THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Combined Assessment of Future Heat Supply and Demand

A Dynamic Systems Approach

KARL VILÈN

Department of Space, Earth and Environment, Division of Energy Technology

CHALMERS UNIVERSITY OF TECHNOLOGY

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Department of Space, Earth and Environment
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

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Department of Space, Earth and Environment
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Abstract

In order to meet climate change mitigation targets, the use of fossil fuels has to be reduced and, eventually, be phased out in all sectors. As the heating sector occupies a central place in energy systems, especially in Nordic countries, it is affected by and affects other energy sectors. The demand for space heating and hot water has traditionally been covered by: district heating (DH) systems, whereby buildings are connected through a grid to power plants; and the installation of individual heating technologies within each building. As there are several heating solutions available, the ways in which heating systems will develop in the future when fossil fuels are phased out depend on several factors, which are currently uncertain.

As many components of heating systems have long lifetimes, the investments made in the near future will have long-term impacts on the development of heating systems. It will be important to understand how investments and the dispatch of different components depend on the phasing out of fossil fuels and other factors. Therefore, this thesis aims to investigate how the different parts of heating systems develop under different climate policies, electricity prices and heat load profiles.

To investigate heating system development when both the supply and demand sides evolve simultaneously, a dynamic systems approach is used in which an expanding heating system is investigated for several decades in the future and new housing is treated heterogeneously.

In this thesis, the TIMES modeling framework is used, and the heating system of Gothenburg is applied as modeling case. The demand side is treated heterogeneously by investigating several types of new housing, which means that the resulting cost-efficient solution may be different for different types of housing. The investment cost for new DH grid connections is therefore assessed for each housing type.

The modeling results show that the main effect of a climate policy is decreased investments in new natural gas heat-only boilers (HOBs) in the DH supply side. New natural gas HOBs compete with new large-scale heat pumps (HPs) but does not affect new combined heat and power (CHP) plants. Investments are made in large-scale HPs in the cases of increasing and decreasing electricity prices, whereas no investments are made in biomass CHP plants if the future electricity price decreases.

The results further shows that apartment buildings use DH exclusively, while single-family housing with low heat demands and small single-family housing with high heat demand are not connected to the DH system at all. The heating solution for large single-family housing with high heat demands is dictated by both future electricity prices and whether a climate policy is introduced. A heat demand load with a higher relative use during wintertime generally discourages the use of individual HPs.

The findings of this thesis may be of interest to city planners and DH utilities, as the findings shows that both the DH supply side and the heating solution for new large single-family housing with high heat demand are affected by climate policy, future electricity prices, and the heat load profile.

Keywords: Heating system, Housing, Low heat demand housing, District heating, Climate policy, Dynamic energy system modeling, TIMES

List of publications

The thesis is based on the following papers, which are referred to in the thesis by their assigned Roman numerals:

I. Vilén K, Selvakkumaran S, Ahlgren EO. *The Impact of Local Climate Policy on District Heating Development in a Nordic city – a Dynamic Approach*. Int J Sustain Energy Plan Manag 2021. https://doi.org/10.5278/ijsepm.6324.
II. Vilén K, Selvakkumaran S, Ahlgren EO. *Communal or Individual – Exploring Cost-Efficient Heating of New City-Level Housing in a Systems Perspective.* Submitted for review.

Karl Vilén is the principal author of both papers. Sujeetha Selvakkumaran and Erik Ahlgren contributed with discussions and the editing of both papers.

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Karl Vilén

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List of abbreviations

CHP	Combined Heat and Power
COP	Coefficient of Performance
DH	District Heating
EH	Excess Heat
HOB	Heat-Only Boiler
HP	Heat Pump

1. Introduction and background

Energy consumption related to the building sector constitutes about 40% of total energy use in Europe. Since the heat to be used in buildings can be, and historically has been, associated with emissions of CO_2, reducing and ultimately eliminating these fossil fuel emissions are essential steps towards meeting the global emissions targets. Since heating systems are coupled to other parts of the larger energy system, the emissions from the overall energy system could be reduced depending on the heating solution, thereby contributing to attaining climate change mitigation goals. Furthermore, the cost-efficiency of the full energy system could be reduced depending on the heating solution. It is, therefore, of great importance to study heating systems together with the other parts of energy systems.

The demand for heat in buildings is related to the need for space heating and hot water, which can be supplied by various means. In general, the paths for supplying heat can be divided into communal and individual. The communal path is often a city-wide district heating (DH) system or a smaller, local on-site system. Individual paths mean that each individual building has its own heating solution, which can be used only for that specific building. On a general level, DH is mainly used in densely populated areas, while individual heating technologies are more common in less densely populated areas, e.g., detached housing.

As cities continue to expand, the future housing units need to be heated using either communal or individual options. In Sweden, around 50% of the demand for space heating and hot water is supplied by DH, while almost 90% of multi-family dwellings are heated by DH. The higher prevalence of DH in densely populated areas is because it is more economical to build and expand DH grids in areas where the heat demand density is higher, and also because distribution losses can be minimized. Not only is the heat demand density of importance when investigating which heating technology to use, but also the heat demand load profile can have a major impact.

Historically, the supply of heat in Sweden has contributed to fossil carbon emissions, although total emissions have generally decreased. The almost complete phase out of oil in both individual heating and DH systems is one of the major factors contributing to this decrease. However, there is ongoing use of fossil fuels, such as natural gas, in the heating sector, which has to be phased out if the climate goals are to be met.

As the heating sector is a major part of a full energy system, its future development is of importance. Due to linkages to the other energy sectors, especially the electricity sector, the heating sector cannot be investigated in isolation; other sectors have to be included as well.

Previous studies have looked at how heating systems can develop in the future. However, there are few studies that treat both the supply and demand together for heating systems that expand in line with the emergence of new housing.

2. Aim and scope

As presented in the *Introduction* chapter, there are several factors that potentially affect how heating systems develop, with the fulfillment of climate change mitigation goals being a major factor. In addition, since economic concerns are often central to decisions as to which heating solution to use, regardless of whether the solution is communal or individual, cost considerations are crucial when assessing future heating solutions.

Thus, this thesis aims to:

- Understand how different climate policies aimed at phasing out the use of fossil fuels will affect the development of an existing heating system in the coming decades.
- Elucidate the impacts of long-term electricity prices (and development thereof) on the cost-effective heating solution mix.
- Show how the different heat load profiles of new housing will affect the future heating solution mix.
- Develop a dynamic systems approach that enables investigations of how both the supply and demand will develop together in a cost-efficient manner in future heating systems.

2.1. Outline of the thesis

The thesis consists of the two appended papers and a summary essay.

The same methodological approach is used for the same existing heating system in both papers. This approach involves assessment of the heat supply options and future heat demands in the heating system.

In both papers, the cost of connecting new housing to an existing DH grid is assessed. This is linked to the central aim to investigate how heating systems can be developed in a cost-efficient manner. As an entire heating system is investigated, and not only DH, the cost of installing and using DH must be compared to installing and utilizing individual heating options.

As the two papers use the same approach and are based on the same existing heating system, the different parts of the system can be investigated and analyzed. In **Paper I**, the focus is on the development of the supply side of DH, while in **Paper II** the focus is on the demand side, the different types of new housing and the development of their respective heating solutions.

In both papers, the impact of phasing out the use fossil fuels through either a ban or an increased carbon tax is investigated. This is done for several future electricity prices in both papers. Two different fossil fuel phase-out years are investigated in **Paper I**, while in **Paper II**, 1 year is considered. Both papers investigate the development of the heating sector up until Year 2050. Two different future electricity price profiles are considered in **Paper I**, and three in **Paper II**. In **Paper II**, two different heat load profiles are investigated for large, single-family housing with high heat demands, while one heat load profile is used for the remainder of the housing stock.

It should be noted that the results presented here are not predictions for the future. Instead, they indicate how the different parts of heating systems interact, and more importantly, highlight the dynamic natures of the heat demand and supply.

3. Related research

This chapter is divided into three subchapters that relate to the four research aims. The first subchapter relates to research on heating systems and includes research on fossil fuel emissions from such systems (the first aim). The second subchapter relates to research aims two and three, which are concerned with sector coupling. Lastly, the third subchapter addresses the fourth research aim, which relates to the methodology used to investigate how future heating systems can develop in a cost-efficient manner.

This thesis uses a societal systems perspective, in contrast to the perspective of individual consumers. As a consequence, the related research presented in this chapter mainly comprises studies that are of interest from a systems perspective. Although various components and aspects can be included when investigating heating systems, the general guideline followed in this chapter is that studies concerning heating systems within cities are considered, which contrasts with taking a broader national perspective or having a narrower perspective in investigating the roles and components of individual houses.

3.1. Heating systems and its components

As heating systems consist of multiple components that interact with each other, there is a need to investigate heating systems as systems. If heating systems are not treated in this way, important dynamics are missed, which in turn leads to a poor understanding of how heating systems may develop in the future.

Various means to reduce and eventually eliminate the fossil fuel emissions stemming from the production and distribution of heat to the building stock have been investigated in several studies. As there are several methods available for reducing fossil emissions from the heating sector, it is of importance to investigate all the components of heating systems, so as to ensure that the transition to a fossil fuel-free heating system can be achieved. Low-energy buildings and their impacts on CO_2 emissions have been investigated previously [1]. That different energy-saving measures in existing buildings have different impacts on the primary energy saving has been pointed out [2,3]. Reduction of the energy demand of households by changing consumer behavior versus using more efficient technologies has also been investigated [4].

The choice as to whether to use DH or individual heating options has been investigated in different ways in several studies. The difference between using consumer-economy and socio-economy approaches has been investigated [5]. The differences in system cost for different heating options of a new building area have been examined [6] while in [7] the differences in direct and indirect emissions between different heating options have been investigated. Both these studies have performed the comparisons when only DH or individual heating options are used, and they do not delve into a mix of these heating options.

There are studies available that focus on the housing aspect of heating systems, but the DH system is often the central focus. The effect of improving insulation, as compared to the development of a DH system, has been investigated [8–11]. Furthermore, the possibility and potential to use demand-side management to improve flexibility has been evaluated. The improved potential of the demand-side response has also been highlighted as a potential important aspect of future DH systems [12,13]. That DH may have a reduced cost-competitiveness in areas with low heat density has also been pointed out [14].

The potential role of DH in decarbonization has been the focus of several studies (see, for example, [10] and [15]), which have proposed that DH can contribute to decreasing the primary energy consumption and decreasing the heating cost.

Using DH to provide heat is not something new. Sweden has used DH since the 1950's and research in the field is actively ongoing, with investigations into various aspects of DH performed in the past decades [16].

One area of research has been excess heat (EH) and its potential usage. EH for heating purposes can only be recovered by a DH system, which explains why these two items are often studied together. For example, studies [17,18] have indicated that Sweden and Denmark have untapped potentials to use more EH.

The primary motivation for using DH systems has changed over time, from increased comfort, to reducing costs and increasing the security of supply, through to today's transformation to sustainable energy systems [19]. Due to differences in how they are built and utilized, different DH systems can be classified according to different generations. Each generation uses lower supply and return temperatures compared to the preceding generation, although other differences between the generations have enabled new energy sources to be used in the supply side of DH systems.

Next-generation DH systems, often called *4th generation DH*, differ from the 3rd generation DH. Even though there is no exact definition of what differentiates the two generations from each other, there are some general differences that could affect heating systems as a whole [19,20]. The lower supply and return temperatures in the 4th generation compared to the 3rd generation DH systems decreases the distribution losses, and it is possible to use alternative materials in the pipes to decrease further the cost of new distribution grids. The lower temperatures can also affect the efficiency of power plants in several ways. The power-to-heat ratio of combined heat and power (CHP) plants may increase, as can the coefficient of performance (COP) of heat pumps (HPs) [21]. That the COP of central DH HPs can be improved by decreasing the temperature in future DH systems has been described [22]. Reduction of the supply and return temperatures even further, to achieve "ultra-low-temperatures" has also been investigated [21,23]. The potential of 4th generation DH has been investigated for several cities [24,25]. It is also possible to utilize more waste heat, which is not recovered in any way in current DH systems [19]. The ability of DH to use energy sources that individual heating technologies cannot use has been pointed out [14], and this ability can contribute to increasing energy efficiency and avoiding the use of fuels for heat-only usage.

Smart control and metering tools are expected to be used more frequently in future-generation DH systems [26,27]. The potential to exploit central heating storage and the thermal inertia of buildings as heat storage has been investigated [28], in which it has been shown that the total system cost of a DH system can be decreased by using heat storage units. That HPs have a strong potential to provide heat in future DH networks is clear [29]. However, it is also argued [29] that there is no universal solution through which HPs can be used in all EU countries, and that each country should be analyzed individually.

3.2. Sector coupling related to heating systems

There is increasing interest among researchers in connecting the different parts of large energy systems, in so-called *sector coupling*. This allows investigations of the dynamics of the different energy sectors when they can both benefit and compete with each other.

The electricity price affects how DH systems are operated [30]. It is argued [31] that the core business of CHPs may become the production of electricity, assuming that the electricity price is sufficiently high. Furthermore, it has been shown [32] that a base-load waste incineration CHP plant can benefit economically by providing flexibility to both the electricity and heat sectors. In addition, the electricity system can be balanced by using CHP plants and HPs within the heating sector [33,34].

Integrating and storing fluctuating renewable energy have been investigated [35], revealing that electricity storage is not the most-cost-optimal solution. By combining the electricity sector with other parts of the energy system, it has been shown that using thermal storage is cheaper for the whole system. Solar PV together with thermal storage increases the value of HPs [36]. All of these previous studies [31–36] have in common that the heat demand is set beforehand and does not change over time, whereas [30] investigates future heat demand reductions.

There is increasing interest in the use of so-called *smart systems*, as opposed to *smart grids*, which only include electricity [37]. It has been demonstrated that smart systems can decrease the system cost when the entire energy systems that currently use fossil fuels are transformed into fully renewable systems [38].

The transport sector can affect the heating system within the larger energy system by utilizing smart charging and discharging of electric vehicles [39]. The smart charging and discharging increase the competitiveness of HPs, while decreasing the competitiveness of CHPs and heat-only boilers (HOBs).

One of the main factors differentiating DH systems from other energy systems is their ability to recover EH from the industrial sector. Utilizing EH from an industry cluster located outside a city can reduce the DH system cost [40]. The use of such EH can reduce the carbon emissions from the DH system, although the total CO_2 emissions on a system level could increase in the short term [41]. It is also important to determine whether the EH used in DH systems could have instead been used within the industry itself, as this can severely affect the results when assessing the carbon emissions on a system level [42].

3.3. Using modeling for investigations of energy systems

A common way to investigate investments and the dispatch of various parts of energy systems is to apply optimizing energy systems models [43]. Many model frameworks have been developed and used over the years, including TIMES [44], MARKAL [45], and EnergyPLAN [46]. Several of the studies presented earlier in this chapter have used a modeling framework to investigate their respective research questions. TIMES has been used in [6,7], MARKAL has been used in [41] and EnergyPLAN has been used in [10,15,20,21,38]. Other modeling frameworks have also been used in the previously cited studies, and self-developed models have been customized according to the specific research questions being addressed.

By using energy models, it is possible to study complex and data-rich systems that would have been too cumbersome to investigate without using the computational power of a computer. Energy system models have, however, often been analyzed with the electricity sector as their focus, which means that the heating sector is often overlooked [47].

Many of the previously presented studies using computer modeling have used so-called *bottom-up models*. In these kinds of models, the data inputs to the model include investment costs, plant efficiencies, fuel costs and technical lifetime. Different types of constraints are also of great importance for these models. Such constraints include the requirement to provide sufficient energy at every given time, through either producing the energy at the right time or by filling and emptying storage units. There could also be constraints on fuel availability or on how a certain technology may be used throughout a year.

3.4. Identified research gap

The studies presented in this chapter focus exclusively on DH or do not allow mixes of individual heating options. Some studies [5,6] have investigated one specific heating solution for a new housing area in each modeling run and have compared the results of the modeling runs in a post-analysis. Studies in which the heating solution of an expanding heating system develops over time are lacking. Furthermore, previous studies have not looked in detail as to whether differences in the heat load profile of new housing have any effect on the resulting heating solution for such housing.

Similarly, there are few studies investigating how new buildings, apart from apartment buildings, interact with the heating system. As apartment buildings often use DH (if available), it is of interest to investigate the interactions between DH and apartment buildings. However, if other housing types are omitted the whole heating system is not investigated thoroughly. Moreover, many studies have not investigated the development of heating systems over time, which is of the utmost importance when looking at the transitions of heating systems. While some studies have investigated the different components within heating systems, studies that have both a system and a temporal perspective are few.

Furthermore, there is a lack of studies that perform a sensitivity analysis to investigate how different heat load profiles within the same year(s) affect the heating solution.

4. Method, modeling and case

This chapter describes the method, modeling and case used in this thesis to address the research aims.

The main contribution of this thesis is the application of a method whereby both the supply and demand sides are considered together over a period of several decades. Thus, the cost of connecting new housing types to an existing DH grid is included in a cost-optimization model, together with the costs for other heating technologies. The inclusion of the DH connection cost is necessary because different heating solutions for the different housing types need to be able to be put in relation to each other to allow the most cost-efficient solution for the system as a whole to be identified.

As the supply and demand sides of the heating are considered simultaneously for several decades into the future, the problem becomes complicated and highly data-intensive. The research aims have, therefore, been addressed through the formulation of a bottom-up, cost-optimizing model of the heating system of an existing and expanding city. In this thesis, the city of Gothenburg on the west coast of Sweden, which already has a DH system in place, is used as the test case.

A techno-economic perspective is used in this thesis in which the costs of different technologies and their technical characteristics are of central importance. This techno-economic perspective is applied because, for central planners (such as city planners), for DH utilities, and for customers, cost considerations are often crucial when deciding what investments to make. To be able to compare different heating solutions, assessing the cost of using and investing in new heating options, both for the individual and the DH system, is therefore of high importance, as the most cost-efficient heating option is probably different for different housing types.

The previously stated aims have been investigated by introducing various climate policies, assigning various electricity prices and different heat load profiles as inputs to the model (Table 1).

Table 1 Focal topics of the two papers and their connections to the aim and scope of this thesis.

	Title	**Focus area**	**Climate policies**	**Future electricity prices**	**Heat load profiles**	**Methodology**
Paper I	The Impact of Local Climate Policy on District Heating Development in a Nordic City – a Dynamic Approach	District heating supply	Five policies	Two profiles	One profile	Bottom-up dynamic energy system modeling, DH connection cost assessment.
Paper II	Communal or Individual – Exploring Cost-Efficient Heating of New City-Level Housing in a Systems Perspective	Heating solution of new housing	Three policies	Three profiles	Two profiles	

4.1. The dynamic systems approach

In both **Paper I** and **Paper II**, a dynamic systems approach is used. This entails a long-term optimization in which the supply and demand sides of the heating system are interconnected ("system") and, therefore, develop ("dynamic") together in the future because they are mutually dependent upon each other. An overview of the approach is shown in Figure 1. With this approach, the different components that are in focus in the two respective papers can be investigated when the whole heating system develops in the future.

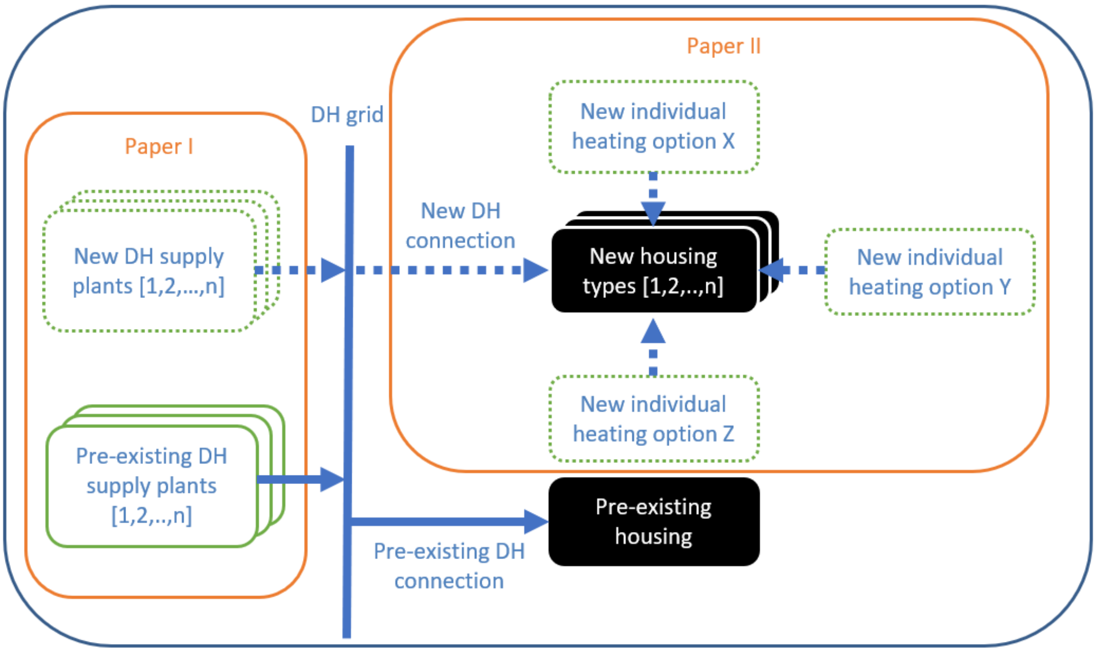


Figure 1. Schematic overview of the heating system and the focus of the papers.

4.2. Heat supply technologies

The heat plants available for the DH supply side are separated into two parts in the modeling: already existing plants, and new plants in which investment can be made.

For both papers, already existing DH supply technologies are assumed to be available from the starting year but become unavailable in later years due to reaching the end of their technical lifetime. No early dismantling or selling of the units or extensions of the lifetimes are considered.

For the DH system, the new CHP plants available are of the biomass, closed cycle natural gas, and gas turbine natural gas forms. The available HOBs are biomass and natural gas. HPs are also available. For economy of scale, for some of the plants, there are restrictions on the minimum size that can receive investment.

Even though the focus of **Paper I** is on the DH supply side, as the new housing does not have to use DH as the heating solution, the heating solution for the new housing can affect the DH supply side.

The individual heating options for new housing are HPs, biomass boilers, and electric boilers. The specific cost of the chosen option is the same for all housing types and no minimum size restrictions are imposed on these options.

The impact of a climate policy affects the use of oil and natural gas, as no other fossil fuels are considered. While there are existing oil HOBs in the system, it is assumed that no new oil plants HOBs will be built. Natural gas can, however, be used in both existing and new HOBs and CHP plants if it is cost-efficient and permitted.

4.3. Existing and new housing

This thesis aims to investigate the heating system for several decades into a future in which new housing is added. The new housing has characteristics such as size and heat demand. Seven different heat demands are considered in both papers:

- The pre-existing housing that currently uses DH;
- Two apartment buildings of different sizes with the same energy use per m^2;
- Two single-family housing types of different sizes with high energy use per m^2; and
- Two single-family housing types of different sizes with low energy use per m^2.

The already existing housing that currently does not use DH is not considered, as it is assumed that these building already have individual heating options installed and will not adopt a different heating solution in the coming decades.

One of the main reasons to differentiate between the different housing types is to allow investigations of how different housing types interact with the DH system, as compared to using individual heating options. Apartment buildings today are often using DH if it is available in the town/city in which they are located, although there are many single-family houses that also use DH as their heating solution. By differentiating the characteristics of the different housing types, it is possible to investigate whether there are differences in heating solutions between the different housing types.

Instead of requiring each house type to install one, and only one, technology, it is allowed to make investments in new technologies at whatever level that is most cost-effective. Although mixes of several technologies are not very commonly used as the heating solution within the same building, by allowing mixes it can be determined whether a specific technology is used preferentially as a base-, intermediate- or peak-production technology.

4.4. Climate policies

Several countries and municipalities in Sweden have stated intentions to transition to climate-neutral heating systems, and different kinds of climate policies are being implemented to address this transition. In general, climate policies can be divided into economic and regulatory policies. Economic policies include taxes, subsidies, and loans, while regulatory policies include technology-neutral feed-in-tariffs and bans of the use of fossil fuels.

The ways in which different climate policies aimed at phasing out fossil fuel use in a specific target year affect the system are, therefore, investigated in both papers. Two different kinds of policies are investigated in both papers: an annually increased carbon tax and a fossil fuel ban in the target year. In **Paper I**, the impacts of the two policies are investigated for a fossil fuel phase out in Year 2030 or 2045, while in **Paper II**, only Year 2030 is investigated. In both papers, whether or not the pre-existing carbon tax remains constant in the future is also investigated.

4.5. Future electricity prices

As the electricity price affects different technologies in different ways, this has been considered in both papers. In **Paper I**, two future electricity prices are considered: one where the price increases for all months, and one where it decreases for all months. In **Paper II**, the same profiles as in **Paper I** were used, and a third, more-varying price profile was considered in which the prices decrease in summer but increase in the colder months.

4.6. Heat load profiles

To be able to represent the variations of the heat demand throughout the year, a heat load profile is used in both papers. One heat load profile is used in **Paper I**, whereas in **Paper II** two profiles are used for the housing units with high heat demands. The heat load profile is acquired from measurements made in a new housing area outside Kungsbacka, a city located just south of Gothenburg. The buildings in that area have been built according to low-energy-use standards, and this is the main reason why in **Paper II**, one more profile is used; this profile is computed from the measured data from the housing area. The extra profile is computed by assuming that the hot tap-water demand is the same for high- and low-energy buildings, even though the space heat demand is different. This results in a higher relative use during winter for the high-demand profile.

4.7. DH connection cost

Assessing the cost of installing DH in new housing is one of the core topics of this thesis. The cost to install DH for all housing types has been assessed by linearizing the cost into a specific cost (in k€/MW) by taking the total cost (in k€) to install a substation and piping for a specific housing type and dividing that total cost by the maximum heat power needed during winter for that housing type. The total cost is assumed to be the same for all kinds of single-family housing, although the maximum power needed varies between the types. Therefore, the specific cost of installing DH is heavily dependent upon the total heat demand and the heat load profile for each type of housing.

In **Paper II**, due to the use of two different heat load profiles for single-family housing with a high total heat demand, the maximum power needed is different. Using the method presented in the previous paragraph to calculate the specific cost, the corresponding specific costs are lower when having a larger peak power demand. In **Paper II**, this is investigated when having the same specific cost for the two heat load profiles, as well as having the same total cost if DH is installed to cover the full heat demand.

The same procedure is used for apartment housing, although the total cost is higher compared to single-family housing. The total cost increase is due to the fact that a substation that is sufficiently large for a single-family house is too small for an apartment building, such that the cost is higher, as is the cost for installing the piping.

The result is that the specific cost for installing DH in both types of apartment building is lower compared to that for all the single-family housing types.

4.8. Modeling

Considering both the supply and demand sides of the heating system simultaneously in an expanding city over several decades into the future is a complex and data-intensive undertaking. The application of an energy systems optimization model (ESOM) makes it possible to investigate the different parts using the computational power of a computer. As the aim is to investigate the cost-efficient development of the heating system, a cost optimization model that covers investments and the dispatch of heating technologies is used in both papers. By imposing different constraints, such as prohibiting the use of fossil fuels or increasing the carbon tax, the ways in which the heating system can develop cost-efficiently in different future scenarios can be investigated.

The Integrated MARKAL-EFOM System (TIMES) energy modeling framework is used for both papers. TIMES, which is a cost-optimizing framework developed by the International Energy Agency (IEA), uses a bottom-up modeling approach in which technical and economic data are provided to the model, which is then solved to find the lowest-cost solution while still following all the constraints applied to the model. The model uses perfect foresight, meaning that there is no uncertainty about future prices, demand etc. This makes it possible for the model to plan ahead for future years without any uncertainty. The objective function that is minimized in TIMES is the following:

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

- *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 any costs are present
- *R* is the set of regions investigated. In this study, only one region is included.

In addition, a salvage value is considered for technologies that have not yet reached their end of technical lifetime at the end year. This salvage value is recovered, which makes it economically feasible for the model to invest in technologies even in the end years.

The TIMES framework is formulated mainly using linear programming (LP). A downside to only allowing linear equations is that it restricts the types of physical behaviors that can be simulated and implemented in the model. The upside is that the computational time can be kept reasonably short, and it can be proven that the solution found is the global minimum, i.e., the lowest cost for the set problem.

As stated above, economy of scale is considered for some heating supply plants, which means that some plant types can only be built if they exceed a certain minimum size. The lumpy investment feature available in the TIMES framework can be used to transform the model formulation into a mixed-integer programming (MIP) model that resembles LP.

4.9. Modeling case

Both papers use Gothenburg as the modeling case. As many types of technologies are already present in the DH supply side in Gothenburg, it is possible to see how the different technologies will be used in the future, if indeed they are used at all.

In Gothenburg, oil refineries and energy recovery from waste incineration cover almost the full heat demand during the summer months. However, a mix of other technologies is also installed, and these technologies are used to meet the heat demand during the colder months. Since there is a mix available, the DH system in Gothenburg has the flexibility to decide which technologies to use according to the different future scenarios stated in the aim of this thesis.

5. Main results and discussion of results and method

In this chapter, the main results from the two papers are presented. The results are categorized under three subchapters corresponding to the first three research aims, respectively. This is followed by two subchapters that discuss the results and the method.

In **Paper II**, it is shown that the DH and individual heating options for apartment buildings, small single-family housing units with high heat demand and single-family housing units with low heat demands are the same for all future scenarios. Apartment buildings use DH, whereas the small high-heat-demand single-family housing and low-heat-demand single-family housing uses individual heating options. The results for these types of housing are, therefore, not presented further in this chapter.

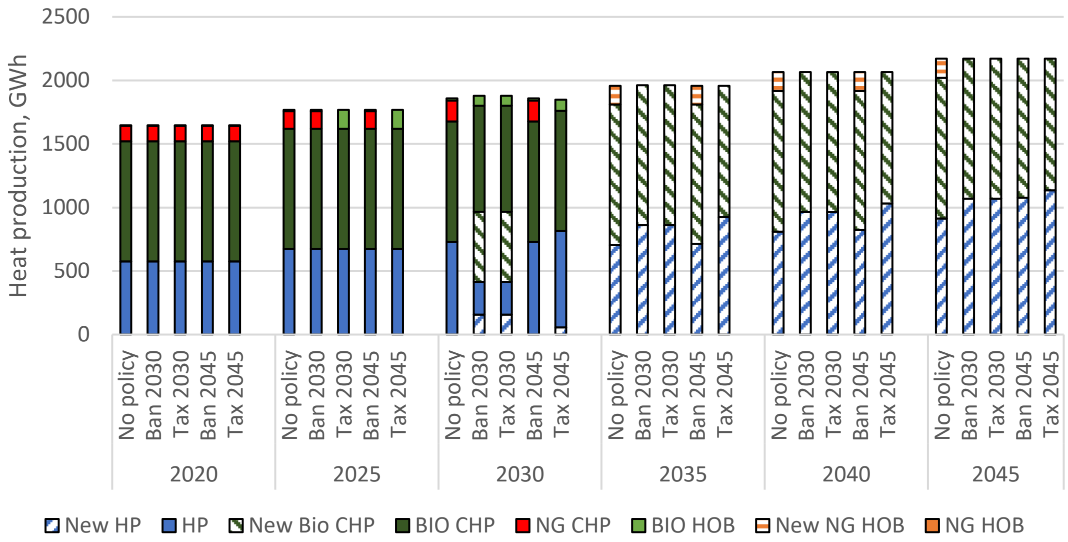
5.1. Climate policies

Paper I show that the DH system benefits economically from continuous use of natural gas unless a climate policy is introduced. If no climate policy is introduced, investments are made in new natural gas HOBs after Year 2030, and approximately one-third of the new capacity consists of natural gas HOBs. The total heat produced is, however, quite low since these HOBs are only used as peaking units during wintertime. One of the important results of this thesis is that for both electricity price cases, if there are investments in new natural gas HOBs, they only replace HPs, while the biomass CHPs are unaffected regardless of climate policy. It is also found that a fossil fuel ban has an impact only from the year in which it is introduced, while an increasing carbon tax decreases fossil fuel use and investments before the fossil phase-out target year.

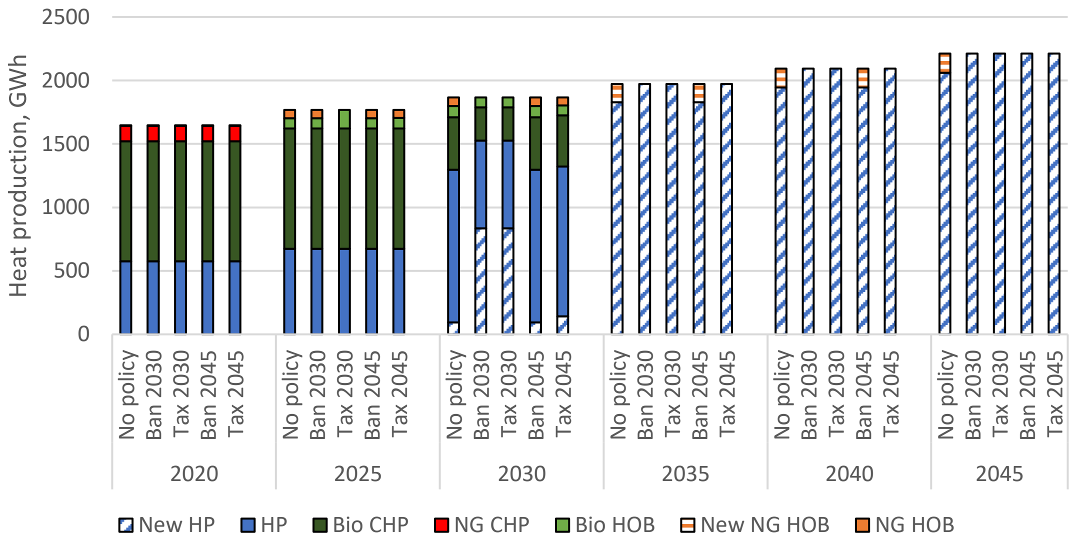
In **Paper II**, a climate policy has a low effect on the heating solution for the different housing types after 2030, if it has any effect at all. Some differences are found in 2030, but there is no clear trend.

5.2. Electricity price profiles

The results in **Paper I** show that with a decreasing electricity price, the DH system becomes dominated by new HPs after Year 2030. With a high electricity price, there are investments in biomass CHP and HPs, each of which produce roughly half of the heat (see Figure 2). If fossil fuels are allowed, there are investments also in natural gas HOBs, which produce some heat during the coldest months for the two electricity price cases investigated in **Paper I**. There are no differences in the amounts of heat produced by the natural gas HOBs between the two electricity price cases. For both cases investigated in **Paper I**, the natural gas HOBs replace new HPs, while the new CHP plants are unaffected.



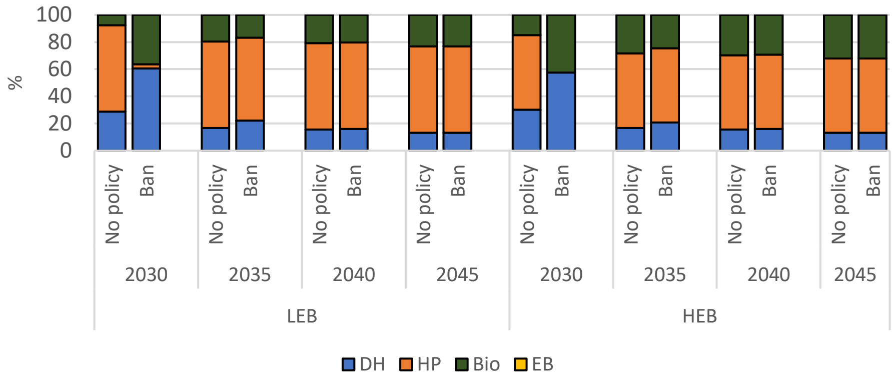
(a) High electricity price case



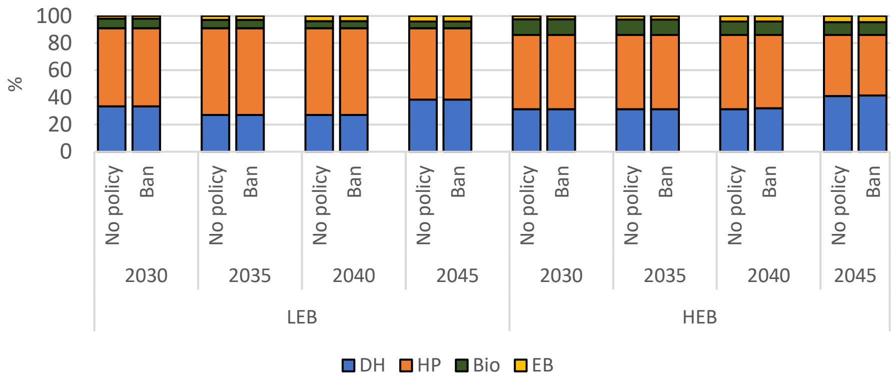
(b) Low electricity price case

Figure 2 Projected heat production in DH plants with different investments in HP, HOB, CHP. Data shown are for two electricity price cases and scenarios with different policies implemented in the indicated years. Excess heat and incineration of municipal solid waste have been omitted to improve readability. Results are from Paper I.

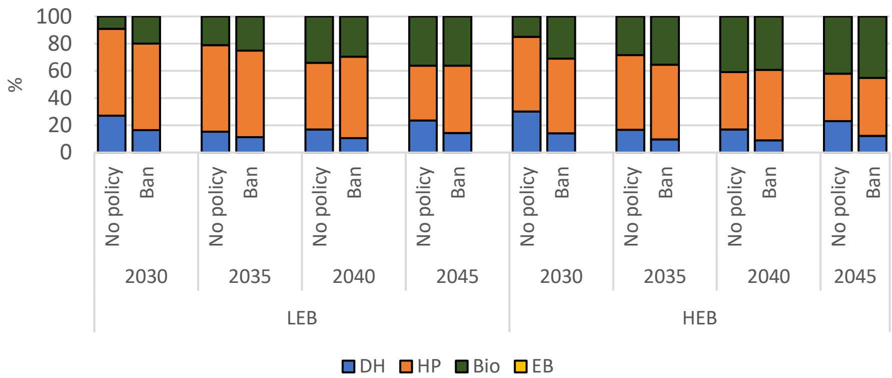
It is shown in **Paper II** that the resulting heating solution for the new single-family housing with high heat demands is dependent upon the electricity price, climate policy, and the heat load profile (see Figure 3). There is no clear trend showing how the electricity price alone affects the heating solution. However, with a decreasing electricity price and a flatter heat load profile, a higher percentage of the heat demand is met by DH, as compared to a high electricity or varying electricity price. No clear trend is seen for the heat load profile with higher relative demand during wintertime. Individual HPs are present for all electricity prices for both heat load profiles but are used less for the heat load profile with higher relative demand during wintertime.



(a) High electricity price



(b) Low electricity price



(c) Varying electricity price

Figure 3 Heating solutions for large single-family housing units for which there is no change in the available EH in the future. LEB (low-energy building) indicates the flatter heat load profile, while HEB (high-energy building) indicates the profile with a higher relative demand during wintertime. Figure based on the results presented in Paper II.

5.3. Heat load profile

It is shown in **Paper II** that with a heat load profile with higher relative load during wintertime for all electricity prices, biomass boiler usage and DH usage are slightly higher compared to the case with a flatter profile (see Figure 3). For all the electricity price cases, the use of HPs is lower for the profile that has a higher relative demand during wintertime.

With a 10% lower specific cost for connection to DH, the heating solution is slightly changed for all electricity price cases. For the low electricity price case, DH supplies almost all the heat, except for some use of biomass boilers and EBs during the winter months. For the varying electricity price case, there is some increase in the use of DH and decreased use of both HPs and biomass boilers.

5.4. Discussion of results

As seen in the results, there is extensive use of HPs in both the DH supply side and as individual heating options. As HPs use electricity as input, sufficient electricity needs to be produced and transmitted to the HPs. In the two papers, this is not a limiting factor for the model. However, which is not the case in real-life situations. For example, in the City of Gothenburg (the case studied in this thesis), there have been indications that the electricity grid supplying the city is approaching maximum capacity/load. There may also be limits for the individual houses, especially if the use of electric vehicles, which are charged at home, continues to increase.

The biomass used in CHPs and HOBs are most often woodchips, which are a residual product from other industries, e.g., sawmills. Woodchips are cheap as they have few uses other than in energy production, though it is possible to use them in the production of biofuels that can be used in the transport sector. In both papers, it is assumed that the availability of biomass is unlimited, which is not the case in reality. The amount of biomass that can be extracted in a sustainable way while taking biodiversity into regard is a matter of ongoing debate.

As shown in **Paper I**, when it is cost-efficient and allowed to use fossil fuels, natural gas is used, which in turn decreases the use of HPs, but not CHPs. The further implication of this is that in the case of a limitation on the electricity transmission capacity, the use of fossil fuels could mitigate this issue, albeit not through increased electricity production, but rather through decreased electricity usage.

It is clear from **Paper I** that with a high electricity price, investments are made in biomass CHPs owing to the decreased system cost associated with such a solution. Here again, it is of importance that there is sufficient biomass fuel available. In previous-generation DHs, CHPs have been built primarily as a heat source for DH [19]. However, having CHPs within the city borders is also a way to mitigate transmission problems when the electricity transmission capacity is limited, as the electricity is then produced locally. The heat produced by the CHP also substitutes for HPs, thereby further decreasing the burden of the transmission grids. It has been argued [31] that the core business of CHPs is to produce electricity, rather than heat, if the electricity price increases. It has also been pointed out [19] that in 4th generation DH systems, CHP plants may be operated on regulating, reserve power and on the spot markets for electricity.

In **Paper I**, it is shown that the already existing heating technologies in the DH supply side continue to be used until their respective technical lifetimes come to an end. An interesting observation is that while the natural gas-fired CHPs and biomass-fired HOBs are used until Year 2030, there are no investments in new capacity for these technologies. As the heating sector consists of large infrastructure facilities and grid networks, which are capital-intensive and have long technical lifetimes, the transition of today's systems into future systems must consider the already existing systems. This behavior is of importance since if fossil fuels are to be phased out in the near-term future, investments made here and now in fossil technologies will affect future fossil emissions.

As the model has perfect foresight, the future for the model lacks any uncertainty, which means that it knows exactly how to make investments in new plants, and when to run existing and new plants to decrease the total system cost. In reality, there are large uncertainties surrounding several aspects, with future fuel costs being one of the aspects of high importance.

5.5. Discussion of method

The main contribution of this thesis is the fact that a dynamic systems approach is used to assess the long-term development of a heating system. To be able to calculate the costs for different heating solutions, the costs for different technological solutions are assessed individually. The cost of connecting new housing to the DH grid is assessed by taking the total investment cost for piping and a substation for each housing type, and then dividing it by the maximum load, which gives the specific cost for each housing type. The specific costs obtained using this method indicate that apartment buildings have the lowest specific cost, followed by high heat demand single family housing units, which in turn have lower specific costs than low heat demand single family housing units. These results confirm that it is mainly cities that use DH, due to their higher density of housing.

The cost assessment method comes with certain drawbacks. As shown in **Paper II**, the heat demand profile affects the specific investment cost of the DH connection. That a higher relative demand during wintertime (as compared to the summer months) would decrease the specific cost of DH connections, making is possible to invest in a certain heat capacity at a lower total cost, does not reflect reality. The results for this are described in **Paper II**, where a lower specific cost for DH connections of only around 10% increases the use of DH as part of the heating solution.

Furthermore, the cost assessment method in combination with the use of a cost-optimizing model and allowing a mix of technologies could give some unintended consequences. As the specific cost becomes very low if the maximum load is even higher during winter, the model will install an unreasonably low level of DH in new housing at a very low cost, so as to only cover the demand for certain time periods, i.e., summer, when there is a low demand and high availability of cheap DH supply, e.g., EH.

To prevent the model from using mixes of heating solutions within the same housing system, it is possible to restrict the model to only being able to invest in new DH connections at discrete levels. However, doing so raises some issues. First, the computational time increases, as the problem is no longer linear, which generally makes it harder to find a global minimum. Moreover, due to the perfect foresight of the model, it is possible for it to “cheat”, since it can in an early year invest only in, for example, DH, and in a later year invest only in, for example, individual HPs, thus achieving a mix of technologies, which is the goal to forbid the model to do in the first place.

In addition, the DH cost assessment method would not be well suited if the time resolution increases too much. If the time resolution, for example, is on a daily or even hourly level the DH connection cost will also be unreasonably low if there is a single, or very few, time slots with much higher heat demand compared to the rest of the time slots.

As stated in the aim and scope, the results generated by the model are neither predictions of nor recommendations for future heating systems. The usefulness of the heating system model lies in allowing one to investigate and analyze the dynamics of heating systems. The finding that for some housing types, the heating solution consists of a mix of individual technologies is not a commonly used solution in reality. Allowing mixes of individual heating technologies contrasts with previous studies [6,7] that have investigated the heating solution of one new housing area by forcing the model to use one specific heating solution in each modeling run and performing a post-analysis of the modeling results. The DH supply side development is, however, considered in a dynamic method similar to that used in this thesis. One of the problems associated with disallowing a mix compared to allowing a mix of technologies observed for a new housing area [6,7] is that it becomes more difficult to compare the dynamics of the different heating technologies.

This thesis uses a method in which more housing is added annually and the costs and prices for several factors change over time. With this method, it becomes possible to see if new housing added at the beginning of the modeling period uses the same heating solution as similar new housing added in the future. This makes it possible to see whether the presence of pre-existing DH supply plants or future developments of the electricity price differentially affect the heating solutions for housing built in the near future and housing that is built later. This approach contrasts with that used earlier [6,7] where the investigated new housing area is added at the beginning of the modeling period. In addition, the method used in another previous study [5] contrasts with the method of this thesis, in that the cost data for only 1 year were considered.

The choice of the city/region/country to be investigated could influence the results for the heating solution due to the latitude or distance to large bodies of water, as these factors affect the outdoor temperature, which in turn affects the heating demand and distribution. Not only natural aspects affect the heating sector. For instance, in Luleå in the northern part of Sweden, the availability of industrial waste heat from the steel industry is sufficient for the DH system to cover almost all of its heat demand from utilizing only that EH. The resulting future heating system in such a city would probably differ significantly from the results presented in this thesis. Similarly, constructing a DH system from scratch would incur the cost of a central distribution grid, which is not taken into account in the papers of this thesis.

Although every case has its own specific preconditions, the methodology used in this thesis is applicable to other heating systems. The results obtained from the case study in this thesis are probably generalizable to other systems. However, the electricity price has a strong impact on the resulting heating solution, which is one of the major challenges to address. However, if other heating systems have heat load profiles similar to that of the system investigated in this thesis, which is likely the case for many countries in northern Europe and other places, the results are probably generalizable to those systems as well. However, as seen in the results, the heat load profile affects the heating solutions for some types of new buildings. In addition, the investment and running costs for new DH plants should be similar between countries that already have good expertise in using DH. This ensures that the results for the development of the DH supply side are generalizable to other systems as well.

The model uses perfect foresight, which removes any uncertainty about the future. Given the lack of uncertainty, there is no need to install any reserve power in the DH system. Furthermore, the time resolution (each time period is 1 month) means that the need for reserve capacity is underestimated in the model.

It is assumed in both papers that there is no need to make investments in the already existing DH grid when new DH connections are built. This and the fact that it is possible to install new DH connections at any capacity and underestimation of reserve capacity give DH somewhat of an economic advantage, although the “free” upgrade cost of existing grids should be rather low.

When fossil fuels are not phased out, there are new investments in HOBs and increased use of natural gas in HOBs during the wintertime. This comes from the low investment cost, but the rather high running cost, of such plants. As the reserve capacity is underestimated, in a “real” system, there would probably be more investments in natural gas-fired HOBs. However, if fossil fuels are phased out, instead of natural gas HOBs, there will be greater investment in and increased use of large-scale HPs for both high and low electricity prices. As there is no scarcity of electricity or heat sources for the HPs, in this thesis it is found to be cost-efficient to invest in HPs for peak power, although this may not be the case for a real-life system. Furthermore, biogas, which could have been used instead of natural gas, is not available.

6. Main contributions and conclusions

In this thesis, four aims are articulated, with the fourth aim being to develop an improved methodology to investigate how in future heating systems, new housing can be heated cost-efficiently.

A dynamic systems approach is used to address both the supply and demand sides of the heating system for several decades in the future, and the cost of installing different types of heating technologies for different types of housing are assessed individually. To investigate how the system can develop in a cost-efficient manner, a cost-optimizing model is developed in which the heating solution is not determined beforehand. To be able to compare different heating solutions, the model is supplied with cost and technological data for different heating technologies, as well as heat demand data for existing housing and housing that will be built in the future.

The specific costs for many heating technologies are readily available and are used as inputs to the model, although the specific cost of installing a DH connection to the different housing types is in this thesis assessed individually for each housing type and used as input to the model. This thesis uses a method to assess the cost of new DH connections for the different kinds of new housing by taking the total cost of a DH connection and dividing it by the maximum power load during winter. This gives the lowest specific cost for apartment buildings, followed by single-family housing with high heat demands, and finally, single-family housing with low heat demands.

The model reveals that new apartment buildings use only DH, while single-family housing units with low heat demands do not use DH at all, which reflects quite well the situation with existing heating systems. However, it is shown that a small difference in the specific cost of DH connections can result in alternative solutions for housing that involve a mix of heating technologies, i.e., single-family housing with high heat demands.

The general results from the developed model, in terms of addressing the first three aims, are described below.

The introduction of a climate policy phasing out the use of fossil fuels in heating systems affects the DH supply side by decreasing the use of natural gas in existing CHP plants and new HOBs, while increasing the use of and investments in HPs. The heating solution for most kinds of new housing is not affected by the phase out. There are, however, some differences in the heating solutions for new single-family housing with high heat demands. How the heating solution is affected is dependent upon the future electricity price.

The heat supply of DH is affected by the future electricity price mainly through impacts on investments in future supply plants. With a low electricity price, the DH supply is dominated by HPs, whereas with a high price for electricity there is a mix of HPs and biomass CHP plants. The investment cost for CHP plants is too high for it to be economical for the system to invest in such plants to cover the intermediate and peak demands. These demands are instead covered by HPs. The electricity price has almost no effect on the total amount of heat produced in the DH system, as most of the new heat demand stems from apartment buildings, which are always connected to the DH system.

It is also shown that the heat load profile affects the heating solution for single-family housing with high heat demands. The comparison is made between a heat load with a higher relative heat demand during wintertime and a flatter load curve. The general outcome is that the higher wintertime demand increases the use of individual biomass boilers and DH while reducing the use of individual HPs.

7. Future work

As described in this thesis, the electricity price exerts a strong impact on the development of the heating system, as does a climate policy that affects the DH supply side and the heating solution for some housing types. A system that is dominated by HPs in terms of both the DH supply side and individual heating options, as in the case where the electricity price decreases, would consume only electricity to provide heat. From this, several important questions arise.

- Is sufficient carbon-free electricity available during every time period?
- Is sufficient transmission capacity available? What are the consequences of insufficient transmission capacity?
- Are there wider environmental impacts from increasing/decreasing the usage of biomass in the heating system?

In **Paper I**, it is shown that natural gas will continue to be used in CHP plants if so allowed and if the carbon tax is not increased substantially. There are even investments in new natural gas HOBs. As natural gas is a fossil fuel, a fossil-free system needs to abolish completely the use of natural gas at some point. However, from a technical point of view, instead of using natural gas it would be possible to use biogas, which also consists mainly of methane. The production of biogas is currently limited, and most of the biogas produced is used in the transport sector. It could, however, be of interest to study how much biogas production could be increased and how strong the willingness to pay would be for a future heating system.

One aspect that is seldom incorporated into the kind of modeling used in this thesis is how the role of reserve capacity can be assessed. One of the core issues is that for a model with perfect foresight there is never any need for reserve capacity, since the model knows exactly what is needed and when. Reserve capacity would never be added because that would simply create an economic burden. The solution would be to avoid requiring the model to always have a certain amount of reserve capacity available, and this solution is never used. What the model would do in that case would be to invest exclusively in the technology with the lowest investment cost, since the fuel and O&M costs would not matter. One way which could be used handle this issue would be to perform a large amount of modeling runs where the input data is varied according to stochastic methods, but the issue could probably be handled in other ways as well.

Another topic that warrants investigation, especially in the context of Sweden, is the extent to which heat consumers are willing to decrease their heat usage through behavioral changes (as opposed to technical solutions). While this has been partly investigated previously [4], the results have not been placed in a systems perspective. Many Swedish consumers who live in apartment buildings do not pay directly for their heat, as the cost is included in the rent. If economic incentives were introduced for consumers to decrease their heat usage, this could have implications for the system. In particular, since a decrease in heat usage would probably not only affect the total heat demand, but also the heat demand load profile. Even though it is cost-effective to connect apartment buildings to the DH grid, the flatter heat demand curve could affect the DH supply technologies.

Closely related to this is the issue of improving the insulation of already existing housing. This is not only interesting from the systems point-of-view, as investigated in [8] , but is also relevant for consumers. If consumers improve the insulation of their dwellings, they will pay less for heating. However, in a model such as that used in this thesis, it is the cost of producing and distributing heat that is minimized. If the price of heat for the consumers is not the same as the cost of producing this heat, which is often not the case (see, for example, [21]), the cost saving achieved by improving insulation will differ depending on the economic view applied. Therefore, the answer to the question as to how much the heat demand can be decreased in a cost-efficient manner by improving insulation is different depending on the economic view. To complicate matters further, when improvements are made to insulation, they are often carried out at the same time as other more-extensive maintenance is performed, which means that it is unlikely that, in the short term, insulation will not be improved in the present housing stock. This topic is included as a sensitivity analysis in **Paper II**, in which some changes to the results can be seen from Year 2040 onwards if the electricity price decreases and the EH level increases, although the cost of the insulation is not included and there is no flexibility as to how much or when the demand is reduced.

It would be of interest to see how the heating system reacts to limitations in the transmission grids. This topic has been investigated previously [33] for an interconnected energy system with several energy sectors, albeit for only a single year in the future. Building CHPs would increase the level of electricity produced locally, thereby mitigating the transmission capacity problem. It is also common, for energy supply security reasons, to build CHP plants within city limits so that it is possible to produce electricity if there are production or transmission problems outside the city. Large-scale HPs usually have a higher COP compared to individual HPs, which means that they have the potential to limit the use of electricity. Here, it is important to note that there may be resource limitations for large-scale HPs as well. In this thesis, sewage water has been used as the heat source, which is limited in reality. Using other heat sources, such as ground-source HPs, is technically possible, although the economics of such solutions are uncertain. While improvements to the insulation of existing housing have not been investigated in this thesis, such changes could also affect the heating solution, thereby affecting the need for electricity.

References

[1] Thyholt M, Hestnes AG. Heat supply to low-energy buildings in district heating areas. Analyses of CO2 emissions and electricity supply security. Energy Build 2008;40:131–9. https://doi.org/10.1016/j.enbuild.2007.01.016.

[2] Truong N Le, Dodoo A, Gustavsson L. Effects of energy efficiency measures in district-heated buildings on energy supply. Energy 2018;142:1114–27. https://doi.org/10.1016/j.energy.2017.10.071.

[3] Truong N Le, Dodoo A, Gustavsson L. Effects of heat and electricity saving measures in district-heated multistory residential buildings. Appl Energy 2014;118:57–67. https://doi.org/10.1016/j.apenergy.2013.12.009.

[4] Gram-Hanssen K. Efficient technologies or user behaviour, which is the more important when reducing households' energy consumption? Energy Effic 2013;6:447–57. https://doi.org/10.1007/s12053-012-9184-4.

[5] Grundahl L, Nielsen S, Lund H, Möller B. Comparison of district heating expansion potential based on consumer-economy or socio-economy. Energy 2016;115:1771–8. https://doi.org/10.1016/j.energy.2016.05.094.

[6] Sandvall AF, Ahlgren EO, Ekvall T. Cost-efficiency of urban heating strategies – Modelling scale effects of low-energy building heat supply. Energy Strateg Rev 2017;18:212–23. https://doi.org/10.1016/j.esr.2017.10.003.

[7] Sandvall AF, Ahlgren EO, Ekvall T. Low-energy buildings heat supply–Modelling of energy systems and carbon emissions impacts. Energy Policy 2017;111:371–82. https://doi.org/10.1016/j.enpol.2017.09.007.

[8] Romanchenko D, Nyholm E, Odenberger M, Johnsson F. Balancing investments in building energy conservation measures with investments in district heating – A Swedish case study. Energy Build 2020;226:110353. https://doi.org/10.1016/j.enbuild.2020.110353.

[9] Pavičević M, Novosel T, Pukšec T, Duić N. Hourly optimization and sizing of district heating systems considering building refurbishment – Case study for the city of Zagreb. Energy 2017;137:1264–76. https://doi.org/10.1016/j.energy.2017.06.105.

[10] Connolly D, Lund H, Mathiesen B V., Werner S, Möller B, Persson U, et al. Heat roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. Energy Policy 2014;65:475–89. https://doi.org/10.1016/j.enpol.2013.10.035.

[11] Hansen K, Connolly D, Lund H, Drysdale D, Thellufsen JZ. Heat Roadmap Europe: Identifying the balance between saving heat and supplying heat. Energy 2016;115:1663–71. https://doi.org/10.1016/j.energy.2016.06.033.

[12] Romanchenko D, Nyholm E, Odenberger M, Johnsson F. Impacts of demand response from buildings and centralized thermal energy storage on district heating systems. Sustain Cities Soc 2021;64:102510. https://doi.org/10.1016/j.scs.2020.102510.

[13] Ma Z, Knotzer A, Billanes JD, Jørgensen BN. A literature review of energy flexibility in district heating with a survey of the stakeholders' participation. Renew Sustain Energy Rev 2020;123. https://doi.org/10.1016/j.rser.2020.109750.

[14] Persson U, Werner S. Heat distribution and the future competitiveness of district heating. Appl Energy 2011;88:568–76. https://doi.org/10.1016/j.apenergy.2010.09.020.

[15] Xiong W, Wang Y, Mathiesen BV, Lund H, Zhang X. Heat roadmap china: New heat strategy to reduce energy consumption towards 2030. Energy 2015;81:274–85. https://doi.org/10.1016/j.energy.2014.12.039.

[16] Sernhed K, Lygnerud K, Werner S. Synthesis of recent Swedish district heating research. Energy 2018;151:126–32. https://doi.org/10.1016/j.energy.2018.03.028.

[17] Bühler F, Petrović S, Karlsson K, Elmegaard B. Industrial excess heat for district heating in Denmark. Appl Energy 2017;205:991–1001. https://doi.org/10.1016/j.apenergy.2017.08.032.

[18] Broberg S, Backlund S, Karlsson M, Thollander P. Industrial excess heat deliveries to Swedish district heating networks: Drop it like it's hot. Energy Policy 2012;51:332–9. https://doi.org/10.1016/j.enpol.2012.08.031.

[19] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. https://doi.org/10.1016/j.energy.2014.02.089.

[20] Lund H, Østergaard PA, Chang M, Werner S, Svendsen S, Sorknæs P, et al. The status of 4th generation district heating: Research and results. Energy 2018;164:147–59. https://doi.org/10.1016/j.energy.2018.08.206.

[21] Lund R, Østergaard DS, Yang X, Mathiesen BV. Comparison of low-temperature district heating concepts in a long-term energy system perspective. Int J Sustain Energy Plan Manag 2017;12:5–18. https://doi.org/10.5278/ijsepm.2017.12.2.

[22] Østergaard PA, Andersen AN. Booster heat pumps and central heat pumps in district heating. Appl Energy 2016;184:1374–88. https://doi.org/10.1016/j.apenergy.2016.02.144.

[23] Best I, Orozaliev J, Vajen K. Economic comparison of low-temperature and ultra-low-temperature district heating for new building developments with low heat demand densities in Germany. Int J Sustain Energy Plan Manag 2018;16:45–60. https://doi.org/10.5278/ijsepm.2018.16.4.

[24] Ziemele J, Gravelsins A, Blumberga A, Vigants G, Blumberga D. System dynamics model analysis of pathway to 4th generation district heating in Latvia. Energy 2016;110:85–94. https://doi.org/10.1016/j.energy.2015.11.073.

[25] Köfinger M, Basciotti D, Schmidt RR, Meissner E, Doczekal C, Giovannini A. Low temperature district heating in Austria: Energetic, ecologic and economic comparison of four case studies. Energy 2016;110:95–104. https://doi.org/10.1016/j.energy.2015.12.103.

[26] Blumberga A, Vanaga R, Freimanis R, Blumberga D, Antužs J, Krastiņš A, et al. Transition from traditional historic urban block to positive energy block. Energy 2020;202. https://doi.org/10.1016/j.energy.2020.117485.

[27] Lund H, Duic N, Østergaard PA, Mathiesen BV. Smart energy systems and 4th generation district heating. Energy 2016;110:1–4. https://doi.org/10.1016/j.energy.2016.07.105.

[28] Romanchenko D, Kensby J, Odenberger M, Johnsson F. Thermal energy storage in district heating: Centralised storage vs. storage in thermal inertia of buildings. Energy Convers Manag 2018;162:26–38. https://doi.org/10.1016/j.enconman.2018.01.068.

[29] Sayegh MA, Jadwiszczak P, Axcell BP, Niemierka E, Bryś K, Jouhara H. Heat pump placement, connection and operational modes in European district heating. Energy Build 2018;166:122–44. https://doi.org/10.1016/j.enbuild.2018.02.006.

[30] Åberg M, Widén J, Henning D. Sensitivity of district heating system operation to heat demand

reductions and electricity price variations: A Swedish example. Energy 2012;41:525–40. https://doi.org/10.1016/j.energy.2012.02.034.

[31] Romanchenko D, Odenberger M, Göransson L, Johnsson F. Impact of electricity price fluctuations on the operation of district heating systems: A case study of district heating in Göteborg, Sweden. Appl Energy 2017;204:16–30. https://doi.org/10.1016/j.apenergy.2017.06.092.

[32] Beiron J, Montañés RM, Normann F, Johnsson F. Combined heat and power operational modes for increased product flexibility in a waste incineration plant. Energy 2020;202. https://doi.org/10.1016/j.energy.2020.117696.

[33] Heinisch V, Göransson L, Odenberger M, Johnsson F. The impact of limited electricity connection capacity on energy transitions in cities. Smart Energy 2021;3:100041. https://doi.org/10.1016/j.segy.2021.100041.

[34] Levihn F. CHP and heat pumps to balance renewable power production: Lessons from the district heating network in Stockholm. Energy 2017;137:670–8. https://doi.org/10.1016/j.energy.2017.01.118.

[35] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F, et al. Energy storage and smart energy systems. Int J Sustain Energy Plan Manag 2016;11:3–14. https://doi.org/10.5278/ijsepm.2016.11.2.

[36] Heinisch V, Göransson L, Odenberger M, Johnsson F. Interconnection of the electricity and heating sectors to support the energy transition in cities. Int J Sustain Energy Plan Manag 2019;24:57–66. https://doi.org/10.5278/ijsepm.3328.

[37] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65. https://doi.org/10.1016/j.energy.2017.05.123.

[38] Thellufsen JZ, Lund H, Sorknæs P, Østergaard PA, Chang M, Drysdale D, et al. Smart energy cities in a 100% renewable energy context. Renew Sustain Energy Rev 2020;129. https://doi.org/10.1016/j.rser.2020.109922.

[39] Heinisch V, Göransson L, Erlandsson R, Hodel H, Johnsson F, Odenberger M. Smart electric vehicle charging strategies for sectoral coupling in a city energy system. Appl Energy 2021;288. https://doi.org/10.1016/j.apenergy.2021.116640.

[40] Sandvall AF, Ahlgren EO, Ekvall T. System profitability of excess heat utilisation - A case-based modelling analysis. Energy 2016;97:424–34. https://doi.org/10.1016/j.energy.2015.12.037.

[41] Sandvall AF, Börjesson M, Ekvall T, Ahlgren EO. Modelling environmental and energy system impacts of large-scale excess heat utilisation - A regional case study. Energy 2015;79:68–79. https://doi.org/10.1016/j.energy.2014.10.049.

[42] Pettersson K, Axelsson E, Eriksson L, Svensson E, Berntsson T, Harvey S. Holistic methodological framework for assessing the benefits of delivering industrial excess heat to a district heating network. Int J Energy Res 2020;44:2634–51. https://doi.org/10.1002/er.5005.

[43] Keirstead J, Jennings M, Sivakumar A. A review of urban energy system models: Approaches, challenges and opportunities. Renew Sustain Energy Rev 2012;16:3847–66. https://doi.org/10.1016/j.rser.2012.02.047.

[44] ETSAP, Energy Technology Systems Analysis Program n.d. https://iea-etsap.org/index.php/etsap-tools/model-generators/times (accessed February 26, 2020).

[45] MARKAL model n.d. https://iea-etsap.org/index.php/etsaptool/model-generators/markal

(accessed October 5, 2021).

[46] Lund H, Thellufsen JZ, Østergaard PA, Sorknæs P, Skov IR, Mathiesen BV. EnergyPLAN – Advanced analysis of smart energy systems. Smart Energy 2021;1:100007. https://doi.org/10.1016/j.segy.2021.100007.

[47] Connolly D, Lund H, Mathiesen B V., Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87:1059–82. https://doi.org/10.1016/j.apenergy.2009.09.026.