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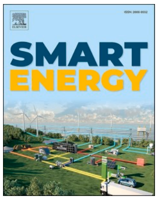

Communal or individual – Exploring cost-efficient heating of new city-level housing in a systems perspective

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ABSTRACT

As cities expand, new buildings are constructed and they require heating. With increasing integration of the heating and electricity sectors and forecasts of rapid growth in electricity demand, heating choices become critical for the sustainability transition. The main heating options are communal or individual, where the communal option is represented by district heating (DH) and the individual option mainly by heat pumps or biomass heating. Which option is best from the cost perspective depends on the building type and on the energy system development. Thus, this paper investigates cost-efficient heating of new city-level housing in a systems perspective under various scenarios.

The investigation was carried out using an energy systems optimization model based on a case representing Swedish conditions. A dynamic approach was used to investigate cost-efficient development of the supply side and demand side simultaneously.

The results indicate that the most cost-efficient heating systems are: DH for apartment buildings; and individual heating options for single-family housing with low heat demands. For large single-family housing with high heat demands, the cost-efficient solution depends on the heat demand profile. Higher heat use during winter favors DH and individual biomass boilers, but diminishes the economic feasibility of individual heat pumps.

1. Introduction

Space heating is one of the most important uses of energy in cold regions of the world, such as Northern and Central Europe, North America and North and East Eurasia. In general, space heating options can be divided into communal and individual heating systems, where 'communal' is heating provided by either a district heating (DH) or a near-heating system, and 'individual' represents the case in which each building has its own heating supply.

The heating technology used, irrespective of whether it is communal or individual, depends on the existing infrastructure, among other factors. When it comes to new building stock, the decision as to which heating option to adopt needs to be taken, and it is often the case that external factors, such as political inclination and how heating is perceived, influence the choice. In countries such as Sweden and Finland, communal and collective heating systems are regarded as a public good, and the 1980's saw heavy investments being made in DH systems. However, this is not the case anymore. Individual heating technologies, such as biomass boilers and various heat pumps (HPs), are also viable options for heating houses.

The housing stock of a geographic place, such as a city, develops with time. During the past decades, the preferred heating options, from both the societal and private points-of-view, have also been changing, mainly for environmental and economic reasons. Heating systems develop in line with the supply side and demand side developments, which is why the heating options and housing change with time. Thus, the heating system and choices may be considered parts of a dynamic system.

When cities expand with the construction of new housing, decisions as to how to heat these new houses must be made. The building owner may prefer a low investment cost option and the tenant may opt for a low running cost option, while the city planner must also take into account other city objectives, such as the climate goals set by the city itself or by the State. Furthermore, while communal heating options may fare better from a societal-economic perspective, certain individual heating options may be better from the consumer-economic perspective. This aspect has been studied using Geographical Information Systems (GIS) analysis for Denmark [1] and using the energyPRO tool for Helsingør [2].

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Different heating technologies suit different types of housing because, for instance, single and multi-family dwellings differ in size and total heat demand, resulting in different heating densities. The different heat demands may affect the heating load profile, impacting which option that is most economical, which in turn may influence the future energy system and its environmental impact. This has been studied for the DH system of Linköping [3], Uppsala [4] and for hypothetical cases representing typical DH systems [5].

Previous studies of the building stock have often focused on the interactions of buildings with the DH system, while studies have also been conducted on how energy efficiency measures in the existing building stock and new apartment buildings affect the connected DH system. That energy saving measures in apartment buildings can increase the heat demand but decrease the primary energy use is concluded in Ref. [6]. The primary energy saving can be highly dependent on the existence of co-generation units in the DH system [7]. Investments into increased energy efficiency can be economical mainly through installations of ventilation heat recovery systems [8]. However, studies of how new buildings, apart from apartment buildings, interact with heating systems in the long-term are scarce despite the importance of such interactions for smart energy systems [9].

Mandatory connection to DH systems has been shown to be a barrier to the construction of new low-energy buildings in Norway [10]. The authors showed that the building developers preferred not to use DH when building housing with low energy demands, and that they instead chose to build housing with high heat demands and connect them to the DH system. Mandating connection to the DH for heating purposes was an action taken by the city authorities with the economic and predictability considerations of the DH company in mind, as well as the national aim in Norway to reduce its dependency on electricity for heating purposes.

Many studies have focused on DH and its role in a fully renewable energy system. The high fuel efficiency of DH and its ability to recover waste heat contribute to decreasing the primary energy use, thereby decreasing emissions. Furthermore, later generations of DH have even higher efficiencies, contributing to even lower primary energy use [11] and to a possibility of decreasing DH system costs [12]. Decreased distribution losses, increased excess heat availability and increased efficiencies in production units are shown to decrease the primary energy use, as well as the system cost for the case of Aalborg [13]. Utilizing the thermal inertia of buildings connected to a DH system can contribute to decreasing the DH running cost [14]. However, many studies have often been focused on DH, excluding the roles of individual heating options in future heating systems. Technical details of future DH systems are well understood, but there is a challenge to the actual implementation [15].

Even if there are studies that have not focused primarily on DH when investigating how new buildings can be heated, they are few compared to the amount focusing on the DH system. It can be cost-efficient for new low-energy buildings to use DH as heating solution, especially at building sites with a high linear heat density, although individual heating options in some cases have the lowest heating cost for new housing not sufficiently close to an existing DH grid [16]. In Ref. [16] it was assumed that fossil fuel-fired plants are the price setters on the electricity market, although more-fluctuating electricity prices affect the use of HPs and combined heat and power (CHP) plants, indicating that the core business of CHP plants in the future may not be to produce heat [17].

The ambition of the climate goals of Sweden is to reach net-zero greenhouse gas (GHG) emissions by Year 2045 and have no emissions from 2050 onwards. In addition, some Swedish cities have established goals to decrease their CO_2 emissions to specified levels in some predefined year. Such city-level ambitions are directly impacted by the heating of houses within those cities. The heating choices of houses are, in turn, influenced by the housing dynamics and the choice of individual or communal heating technologies.

Most cities in Sweden today use DH to meet the heat demand at least partially, and DH covers the main share of the heat demand in many cities. The almost fully fossil-free electricity generation in Sweden, in combination with a decreasing share of fossil fuels being used in the DH sector, means that the CO_2 emissions from DH and electricity generation account for only about 8% of Sweden's annual emissions. The production of DH has increased by 50% between 1990 and 2018, while the use of fossil fuels in DH and electricity generation has decreased by 69% in the same period [18].

The Swedish DH sector has transitioned from an oil-dominated system in the 1960's to 1980's into a system with a low dependency on fossil fuels [19]. Biomass supplied only a few percent of the total energy in the 1980's, whereas in 2010, biomass supplied almost half of the energy. The utilization of excess heat (EH) from industries also began around 1980 and increased somewhat in the following decades, although contributing only to a small fraction of the total energy. The increased demand for cellulose-based biofuels in the transport sector may lead to competition for limited bio-resources, as well as to an increased availability of EH from biofuel production in biorefineries [19].

Still, it can be cost-efficient to continue using fossil fuels in DH systems, which means that the complete phase out of fossil fuels may not occur if additional incentives are not introduced regarding the use of fossil-free technologies or restrictions on using fossil fuels [20].

Between 1990 and 2019, the emissions arising from the heating of buildings that were not using DH decreased by over 90% [21], indicating a very successful transition. However, even though the share of Sweden's total emissions from electricity and heating is small, to reach the climate goals, the heating sector must continue to decrease its emissions. Additional individual heating units installed in new low-energy housing would result in more carbon emissions in a broader systems perspective, while DH solutions have a more complex impact [22] arising from the integration of the heating and electricity sectors. This integration is already important, and its importance will certainly grow when increasingly stringent climate goals need to be met in efficient and low-cost manners. These complex interdependencies of the seemingly simple heating sector and the importance of near-term heating choices for long-term climate goals, in combination with the above-described dynamics of the system constitute the background of the current study.

From the above, it may be concluded that there are a few studies that have treated supply and demand sides simultaneously, crucial for smart energy systems in a long-term perspective, and one that also has investigated cost-efficiency of individual versus communal heating options for both apartment and single-family buildings but none that has combined this with allowing for mixing of heating technologies, something which will likely be of importance for smart energy systems both due to potential resource and cost efficiency gains. Thus, the aim of this study is to investigate cost-efficient heating in new city-level housing under various scenarios, with the future electricity price development in focus and allowing for mixing of heating technologies. The following research questions form the foundation for this study.

- How do cost-efficient heating solutions differ for new housing in various scenarios?
- Does the heating load profile affect the solution and how do different future scenarios affect the solution?

Cost-efficiency is defined from the societal-economic point-of-view, where the total cost for society is minimized. This contrasts with the private consumer cost-efficiency point-of-view, where the total cost for consumers is minimized.

2. Method

This study uses a dynamic systems approach, implying consideration of both the supply side and demand side developments during the studied time period. Most previous works, in only considering one of the sides at a time, have not taken into account the full dynamics and interdependencies of the studied system. The dynamic systems approach is considered especially important when studying heating due to the very long lifetimes of both buildings and heating infrastructures. Thus, this paper applies a long-term time horizon, until Year 2050.

The paper uses a case study approach in which the existing DH system of the chosen case city, Gothenburg, is represented and different types of new buildings and new heating options, communal and individual, can be added to the existing system.

The demand side is represented by already existing housing and new housing that is added annually to the existing stock. These additions represent a city-level situation that combines apartment and single-family buildings constructed in proximity to an existing DH grid. Their heating demand should be covered either through connection to communal heating, represented by a DH system, or through investments in individual heating options. New DH demands may require additional DH supply-side investments. Fig. 1 shows a schematic of the studied system.

To answer the research questions and calculate the cost of long-term cost-efficient heating of new city-level housing in a systems perspective under different scenarios, the use of an energy systems optimization model was found to be appropriate.

In the remainder of this section, the heat demands and supply are presented first, followed by presentations of the investigated scenarios and the sensitivity analysis. Finally, the modeling is introduced.

2.1. *Heat demand*

Due to different characteristics of future housing, like size and whether they are high energy buildings (HEBs) or low energy buildings (LEBs), the total heat demands of the different kinds of housing differ. The total heat demand of the whole heating system therefore consists of several sub demands where each sub demand is derived from each housing type characteristics.

Six different kinds of new housing are investigated in this study: large and small apartment buildings, large and small single-family high heat demand housing (HHDH), and large and small single-family low heat demand housing (LHDH).

2.1.1. *Heat load profile*

As the heat demand varies throughout the year, two different heat load profiles are used: one LEB and one HEB. It is assumed that the domestic hot water use is the same per m^2 for HHDH and LHDH but that HHDH has a higher space heating demand per m^2, resulting in the HEB heat load profile having a larger share of its demand during winter compared to the LEB profile.

2.2. *Communal heating*

For DH to be used as the heating solution for new housing, a substation and piping must be installed. The same costs for the substation and DH grid connection are assumed for all the single-family housing types. The maximum heat load within a year differs for the different types of housing because the total heat demand in combination with the heat load profile results in a varying specific cost in terms of k€/MW_{max_heat}, calculated by dividing the installation cost by the maximum winter load.

The assessment is the same for the apartment buildings, albeit with a higher total cost for the substation and piping installation.

As this study investigates heating on the city level, the new housing investigated in this study is built close to already existing housing, so there is no extra cost for transmission pipes. It is also assumed that the total capacity of the new DH connections is sufficiently low that there is no need to upgrade the existing DH grid.

As supply plants in DH networks are often relatively large, economies of scale are considered in this study through imposing restrictions on the minimum investment size for some plant types. The available plant types for new investments include biomass, natural gas (NG) and oil heat only boilers (HOBs), biomass and NG CHPs, and HPs.

2.3. *Individual heating*

Three individual heating options, biomass (pellets) boilers, ground source HPs and electric boilers, are investigated in this study. In each new building one or a combination of these options may be installed, providing heat only to the actual building in which they are installed. Due to the high market availability with respect to sizing, the specific cost in terms of k€/MW_{max_heat} is assumed to be the same regardless of the size of the heating option. All types of housing may install any type of individual heating option at any time or of any size, and all options can supply both space heating and hot tap water.

For this study, the HP technology considered is ground source HPs using vertical collectors. The ground temperature only varies seasonally at the surface and since vertical collectors extract heat much further down, the coefficient of performance (COP) of the HPs is assumed to be

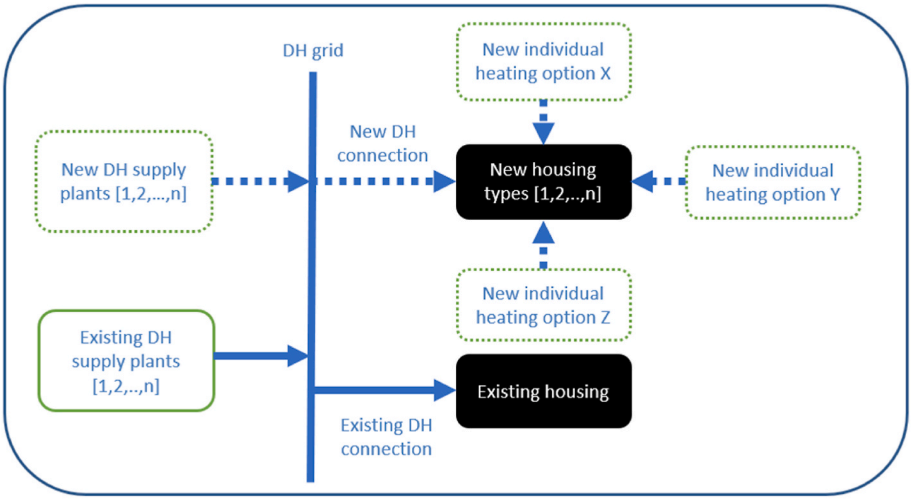


Fig. 1. Schematic of the dynamic systems approach applied to represent simultaneously the supply-side and demand-side developments. The black boxes represent the existing and new heating demands that must be fulfilled. Dashed lines indicate where new investments can be made. New housing is added annually, whereas the amount of existing housing remains constant.

constant throughout the year. Further, the housing considered is assumed to use radiators resulting in a lower COP compared to floor heating, as radiator heating requires a higher water temperature.

Modern HPs are equipped with an inverter, enabling adjustment of the HP power output according to the demand. This enables the HPs to run at a constant COP at different output levels.

Electric boilers are considered in this study even though this solution is seldom used to cover the full heat demand of new housing, as they may be unable in such a situation to meet the required energy standards for new housing. Electric boilers are still considered as it is allowed to use a combination of technologies and it may be economically feasible to use electric boilers to cover some of the heat demand during peak hours (because of the low investment cost) and still meet the required energy standards.

2.4. Scenarios and sensitivity analysis

Three heat load profile scenarios are investigated in this study: one in which the LEB profile is applied to all housing; one in which the single-family HHDH uses the HEB profile; and a third scenario in which the single-family HHDH uses the HEB profile and the DH connection cost for these types of housing is reduced. This reduction is because the HEB profile has a higher peak demand, and the DH connection cost is assessed by dividing the installation cost by the maximum load during winter.

Four parameters were chosen for the sensitivity analysis to evaluate the robustness of the results: electricity price; EH level; introduction of a climate policy; and a reduction of the DH demand of existing buildings. For each of these parameters, several different assumptions were tested, as presented in Table 1.

2.4.1. Electricity price

The electricity price affects heat production technologies depending on whether they are consuming or generating electricity. Electric boilers and HPs benefit from low electricity costs, while CHP plants benefit from selling electricity at a high price. Three different price cases are investigated: high, low, and varying price. Electricity-consuming technologies also pay an electricity tax, which does not affect the electricity producers, while producers of renewable electricity benefit from green certificates.

2.4.2. Excess heat

The future availability of EH in the DH system may influence the relative cost-efficiency of the heating options due to the low cost of EH. Thus, the impact of EH availability is investigated by assuming three different future EH levels: high, low, and unchanged. The low EH level is motivated by the assumption that the EH comes from oil refineries and their future is uncertain due to national climate goals. On the other hand, there is untapped potential for increased EH utilization in Sweden [23], and there are plans to increase biofuel production [24,25], which would result in increased EH availability (the high EH level).

2.4.3. Climate policies

The impacts of three different climate policies (i.e., no policy is implemented, the use of fossil fuels is banned in Year 2030, and the existing CO_2 tax is increased sufficiently to phase out fossil fuels in Year 2030) are investigated. The phase-out year of 2030 is inspired by the climate plan of the City of Gothenburg [26].

2.4.4. Decreased DH demand of existing buildings

Two different levels of DH demand of existing buildings already using DH are investigated, one where the current demand remains unchanged in the future and one where the demand decreases annually. This decrease represents improvements in insulation of existing buildings, higher outdoor temperatures due to climate change, and the possibility that some buildings disconnect from the DH supply and starts using other heating technologies.

2.5. Modeling

The use of an energy systems optimization model (ESOM) enables investigation of different parts of a complex system and can provide insights into the interactions between the different parts of the system. Using a cost-optimizing model, future possible cost-efficient evolutions of the system can be assessed regarding investments in and the dispatch of DH power plants, DH connections, and individual heating options.

The TIMES (The Integrated MARKAL-EFOM System) modeling framework [27], developed by IEA, was chosen for this study. TIMES is a total system cost minimizing model mainly used for long-term studies, over decades, to investigate optimal dispatch of existing power plants as well as investments and dispatch of new power plants. The objective function is formulated in Ref. [28] as:

$$NPV = \sum_{r=1}^{R} \sum_{y \in \mathrm{YEARS}} \left(1 + d_{r,y}\right)^{REFYR-y} * ANNCOST(r,y)$$

where.

- *NPV*, net present value, is the total cost that is minimized
- *ANNCOST(r,y)* is the annual cost in region *r* in year *y*. This includes investment costs, running costs, taxes, etc.
- $d_{r,y}$ is the discount rate
- *REFYR* is the discounting reference year
- *YEARS* are the years for which there are any costs present
- *R* is the set of regions that are investigated. In this study, only one region is included

In TIMES, the demand(s) is(are) exogenously given, the model uses perfect foresight and there is no price or demand elasticity. In the developed model, investments in new heating technologies can be made at any time, technology mixes are allowed, investment in better insulation is not considered in this study, and already existing power plants are treated as sunk costs.

The TIMES model output is the cost-minimized solution over the entire modelling horizon including technology investments and dispatch

Table 1
Summary of the heat load profile scenarios and the parameters used in the sensitivity analyses.

Heat load profiles:	LEB for all housing	HEB for single-family HHDH, LEB for the rest[a]	HEB and DH grid connection cost decrease for single-family HHDH, LEB for the rest[a]
Electricity prices:	High	Low	Varying
EH levels:	Unchanged	Low	High
Climate policies:	No policy	Fossil fuel ban	Increased carbon tax[b]
Decreased DH demand of existing buildings:		No change	Annual decrease until Year 2050[a]

[a] All electricity prices, EH levels and climate policies were run for the LEB profile. The results show that a low EH level has no effect on the high and low electricity price cases while a high EH level has no effect on the varying electricity price cases, as compared to unchanged EH levels. Therefore, all the EH levels and decreased heat demand of the existing buildings are not run for the HEB profile to reduce computational time.

[b] A ban on fossil fuels and increased carbon tax generate similar results in the LEB scenario runs, so only the ban is run for the HEB profiles.

of the different technologies. Since this study is focusing on heating solutions, these heating solution results will be presented (as shares of the end heat energy supplied by the different technologies).

3. Data and assumptions

In this chapter, the data and assumptions used in this study are presented. The data used is based on the heating system of Gothenburg, which is an expanding city on the west coast of Sweden. The costs for the different available fuels are presented in Table A1 in the Appendix.

3.1. Heat demand of new housing

The assumed amount of new housing and the corresponding heat demand, added to the existing building stock, are based on the building stock evolution in Gothenburg for the period 2014–2018 [29,30]. Approximately 10% of the new single-family housing is assumed to have a low heat demand (Table 2). The heat demand is the sum of the space heating demand and hot tap water demand.

The heat demand for new apartment housing is based on [31] in which the heat use for buildings connected to DH and built in the period of 2011–2015 is stated to be 75 kWh/(m^2*year). The heat demand for new single-family housing, at 105 kWh/(m^2*year), is based on the heat demand of single-family housing built in the period of 2011–2015 using DH as the heating source [32]. For new apartments and single-family housing, slightly lower heat demands are assumed for new housing built after 2015, given that historically the heat demand has decreased.

This study does not consider investments in improved insulation for the newly built housing after construction, as it is assumed that the new housing will not undergo any significant renovations in the coming decades.

Although climate change may affect the outdoor temperatures in such a way that the heat demand changes for buildings in the future, this is not investigated in this study.

3.1.1. Heat load profile

The LEB profile is derived from real measurements collected for a housing area in western Sweden that consists of both single-family housing and multi-family housing with LEB heat demands [33]. The heat load profiles used in this study are shown in Fig. 2. The study considers long-term development over several decades with a time resolution on a monthly level.

A higher time resolution, such as on a daily or hourly level, could influence the results if short term storages are available and there are significant differences in the heat demand or electricity price within those short time scales. These short time variations are however not considered in this study.

3.2. Communal heating

The DH system in this study is based on that in Gothenburg, which has used DH since the 1950's. Today, the DH system supplies almost 90% of the heating demand. The DH supply mix includes sewage water HPs, CHP plants, HOBs, municipal solid waste (MSW) incineration, and industrial EH. At present, MSW incineration and industrial EH produce the bulk of the heat, at roughly one-third of the annual demand each, while the remainder of the technologies produces the remaining heat. This technology mix allows the model to choose which technology to use to supply the required heat at different times. It is assumed that the temperatures currently used, 80 °C for supply and 40 °C for return, in the DH grid will be the used also in the future.

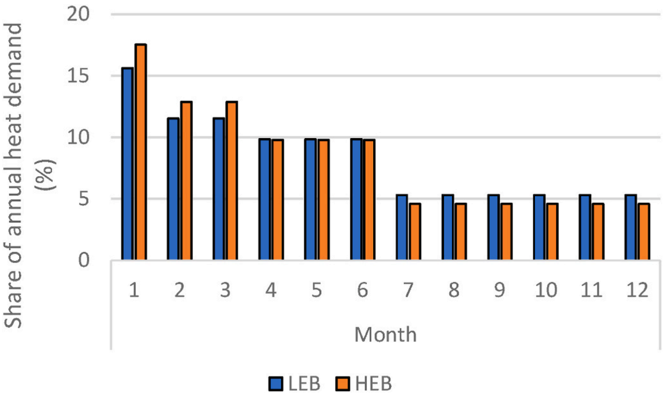


Fig. 2. Heat demand load distribution. The months are arranged from the coldest to the warmest.

The cost of installing DH piping and substations for single-family housing has been compared between Göteborg Energi AB and Vattenfall AB in Uppsala [34,35]. The cost difference between them is low, and the total installation cost is around €8000 per building for installation of both the piping and substation. The same total cost for installing piping and a substation has been assumed for all single-family housing.

For the apartment buildings, it is assumed that a larger substation is required, and that the piping is also more expensive. The investment cost per installation is assumed to be €20,000 for both types of apartment building.

Costs and technical details for new DH supply plants are acquired from the Danish Energy Agency [36] and are presented in Tables A2 and A.3 in the Appendix.

The calculated installation costs for all housing for the LEB heat profile are presented in Table 3.

3.3. Individual heating

The specific costs and efficiencies for individual heating options are acquired from the Danish Energy Agency [37] and include improvements in efficiency and COP as well as decreases of investment costs that occur in the future for all options. The data is presented in Table A.4 in the Appendix.

3.4. Sensitivity analysis data

The data for the four parameters presented in chapter 2.4. undergoing a sensitivity analysis is presented in this subchapter.

Table 2
Data for new housing used in the model. The heat demand for the new housing that is added each year is constant between 2020 and 2025, and decreases linearly between 2025 and 2050. The heat demand for housing that is already built remains the same until the end-year of the modeling.

	Heat demand in 2020 (in 2050) kWh/(m^2*year)	House area (m^2)	Number of houses built annually
Apartment large	70 (57.5)	2800	40
Apartment small	70 (57.5)	1400	80
Single-family large HHDH	95 (70)	175	200
Single-family small HHDH	95 (70)	105	150
Single-family large LHDH	47.5 (35)	175	20
Single-family small LHDH	47.5 (35)	105	15

Table 3

Calculated investment cost for installing DH in new housing. Distribution efficiencies and lifetime of the DH connection are acquired from Ref. [22]. The DH distribution efficiency reflects losses of heat stemming from transporting heated water from DH supply plants to buildings through the DH grid. The lifetimes of piping and substation have been combined into a single lifetime, DH connection lifetime, as the average of piping and substation lifetimes.

	Investment cost for DH grid connection[a] (k€/ $MW_{max\ heat}$)	DH distribution efficiencies Summer/spring & autumn/winter/ cold winter	DH connection lifetime (years)
Apartment large	477	0.63/0.85/0.9/0.915	35
Apartment small	955		
Single-family large HHDH	2252 (2005)		
Single-family small HHDH	3753 (3341)		
Single-family large LHDH	4503		
Single-family small LHDH	7505		

[a] For the single-family HHDH, the value within parentheses indicates the HEB reduced cost scenarios. The other housing types uses the same investment cost for all scenarios.

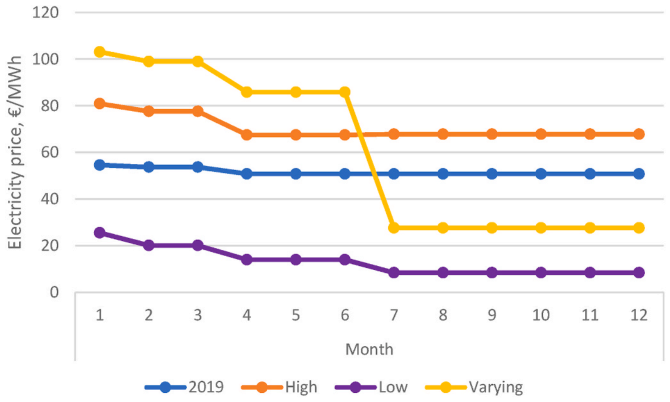


Fig. 3. Electricity price cases. Monthly prices for each year in the period 2019–2050 are based on linear interpolation between the end years. Values shown are exclusive of tax or green certificate costs. The months are arranged from the coldest to the warmest. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.4.1. *Electricity prices cases*

Each of the three electricity price cases starts with the same electricity price profile in 2019 and 2020, and gradually changes each year thereafter. The three different electricity price cases are presented in Fig. 3 and are described as follows (Year 2019 is used for comparison).

- High price: In this case is represented by that the price is set by a fossil fuel-fired electricity source on the margin and the data are acquired from the BAU scenario [16].
- Low price: This case represents a scenario in which the production capacity of intermittent renewable energy sources is vastly expanded, with the consequence that the marginal pricing fluctuates significantly, although the average price for electricity is low for all seasons of the year.
- Varying price: In this case, there are large seasonal variations in the price of electricity. The price data have been acquired from the *No flex* scenario for southern Sweden described in Ref. [38].

The taxes and certificate price levels included in the model are presented in Table A.5 in the Appendix.

3.4.2. *Excess heat levels*

In the unchanged scenario, the EH level remains at the current level. In the high EH levels it is increased by 50% while in the low EH levels it is decreased by 50%. When the EH level is changed, it is changed linearly from Year 2019 until Year 2030 when the annual level becomes constant until the final modeling Year 2050.

3.4.3. *Carbon policies*

The required carbon tax is not known beforehand, so it must be calculated. In this paper, the same procedure as that described previously [20] is used to calculate the carbon tax increase required to phase out fossil fuels. This procedure consists of rerunning the model with a greater increase in the carbon tax until the increase is high enough to phase out fossil fuel use in the target year.

In the fossil fuel ban policy, the existing carbon tax remains unchanged until the year when the use of fossil fuels is prohibited.

3.4.4. *Decreased DH demand of existing buildings*

Two scenarios for the DH demand of existing buildings are investigated. In one scenario, the demand remains unchanged, and in the other scenario, the demand decreases by 25% up to Year 2050, roughly corresponding to a decrease of 1% annually.

3.5. *Model properties and CO_2 assumptions*

The studied time horizon is 2019–2050, which is divided into nine time periods. Years 2019 and 2020 are individually modeled, 2021–2022 is followed by a 2-year period, and from 2023 onwards the modeling periods are 5 years. Each year is divided into 12 periods of 1 month each.

The use of electricity, biomass, and EH is assumed to be carbon-neutral in accordance with [20], implying that it is not affected by neither climate policy nor carbon tax. CO_2 emissions from CHP plants have been allocated according to the power-to-heat ratio. The CO_2 emissions calculations do not consider the impact of CHP-generated electricity substituting for other forms of electricity generation.

4. Results

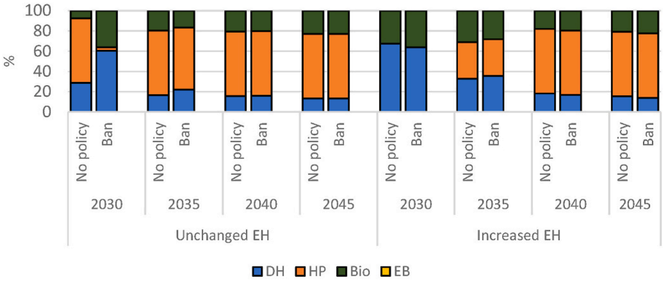
The modeling results present the heating solutions, in terms of shares of heat produced by communal and individual means, for each type of housing.

The results for the new apartment buildings are presented initially, followed by those for new large single-family HHDH, for which the results for the LEB heat load profile are presented first. Lastly, the results for the new small single-family HHDH and single-family LHDH are presented.

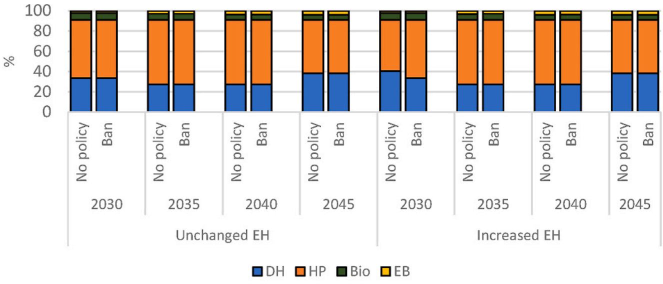
The results obtained for the same electricity price show only minor differences in the years before 2030 and are, therefore, not elaborated upon further in the following sections. The results obtained for an increased carbon tax and a ban on fossil fuels are very similar, so only the results for the ban are presented.

The results for the low EH level are similar to those for the unchanged EH level for both the high and low electricity prices, while for the varying electricity price the unchanged scenarios are similar to the increased EH levels. Therefore, these results are not considered further.

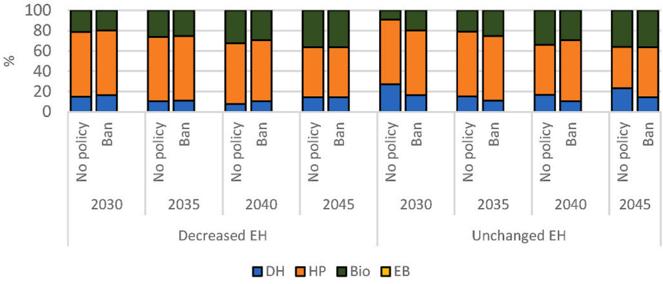
The effect of a reduction in the DH demand of the existing housing has generally no or low effect on the heating solution. The results for the DH demand reduction scenarios are therefore not presented further in this chapter.



(a) High electricity price



(b) Low electricity price



(c) Varying electricity price

Fig. 4. The figure presents the modeling results as shares of heat energy supplied by the different technologies for new large single-family housing for the LEB heat load profiles in the cases of a climate policy not being implemented (No policy) or a ban on the use of fossil fuels (Ban) in the indicated years. EH, Excess heat; DH, district heating; HP, heat pump; Bio, biomass boiler; EB, electric boiler; LEB, Low-energy building.

4.1. New apartment buildings

All apartment buildings are connected to the DH system and are entirely supplied by DH heat in all the scenarios. This indicates that climate policies, electricity price and EH level do not affect the amount of heat delivered by DH to the apartment buildings in the future.

4.2. New large single-family HHDH – LEB profile

In all the electricity price cases, the main pattern observed is that when the DH share is increased, the use of HPs is decreased, and *vice versa* (Fig. 4). For the high and varying electricity prices, an increase in the use of HPs also somewhat decreases the use of individual biomass boilers (Fig. 4b and c).

For all the electricity price cases, there is a reduction in the use of DH from Year 2030 to Year 2035. The drop is more significant for the high electricity price case, as compared to the other two price cases. This drop reflects that several of the existing DH supply plants are dismantled after Year 2030.

In the high electricity price case, there is a general decrease in the use of DH in future years, although if the EH level increases the decrease is slowed. For the low electricity price case, there is, however, a small increase in the use of DH from Year 2035 onwards, although it is not affected by the EH level. Furthermore, in the varying electricity price case, there is a small increase in the use of DH from year 2035 onwards although the share of DH is small, and even smaller if the EH level is decreased.

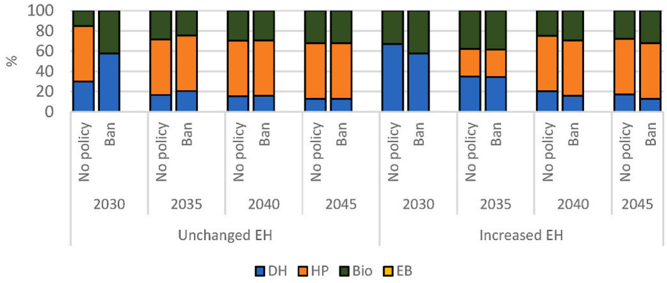
A climate policy has a weak impact of the heating solution from Year 2035 onwards, if it has any effect at all.

4.3. New large single-family HHDH – HEB profile

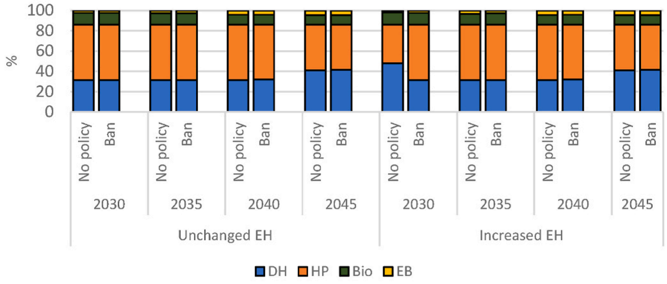
The general trend observed in the LEB profile scenarios in which DH competes with HPs in all the electricity price cases, is also found in the HEB profile scenarios (Fig. 5, a–c). In the high and varying electricity price cases, HPs also compete with biomass boilers. In general, there is increased usage of biomass boilers and DH and decreased usage of HPs in the HEB profile scenarios, as compared to the LEB scenarios.

For all the electricity price cases, the impact of a climate policy follows the same pattern as for the LEB profile in that it only has a minor effect after Year 2035.

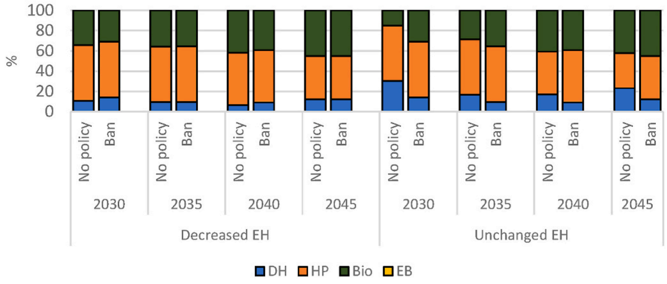
For the scenarios with a 10% reduction in the cost of the DH



(a) High electricity price



(b) Low electricity price



(c) Varying electricity price

Fig. 5. The figure presents the modeling results as shares of heat energy supplied by different technologies for new large single-family housing for the HEB heat load profiles in the cases of a climate policy not being implemented (No policy) or a ban on the use of fossil fuels (Ban) in the indicated years. EH, Excess heat; DH, district heating; HP, heat pump; Bio, biomass boiler; EB, electric boiler; HEB, High-energy building.

connection, there is an increase in the use of DH for all the scenarios, indicating that the heating solution is sensitive to the cost of the DH connection. For both the high and varying electricity price cases, it is mostly the biomass boilers that are affected. For the low electricity price case, it is only the HPs that are affected. They are, however, affected to such an extent that there are only some investments in HPs in Year 2030 and no new investments in HPs after Year 2030.

4.4. New small single-family HHDH and single-family LHDH

The small single-family HHDH and large and small single-family LHDH are not connected to the DH system in any of the scenarios, or to a very marginal level, indicating that the investment cost for the DH connection is too high to ever be economical.

5. Analysis

As the results show, the heating solution dynamics differ between the scenarios. Apartment buildings, small single-family HHDH, and single-family LHDH are all insensitive to electricity price variations, EH level, and climate policy, while large single-family HHDH are more sensitive to varying scenario conditions.

The heat demand load profile was found to have an impact on the heating solution. In general, in the HEB profile scenarios, with a higher heat share during wintertime, the investment in and use of DH and/or the use of individual biomass boilers are both higher, while the investment in and use of HPs are both lower for large single-family HHDH.

The results for all the electricity price cases relate to the lower investment cost of biomass boilers compared to HPs, which in turn have a lower investment cost than DH. The higher demand during winter favors the use of peak power, thereby benefiting biomass boilers.

For the LEB profile scenarios, the use of individual biomass boilers is highest in the varying electricity price case for the large single-family housing. This stems from the fact that most of the demand during summertime is covered by individual HPs, while DH has a higher share during the intermediate months. There are also investments in individual biomass boilers used as peak power during the winter months. The result is that biomass boilers supply around 20%–40% of the heat after Year 2030, while in the high electricity price case, biomass boilers supply around 20% after Year 2030 and in the low electricity price case, biomass boilers supply <10% of the heat.

A 10% decrease in the cost of the DH connection cost affects the results. Most significantly, there is almost no use of HPs in the low electricity price case with the HEB heat profile. This indicates that DH is mainly competing against individual HPs for use as base load or intermediate load. This leads us to surmise that given a sufficiently high peak demand and sufficiently low connection cost for DH, the use of HPs decreases significantly.

There is no clear indication as to how the introduction of a climate policy would affect the results. A climate policy mainly affects investments in new peak NG HOBs in the DH supply side, which in turn affects the heating solution for new buildings. However, the effect on the heating solution is weak for most of the scenarios.

It is noteworthy that in the high electricity price case, the main heating solution is individual HPs for the large single-family housing. The reason for this is that more heat is produced in the CHP plants, which have high investment costs and are used as base-load units in the DH system, although the electricity price is not high enough to have CHP plants as peak-power plants. However, in the varying price case, the prices during the winter and during intermediate months are higher compared to the high price case, which in turn increases the heat production from the CHP plants during those months, as compared to the summer months.

The EH level does not have a significant impact on the heating solution for new buildings. This reflects the fact that the model makes investments in new DH supply plants in relation to the EH level, which means that in the case of a high EH level, investments in other plants are decreased and *vice versa* for a low EH level.

There is almost no difference between the two climate policies with respect to how the heating system evolves. This is probably a consequence of the perfect foresight of the model, since both climate policies are designed to phase out fossil fuel use in the same year.

6. Discussion

This study investigated how the heating demand of new housing of different kinds can be fulfilled in a cost-efficient manner. We studied how the heating solution differs for different heat load profiles under different future electricity prices at different levels of EH and with the introduction of a climate policy. The results from the model show differences between the types of new housing and their respective heating solutions.

The results show that the method presented and used in this study where the supply and demand are treated simultaneously and together contributes to the understanding of interactions between the supply and demand sides. The demand side disaggregation into several types of new housing enables the study to show that the cost-optimal heating solutions differ for different types of new housing. Further, that the most economical heating solution changes over time shows the importance of performing long-term investigations of local systems since technologies eventually reach their end of technical lifetime and technologies improve over time with increased efficiency and decreased investment costs for new installations. Allowing the model to mix technologies in a single building is reflected in the results, further highlighting that mixes within the same building may become more common over time as the improvement of technologies continue.

The results from this study are in accordance with the results of a previous study [10] in which apartment buildings were connected to the DH system, although other types of housing were not investigated in Ref. [10]. Focusing exclusively on apartment buildings when investigating new DH connections, as was also the case in Ref. [4], does not give a complete picture. It might even be cost-efficient for the heating system to connect single-family housing units to the DH system, although as found in the present study, the future electricity price and profile and the heat load profile have significant impacts on the connection share for new single-family housing.

In this study, there are investments in and usage of DH for large single-family HHDH areas, even though DH does not dominate as the heating solution, while for large and small single-family LHDH housing, DH is not used at all. This contrasts with the findings of a previous study [16] where it was found to be more cost-efficient to connect an area consisting of single-family LHDH and apartment housing to the DH system of Gothenburg, as compared to using individual heating options. The discrepant results are attributable to several factors, with the main ones being that [16] assumed significantly higher investment costs for individual HPs and somewhat greater availability of MSW. Even though the investment cost for DH grids for the area investigated in that study [16] was approximately 20% higher than that for the large single-family HHDH in the present study, it was concluded that DH is the more cost-effective heating solution for an LHDH area if it is built close to an already existing DH grid.

The implications of the different results in this study, in accordance with [16], are that the investment costs of individual HPs have a major impact, regardless of whether communal or individual heating is the most cost-effective heating solution for new city-level single-family housing. This is supported by the results of the present study, where a heating profile with a higher relative demand during winter decreases the use of HPs and increases the use of DH. It is important to note that in Ref. [16], the constructors of the new buildings did not have the option to choose a mix of heating technologies.

The results of this study further indicate that a flatter heat demand downgrades the value of using DH. As it seems likely that LHDH has a flatter heating profile than HHDH, it may be even less desirable to connect future housing to the DH grid. The heat demand for new housing has being decreasing for decades [31,32] and this trend is likely to continue for future housing. Not only low energy demand housing may find it undesirable to connect to the DH grid, but also housing with a higher heat demand may find it more economical to use individual heating options.

The total system cost can decrease when utilizing more EH [39], and the authors of a previous paper [40] evaluated a transition in which future housing produces more energy than it uses and utilizing EH recovery is deemed to be a potential factor when available. This could have an impact on the actual price for consumers of DH, as the price for DH may be set using the average cost of producing heat [41]. With a lower price for heat when the level of EH is increased, more consumers may want to connect to the DH system even though the total system cost would be higher compared to a situation in which new consumers instead used individual heating options. In this context, it has been argued that the price setting scheme for DH companies needs to be adjusted [42]. The impact of using consumer prices is, therefore, of interest [1], and warrants further research.

It is important to note that the model used in this study is a perfect foresight model that achieves the lowest total cost. Due to the exogenously given costs, the model can take decisions without any uncertainty, which is not the case for decision makers who have to make choices with limited knowledge of the future.

In addition, due to the optimizing nature of the model, even small changes in the input data can have large effects on the results if two technologies have similar costs. As the results indicate that it is DH and individual HPs that are the main competing technologies, small differences in the cost trajectories of these two technologies can have substantial impacts on the results. The future application of other technologies, such as air-to-air and air-to-water HPs could also affect the results. It is, however, important to note that some technologies, such as air-to-air HPs, do not provide both space heating and hot tap water. Therefore, they have to be combined with some other technology if they are to supply the entire heat demand.

Furthermore, allowing the model to install a mix of technologies for the same type of housing could give results that are not commonly seen with current heating systems, as it is usual to employ only one heating technology in a building, although examples exist whereby individual heating technologies have been mixed with DH.

For some scenarios, individual biomass boilers are used for new housing. This could have a negative effect on the air quality in the vicinity of new housing due to particulate matter emissions. The $PM_{2.5}$ emissions from individual heating technologies constitute around one-third of the total emissions in Sweden, and the levels have decreased by two-thirds in absolute terms since 1990 [43]. This reduction arises from the increased use of DH and individual heating technologies that use electricity, as well as from technological improvements to biomass boilers. Stricter particle emission standards for biomass boilers in Sweden, combined with ongoing technological improvements of biomass boilers will continue to reduce the particle emissions from this technology. Thus, the problem of bad air quality stemming from particle emissions from burning biomass could be resolved in the future.

7. Conclusions

This study has investigated how the heat demands of different types of future housing can be fulfilled in a cost-efficient manner using an approach that simultaneously addressed both the supply and demand sides of a heating system. The impacts of different heat demand load profiles have been investigated under different future electricity prices, EH levels, and the introduction of a climate policy designed to phase out fossil fuel use in the future.

The most significant factors determining whether new housing will be connected to the communal heating option, DH, are the grid connection cost and the electricity price. In this study, the apartment buildings are connected to and supplied entirely by DH, while small single-family HHDH and single-family LHDH are heated using individual heating options. The results for these types of housing are generally unaffected by either the EH level or climate policy.

Large single-family HHDH is connected partly to the DH grid and uses both DH and individual heating options to meet its heating demand. The heating solution is mostly affected by the future electricity price. A heating profile with higher relative usage during wintertime promotes DH and individual biomass boilers, while HPs are demoted in the ranking of desirable solutions. Due to the impacts of the heating demand profiles, investigations into the heat load profiles of future housing are of great interest.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix

Table A.1
Costs for different fuels. The prices shown for Bio oil, Excess heat and Municipal solid waste are based on [16], and the biomass and pellets prices are based on [44] together with own calculations. Natural gas price is based on [45] together with own calculations.

Cost of fuel (k€/GWh)	Year 2019	Year 2030	Year 2050
Biomass (woodchips)	25	30	40
Pellets	40	45	55
Bio oil	42	50	60
Natural gas	18.4	26.5	41.2
Excess heat	0.56	0.56	0.56
Municipal solid waste	−14,5	−14,5	−14,5

Table A.2
Data for new DH HOBs and HPs

	Investment cost, k€/MW$_{\text{heat}}$	Efficiency	Fixed O&M cost, k€/MW$_{\text{heat}}$	Variable O&M cost, k€/GWh$_{\text{heat}}$	Lifetime	Minimum size, MW$_{\text{heat}}$
Woodchips HOB	700	1.15	32.8	1	25	0.5
Oil HOB	700	0.9	32.8	1	25	0.5
NG HOB	60	1.03	2	1.1	25	–
HP small	700	3.5	2	3.3	25	4
HP large	600	3.5	2	0.9	25	12

Table A.3
Data for new DH CHPs

	Investment cost, k€/MW$_{\text{electricity}}$	Electrical efficiency	Fixed O&M cost, k€/MW$_{\text{elc}}$	Variable O&M cost, k€/GWh$_{\text{elc}}$	α-value (electricity/heat)	Lifetime	Minimum size, MW$_{\text{electricity}}$
Woodchips CHP small	6700	0.14	292.7	7.8	0.14	25	2.9
Woodchips CHP medium	3700	0.27	158.4	3.8	0.33	25	23
Woodchips CHP large	3500	0.28	100.5	3.8	0.34	25	177
NG CHP combined cycle	900	0.55	30	4.5	1.59	25	0.5
NG CHP open cycle	1300	0.47	30	4.5	1.09	25	0.5

Table A.4
Data for new individual heating options

	Investment cost, k€/MW 2019/2030/2050	Fixed O&M cost, k€/MW$_{\text{heat}}$ 2019/2030/2050	Efficiency 2019/2030/2050	Lifetime
HP	2750/2500/2250	68/61/56	3.45/3.6/3.75	20
Pellets boiler	697/665/603	41/39/35	0.82/0.86/0.88	20
Electric boiler	976/933/833	8/7.67/7	1	30

Table A.5
Policy pricing used in the model.

	Year 2019	Year 2030	Year 2050
Carbon tax, €/t CO_2	100	100	100
Electricity tax*, €/MWh	40	47	60
Green certificates**, €/MWh	4	0	0
Discount rate		5%	

*Only paid by electricity users.

**Only paid for electricity from renewable sources. Assumed to be abolished in Year 2030.

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