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Heat demand in the Swedish residential building stock - pathways on demand reduction potential based on socio-technical analysis

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ABSTRACT

A transition to a more efficient heat energy system requires the consideration of drivers covering behavioural change, upgrades of the building stock and substitution or improvements in technologies in use. Sweden has set the target to reduce total energy demand per heated area in buildings by 50% by 2050 compared to 1995. This study aims to estimate the potential for reducing heat energy demand in the Swedish residential building stock taking into account behavioural, structural and technological categories of drivers. A combination of bottom-up energy modelling with scenario methodology informed by socio-technical analysis of barriers was used. Our results show that the target can be achieved by combining at least two of the categories of drivers. However, it is noteworthy that the technological category, which has by far the lowest level of barriers, almost reaches the target largely owing to the high impact for single-family houses, showing the crucial role of changes in the technology mix. However, as the same drivers have different demand reduction potential in the two main building types in Sweden, single and multi-family houses, this calls for policymakers to lead on initiatives that foster a combination of technological, behavioural and structural improvements for the latter.

1. Introduction

Transitioning to a fundamentally more efficient residential heat energy system can be driven by improvements in several aspects of the system (Diefenbach et al., 2016; Nilsson et al., 2018; Sandberg et al., 2017; Turnheim et al., 2015). A broad set of drivers needs to be considered, covering behavioural change, changes in the building stock and substitution or improvements in individual technologies. However, the majority of current research on residential heat energy demand tends to focus purely on one or two of these aspects. Examples of studies for heat energy systems analysis include forward-looking analyses of the European residential heat energy demand in Switzerland (Siller et al., 2007), Norway (Sandberg et al., 2017; Sartori et al., 2009a), Sweden (Åberg, 2014; Brown et al., 2013; Mata et al., 2013), Germany (Blesl et al., 2007; Diefenbach et al., 2016), Greece (Dascalaki et al., 2016) as well as the European level (Balaras et al., 2005; Lechtenböhmer and Schüring, 2011; Petersdorff et al., 2006; Sandberg et al., 2016a). From these studies, the majority focuses purely on structural changes in the building stock through renovation, disregarding both behavioural and technological changes that influence the energy demand (Balaras et al., 2005; Brown et al., 2013; Dascalaki et al., 2016; Lechtenböhmer and Schüring, 2011; Petersdorff et al., 2006; Sandberg et al., 2016a), a range of studies combine analysis of structural and technological substitution or improvement but does not address behavioural change (Balaras et al., 2007; Blesl et al., 2007; Diefenbach et al., 2016; Sartori et al., 2009b; Siller et al., 2007), and few extend on all three aspects of behavioural, structural and technological change (Mata et al., 2013; Sandberg et al., 2017). In addition, studies tend to focus in depth on one building stock type such as apartment buildings (Balaras et al., 2005; Brown et al., 2013). Studies that focus on the national level tend to look into average national levels, missing out the particularities of building types (Mata et al., 2013; Petersdorff et al., 2006; Tommerup and Svendsen, 2006) and often investigate energy saving potentials only on the existing building stock (Balaras et al., 2007; Blesl et al., 2007; Connolly et al., 2014; Isaac and van Vuuren, 2009; Lund et al., 2010; Mata et al., 2013). Estimating the energy demand of new building stock is important, especially in countries with high population growth rate such as Sweden. According to Eurostat, Sweden has the third highest rate of population growth in the European union.[1]

Most notably, a common limitation of all the studies above is the lack of socio-technical analysis investigating not only the drivers for

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[1] https://ec.europa.eu/eurostat/statistics-explained/index.php/Population_and_population_change_statistics#EU-28_population_continues_to_grow.

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Nomenclature

End-use: End-use is the ultimate specific use for energy. The end-use categories in the building sector are space heating, domestic hot water, cooking, lighting and appliances

Useful energy: Useful energy is the energy required to satisfy the energy of end-use in a building, excluding conversion losses in the technical systems of the building. It is also commonly referred to as 'net energy'

Final energy: Final energy is the energy supplied to the building, including conversion losses in the technical systems within the building. It is also commonly referred to as 'delivered energy' or 'end energy use'

Energy Intensity: Energy Intensity is the amount of energy used in producing a given level of activity. It is expressed as energy per unit of activity measure of service. In the building sector, it expresses a building's energy use as a function of its size or other characteristics

Acronyms

DH	district heating
HP	heat pumps
DHW	domestic hot water
SFH	single-family houses
MFH	multi-family houses
COP	coefficient of performance
MLP	multi-level perspective
HDD	Heating degree day

potential energy improvements but also the barriers for this development. Combining approaches of quantitative modelling and socio-technical analysis broadens the perspective on transitions (Geels, 2016; Nilsson et al., 2018; Turnheim et al., 2015) in that it provides a system understanding of the barriers to the implementation of a policy measure (Dzebo and Nykvist, 2017; Egbue, 2012) and a socio-technical lens on energy transitions helps assess the feasibility of a given strategy (Nilsson et al., 2018; Turnheim, 2019). An increasing body of literature points to the importance of bringing analytical approaches. The potential of any energy demand reduction measure, whether on structural, technological or behavioural change, is likely to face barriers based on the status of technological development, the actors and networks in the sector, the governance and institutions and the costs of implementation in the country. While, for example, the high indoor temperatures are historically a norm in Sweden and backed by informal institutions resulting in average indoor temperature in apartment buildings as high as 22.4 °C, this is not the case in many other countries. Similarly, looking at heat pumps, a continuous technology progress together with a strong network of actors are resulting in the technology to be cost-effective in both old and new buildings. Clearly, those factors vary considerably between different countries and the need for overcoming a set of barriers for the implementation of measures in practice is recognized by Diefenbach et al. (2016). Socio-technical factors with regard to demand savings are particularly difficult to quantify (Kavgic et al., 2010a) and just as Kavgic et al. (2010b), Nässén and Holmberg (2005) and Nilsson et al. (2018) argue, we agree that the majority of quantitative models used for heat energy system analysis fail to analyse demand reductions with a broad socio-technical lens.

As stated in the program of the Swedish Environmental Objectives Council (Miljömålsrådet in Swedish), Sweden has set the target to reduce total energy demand per heated area in residential housing and commercial premises by 50% by 2050 compared to the 1995 consumption level (Regeringskansliet, 2010). Unlike most EU countries, reducing CO_2 emissions in the building sector in Sweden does not seem to be a challenge since the sector is almost fully decarbonized (Nilsson et al., 2018). However, looking at the energy efficiency index between 2000 and 2009, Sweden's performance appears to be lower than the average EU value, scoring well below countries such as France, Netherlands, United Kingdom, Germany and Ireland (European Environment Agency, 2017).

Most energy models for heating in Sweden are supply oriented and often do not sufficiently study energy demand. According to historical analysis of Sweden (Nässén and Holmberg, 2005), measures for improving energy efficiency have not been utilized properly despite great potentials due to the focus on reducing oil dependency. The strong focus on the supply side analysis is mirrored with an equally strong discourse of the importance of heat energy supply in general (Dzebo and Nykvist, 2017). As a result, energy efficiency improvements in Sweden have historically primarily been driven by factors such as the oil crisis in the 1970–1980s. The results for the Swedish energy system have been a gradual but forceful phase out of oil from the energy system (Fig. 1, Fig. 2). However, energy improvements levelled off in the 1990s (Nässén and Holmberg, 2005; Unander et al., 2004). Today, some improvement is again taking place since around year 2000 but despite demand reduction being a comparatively more important factor, it has historically been understudied (Nässén and Holmberg, 2005). Focusing on demand reduction potentials in the residential heating sector can provide room for energy demand in other sectors. For example, it can contribute to the increasing demand of biofuels or electricity in transport.

The purpose of this study is to estimate the potential for reducing heat energy demand in the Swedish residential building stock. Given the gaps in research mentioned above, a more detailed analysis of the demand side, which includes the two main building types in Sweden (single and multi-family houses), existing as well as newly built stock and measures that cover a spectrum of technological, behavioural and structural drivers taking into account the associated socio-technical barriers is considered a worthwhile approach. Our aim is to contribute to the growing understanding of the relative importance of different socio-technical drivers for, and barriers against, achieving deep demand reductions towards ambitious energy efficiency targets. With this broad aim, our paper looks explicitly at the following questions:

1. Which drivers for change have the highest potential in single and multi-family houses, stemming from the particularities of each building type?
2. What combinations of drivers can result in achievement of the long-term energy efficiency target for Sweden?
3. Comparing quantitative results with socio-technical barriers for each scenario, what lessons are there for different governance options realising energy demand reductions?

Our approach combines bottom-up energy modelling with scenario methodology informed by analysis of the socio-technical drivers for change. We analyse the energy savings potential from changes of the existing and new buildings until 2050 including both space heating and domestic hot water (DHW). Our aim is to compare the broad range of options that are available to realise demand side scenarios that both include technical potentials and analyse policy options given the assessment of socio-technical barriers and drivers for deep energy efficiency improvements.

The rest of the paper is organised as follows. We first provide some more background to the Swedish residential building stock and heat energy system in section 2. Section 3 explains our methodology, both for our energy model and scenarios, and how we complement our quantitative analysis with qualitative assessment of socio-technical drivers. Section 4 provides results and the final sections provide a discussion (section 5) of results and the socio-technical barriers to each scenario, and conclusions including policy recommendations (section 6).

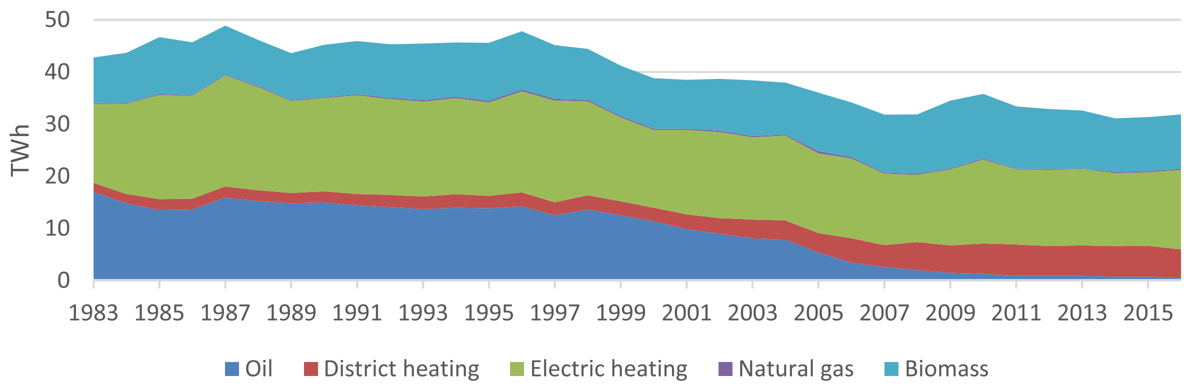

Fig. 1. Final energy demand for space heating and domestic hot water in the SFH.

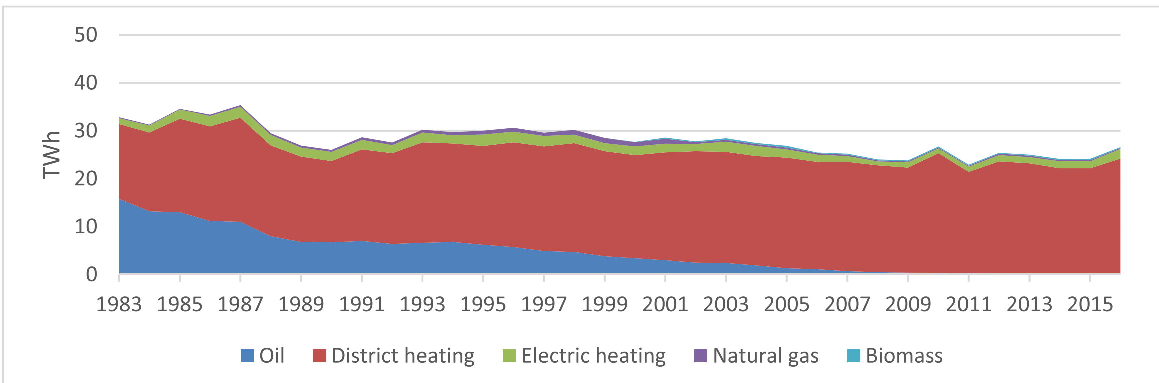

Fig. 2. Final energy demand for space heating and domestic hot water in the MFH.

2. Data sources

2.1. The Swedish residential building stock

Following the national TABULA residential building typology (Ballarini et al., 2014), the two main types of residential building stock in Sweden are single-family houses (SFH) and multi-family houses (MFH). SFH cover 46% of the stock with about 2 million units, and MFH are about 2.3 million units. The average heated area per dwelling in SFH and MFH is 146 and 76 m^2, resulting in total heated area of 292 and 175 million m^2 respectively. A detailed study of the building typology in Sweden based on data up to 2005 from the National Board of Housing, Building and Planning (Boverket) divides the building stock in five age categories, based on their thermal performance, and three climatic zones (Boverket, 2010) (Appendix A). About 70% of the building stock was constructed before 1975 and over 80% is concentrated in one climate zone in the south of Sweden (Fig. A1 and Table A.3), representing climate comparable to the one in Stockholm. The average number of persons per dwelling is 2.12.

Between 2000 and 2015, the average construction rate for SFH was 0.4%, while MFH had a higher rate at 0.7% (Statistics Sweden, 2018). Demolition data was only found for MFH, showing a 0.1% rate of demolition activity. Passive house energy requirements for Swedish conditions have been established by the Boverket. These requirements differentiate between north and south Sweden. Tangible opportunities exist to save energy when carrying out renovations, especially in MFH (Brown et al., 2014, 2013). In particular, buildings constructed between 1965 and 1975 under the so-called Million Programme, which aimed at solving the housing shortage problem, are in need of renovation (Åberg and Henning, 2011). It is estimated that by 2050 the incidences of renovating buildings will be three times that of constructions (Boverket, 2010), corresponding to about 1.5–2 million renovated apartments.

2.2. The Swedish residential heat energy system

During the past 30 years the Swedish residential heat system has undergone a shift away from oil as an important fuel driven by factors such as the oil crisis in the 1970–1980s (Nässén and Holmberg, 2005). Direct use of oil and other fossil fuels, which currently accounts for less than 3% of the total energy use for heating, was replaced mainly by two energy systems, district heating (DH) and electricity through resistive heating and heat pumps (HP). These two systems satisfy over 75% of the energy demand for heating in households. In particular, DH accounts for about 50% of the heat generation in the building stock, compared to around 6% in the EU (Andrews et al., 2012), and resistive electricity and HP cover about 21% and 8% respectively. According to Dzebo and Nykvist (2017), Sweden was instrumental in the deployment of HP by encouraging research and experimentation, supporting technology development, involving important actors and providing subsidies to encourage the replacement of oil boilers and resistive heating, making HP cost-competitive with fossil-fuel systems. In combination with a general tendency among Swedish citizens of not moving often, justifying, therefore, relatively high long-term investments, this climate policy resulted in Sweden having among the highest number of installed HP per capita (Grübler and Wilson, 2013). Both DH and electricity generation are almost completely decarbonised today. In particular, the penetration of renewables in heating increased over time resulting in about 70% today, with some variations depending on annual average temperatures, making Sweden the country with the highest total amount of renewable energy sources in heating in the European Union (Dzebo and Nykvist, 2017).

Residential housing represents 15% of total final energy demand in Sweden (Swedish Energy Agency, 2016), of which the majority (around 66%) is attributed to space heating and domestic hot water (DHW) demand. Of this, about a third is attributed to space heating and the remainder to DHW. In 2014, SFH consumed around 31.5 TWh, while MFH about 24.1 TWh compared to 45.6 TWh and 30 TWh in 1995 (Swedish Energy Agency, 2017). The two dominant energy carriers, electricity and DH, are also the prevailing carriers for SFH and MFH respectively, as seen in Figs. 1 and 2. According to Dzebo and Nykvist (2017), the dominance of DH in MFH has now resulted in a lock-in of these two technologies. Sartori et al. (2009a) further state that the profitability of this supply-oriented regime, which is higher in areas with high energy intensity, might be compromised by the promotion of energy efficiency measures and therefore result in conflict with investments for energy efficiency. Electric heating has been reduced by 19% since 1995, mainly due to replacement of resistive heating by HP and the efficiency improvements of HP technology. In particular, the coefficient of performance (COP), which represents the ratio of heat produced over electricity used, has increased by 2% per year since 1995 (Swedish Energy Agency, 2015). Biomass also plays an important role, both in SFH with the use of pellet boilers and in MFH as the main fuel in DH systems.

Globally, the desired indoor temperature varies across space and time, as it is dependent upon aspects such as lifestyle and income (Isaac and van Vuuren, 2009). In Sweden, indoor temperatures are higher compared to other countries. Furthermore, it appears that MFH have higher indoor temperatures with an average of 22.4 °C compared to 21.2 °C for SFH (Boverket, 2010). This can be explained by the fact that heating consumption in MFH is not measured per unit and heating expenditures comprise a fixed part of the rent which results in low incentives for MFH residents to save on their heat energy use (Nässén and Holmberg, 2005; Nilsson et al., 2018).

3. Methodology

This section first describes the approach used to develop a quantitative model for calculating energy intensity (energy per activity level) in the residential heating system in Sweden. We then characterize the drivers of change used in the model, and the treatment of concurrent effects. Then, we explain how qualitative data from in-depth case study work of the Swedish heat system informed the creation of explorative scenarios to show the demand reduction potentials for the time period 2015 to 2050. Finally, a sensitivity analysis on input parameters with uncertainty is described.

3.1. Bottom-up energy model

In order to estimate residential heating energy intensity, this study used an approach referred to as bottom-up engineering (Swan and Ugursal, 2009) or bottom-up buildings physics technique (Kavgic et al., 2010a). An end-use oriented model was developed in the Long-range Energy Alternatives Planning System (LEAP) tool (Charlie Heaps, 2016), in which space heating and DHW were calculated. The model distinguishes between SFH and MFH, which represent the main residential building typology in Sweden. The activity level of the model is floor area which is calculated for both existing and new dwellings. The floor area is determined by adjusting the building stock with regard to population, household size, demolition and construction rates. For the base year the average heated area per dwelling in SFH and MFH is 146 and 76 m^2 (Statistics Sweden, 2018). A common demolition rate of 0.1% (Statistics Sweden, 2018) for both SFH and MFH was used, in absence of specific data for SFH. For new buildings, a 0.4% and 0.7% construction rate were used for SFH and MFH respectively. In addition, a renovation rate was introduced to reflect the pace of renovation in the building stock and the associated demand reduction. Renovation rate was set at 1.5% and 2% for SFH and MFH respectively, in line with a report from Boverket (2010), reflecting the higher potential for renovations in MFH. Demolition, construction and renovation rates are the same across scenarios. However, recognising the uncertainty stemming from these parameters, a sensitivity analysis was conducted (section 3.5).

Changes in the occupants' behaviour or in the buildings' structure can affect the useful energy intensity of a building, while changes regarding the technologies for delivering heat affect its final energy intensity (Table 1). Therefore, in order to provide a holistic approach toward energy demand reduction, the model allows to independently consider measures that affect both useful and final energy intensities.

The useful energy intensity of each end-use (space heating and DHW) is calculated by combining information on final energy intensity of the end-use, energy carriers' shares and efficiencies for the respective heating technologies. Equation (1) shows this relation.

$$\textit{Useful energy intensity} = \textit{Final energy intensity} \times \sum_{i=1}^{I} s_i \ \eta_i$$

i = number of energy carriers, s = share of energy carriers, η = efficiecy

Data for the final energy intensity and the associated energy carriers is provided by the Swedish Energy Agency (Swedish Energy Agency, 2017), for both SFH and MFH. In order to calibrate the measured final energy intensity data with the data provided by SEA, conversion factors for the efficiencies of heating technologies were used. For simplicity reasons the estimated heat from HP is treated like an energy carrier. In particular, the use of HP was differentiated from the use of direct resistive electricity for heating by defining the coefficient of performance (COP) of HP. Calculation principles for the scenario development are described in Appendix B (Table B.3).

3.2. Socio-technical drivers of demand reduction

In order to explore and assess the potential for energy savings, both social and technical drivers were considered. In particular, three categories of socio-technical drivers were implemented: (i) occupants' behavioural change, (ii) structural change in the building stock and (iii) technological change. The former two were implemented by changes in useful demand, while the latter was implemented by changes in the

Table 1
Types of drivers and their influence in the bottom up energy model.

Driver	Category of drivers	Influence on	Description of change
D1. Lower indoor temperature	Behavioural change	Useful energy demand	Lower heating degree days per climate zone assuming reduction of indoor temperature to 20 °C by 2050
D2. Lower DHW use	Behavioural change	Useful energy demand	20% reduction of useful demand by 2050 according to Boverket (2010)
D3. Renovation of existing building stock	Structural change in the building stock	Useful energy demand	Improved heat transfer coefficients (U-values) for the main building components of each building age category (Table A.1, A.2, B.1 and B.2)
D4. Passive energy standard for new building stock	Structural change in the building stock	Useful energy demand	Passive house energy heating requirements (45 kWh/m^2) from 2020 onward
D5. More energy efficient technology mix	Technological change - Substitution	Final energy demand - Share of energy carriers	By 2050: phase out of the remaining fossil fuels, replacement of electricity for direct resistive heating use by HP, small-scale biomass and DH kept stable (Table B.4)
D6. Efficiency of heating technologies	Technological change- Learning	Final energy demand - Efficiency of heating technologies	Improved energy efficiency of heating technologies (Appendix B, Table B.5) – Most notable change is in the COP of HP from 2.4 to 3.2 by 2050

specifications of the heating technologies influencing the final demand. Behavioural change was captured in two drivers, lower indoor temperature (D1) and lower DHW use (D2). For structural changes, refurbishments in existing buildings (D3) and energy standards in new buildings (D4) were considered. Finally, technological change was reflected both as change in the technology mix (D5) and technological learning through improvement of the efficiency of heating technologies (D6). A detailed description of the data and methods followed to model each driver is provided in Appendix B.

The choice of this particular set of drivers is aligned with the energy saving measures presented by Mata et al. (2013). The work presented in their paper was initially conducted as part of a study commissioned by Boverket, which had the aim of evaluating a number of measures in existing Swedish residential buildings. These measures include lower indoor temperature (D1), lower DHW use (D2) and renovation of existing building stock (D3). Since, unlike Mata et al. (2013), our analysis includes newly built buildings, we added the passive energy standard for new building stock (D4) assuming that all newly built housing will need to follow certain standards. Finally, Mata et al. (2013) only take into account measures that influence the useful energy demand. In our analysis, in an attempt to offer a holistic approach to potential demand reductions, we add measures that influence final demand such as fuel substitution (D5) and improvements in the efficiency of heating devices (D6).

3.3. Concurrent effects

Some drivers interact with each other, and therefore, their effect when combined in scenarios is not additive (Mata et al., 2013; Wang et al., 2015). Therefore, in addition to the quantification of energy reduction potential under each driver, concurrent effects between some drivers were identified and included in the model. Concurrent effects were found between lower indoor temperature (D1), renovation of existing building stock (D3) and efficiency of heating technologies (D6). The concurrent effect between D1 and D3 was calculated by quantifying the aggregate energy demand reduction potential from the interaction between heating degree days and heat transfer coefficients. The concurrent effect between D1 and D6 occurs at the COP of HP which is influenced by the change in indoor temperature. This effect was captured by quantifying the changes in the condensation temperature of the HP.

3.4. Analysis of socio-technical barriers and scenario development

The basic scenario methodology used is usually referred to as strategic explorative scenarios (Börjeson et al., 2006) and essentially asks the question "what if" we act in a certain way, in our case, promoting system change through different sets of drivers. However, many combinations of drivers can be considered in such scenarios. Therefore, a selection of a limited set of combinations aimed to be policy relevant was created. This was achieved by synthesizing in-depth case study data from studies[2] on the Swedish heating system. We followed a desk based case study methodology (George and Bennett, 2005) conducting socio-technical analysis using the multi-level perspective (MLP) theory (Geels, 2002; Geels et al., 2017). In doing this, the level of momentum, defined as the recent socio-technical progress of the past 10 years, and the relative level of socio-technical barriers to each driver were estimated. The analysis provided a rich set of data on four variables: i) technological development, ii) actors and networks, iii) governance and institutions and iv) costs of implementing each driver. We assessed qualitatively the strongest patterns in the recent years under each variable, showing if there is predominantly positive momentum (low or no degree of barriers), no clear development, or high degree of barriers to potential development. These four variable assessments were in turn summarized to one final quantitative indicator of the level of barriers ranging from 0 (no degree of barriers - all four variables having positive momentum) to 8 (all four variables having barriers). Finally, we combined different drivers into scenarios ranked according to the degree of barriers. More specifically, scenarios were created by first grouping the drivers in similar category of driver (behavioural, structural, technological), and then combining these sets of drivers so that each scenario has successively higher level of barriers. To estimate this total socio-technical barrier to a scenario we apply a simple summation of the individual quantified estimates of each variable and qualitatively describe total level of barriers as low, medium and high for each scenario. While the degree of barriers does not necessarily scale linearly, the importance of each variable might be weighted differently, and similarly to the presence of concurrent effects in modelling of energy demand, there might be significant overlaps in underlying factors influencing each barrier. This uncertainty introduced should be taken into account when comparing the final results of each scenarios. But the final scoring illustrates how it becomes successively harder to implement each strategy due to growing total amount of barrier. Finally, we use the relative difference in barrier level and demand reduction potential to discuss the different pathways to reach energy efficiency goals.

3.5. Uncertainty of input parameters

For our analysis, many of the input parameters such as population, persons per dwelling, number of dwellings per age category, average floor area for SFH and MFH, energy carrier mix were collected from official statistics, and therefore, their uncertainty is low. The final energy intensity was calibrated for the efficiency of heating devices in the system.

However, there is clear uncertainty in the parameters related to future construction, demolition and renovation, due to either lack of empirical data or the short time period of historical empirical data (15 years as described in section 2 compared to the scenario period of 35 years). Therefore, a sensitivity analysis was conducted for the parameters construction, demolition and renovation rates, where the uncertainty was considered high. These input parameters were varied based by −25% and 25% creating low and high variants of each scenarios respectively.

4. Results

In this section we first present the analysis of barriers of each driver. Then we combine the aggregated quantified indicator of level of socio-technical barriers with results on the potential of implementing each demand reduction approach. Finally, we show results on the developed scenarios combining the energy demand and level of barriers in each scenario, followed by the results of the sensitivity analysis.

4.1. Socio-technical barriers

The MLP analysis in general found a high level of barriers for both the behavioural change (D1 and D2) and the structural change (D3 and D4) variables. The highest level of barriers and lowest socio-technical momentum is found with reduction of indoor temperature (D1) and passive energy standards (D4). There are strong cultural norms surrounding both high indoor temperature and, in the construction sector, formation and regulation of new norms of more energy efficient approaches. The highest momentum and lowest level of barriers is found in terms of more energy efficient technology mix (D5). Improvements to HP technology continued but also adoption of technologies enabling waste heat in DH systems and continued adoption of heat systems

[2] The studies were undertaken in PATHWAYS, an EU FP7 research project which explored the possibilities for transitions to a low-carbon, sustainable Europe (2013–2016). The individual studies are available online on the PATHWAYS website: http://www.pathways-project.eu/output.

designs such as HP combined with ventilation systems in SFH. Table 2 shows the results of the barrier assessment based on the MLP analysis.

4.2. Comparing demand reduction potential with socio-technical barriers

To further assess the possible pathways to reach demand reductions, Fig. 3 shows the reduction potential for demand per heated area in SFH and MFH from individual drivers and compares with the identified level of socio-technical barriers. The figure shows the potential of each individual driver for SFH and MFH compared to current levels (2015). It can be observed that the same drivers have different potentials in the two types of building stock, while also the behavioural drivers (D1 and D2) have different level of barriers. While in SFH, changing the technology mix (D5) has the highest reduction potential (33%) compared to current consumption, in MFH it has among the lowest reduction potential compared to the other drivers. This reflects the high efficiency gains from the increased uptake of HP that replace the use if direct electricity. There follows the driver of renovations (D3) with 26% reduction potential for SFH. This appears to be one of the drivers with the highest potential in MFH buildings, reaching a 27% reduction in energy demand. Lower indoor temperature (D1) has similar reduction potential, reflecting the particularly high indoor temperatures in MFH. However, lower indoor temperature in MFH appears to have the highest level of barrier. In general, the behavioural drivers in MFH have higher energy reduction potentials but also higher level of barriers compared to the SFH.

4.3. Scenarios

Drawing from the barrier assessment and the demand reduction potentials, scenarios were developed comprising combinations of drivers as shown in Table 3. The scenarios have successively higher level of barriers as indicated in the table.

The final energy demand per heated area per carrier along with the level of barrier in each scenario is depicted in Figs. 4 and 5 for SFH and MFH respectively. The term ‘‘electricity direct’’ represents the use of resistive electric heating and therefore, it does not include the electricity use from HP. The energy carriers of the integrated scenario in both SFH and MFH are biomass, DH and electricity from the use of HP, although it is clear to see the dominance of DH in MFH. In SFH, final energy demand is below 90 kWh/m^2 in all scenarios. STR & TEC appears to have the highest reduction potential reaching 58.2 kWh/m^2 and medium level of barriers (16). It is followed by BEH & TEC with 60.8 kWh/m^2 and slightly lower lever of barriers (15), while STR & BEH has a rather low potential with 81.6 kWh/m^2 and high level of barriers (25). In MFH, final energy demand in the scenarios is under 120 kWh/m.[2] Apart from the TEC, which has the lowest reduction potential, the rest of the scenarios appear to have similar potentials. However, BEH & STR in MFH results in the lowest energy demand (89.8 kWh/m^2) which is very different from SFH even though in both SFH and MFH this scenario has high level of barriers. It is also noteworthy that in SFH the behavioural drivers have a relatively lower importance compared to technological drivers for final energy demand, but in MFH the relationship is reversed. This clearly indicates that different policy strategies are optimal for the two building types due to the relative difference in energy demand reduction potential.

Fig. 6 shows final energy demand intensity per carrier under each scenario for the whole building stock along with the contribution of the scenarios toward the target for the residential heat energy demand and the average level of barriers in each scenario. By 2050, the integrated scenario, which combines all drivers, results in total final energy demand of 66.1 kWh/m.[2] Under the scenario, the target of halving the energy demand per heated area by 2050 in relation to the reference year 1995 is exceeded. In particular, 61% reduction is achieved. The heat demand in this scenario is covered by biomass, DH and electricity, through the use of HP. The target is also exceeded in the scenarios STR + TEC, BEH + TEC with 57% and 56% reduction respectively and reached under the BEH + STR scenario. Scenarios BEH, STR and TEC are approaching the target but do not reach it. However, it is important to note that the TEC scenario, which has by far the lowest average level of barriers (3) and much lower than the scenarios combining categories, is very close to reaching the target with a reduction of 49%.

Results so far have been compared to 1995 and presented on final energy intensity, since this is the way the energy target for buildings in Sweden is formulated. However, it is interesting to also illustrate the potential for final energy savings in the future by presenting the reduction on final energy between the base year and 2050. Fig. 7 shows the final energy demand in the two building stock types and the total residential energy demand per carrier for 2015 and 2050 in the integrated scenario. Compared to the 56.1 TWh final residential energy demand in 2015, the integrated scenario results in 38.2 TWh, a 32% reduction in final energy demand. Focusing on the final electricity demand, there is a decrease of 10.4 TWh, corresponding to 65% reduction between 2015 and 2050 in the integrated scenario, largely owned to SFH. Further, it can be observed that, while there is reduction in final energy demand in both SFH and MFH, the majority of energy demand reduction is attributed to SFH in 2050. In particular, between 2015 and 2050, there is a reduction of 12.6 TWh and 5.3 TWh in SFH and MFH which correspond to the total residential energy demand reduction of 17.8 TWh by 70% and 30% respectively .

4.4. Sensitivity analysis

The sensitivity analysis reveals the impacts on energy demand from varying uncertain input parameters not captured in the explorative scenarios. As seen in Fig. 8, a 25% change in the renovation rate parameter leads to a corresponding 4% change in the model results, leading to a final energy demand that exceeds the target of 50% reduction, while a −25% change increases the final energy demand by 3%. A −25% and 25% change in the construction rate leads to a 1% and 3% change in the model results respectively, while a −25% and 25% change in the demolition rate results to a 1% and 2% change respectively. The low change in model results from the variations of demolition rate is associated to the low original demolition rate of 0.1%, while the low change in the results from construction rate variations can be explained to the very low energy demand of newly built dwellings that follow passive standard according to the scenario development. Even though there are some important uncertainties in these input parameters and assumptions on their future development, that is not captured in the scenarios, this sensitivity analysis shows that the model results are not very sensitive to changes in either construction, demolition or renovation activities.

5. Discussion

Our results show that the target of 50% reduction in total energy demand per heated area by 2050 compared to the 1995 consumption level can be achieved by combining different drivers on behavioural, technological or structural change. In our model, there is a need for combining at least two of the categories of drivers to go below 50% reduction in energy demand. This illustrates that in order to reach ambitious efficiency goals, analysis and modelling of the heat energy system need to have broad approach and consider a range of measures and drivers of demand reduction. Looking at total energy in both SFH and MFS the target is reached or exceeded under the integrated, BEH + TEC, STR + TEC and BEH + STR scenarios, combining two of the three categories of change is necessary and enough. However, it is important to note that the target is also almost reached under the TEC scenario (49% reduction) driven by a large potential for improvement in SFH. For the BEH and STR scenarios this focus on a single strategy is not possible, and technological drivers have a large potential in energy demand reduction. This is in line with a study that analysed the historical energy

Table 2
Assessment of the level of socio-technical barriers for each driver based on negative, neutral or positive momentum of barriers.

Driver	Technology	Actor and Networks	Governance	Costs	Average level of barrier
D1. Lower indoor temperature	Limited technological challenges in terms of devices needed to regulate, but challenges to monitor temperature, and clear technological barriers for individual net metering in MFH. **SFH and MFH: Negative momentum**	Strong normative and behavioural barriers. Supply oriented discourse coupled with strong cultural preferences. Very few actors influencing behavioural change. **SFH and MFH: Negative momentum**	Strong informal institutions on high indoor temperature. Some historically progress for SFH, and conversely, regulation of minimum temperature in MFH. **SFH: Neutral** **MFH: Negative momentum**	Possible to realise cost savings but savings are not valued as they are rather low in absolute terms and split incentives with heating cost included in rent. **SFH: Neutral** **MFH: Negative momentum**	**SFH: 6** **MFH: 8**
D2. Lower DHW use	Some limited technical options to limit DHW use by new funnels, but no momentum in adoption or prospect to reduce DHW use in either building type. **SFH and MFH: Neutral**	Strong normative and behavioural barriers. Supply oriented discourse coupled with strong cultural preferences. Very few actors influencing behavioural change. **SFH and MFH: Negative momentum**	Some governance initiatives support lower DHW use but driven by water scarcity rather than heat reduction. Strong informal institutions on high DHW use. **SFH and MFH: Negative momentum**	Very limited cost savings not valued as they are very low in absolute terms and split incentives with heating cost included in rent. **SFH: Neutral** **MFH: Negative momentum**	**SFH: 6** **MFH: 7**
D3. Renovation	Technology (for low energy house standard) is already developed. But integration can be challenging. **SFH and MFH: Neutral**	Competences and learning in networks lacking especially for SFM. For MFH, rather economic barriers. **SFH: Negative momentum** **MFH: Neutral**	Limited support and lagging implementation of EU directive. Some focus on information campaigns to SFH owners and tax deduction on labour costs for new installations in SFH. **SFH: Neutral** **MFH: Negative momentum**	Cost neutral, investments roughly same as savings, but high upfront cost and long payback time limits interest. **SFH and MFH: Negative momentum**	**SFH: 6** **MFH: 6**
D4. Passive energy standard for new building stock	Technology largely known but more development outside of Sweden. **SFH and MFH: Neutral**	Weak networks, some smaller and local/ reginal initiatives but large barriers due to limited interests among key actor in housing sector. **SFH and MFH: Negative momentum**	Policy is lagging, less sharp definition of passive houses in Sweden. Constructors and municipal landlords not interested in working toward higher cost passive house. **SFH and MFH: Negative momentum**	High up-front investment costs are clearly limiting interest. **SFH and MFH: Negative momentum**	**SFH: 7** **MFH: 7**
D5. More energy efficient technology mix (technological substitution)	Technology progress and learning steadily enabling lower cost HP. **SFH and MFH: Positive momentum**	Strong network of actors including domestic manufactures and knowledgeable installers. **SFH and MFH: Positive momentum**	Earlier monetary incentives removed, few specific incentives to change technology mix in either MFH or SFH **SFH and MFH: Neutral**	Cost effective in both many old and new buildings. **SFH and MFH: Positive momentum**	**SFH: 1** **MFH: 1**
D6. Efficiency of heating technologies	Continued technological learning likely, no barriers. **SFH and MFH: Positive momentum**	Good network of manufactures, installers and research on, e.g., HP. **SFH and MFH: Positive momentum**	No special instruments or initiatives supporting development. **SFH and MFH: Neutral**	Relative additional cost savings potential limited **SFH and MFH: Neutral**	**SFH: 2** **MFH: 2**

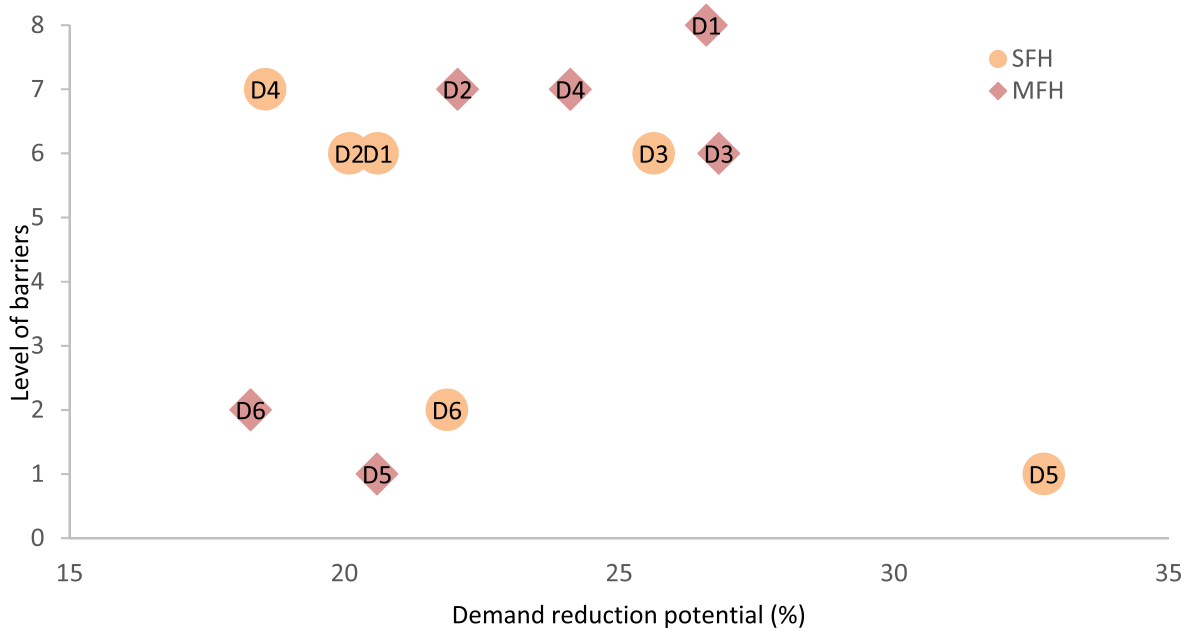

Fig. 3. Reduction potential of demand energy intensity of individual drivers and their level of barriers.

Table 3
Scenarios selected, their drivers and their barrier assessment.

Scenario Name	Description	Drivers	Level of barrier	
			SFH	MFH
TEC	Technological drivers only	D5, D6	Low (3)	Low (3)
BEH	Behavioural change drivers only	D1, D2	Medium (12)	Medium (15)
STR	Structural drivers only	D3, D4	Medium (13)	Medium (13)
BEH & TEC	Behavioural and Technological change	D1, D2, D5, D6	Medium (15)	Medium (18)
STR & TEC	Structural and Technological change	D3, D4, D5, D6	Medium (16)	Medium (16)
BEH & STR	Behavioural and Structural change	D1, D2, D3, D4	High (25)	High (28)
Integrated	All drivers	D1, D2, D3, D4, D5, D6	High (28)	High (32)

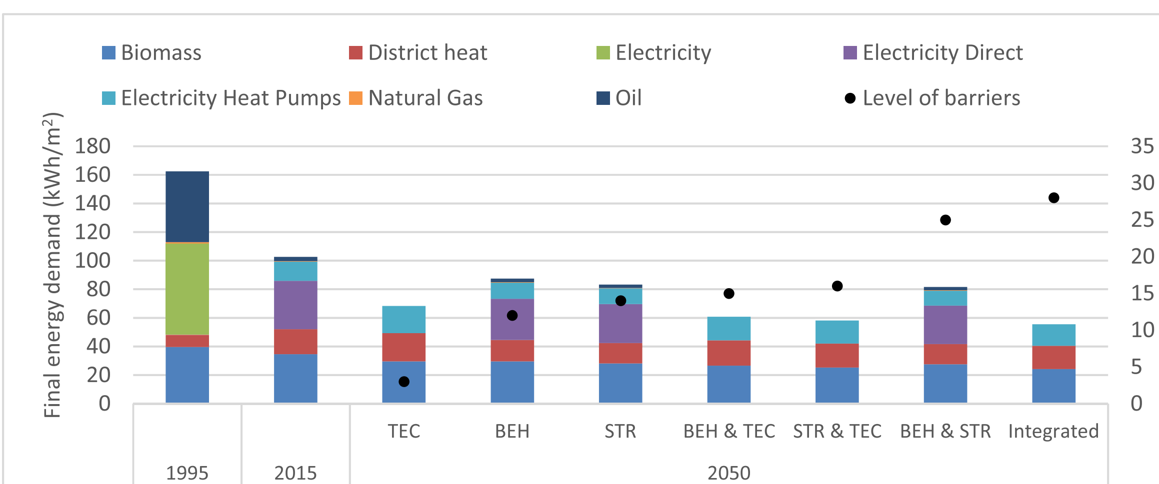

Fig. 4. Final energy demand intensity per carrier for all scenarios in SFH along with the level of barriers.

use of the Norwegian building stock between 1960 and 2015, concluding that changes in the energy mix provided higher demand reductions than energy efficiency measures (Sandberg et al., 2016b). The high potential of technological drivers, together with the finding that the TEC scenario faces by far the lowest level of barriers, points to one possible strategy being to focus more on only technological drivers.

However, there are important differences between demand reduction potentials between SFH and MFH housing. The same drivers have different potential in the two building types due to the differences in building structure, occupants' behaviour and in energy demand mix

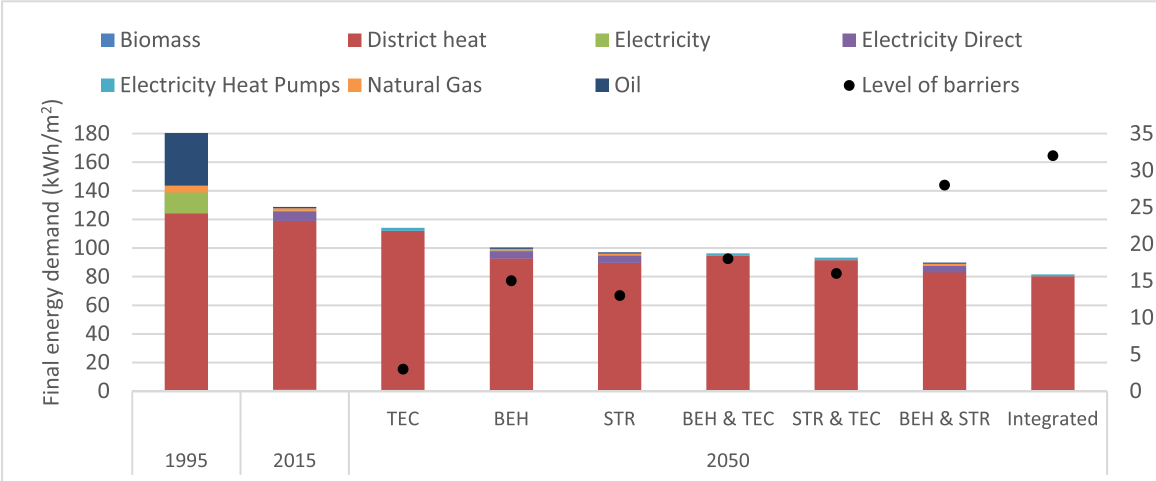

Fig. 5. Final energy demand intensity per carrier for all scenarios in MFH along with the level of barriers.

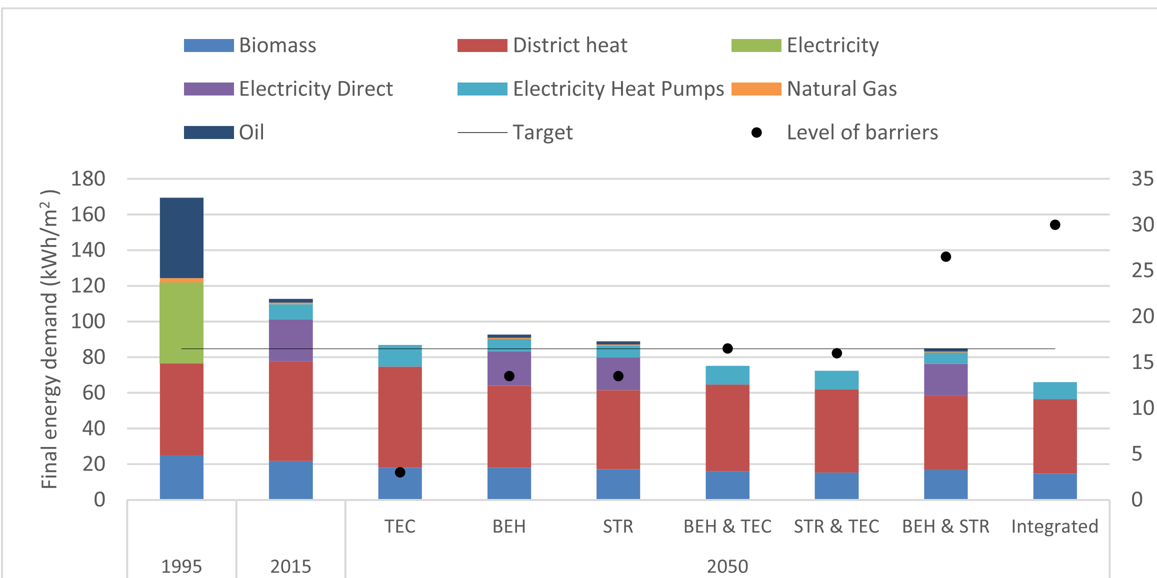

Fig. 6. Total residential energy demand intensity per carrier for all scenarios compared with the target for demand reductions and the average level of barriers.

between the two. This indicates the importance to consider different policy strategies for each. For SFH continued technological improvements play a crucial role. Technological change is both the category with the lowest level of barriers and the highest demand intensity reduction potential. Among the scenarios combining categories of drivers (BEH + TEC, STR + TEC and BEH + STR), the two scenarios where technological drivers are included clearly have lower level of barriers as well as the highest energy reduction potential. For MFH, technological drivers have the lowest reduction potential, and a broader set of combinations of drivers has to be considered. Between the three combined scenarios, STR&BEH has the highest energy demand reduction potential. However, the STR & TEC faces much lower lever of barriers and has only slightly higher (by 3.4 kWh/m^2) final energy demand.

Looking only at the energy demand potentials – excluding the integrated scenario which combines all drivers and necessarily performs best – STR&TEC has the highest potential in SFH while in MFH, STR&BEH has the highest potential. On the one hand, this reflects a common aspect between the two housing categories, i.e. the high efficiency gains from renovations for both building types. This is observed in other developed countries in which the majority of building stock was built before 1975 or earlier, such as Denmark. On the other hand, it shows the high efficiency gains of a potential replacement of direct electricity use in SFH by HP and of lowering indoor temperatures in MFH. Factoring in the socio-technical analysis, the technological change in SFH should be easier to realise than high efficiency improvements in MFH that depend more on structural and behavioural changes, both of which have clearly higher levels of socio-technical barriers and require more policy interventions to realise. More specifically, research shows a reluctance toward the introduction of demand-side policies for low-energy buildings in Sweden (Dzebo and Nykvist, 2017) associated with the infrastructure (DH plants) lock-in and the split-incentive dilemma[3] in MFH (Nilsson et al., 2018). In addition, MFH residents have low incentives for heat energy savings since heating expenditures are a fixed part of the rent (Nilsson et al., 2018). It can be argued that

[3] Split incentive dilemma refers to the situation where tenants, who are responsible for paying energy bills, are not the same as those making the capital investment decisions (the landlord or building owner). Therefore, the latter may not be willing to take the required energy efficiency measures when the benefits related to energy savings accrue to the tenant.

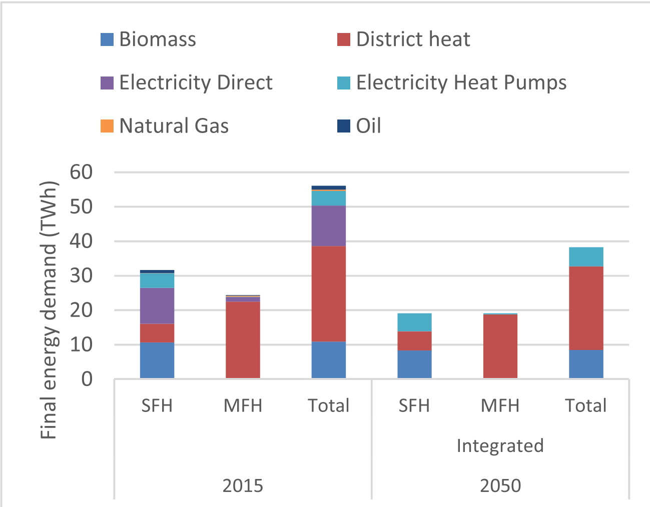

Fig. 7. Total energy demand in SFH, MFH and total residential system per carrier in 2015 and 2050 Integrated scenario.

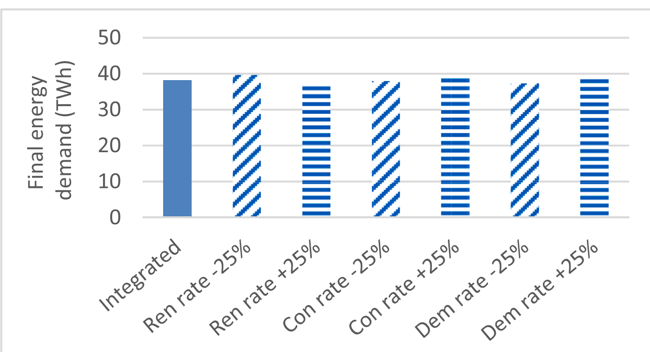

Fig. 8. Total residential energy demand in 2050 under sensitivity analysis relative to the integrated scenario.

lowering indoor temperature and DHW use would face higher level of barriers in MFH than in SFH, since in Swedish MFH there is a collective heat control system, which is regulated by the building owner (Nilsson et al., 2018).

Furthermore, examining our results on the final energy demand instead of the final energy intensity, the importance of the two building stocks on the total residential energy demand is revealed. Although the increase in the building stock is higher in MFH than SFH, the contribution to the final energy demand reduction of the residential system will be dominated by SFH in 2050. In addition, in the Integrated scenario, which represents the higher level of ambition between the scenarios, the total electric load is reduced by 65% by 2050, freeing up 10.4 TWh of electric load. The need for additional renewable electricity in decarbonizing Sweden has recently been estimated to 37 TWh (Sweco, 2019). Therefore, the electricity savings in our Integrated scenario cover 28% of the estimated additional electric load required.

Stemming from the sensitivity analysis, the additional energy demand reduction potential due to a higher renovation rate is surprisingly narrow. This appears to be in line to the results of Sandberg et al. (2017) on Norway's building stock. They explain the limited potential of a more frequent renovation to a major share of this potential already realized in the past, leaving limited potential for further energy efficiency. It is noteworthy that next to more frequent renovation, a more ambitious renovation scenario could be explored by changing the improved U-values used for the main building components in our analysis (Appendix B, Tables B.1 and B.2) to lower values.

Further research can enhance the results of this study in different ways. Looking at the socio-technical analysis, further research could aim at establishing improved data on which barriers are most important to the main actors such as residents, landlords and investors, assigning different weights for all barriers and enabling more nuanced analysis of policy options. In addition, exploring more scenarios that combine different drivers in the two building types, for example technological for SFH and structural for MFH could offer valuable insights. Further, even though a sensitivity analysis was performed to deal with uncertainty around construction, demolition and renovation rates, it is acknowledged that buildings from different age categories would likely undergo different rates in the coming decades and therefore, adopting a single and exogenously defined rate for all age categories is a rather strong simplification. Therefore, especially regarding renovation, a model in which the needed renovation activity is calculated based on the ageing process of the building stock in the different age categories would improve the results. This approach has been followed in studies such as Dascalaki et al. (2016), Diefenbach et al. (2016) and Sandberg et al. (2017, 2016a). If data availability allows, the differentiation based on age category of the shares and efficiencies of heating devices (especially HP) would also provide useful insights and potential improvement of the results.

In this study, concurrent effects between drivers were estimated but more analysis is warranted. Mata et al. (2013) and Wang et al. (2015) also provide insights on the impacts of concurrent effects on energy demand. Further research on concurrent effects between drivers, such as the effect among the heat transfer coefficients of different building components, which is not taken into account in this study would improve the results. Finally, an important driver of heating demand related to magnitude and overall impact of concurrent effects is outdoor temperature. In the context of climate change, with significantly higher temperature expected in Sweden on the timescales modelled here, variation of outdoor temperature and its impact on the demand is important to study. This could be investigated using changes in the heating degree days index.

There are important variations on system boundaries, assumptions, model methodologies and efficiency measures included across studies. Even though direct comparisons with studies are complicated, an attempt was made to compare our results with other studies on heat demand reduction potential. According to Mata et al. (2013), who estimate the technical potential for energy saving measures in the Swedish residential building stock, the driver of reducing indoor temperature to 20 °C has higher potential in SFH than in MFH. In our study, we found that lower indoor temperature has higher potential in MFH instead. However, Mata et al. (2013) estimates the potential based on the existing building stock while in our approach new constructions are taken into account and the construction rate of MFH is higher than in SFH, making the importance of lower indoor temperature higher in MFH. Our results cannot be directly compared with those of Sartori et al. (2009a), who developed scenarios for the Norwegian building stock. However, it is interesting to compare assumptions between the two studies. Sartori et al. (2009a) follows a similar approach of including demolition, construction and renovation rates in their analysis. Demolition and construction rates between the studies are similar. For renovation, Sartori et al. (2009a) considers three levels of renovation rate (low, medium and high) providing further insights in renovations, which is an important driver in both SFH and MFH. However, in their study they do not disaggregate the building stock in age categories which is essential. While in our study U-values per age category were used, a single renovation rate was used. A combination of different rates of renovation applied in different age categories based an ageing process could yield better results on the demand reduction potential of renovation. Sandberg et al. (2017) conducted a study on the Norwegian building stock that includes a scenario analysis for the period between 2016 and 2050. With regard to renovation they investigate both a higher frequency and a more advanced renovation, reaching however the conclusion that these measures offer a limited potential. Instead, measures like the use of HP offer a higher potential according to the study. This is in line with our results, where the technological drivers (through the substitution of direct resistive heating with HP and increase efficiency of heating technologies) clearly have higher potential than the structural driver. Finally, in our study, behavioural drivers were approached from a perspective of energy demand reduction potential through lower indoor temperature and DHW use. However, studies by Sandberg et al. (2017, 2016b) investigate the competition to energy demand reduction due to user behaviour, stemming from rebound effect as the building stock becomes more efficient in a historical and future context respectively. This is an approach worth investigating in the Swedish case as well and could potentially alter the results on achieving the target.

6. Conclusions and policy implications

In this paper we developed an energy system model based on bottom-up analysis of building stock in Sweden and created scenarios taking into account existing and new building stock and both single and multi-family houses. The model was combined with socio-technical analysis of relevant drivers for demand reduction in order to guide a more policy relevant scenario development. These drivers cover technological, behavioural and structural changes. Our scenario results aim to deepen the understanding of drivers and the potential of energy demand reduction analysis.

We found that, compared to the reference year 1995, a 61% reduction in energy intensity could be achieved by 2050 by applying all the drivers studied exceeding the target. To meet the target, at least two categories among the categories of drivers (technological, behavioural and structural) are necessary and it is likely a more robust strategy to achieve significant improvements in both single and multi-family houses. However, the target is nearly reached by applying the technological drivers alone, owing to the large improvements in single-family houses, while also having the highest assessed momentum and lowest level of barriers. Therefore, for a policy strategy where the goal is not to achieve the highest possible energy demand reduction, but instead to progress on the target with low barriers to implementation, measures focused on technological drivers would likely be effective and adequate. The caveat is that this strategy relies more on progress in single than multi-family houses and might be less robust. This calls for different approaches to single and multi-family houses and a larger role for policymakers to lead on initiatives that foster a combination of technological, behavioural and structural improvements.

Our results differentiate between single and multi-family houses and the age categories in those but could be expanded with more detail based on the renovation rate of each age category. In addition, the impact changing outdoor temperatures under different global warming scenarios and the associated concurrent effects can be explored further in order to clarify how these can influence results and to identify robust policy measures.

Deep demand reduction exceeding the target is possible if multiple strategies are deployed and this has the potential of benefiting other sectors. The building sector in Sweden is almost fully decarbonized owing to a low carbon energy mix in both heating and power. Further measures to reduce CO_2 emissions would give high abatement costs per ton CO_2 avoided and is unlikely to be the main motivation for introducing energy efficiency measures. But there are important indirect benefits from the implementation of ambitious energy efficiency measures including reduced electricity demand, which may provide indirect CO_2 emissions reductions. More importantly, this can contribute toward electrification of sectors which are harder to decarbonize such as transport and industry without increased dependence on imported electricity with higher CO_2 emissions. Therefore, an ambitious strategy is aligned with the vision of the government for Sweden to become a fossil-free nation by 2045[4] and should therefore offer a strong motivation for implementing ambitious demand reductions.

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.

CRediT authorship contribution statement

Georgia Savvidou: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Björn Nykvist:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Funding acquisition.

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Appendix A. Characteristics of building stock

Table A.1
Typological characteristics of SFH (Source: (Boverket, 2010)).

Building age category	Number of dwellings	Building components U-values (W/m^{2}K)			
		Wall	Roof	Floor	Window
−60	846000	0.6	0.29	0.28	2.34
1961–1975	500000	0.31	0.21	0.32	2.3
1976–1985	313000	0.21	0.15	0.27	2.01
1986–1995	154000	0.17	0.12	0.24	1.94
1996–2005	77000	0.2	0.12	0.18	1.87

[4] http://fossilfritt-sverige.se/in-english/.

Table A.2
Typological characteristics of MFH (Source: (Boverket, 2010)).

Building age category	Number of dwellings	Building components U-values (W/m^{2}K)			
		Wall	Roof	Floor	Window
–60	1031000	0.58	0.36	0.36	2.22
1961–1975	768000	0.50	0.28	0.32	2.22
1976–1985	130000	0.41	0.2	0.28	2.22
1986–1995	364000	0.22	0.15	0.26	1.8
1996–2005	102000	0.2	0.13	0.22	1.97

Table A.3
Share of heated area in climate zones (Source: (Mälaraden University, 2012)).

	Climate zone 1	Climate zone 2	Climate zone 3
SFH	0.08	0.14	0.78
MFH	0.06	0.10	0.84

Fig. A1. Schematic representation of the three climate zones in Sweden (Source (Mälaraden University, 2012):).

Appendix B. Detailed descriptions of drivers in the energy system model

- Lower indoor temperature

Heating degree day (HDD) is the most common index which reflects the energy demand for heating buildings. For each day in which the outdoor temperature is below a threshold, it measures the difference between the daily average outside temperature compared to a predetermined level. This level is the base temperature of a building, which is related to the required (desired) indoor temperature. The threshold temperature, which is the minimum outside temperature below which a building is assumed to need heating was set at 15 °C.

Therefore, HDD were calculated as follows:

$$HDD = \begin{cases} T_b - T_i, & 15 - T_i > 0 \\ 0, & 15 - T_i \leq 0 \end{cases}$$

where T_b is the base temperature, T_i is the outside temperature, 15 is the threshold temperature and i is the time index resembling the days of a year (i: 1, ….365).

In this study, heating degree days per climate zone were calculated using SMHI mean daily temperatures from 2010 to 2015. Fig. A1 shows the regional distribution of heated area in the three climate zones.

HDD were calculated for SFH and MFH. The base temperature (old) used are 21,2 °C and 22,4 °C for SFH and MFH as obtained from a Boverket study. Then, in order to show the effect of lowering indoor temperature, a new base temperature setting was applied for both SFH and MFH at 20 °C, which corresponds to the statutory thermal comfort zones in Sweden.

Then both old and new HDD were averaged across the three climatic zones. This was harmonised according to the heated area per each climatic zone for SFH and MFH respectively (weighted average). They were then weighted based on the heated floor area of each climatic zone of SFH and MFH as defined in BBR.

- Lower DHW use

Reduction of DHW use was assumed under the effect of individual metering, which according to Boverket (2010), has a 20% energy reduction potential.

- Renovation of existing building stock

Renovations of the existing building stock were implemented by considering refurbishment options for different age categories of the building stock. This was implemented by improving the heat transfer coefficients (U-values) for the main building components (walls, windows, roofs, floor) of each age category. Values for the current, improved and low energy U-values are provided in a building typology report developed under the TABULA project (Mälaraden University, 2012). The improved U-values were used.

Improved values for heat transfer coefficients (U-values) in SFH.

Building age category	Building components U-values (W/m^{2}K)			
	Wall	Roof	Floor	Window
−60	0.33	0.11	0.21	0.9
1961–1975	0.22	0.1	0.24	0.9
1976–1985	0.16	0.08	0.21	0.9
1986–1995	0.14	0.07	0.19	0.9
1996–2005	0.16	0.07	0.15	0.9

Table B.2
Improved values for heat transfer coefficients (U-values) in MFH.

Building age category	Building components U-values (W/m^{2}K)			
	Wall	Roof	Floor	Window
−60	0.29	0.12	0.24	0.9
1961–1975	0.27	0.11	0.22	0.9
1976–1985	0.24	0.1	0.2	0.9
1986–1995	0.16	0.08	0.19	0.9
1996–2005	0.15	0.08	0.17	0.9

- Passive energy standard for new building stock

The use of passive energy houses in new buildings is reflected by enforcing all new buildings to follow passive housing standards with regard to energy consumption from 2020 onward. For this, passive house energy requirements for Swedish conditions established by Boverket were used. These requirements differentiate between north and south Sweden. In particular, the maximum amount of final energy is recommended not to exceed 45 kWh/m^2 and 55 kWh/m^2 in a south and north climatic zone respectively (Janson, 2008). The value of south was used here as the majority of new buildings are assumed to be built in the south of the country.

- More energy efficient technology mix

Market penetration of the different energy carriers changes over the scenario period. Oil and natural gas shares in heating have decreased rapidly over the last years. It was assumed that their shares in the scenario will decrease linearly and be diminished by 2020. Because it is considered as inefficient, electricity for direct heating use is decreasing linearly and is phased out by 2050 and replaced by an increased penetration of HP. This substitution contributes toward reducing electricity dependency in the building domain, which is one of the Swedish policy goals (Johansson et al., 2006). The use of small-scale biomass systems is kept stable, while district heat fulfils the remaining share. Table B3 and B.4 show the calculation expressions for the carrier mix along with the resulting shares for 2015, 2020 and 2050.

It is reasonable to assume that changes in energy carrier shares can take place independently from renovation work. Therefore, in the combined scenarios the shares of energy carriers are allowed to change regardless of the renovation.

Table B.3
Leap expressions used for the share of energy carriers over the scenario period.

Energy carrier	LEAP expressions
Biomass	BaseYearValue
District heat	Remainder(100)
Electricity Direct	InterpFSY(2050; 0)
Electricity Heat Pumps	InterpFSY(2050; BaseYearValue + Value(Electricity Direct[%Share]; BaseYear))
Natural gas	InterpFSY(2020; 0)
Oil	InterpFSY(2020; 0)

Table B.4
Shares of energy carriers for SFH and SFH for the base year and years 2020 and 2050 of the scenario period.

	SFH			MFH		
	2015	2020	2050	2015	2020	2050
Biomass	24.4	24.4	24.4	0.7	0.7	0.7
District heat	14.0	16.0	16.0	90.8	92.5	92.5
Electricity Direct	28.7	24.6	0.0	5.7	4.9	0.0
Electricity Heat Pumps	31.0	35.1	59.6	1.0	1.9	6.8
Natural gas	0.2	0.0	0.0	1.0	0.0	0.0
Oil	1.8	0.0	0.0	0.7	0.0	0.0

- Efficiency of heating technologies

Regarding efficiency of heating devices, future efficiencies associated with the various energy carriers is shown in table B3. The most prevailing efficiency improvement is related to the COP of HPs. Electricity consumption for heating purposes due to HPs was obtained from Statistics Sweden. In order to assess the average coefficient of performance (COP), the most common situation in residential buildings of air-to-air HP was assumed.

Table B.5
Base year and scenario values for efficiency or COP in heating.

Heating technologies	2015	2050
Gas-Fired Boilers	0.82	0.96
Oil-Fired Boilers	0.84	0.91
Pellet Wood Stoves	0.78	0.87
District heading	0.9	0.9
Electric Resistance Heaters	1	1
Heat Pumps (COP)	2.4	3.2

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