreased load. The number of hours with decreased load is higher than the number of hours with increased load for the spring, summer, and autumn. Applying DR during these seasons results in the load being concentrated into fewer hours compared to a system without DR. For the winters, the opposite is true, with fewer hours with decreased load than with increased load, indicating that the load is being spread out during winter months. It is clear that the maximum increase in load during 1 hour is similar for the winter, spring, and autumn, while it is considerably lower in summer (approximately 4.4 GWh/h). The maximum load decrease during 1 hour is higher for the winter than for the other seasons (approximately 5.5 GWh/h for winter, 3 GWh/h for spring, 1.5 GWh/h for summer, and 4.5 GWh/h for autumn). It can also be seen that for all seasons, the hours with a low (<0.4 GWh/h) increase or decrease in load are considerably more numerous than the hours with a higher (>0.4 GWh/h) increase or decrease in load, i.e., most of the increases and decreases in load comprise small changes in the electric heating demand. Furthermore, it can be seen the maximum decrease in load is higher than the maximum increase during winter, while the opposite is the case for spring and summer.

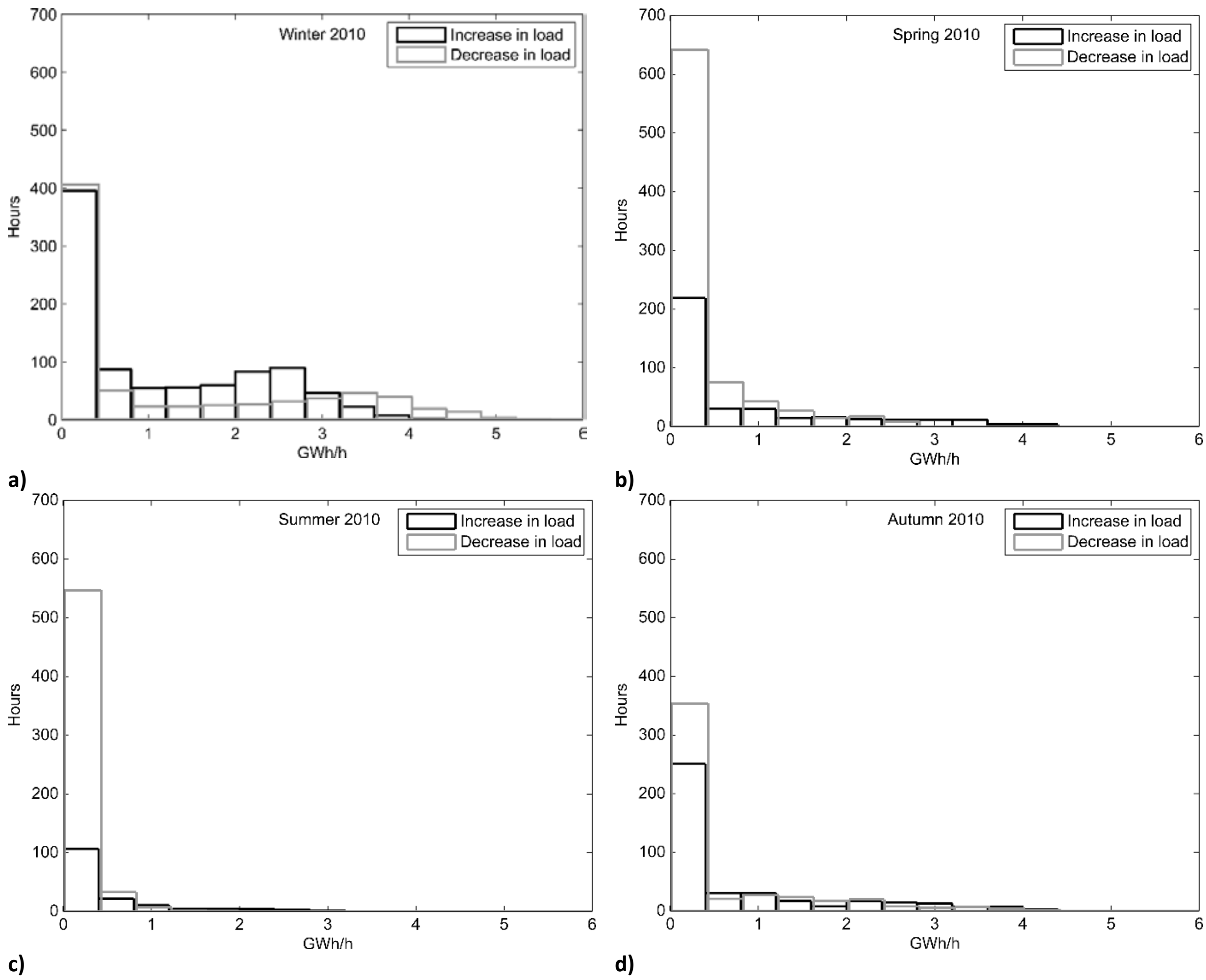


Figure 5. Numbers of hours with a specific amount of GWh/h of electric heating load being shifted for Swedish SFDs, as obtained from the modeling for the high-price year (2010). a, winter; b, spring; c, summer; and d, autumn.

4.2 Demand response impact on the total system load

The required price difference for shifting and the shifting time-frame depend on the characteristics of the buildings and the weather conditions. A high effective heat capacity requires lower price variations between the hours shifted to and from, since the smaller increase in temperature per shifted unit of energy results in a smaller increase in energy demand per shifted unit of energy. The effective heat capacity will also limit the shifting time-frame because it will determine the amount of storable energy available within the indoor temperature range. All parameters that have an impact on the energy flux inside (e.g., solar irradiance) and outside a building will influence the shifting time-frame, as they will determine how quickly the upper or lower temperature limit is reached. Due to the variability of some parameters, such as weather and internal heat gains, the shifting time-frame will not be constant over time. The power of the heating equipment will limit the amount of energy that can be shifted to and from each time-step and will thus limit the extent to which a specific price difference can trigger DR. This is evident in Figure 5a, in that the largest decrease exceeds the largest increase for winter. This is due to the fact that during winter months most of the DR potential, i.e., the 7.3 GW total power rating for the heating systems, is already being used. Thus, turning off all the heating will result in a larger load reduction compared to what it is possible to achieve from a load increase for a given hour.

The modeling results show that the time-frame for shifting, i.e., the number of hours between an initial increase in load and the first subsequent decrease in load, varies greatly during the year. To illustrate the shifting behavior and the impact on the total system load, Figure 6 shows the modeled load curves for the Swedish SFDs for 2 days in December of the high-price year (2010), divided into load not moved, increased load, and reduced load. Figure 6a shows only the electrical space heating load, and Figure 6b shows the total system electricity load. In Figure 6a, a shifting time of up to 10 hours is seen (although the modeling gives up to 12 hours of shifting). Different shifting patterns are observed during the year, and two of these can be seen in Figure 6a. One of these is where the load is increased for several hours before a decrease in load for 2–3 hours, while the other is where the load is increased for 1 hour, followed by 1 hour with decreased load. Figure 6b shows that the first shifting pattern fills up the valleys in total electricity demand seen during the night/early morning (hours 8305-8311 and 8330-8336) and also increases the load during the afternoon (hours 8341-8344). The second pattern is seen during several hours of daytime (hours 8315-8324 and 8339-8340). As shown in Figure 6b, these increases result in new system peaks during the daytime (e.g., around hour 8320). As a consequence, new yearly system peaks are created during approximately 400 hours of the year. The new peaks occur because the DR takes place predominantly during the winter months when the total system load already is high. A similar pattern is seen for the normal-price year (2012). A third shifting pattern also occurs (although it does not appear in Figure 6), whereby the load is increased during 1 or 2 hours and then reduced during several hours, i.e., a concentration of load. This pattern is primarily seen during the summer, as evidenced by the higher number of hours with decreased load, as compared to the hours with increased load during the summer, as seen in Figure 5c.

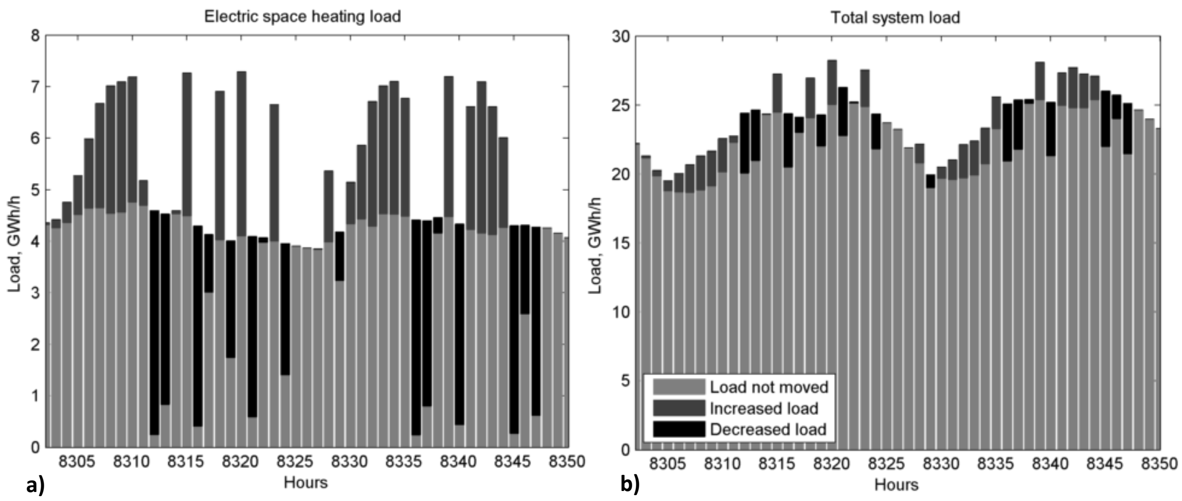


Figure 6. Modeled load curves for the Swedish SFDs for 2 days in December 2010, divided into load not moved, increased load, and reduced load. a, Only the electric space heating; and b, the total Swedish system load.

Figure 7 shows the duration curves for the Swedish SFDs, as obtained from the modeling work for the high-price year (2010). Figure 7a shows the share of the total installed heating capacity that is used during each hour of increased load for the entire year, and Figure 7b shows the share of modeled SFDs that reach the maximum allowed temperature for each hour of increased load. As Figure 7a shows that it is only for a few hours that the total installed heating capacity of 7.3 GW is used during DR, i.e., when all the buildings use the maximum heating capacity. It is also clear that during 1,100 of the roughly 1,800 hours of increased load the installed heating capacity starts to become a limiting factor for parts of the building stock. Furthermore, as shown in Figure 7b, the maximum temperature is reached for one or more of the buildings during the period of approximately 200 hours. Thus, the energy (heat) storage capacity of the buildings is only limiting for a few of the hours with increased load. Consequently, it is mainly the economic gain that governs how and to what extent DR is applied in the modeling.

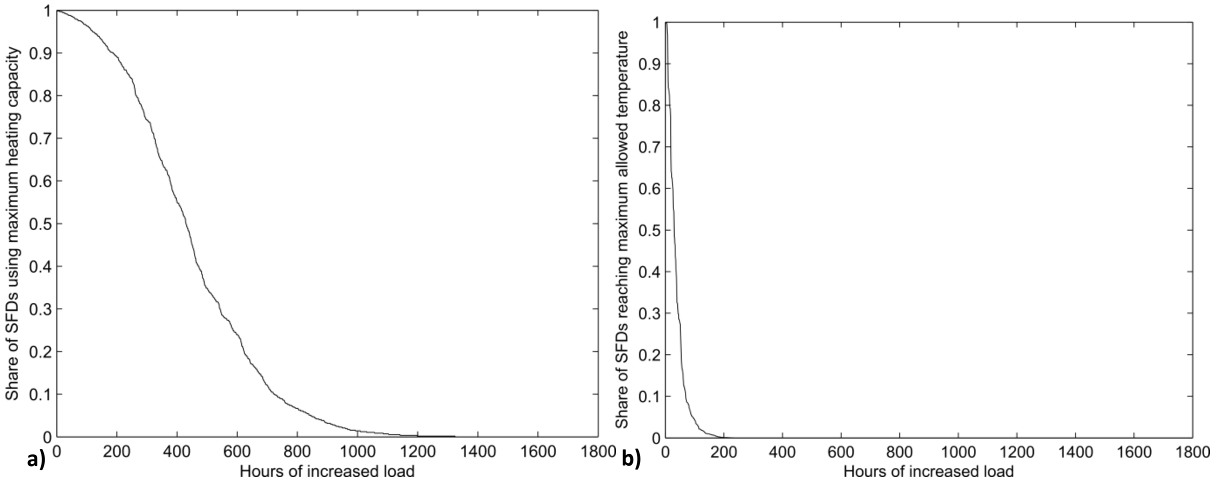


Figure 7. Duration curves for the Swedish SFDs, as obtained from the modeling in this work for Year 2010. a, The share of SFDs using maximum installed heating capacity during hours of increased load. b, The share of SFDs that have reached the maximum allowed indoor temperature during the hours of increased load depicted in panel a.

4.3 Impacts on electric heating demand and on individual dwellings

The annual space heating electricity demand in Year 2010 increases by 0.9% (152 GWh) if DR is employed, which corresponds to a total system increase in electricity demand of 0.1%. This increase is not divided equally between the seasons, as the increases in seasonal electric heating demand are as follows: 104 GWh in winter, 18 GWh in spring, 6.9 GWh in summer, and 25 GWh in autumn. For the Year 2012 case, the annual electric heating demand increases by 0.6% (95.6 GWh), with 68 GWh in the winter, 13 GWh in the spring, 3.4 GWh in the summer, and 12 GWh in the autumn.

Figure 8 gives the percentage increase in electric heating demand caused by the DR for each of the 571 representative buildings modeled. As can be seen, the electrical heating demand increases by 0.2%–2.0% at a building level for the different representative SFDs modeled. The representative buildings with high levels of shifting show smaller increases in demand per percentage of heating demand shifted, as compared to buildings with a low level of shifting.

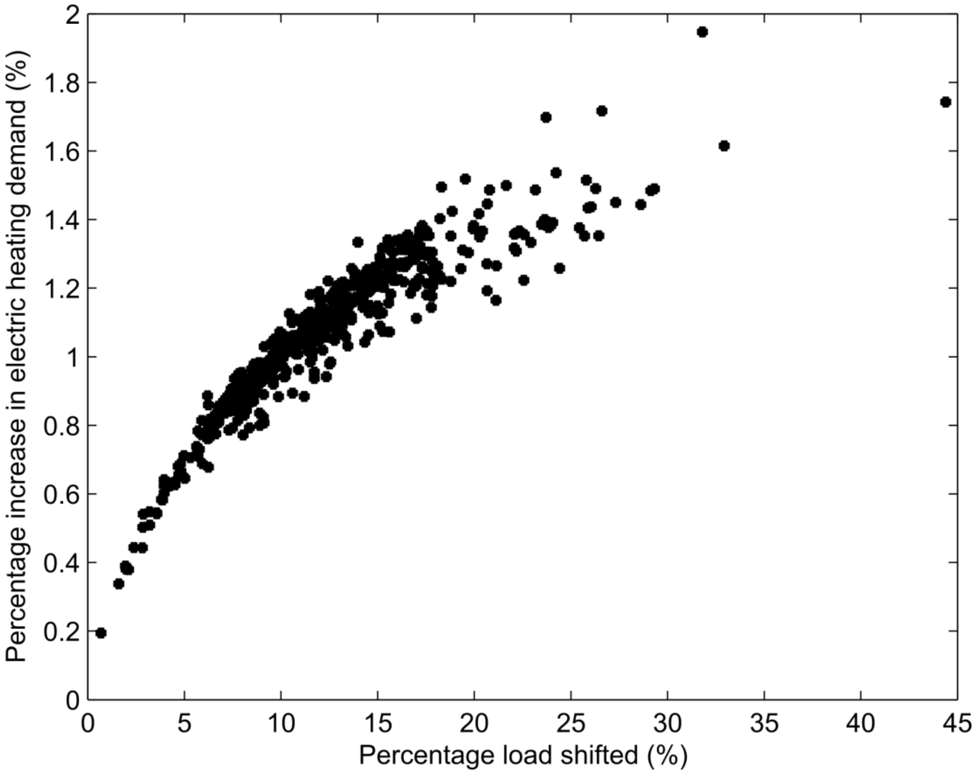
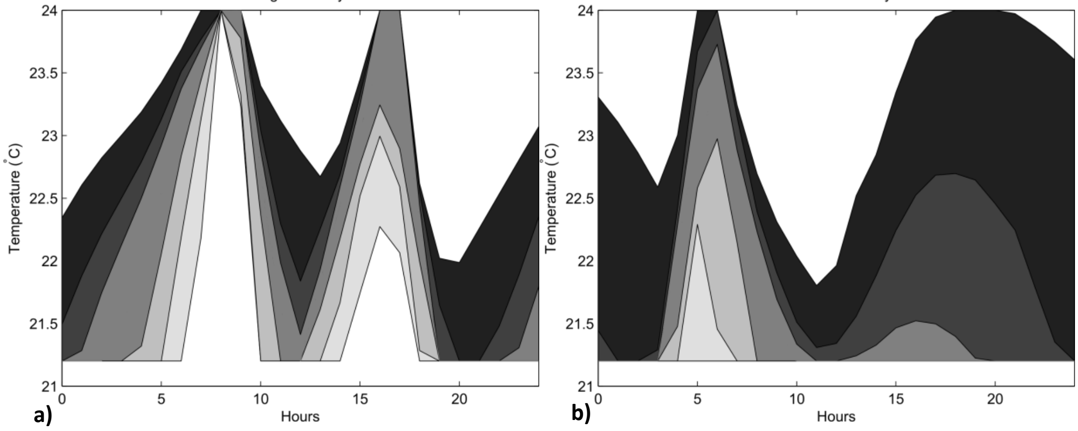


Figure 8. Percentage increases in electric heating demand caused by DR for each of the 571 representative buildings modeled in this study. Each increase is plotted against the percentage of electric heating demand that is shifted for the high-price year of 2010.

Figure 9 gives the indoor temperature profile obtained from the modeling during three 24-hour periods in winter time for a high-shift day (18.9 GWh of electric heating shifted; Figure 9a), a medium-shift day (8.1 GWh shifted; Figure 9b), and a low-shift day (1.1 GWh shifted; Figure 9c). The %-intervals correspond to the percentages of SFDs with a temperature within the observed interval or higher. The temperature rises predominantly during the night, early morning, and early afternoon, and drops during midday and evenings. For a day with a high level of shifting, 100% of buildings are involved in shifting, and virtually all of these reach 24°C during 1 hour. For a medium-shift day, at least 90% of the buildings are involved in shifting sometime during the day and 10% reach the maximum temperature. During the low-shift day, up to 65% of the buildings take part in shifting, although the temperature rise in the buildings is relatively small.



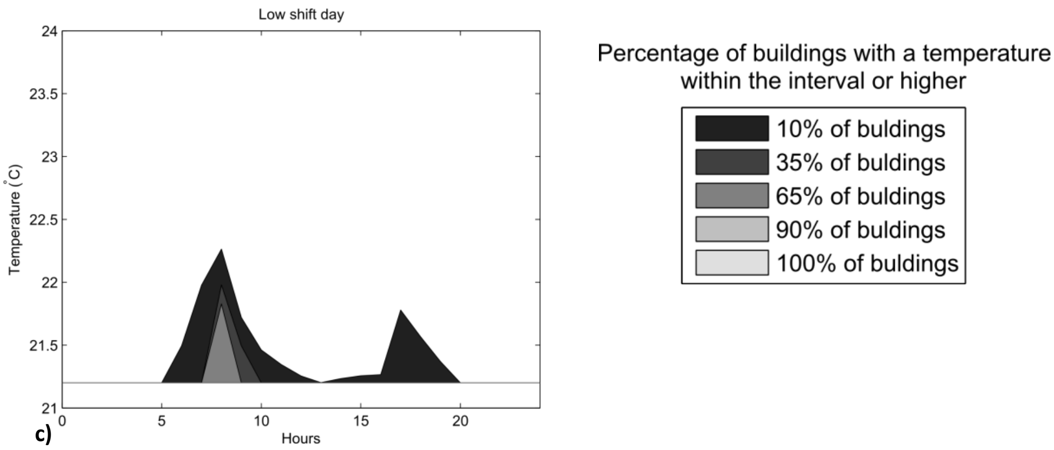


Figure 9. Temperature profiles for three different 24-hour periods during the winter season. a, A high-shift day (18.9 GWh shifted); b, a medium-shift day (8.1 GWh shifted); and c, a low-shift day (1.1 GWh shifted). Each interval represents a certain percentage of the building stock.

Figure 10, the operation of the heating equipment of two different SFDs during a high-shift day is shown as an example, with Figure 10a showing an SFD with a high degree of shifting and Figure 10b showing an SFD with a lower degree of shifting. The discrete jumps are due to the hourly price signal to which the operation of the heating system reacts. As can be seen in the figure, the heating system of a building with a high degree of shifting operates maximally for several hours with a high degree of shifting, and is then turned off for several hours. In contrast, for a building with a low degree of shifting, the maximum is reached for only 1 hour and the heating system is never turned off in the example shown.

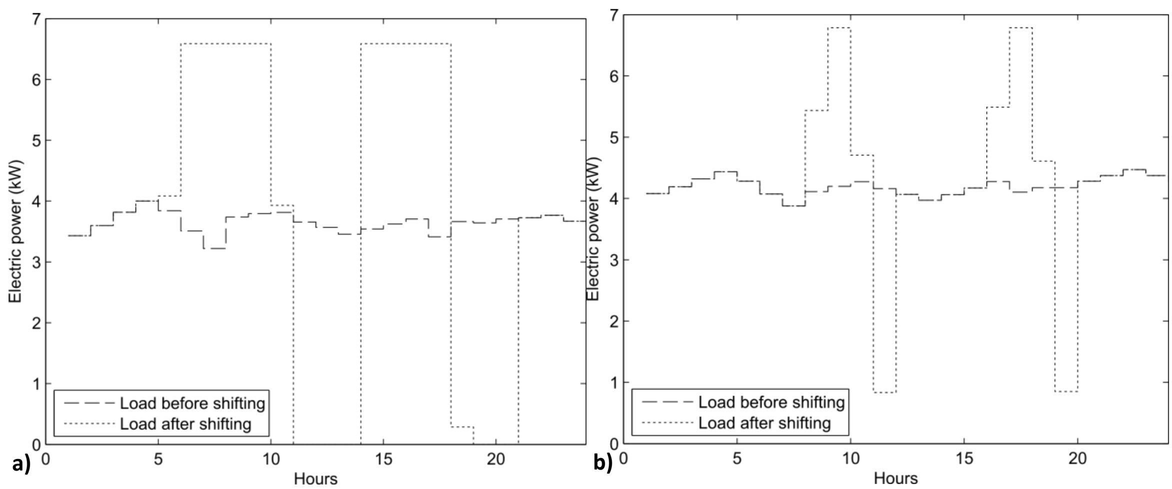


Figure 10. The load patterns of two buildings before and after a DR has been applied for the high-shift day in Figure 9. a, A household with a high level of shifting; b, a household with a lower level of shifting.

The annual cost savings from DR per SFD are generally low, as indicated above. For the high-price year (2010), they are in the range of 0.9–330 €/year (corresponding to 0–1.3% of median disposable income per person living in Swedish SFDs) or 0.3–12.0% of the total electricity bill for space heating without DR, with the median value for the SFD building stock being 72€/year per dwelling or 3.7% of the total electricity bill for space heating. For the normal-price year (2012), the annual cost savings are in the range of 0.36–97 €/year or 0.2–8.6% of the total electricity bill for space heating, with a median of 23 €/year per dwelling or 2.0% of the total electricity bill for space heating. Thus, as expected, the savings are lower for the normal-price year (2012) than for the high-price year (2010), yielding a lower level of energy shifted in 2012 than in 2010 (*cf.* Figure 4). The observed range of cost savings is due to the fact that the buildings investigated differ correspondingly with respect to installed electric heating capacity and building characteristics (e.g., size) and therefore differ in terms of possible economic gain from a shift in demand.

4.4 Sensitivity analysis

The influence of each input parameter on the results given above [i.e., annual load shifted (MWh), annual average indoor temperature (°C), annual electric heating demand (MWh), and annual economic savings (€/per year)] is quantified using a normalized sensitivity analysis. A normalized sensitivity coefficient, i.e., the corresponding percentage change in the output variable of the model given a 1% increase in an input parameter, is calculated according to Firth et al. [49]. Table 2 shows the seven input parameters with the strongest influences on the result variables [*cf*. Mata et al. [29] for the full list of parameters used in the model, all of which have been included in this sensitivity analysis]. The power rating of the heating equipment shows the greatest positive correlation for the amount of load shifted, with a 1% increase in power rating corresponding to a 1.07% increase in the amount of load shifted, followed by the effective heat capacity, which shows a 1.05% increase in the amount of load shifted. This indicates that an increased ability to supply energy during a low-price time-step has a similar impact on the amount of energy shifted as the ability to store more energy per increase in temperature degree. However, the effective heat capacity also shows the greatest positive correlations for temperature and electricity demand, indicating that the increase in shifting due to increased heat capacity is less effective than an increase in power rating. Furthermore, this can also be seen in the higher sensitivity coefficient for economic savings for the power rating, as compared to the effective heat capacity. This indicates that there is greater monetary value in being able to increase the temperature rapidly during a low-cost hour, i.e., use more power, than in being able to store heat for a longer duration, i.e., having a higher heat capacity.

The largest negative correlations for the amount of load shifted are seen for the U-value, surface area of the building, heated floor area, and sanitary ventilation rate, due to the increased heat transfer. However, despite the increase in heat transfer caused by increase in these values, the correlation to electricity demand is negative, as a decrease in load shifts the results to a lower increase in electricity demand (see Figure 8).

Table 2. Normalized sensitivity coefficients for the input parameters with strongest influences on the amount of load shifted, average annual indoor temperature, electricity demand for space heating, and economic savings. The numbers correspond to the response from a 1% increase in the input parameter.

Input Parameter	Amount of demand shifted	Average annual indoor temperature	Electricity demand	Economic savings
Power rating of heating system	1.07	0.33	0.33	1.94
Effective heat capacity	1.05	0.57	0.58	0.94
U-value	-0.70	-0.52	-0.23	-1.42
Surface of building envelope	-0.69	-0.52	-0.22	-1.42
Heated floor area	-0.33	-0.28	-0.12	-0.46
Sanitary ventilation rate	-0.25	-0.25	-0.10	-0.52
Allowed minimum indoor temperature	-0.13	-0.52	-0.52	-0.72

5. Discussion

The modeling carried out in the present work shows that shifting electric space heating can have a considerable effect on the overall load curve, with a maximum decrease in load of 5.5 GW and increases of up to 4.4 GW (see Figure 5). This shifting and its duration (i.e., energy) can potentially be used to facilitate variation management of intermittent power generation on the electricity supply side, depending on the characteristics of the variability of the intermittent generation and on the grid voltage level connected. As a comparison, the total rated capacity of Swedish wind power is currently around 4.4 GW, i.e., corresponding approximately to the maximum increase and decrease seen in the model results of this work. However, the reduction and increase in heating load can obviously not be performed independently of each other, i.e., the time-span of the variations from the production source are important. As mentioned above, the modeling gives that load shifting of the heat demand is up to 12 hours. Thus, only variations in generation within that time-scale can be handled through DR of the electric heating load. The characteristics of aggregated wind power variations also includes longer periods of low output (as is the case for the Nordic region), indicating that the possibility to manage wind variations with the electric space heating load may be limited. Given that a smaller fraction of the heating power capacity is used, it would be possible to cascade the use of the heating systems and thereby achieve longer shift times, albeit with a lower amount of energy shifted. Achieving this type of load-shifting pattern would require more than a single price signal as a driver for shifting, for instance, the use of an aggregator that can control the load. Furthermore, the utilization of the electric space heating demand for managing of solar generation variations is limited. This is due to the low seasonal correlation between electric space heating demand and solar electricity generation for Swedish conditions [50].

Part of the large potential for DR capacity, 7.3 GW, identified in this work may also be used to offer primary and secondary operating reserves in the electricity system. Short-term variations in load and a higher level of intermittent generation in the system brings with it imbalances between planned generation and load, which require regulating reserves. The heating load could possibly be used to supply some of these regulating reserves. As the ramping rate for the aggregated heating demand is instantaneous, it can provide considerable power during hours with rapid changes in electricity generation or load. An increased need for rapid ramp rates can occur in systems where high levels of intermittent generation are ramping down whilst load is ramping up or staying constant. Such a scenario requires a considerable amount of fast-responding reserve capacity, which can be provided by the heating load. The quick ramping rate could also reduce the need for spinning and non-spinning reserves for contingency events. A possible 3–4 hours of reduced load, as seen in this work, would allow for power from the tertiary reserve market to be activated. However, the need for contingency services in the case of a failing power generator or transmission line cannot be planned. Therefore, preheating of the building stock in order to accommodate a reduction in load would not be possible. Instead, consumers would have to accept a reduction in indoor temperature to below the desired level. As indoor temperatures would need to be restored, any tertiary reserve activated would need to handle this increase in demand. A problem in applying the heating load for these types of services is that the available load is weather-dependent. Thus, the heating load brings with it intermittency properties to a greater extent compared to other loads, such as fridges and freezers. During summer months, the potential for reducing load is limited, which hampers the ability of heating loads to replace contingency services. Furthermore, as stated above, the electricity demand forecast is never completely accurate, which means that the exact available load that can be used for these services is not known beforehand.

It should be noted that in the modeling the maximum allowed indoor temperature is seldom reached and the maximum power rating of the heating system is not always fully utilized, indicating that the technical shifting potential, both in terms of time-span and the amount of energy shifted, is larger than that obtained from the modeling in this work. The maximum technical potential is not reached because the modeling is based on an economic optimization, so the DR is only used when it is economically favorable, i.e., the consumers lower their electricity cost. As the Swedish electricity system in 2014 consists of only around 7% (3.5% for the modeled Year 2010) intermittent production (in terms of energy) and regulating hydro power, short-term price fluctuations are relatively small, thereby reducing the need for and use of DR. An electricity system in which non-dispatchable electricity production sets the electricity price for a considerable part of the year (as opposed to price governed by demand) can result in more short-term fluctuations in electricity price. Given that these price fluctuations are on the same time-scale as the time-frame for the shifting observed in the current modeling, the fluctuations would increase the utilization of the buildings for heat storage. In such a system, the creation of new system peaks in electricity demand due to the DR only reacting to day-ahead prices, as showed by the model, might not be so problematic. The new peaks could appear during hours of excess generation and thus be beneficial, whereas in the currently used system, the peaks are likely to increase the use of peak-load plants. However, as discussed above, this might still not be the optimal way for the system to use the load available for shifting. Furthermore, it can be seen that shifting does not take place during all hours with heating demand, which suggests that the shifting potential is greater than identified in this work. However, the results give an indication of the maximum power capacity and probable shifting times and energy levels that can be expected, given the current Swedish system.

As only an increase in temperature is considered as a means for shifting load in the model, the DR is always associated with an increase in total yearly heating demand. This increase may result in increased emissions and thus, the potential environmental benefits that result from shifting would have to be counter-balanced by the effect of increased demand. Allowing the indoor temperature to be lowered below the baseline temperature as a method for shifting avoid the increase in demand. However, households would have to accept temperatures below their comfort level during parts of the day.

The results show that the possible savings from shifting are fairly low, with average savings of 2.0%–3.7% in the annual bill for electric heating. This is obviously far too low and one cannot expect the current price structure to prompt consumers to drive the implementation of DR. This is the situation despite the indoor temperature in the present work being allowed to increase to 24°C as a result of the DR, which is clearly high in terms of what is a reasonable comfort level. The required investment cost needed to execute the shifting could further reduce the possible savings, especially since discount rates applied by consumers are generally high for investments in improvements in energy efficiency [51]. In summary, the value derived from DR must probably be on the supply side, with the utilities offering equipment for DR in a way that it is not perceived as negative by the customer.

Future buildings will likely be more energy-efficient and therefore have a low U-value. As shown in the sensitivity analysis, this should increase the possibility for DR as the time-span for shifting the load would increase. However, the power rating of the heating equipment will also be lower for such buildings. A lower power rating will have the opposite effect to the lower U-value reducing the amount of load shifted, since low-price hours cannot be utilized to the same extent.

Constant COP values are assumed for the heat pumps. This should underestimate their impact during the colder winter months, leading to an underestimation of the power available during these hours. The averaging should also lead to an overestimation of the power available during late spring and early autumn when temperatures are higher. However, as the amount of energy available for shifting during periods of higher temperatures is lower than during periods of lower temperatures, the impact of the overestimation should be smaller than the impact of the underestimation. The higher level of shiftable power during the winter months would also result in a further increase in the new system peaks created by the DR.

As mentioned in Section 3.3, the effective heat capacities have been roughly estimated by multiplying a constant by the heated floor area of the archetype. The ISO13790 standard shows a range of 60% increase and decrease for the value treated as a constant in the modeling, for very heavy and very light buildings, respectively. A refinement of the input with respect to the effective heat capacity of each representative building could substantially change the potentials for DR reported in this work.

As for the inputs for the U-values, surfaces of the building envelope, heated floor areas, and sanitary ventilation rates, these are all based on detailed measurements from the BETSI study and should give a good representation of the building stock [37].

It should also be noted that the optimization is based on the notion that every consumer minimizes their annual electricity bill without this influencing the electricity price. As previously mentioned, this creates new peaks in the system, which suggests that from a systems perspective it is not the optimal way to shift the load. Thus, in order to uncover the real potential and usefulness of being able to dispatch the electric heating demand, the model should be integrated into an analysis/modeling system that also includes the electricity generation system. Furthermore, separation of the indoor air temperature and building structure temperature could make the modeling more precise. This is the case because the air has a lower effective heat capacity than the building structure. Depending on the type of heating equipment, the temperature of the indoor air might increase faster than that of the building structure, limiting the amount of load that can be shifted within a given hour. It is also likely that separating the indoor air temperature from that of the building structure would result in longer periods of high indoor temperature during periods of shifting.

6. Conclusions

A dynamic cost optimization model is developed to investigate the effects of shifting electrical space-heating loads in Swedish SFDs as a means for demand response (DR), using the thermal inertia of the buildings and the current Swedish electricity retail pricing scheme.

The power available for DR in the heating system is found to be substantial (7.3 GW). Given the current Swedish electricity prices, up to 5.5 GW and 4.4 GW of this potential is used for decreasing load and increasing load, respectively, when DR is applied. However, given the price structure applied, there is only a weak economic incentive for DR from the houseowner’s perspective.

The maximum amount of energy that is storable in the SFDs, given an assumed temperature increase of 2.8°C, is 19.2 GWh. The amount of electricity shifted by the model is 1.46 TWh for the high-price year (2010) investigated and 0.6 TWh for the normal-price year (2012). Around 60% of the electricity is shifted during the winter months, 16%–18% during spring and autumn, and 4% during summer. Furthermore, it is evident that for the winter, the number of GWh shifted during days with DR is fairly evenly distributed in the range of 0.1–20 GWh. For the remaining seasons, shifting is dominated by days with shifted levels <1 GWh. During the winter season, the DR results in the load being spread out, i.e., there are more hours with an increase in load than hours with a decrease in load. For the other three seasons, the opposite pattern is noted, with the concentration of loads into fewer hours due to shifting. For all four seasons, the hourly increase or decrease in load is dominated by shifts of <0.3 GWh/h. Furthermore, we show that load can be moved for up to 12 hours, although the primary limiting factor for shifting is weak economic incentives. While the power rating of the buildings limits the shifting during roughly one-third of the shifting hours for 50% of the buildings, the effective heat capacity is only a limiting factor during very few hours.

Implementing shifting under the current electricity pricing schemes will result in new system peaks during approximately 400 hours. The increases in peak demand could necessitate the use of additional peak power plants, thereby increasing the cost of electricity during the hour to which the shift was made, as well as potentially increasing CO_2 emissions. Thus, if large-scale DR of electric space heating is to be implemented other indicators than the day-ahead electricity price are needed given the current system.

Furthermore, if only an increase in temperature is allowed when shifting, as was the case in the modeling of this work, the shift results in an increase in electricity demand for space heating corresponding to 0.1% of the total system demand, which represents a 0.6%–0.9% increase in the total system heating demand, and 0.2%–2.7% of the annual electrical heating demand of a Swedish SFD. Approximately 66% of the increase in demand occurs during the winter months, 11%–16% during spring and autumn and 4% during summer. Therefore, the DR defined in this work cannot be seen as an energy-saving measure.

The potential monetary savings for households range from 0.9 to 330 €/SFD for the higher-price year of 2010 and from 0.36 to 97 €/SFD for the lower-price year of 2012. The large ranges are due to the fact that the buildings investigated differ correspondingly with respect to the installed electric heating capacity and building characteristics (e.g., size), and therefore have different potentials for securing economic gain from a shift in demand.

Acknowledgments

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APPENDIX

Mathematical model for cost optimization of space heating demand

The General Algebraic Modeling System (GAMS) is chosen as an optimization tool. For all building physics equations implemented in the model, i.e., equation 2 and all heat gains and heat losses included in that equation, see Mata et al. [29].

$$\min C_{tot} = \sum_{n=1}^{k} \sum_{h=0}^{t} (p_{h,n} \times e_{heat,h,n}) \tag{A.1}$$

$$\boldsymbol{T}_{int,h,n} = \boldsymbol{T}_{int,h-1,n} + \left(q_{t,h-1,n} + q_{vSa,h-1,n} + q_{int,h-1,n} + q_{r,h-1,n} + q_{heat,h,n}\right)/C_{m,n} \tag{A.2}$$

$$21.2 \leq \boldsymbol{T}_{int,h,n} \leq 24 \tag{A.3}$$

$$0 \leq q_{heat,h,n} \leq S_n \tag{A.4}$$

$$e_{heat,h,n} = q_{heat,h,n} \times E_n/\eta_n \tag{A.5}$$

where:

C_{tot} = Total cost for heating for all the buildings

$p_{h,n}$= The price of electricity at hour h

$e_{heat,h,n}$= Electricity demand for heating in building n at hour h

$\boldsymbol{T}_{int,h,n}$ = Indoor temperature at hour h in building n

$q_{t,h,n}$ = Transmission heat losses from building n at hour h (W)

$q_{vSa,h,n}$ = Heat loss due to ventilation in building n at hour h (W)

$q_{int,h,n}$ = Internal heat gains in building n at hour h (W)

$q_{r,h,n}$= Heat gain due to solar irradiance in building n at hour h (W)

$q_{heat,h,n}$ = Heat provided in building n at hour h from heating equipment (W),

$C_{m,n}$ = Effective heat capacity of building n (J/K)

S_n= Maximum power available from heating system in building n (W)

E_n= Share of heating demand covered by electricity in building n

η_n= Efficiency of heating equipment in building n