THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Evolution of Future Heating Systems

Modeling of an Expanding City Using a Dynamic Systems Approach

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Abstract

Reducing greenhouse gas emissions is central to meeting climate change mitigation targets. Since the energy sector is one of the largest greenhouse gas emitters, it is essential that all the actors within the energy sector reduce their respective emissions. The heating sector is an important component of the larger energy system, especially in the Nordic countries. In the Nordic region as a whole, a large part of the heating demand, both from hot tap-water and space heating, is covered by district heating (DH), especially in cities. In less-densely populated areas, the use of individual heating solutions is more common, although individual solutions are present also in urban areas. The economic viability of an individual solution is, therefore, dependent upon the geographic placement, as well as the surrounding system. How the transformation of existing heating systems into future carbon-neutral systems can be achieved is of great interest.

The components of heating systems often have very long lifetimes, and given the urgency of phasing out fossil fuels, the constitutions of future heating will reflect decisions made in the near future. As there are high levels of uncertainty associated with several factors involved in the development of heating systems, the aim of this thesis is to investigate how different parts of the heating system can be developed in parallel and to maximal efficiency in different future scenarios.

A dynamic systems approach is used in which the supply and demand of an expanding heating system are investigated together and simultaneously over several decades. New housing is treated in a heterogeneous fashion by investigating several types of new housing. The cost-optimizing TIMES modeling framework is used in this thesis, and the heating system of Gothenburg is applied as a modeling case.

The modeling results show that the heating solution for future housing depends on the housing type and the construction year. Individual solutions, mainly ground-source and air-to-water heat pumps, are often cost-efficient for single family housing, as well as for apartment buildings. This is especially the case if the electricity price is low or if the use of biomass in the DH system is phased out. However, the utilization of low-grade excess heat or a lower DH temperature increases the use of DH in the future housing stock. Large-scale seasonal thermal energy storage units in DH systems are economically viable systems that, in some cases, can increase the use of DH for new housing, although the effect is rather weak. Nevertheless, storage systems can significantly reduce the strain on electrical grids during cold periods.

The choice of heating solution represents a serious challenge for the economics of DH systems, which have traditionally been the main heating solution in cities. The development of current DH systems has been incremental in the recent decades, while individual solutions have undergone a dramatic increase in their use. Without more-drastic changes in the investment in and operation of DH systems, the heating systems of the future may become more-decentralized and more-dependent upon electricity as their main energy source.

The findings of this thesis should be of interest to city planners and DH utilities, as the findings show that both the DH supply side and the heating solution for new housing are affected by many factors.

Keywords: *Heating system, Housing, Low-heat-demand housing, District heating, Thermal energy storage, Climate policy, Dynamic energy systems modeling, TIMES*

List of publications

The thesis is based on the following papers, which are referred to in the text 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.* Smart Energy 2023:100097. https://doi.org/10.1016/j.segy.2023.100097.
III. Vilén K, Ahlgren EO. *Linear or Mixed Integer Programming in Long-Term Energy Systems Modeling? – Comparison for the Case of an Expanding Heating System.* Energy 2023:129056. https://doi.org/10.1016/j.energy.2023.129056.
IV. Vilén K, Ahlgren EO. *Thermal Energy Storages as Part of the Evolving Heating System – Long-term Modeling of Interconnected Supply and Demand.* Submitted for review.
V. Vilén K, Lygnerud K, Ahlgren EO. *Policy Implications of Challenges and Opportunities for District Heating – the Case for a Nordic Heating System.* Submitted for review.

Karl Vilén is the principal author of all the papers. Erik Ahlgren contributed with discussions and editing of **Papers I–V**. Sujeetha Selvakkumaran contributed with discussions and the editing of **Papers I** and **II**. Kristina Lygnerud contributed with discussions and the editing of **Paper V**.

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In the last five years, I have had the privilege to pursue my PhD here at Chalmers. Ever since I was young, I have always dreamt of performing science, and even though it is only my name which is on the front page of this thesis, the thesis would not have come into existence, and actually be completed, without all the fantastic people I have the privilege to have around me. To all of you, I want to express my deepest gratitude.

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And lastly, I want to thank you, the reader, for coming this far. If you decide to continue reading the thesis beyond this point, I hope that you will enjoy reading it as much as I have enjoyed writing it.

Karl Vilén

Gothenburg, November, 2023

There is a theory which states that if ever anyone discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable.

There is another theory which states that this has already happened.

Douglas Adams

I think that inside every adult is the heart of a child. We just gradually convince ourselves that we have to act more like adults.

Shigeru Miyamoto

No man is poor who can do what he likes to do once in a while.

Carl Barks

Table of contents

List of abbreviations

CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
COP	Coefficient of Performance
DH	District Heating
EH	Excess Heat
HOB	Heat-Only Boiler
HP	Heat Pump
MSW	Municipal Solid Waste
TES	Thermal Energy Storage

1. Introduction and background

The energy use associated with the building sector has historically been associated with substantial emissions of CO_2. To meet climate mitigation targets, it will be necessary to reduce and eventually eliminate all greenhouse gas emissions from fossil fuels. In Europe, around 40% of the total energy consumption is associated with the building sector. The heating sector is a central part of the overall energy system and is closely connected to other energy sectors, such as the electricity sector. Thus, the emissions from the larger energy sector are dependent upon how the heating sector evolves over time. Furthermore, the cost efficiency of the larger energy sector is affected by how the heating sector evolves. For these reasons, it is important to analyze how the heating sector evolves over time and how it interacts with other parts of the energy system.

In buildings, there is a demand for hot tap-water and space heating, which can be fulfilled in different ways. In general, heat is supplied by either communal solutions or individual solutions. For the communal solutions, which involve mainly district heating (DH) or near heating, the heat is produced in central plants and thereafter distributed via hot water in underground piping to substations within each building. Individual solutions are where each building has its own heating solution, which can only produce heat for that specific building. Communal solutions are generally more prominent in densely populated areas, while individual solutions are more common in less-densely populated areas.

DH is regarded as an important pathway for decarbonizing the energy system in the EU, and as of today, around 12% of the heat demand in the EU is supplied by DH. However, the prevalence of DH as the preferred heating solution varies significantly among EU member states. In Sweden, around 50% of the overall heating demand is supplied by DH, while in multi-family dwellings, around 90% of the heating demand is fulfilled by DH. The higher prevalence of DH in densely populated areas is mainly attributed to the greater economic feasibility of building DH grids in denser areas [1].

In the EU, more than two-thirds of the energy in DH systems stems from fossil fuels, although this fraction varies greatly across the Member States [2]. For the case of Sweden, over 75% of the energy in the DH systems originates from renewable energy sources. However, this has not always been the case. Historically, the Swedish heating system was heavily dependent upon oil as fuel, up until the 1980's [3]. The use of oil in both DH and individual heating systems was rapidly phased out, mainly by increasing the use of biomass, although other heat sources have also been introduced into the system, such as energy recovery from industrial sources, waste incineration and heat pumps (HPs).

Even though the Swedish heating system has phased out a significant proportion of its fossil fuel use over a transition period of decades, fossil fuel usage remains, mainly for peak power in cold periods. It is of great interest to investigate what might happen to the heating system when it continues to develop in a cost-efficient manner as more housing is added, while simultaneously eliminating the use of fossil fuels. As the heating system is connected to other energy systems, the development of the heating sector cannot be examined in isolation, as other sectors must also be considered.

While some previous studies have investigated how the heating sector might develop in the future, few studies have scrutinized the supply and demand for heat together and simultaneously, especially over long time periods, i.e., decades. As cities will continue to expand in the future, it is important to investigate how best to heat this new housing, while also considering that the new housing will likely be built close to existing heating systems, possibly affecting how the supply of existing heating develops over time. Taking economics into account when investigating how energy systems can evolve during the phasing out of fossil fuel usage is crucial, as cost considerations are a central concern of decision makers.

2. Aim and scope

As presented in the *Introduction and background* chapter, few studies have investigated how the supply and demand sides of heating system can develop together in cost-efficiently over a long period of time, while also meeting climate mitigation targets. Given that multiple factors, some which are linked to high levels of uncertainty, can affect how heating systems develop, there is a need to investigate the development of future heating systems under different future scenarios, taking cost considerations into account. Here, a modeling approach is used due to the large volume of data needed for such investigations.

Thus, this thesis aims to:

- Investigate how the cost-efficient heating solution mix of new housing is affected in different future scenarios.
- Investigate how the production and distribution of heat in existing DH systems can evolve in a cost-efficient way over time as new supply plants and storage units can be built.
- Develop a dynamic systems approach that enables investigations of how the supply and demand sides can develop together in a cost-efficient manner in future heating systems.

2.1. Outline of the thesis

This thesis consists of the five appended papers and a summary essay. The respective focus areas of the appended papers are presented in Table 1. The phasing out of fossil fuels from the heating system and how the electricity prices develop in the future are deemed to be of great importance for the development of the heating sector. Therefore, these topics have been included reflected upon in all the papers, albeit in different ways in the different papers.

Table 1. Papers included in this thesis and their respective focus areas.

	Title	**Focus area**	**Climate policies**	**Future electricity prices**	**Methodology**
Paper I	The Impact of Local Climate Policy on District Heating Development in a Nordic City – a Dynamic Approach	DH supply	Five policies	Two profiles	Bottom-up dynamic energy system modeling
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	
Paper III	Linear or Mixed Integer Programming in Long-Term Energy Systems Modeling? – Comparison for the Case of an Expanding Heating System	Programming methods for modeling	No fossil use from Year 2025	Three profiles	
Paper IV	Thermal Energy Storage as Part of the Evolving Heating System – Long-term Modeling of Interconnected Supply and Demand	Seasonal thermal energy storage systems	No fossil use from Year 2025	Four profiles	
Paper V	Policy Implications of Challenges and Opportunities for District Heating – the Case for a Nordic Heating System	External factors affecting DH operation. (Biomass phase out, excess heat availability, DH grid temperature)	No fossil use from Year 2025, no plastic incineration from Year 2030	Three Profiles	

The same methodological approach is used for the same existing heating system in all the papers. This approach involves assessments of the heat supply options and future heat demands within the heating system. The investigated system is investigated up until Year 2050 in all the papers, although **Papers I** and **II** have a slightly earlier starting year than **Papers III–V**. However, the granularity of the new housing areas is significantly higher in **Paper III**. In **Paper III**, restrictions on how investments can be made on the demand side are also investigated. Due to the findings of **Paper III**, both the higher granularity and the investment restrictions are subsequently applied in **Papers IV** and **V**.

In all the papers, the cost of connecting new housing to an existing DH grid is assessed. This is linked to the central aim of investigating how heating systems can develop in a cost-efficient manner. Given that an entire heating system is investigated, and not only DH, the costs of installing and using DH must be compared to the costs of installing and utilizing individual heating options. **Papers I** and **II** use a somewhat simpler method to evaluate the connection cost, as compared to the method used in **Papers III–V**.

As all the 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, whereas in **Paper II** the focus is on the demand side, the different types of new housing, and the development of their respective heating solutions. **Paper III** focuses on how different programming methods can represent the ways in which investments can be made in new technologies on the demand side. **Paper IV** has its focus on how large-scale, seasonal thermal energy storage (TES) can affect the cost-effective heating solutions under different scenarios. **Paper V** has its focus on how the heating solution for new housing is affected by changes in the ways in which DH systems can be operated, more specifically when there is a phase out of biomass use, decreased DH distribution temperature or the addition of more low-grade industrial waste heat to the system. As it is shown in **Paper IV** that seasonal TES are often economically feasible, this technology is also included in **Paper V**.

In **Papers I** and **II**, the impacts of phasing out the usage of fossil fuels through either a ban or an increased carbon tax are investigated. This is done for several future electricity prices in these two papers. Two different fossil fuel phase-out years are investigated in **Paper I**, while in **Paper II**, one year is considered. Both papers investigate the development of the heating sector up until Year 2050. For **Papers III** and **IV**, no direct fossil fuel use is allowed from Year 2025, while in **Paper V**, also the plastic part of municipal solid waste (MSW) incineration is phased out in Year 2030.

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 they highlight the dynamic natures of the heat demand and supply.

3. Related research

Research into different parts of the heating sector is not particularly new; it has been performed for many decades, including research projects looking at Swedish DH systems, which have been around since the mid 1970's [4]. Table 2 presents an overview of the subjects considered in this thesis. There are, of course, many additional topics linked to the heating sector that are not considered in this thesis. As shown in Table 2, there is a wide variety of subjects, and there is ongoing research in all the presented fields.

Table 2. Overview of related research concerning the heating sector.

	Subject	References
Future heating solutions	Cost-efficient heating solution in new housing areas	[5–7]
	Technological development and role of heat pumps	[8,9]
	City planning	[10,11]
	Demand response	[12,13]
	Heat savings versus changed supply	[14,15]
Operation of DH systems	Thermal energy storage systems	[16–20]
	Flexibility in CHP plants	[21–23]
	Role of heat pumps	[24,25]
	Impacts of energy savings	[26]
4th generation DH	Definition and current status	[27–30]
	Decreased DH temperatures	[31–33]
	Economic and environmental benefits	[34–36]
Sector coupling	Smart energy systems	[37,38]
	Challenges and opportunities	[39–42]
	Operation	[20,43]
	Electricity peak shaving by DH	[20,44]
	Barriers	[45]
Biomass in the energy sector		[46,47]
Waste management and circularity		[48]
Excess heat use		[49–57]
Decarbonization		[3,58,59]
Business models and pricing		[60–63]
Energy system modeling methods		[64–67]

3.1. Opportunities and challenges for different components on heating systems

One of the main topics of ongoing research is the 4th generation DH. Previous generations of DH have had different motivations regarding the use of DH as a heating solution, such as comfort and reduction of risks (1st generation), fuel saving and reduction of costs (2nd generation), and security of supply (3rd generation) [27]. Each generation of DH has come with differences in technical aspects, such as going from steam as the distribution medium in the 1st generation to using pressurized water at temperatures lower than and higher than 100°C in the 2nd and 3rd generations, respectively. The trend of applying decreased DH temperatures is continued in the 4th generation DH. Decreased temperatures come with many benefits, such as lower distribution losses, increased coefficient of performance (COP) in HPs, higher electrical output in combined heat and power (CHP) plants, and an increased availability of excess heat (EH) [33].

Other technical differences in 4th generation DH compared to previous generations include improved interconnection of the supply and demand and the use of alternative materials for the piping [29]. However, the main motivations for using 4th generation DH are not only to improve the technical aspects of DH, but also to contribute to the transformation of today's energy systems into sustainable energy systems [27].

The use of EH is not something new for the 4th generation DH, as it is already used in existing DH systems. The use EH heat is desirable for several reasons, e.g., low or no primary energy sources are needed for the energy recovery step [54]. Furthermore, as EH is an surplus product, it is often cheap to integrate it into existing DH systems if the temperature is sufficiently high [49,56]. The EU Energy Efficiency Directive promotes the use of energy recovery at the same level as renewable energy for heating and cooling. EH use is closely connected to the 4th generation DH; with a lower temperature in the DH grid, more EH may be directly used in the DH grids, whereas low-grade heat sources can be more easily upgraded to a sufficiently high temperature through the use of HPs.

EH can be from many different types of sources, such as industrial processes, sewage water, and cooling processed from grocery stores and storage facilities. Depending on the form of activity that produces the EH, the yearly availability and temperature of the EH can differ significantly depending on the source. As the EH is not produced by companies that have heat production and distribution as their main business activity, there is a need for collaboration between the EH producers and actors on the DH distribution side. While it is often technically and economically feasible to utilize EH, other barriers may hinder an increased utilization of EH [56].

Certain challenges can negatively affect the viability of using DH as an economical and reliable heating solution. One of the main challenges is that the use of bioenergy for heating purposes can become highly challenging, for several reasons. Although the shares of bioenergy for heating purposes vary greatly between the EU member states, the Nordic and Baltic countries in particular have high shares of energy originating from bioenergy sources [2].

Bioenergy is available in many forms, such as biogas, bio-oils and solid biomass. For heating purposes, bioenergy is used for the direct production of heat in HOBs, while it is also used in CHP plants to produce heat and electricity simultaneously. Both gas turbines and steam turbines are commonly used in CHP plants, although their technical and economic properties are somewhat different. For example, the electrical output is higher from gas turbines than from steam turbines. In addition, both biogas and bio-oil can be used in gas turbines, whereas solid fuels are mainly used for steam production for steam turbines. Consequently, as the technical and economic properties of HOBs and CHP plants may differ depending on which form of biomass is used, the suitability profiles of different combinations of plant types and fuels in heating systems can vary greatly depending on the specific roles that the plants and fuel should fulfill.

Biomass can be used for purposes other than energy production. For example, both biogas and bio-oils are used in the transport sector, while solid biomass is used in the pulp and paper industry and as a building material. Biomass can also be used as a raw material for the production of plastics. It is important to note that currently, it is mostly residue products from the forest industry that are used as a bioenergy source in the Swedish heating sector.

In Sweden, biogas production mainly involves the anaerobic digestion of feedstocks, such as sewage sludge, food waste, and manure. Nonetheless, it is technically possible to gasify solid biomass for the production of biogas [68]. However, the economics of such gasification represent a barrier to the widespread deployment of such plants, as exemplified by a previously reported plant [68], which has been mothballed since 2018. Although the potential for biogas production is substantial, the supply of biogas of today is limited and is mostly used in other sectors, so it seems likely that this type of fuel will play only a minor role in future heating systems.

Since many sectors can use different types of biomass for different purposes, these sectors also compete for the supply of biomass, e.g., in the production of biofuels [47]. Limitations linked to biomass availability can, therefore, result in sectors other than the energy sector being more willing to pay for the available biomass, with the result that the market price for biomass becomes too high to be viable for the energy sector. Furthermore, the EU promotes the transformation into a circular economy, which increases the desirability of recycling and reusing biomass instead of incineration for energy purposes, all according to the cascading principle of biomass use. Consequently, it may not be for exclusively economic reasons that the supply of biomass for energy purposes becomes more limited in the future heating systems.

3.2. Sector coupling related to heating systems

Heating systems are often closely connected to other energy systems, especially the electricity system. This is because a heating system can both be a producer and a consumer of electricity, and the net production/consumption may be dependent upon both year and season. Electricity can be produced in CHP plants, while it can also be consumed by electric boilers and HPs. This provides heating systems with the possibility to both be affected by and influence the development of electricity systems. Studies have been conducted into how the different parts of heating systems are affected when the electricity price is fluctuating, which can result from a high level of intermittent electricity production. Aspects such as the flexibility provided by CHP plants [22], utilization of TES [18], and demand response flexibility [12,19] have been investigated previously. However, the question as to how heating systems are affected by the addition of intermittent electricity sources is not the same as the issue of how heating systems can support the integration of such sources. Whether heating systems evolve according to what happens on the electricity side or if heating systems develop together with and support the electricity system are different issues. The perspective that is used can provide insights into the different aspects of this dynamic.

A topic that is currently in focus is how the electricity system can be balanced using different types of storage systems, such as batteries and the variable production of hydrogen. While the technical and economic aspects of these options are being extensively researched, closer integration of heating systems with the electricity system can also provide storage or flexibility options. CHP plants and HPs can vary their production levels, and it is also possible to store energy in TES. TES has a significantly lower investment cost compared to batteries, which means that heating systems could potentially support the integration of renewable intermittent electricity sources at a lower cost than using direct electricity storage [20].

The industry sector is another sector that is also often connected to heating systems. Industrial processes often result in the production of EH, which can be utilized in DH systems. Using EH as a heat source can reduce the need for primary energy and, as a result, reduce the associated greenhouse gas emissions [54]. If the temperature of the EH is sufficiently high, it can be used directly in DH networks, thereby lowering the share of primary resources used in DH networks. EH at lower temperatures can also be used, although this requires the use of HPs to increase the temperature to the desired level. The prevalence of EH as a heat source in DH in the EU is relatively low [2], although it is recognized that there is a strong potential to increase the share of EH in DH in Europe [56]. EH is predominantly used in the DH systems of some cities, such as Luleå in the north of Sweden, whereby >90% of the heat supplied to the DH system originates from the steelmaking industry.

3.3. Using modeling for investigations of energy systems

Due to the many components involved in energy systems, computer models of various types are often used when investigating such systems. Different models are more suitable for examining different parts of the system, and for this reason there does not exist any "super" model that is able to answer every kind of question when investigating energy systems. Heating systems often operate on the city level or below, which distinguishes these systems from, for example, the electricity system, which can operate on an international level due to the electricity transmission connections that exist between countries. Given the local nature of heating systems, it is important to consider local conditions that can affect the particular heating system being investigated, such as resource availability and building density. In addition, due to the local level, single units, i.e., power plants, can affect the system to such an extent that it becomes important to consider the effects of single units. On an international level, single power plants are usually too small to affect the overall system, and simplifications that are reasonable to make on the international level are too crude for the local level.

The use of computer models enables investigations of complex and data-rich systems that would be too-cumbersome to investigate without substantial computational power. Depending on the types of questions being investigated, different models can provide different insights. Many computer models have been developed with different focuses [69,70], such as TIMES [71], MARKAL [72] and EnergyPLAN [73].

Optimizing models are widely used to investigate investments in and dispatch of different technologies. With this type of model, a certain goal is set, such as finding the lowest system cost, together with certain constraints, such as setting limits on different types of emissions. By solving such a model, it is possible to gain insights into how different technologies are competing with or complementing each other. The outputs provided by such models include the optimal timing of investments in certain technologies and when to utilize a specific available technology. These results can be of significant interest for heating systems due to their local nature, whereby investments in and production from single power plants can determine how the system functions.

3.4. Identified research gap

Although there has been previous research into many different aspects of heating systems, there is a lack of studies on how already existing heating systems evolve over time. For the Nordic countries, which have multiple DH systems in place for several decades, the ways in which these existing systems can develop in a cost-efficient manner and the interactions between the involved components are important to understand. Furthermore, much of the research on heating systems has focused on DH, thereby overlooking the possibility to use individual heating solutions for new housing. Even though DH has technical properties that make it suitable for greater participation in the transformation of the energy system to a sustainable system, it may be more desirable for end-customers to use individual heating solutions if those solutions are more economically viable than DH. If the supply and demand sides are considered separately, the interaction between them is missing, which will result in a failure to understand how they can evolve together. In previous studies, supply and demand have seldom been considered simultaneously for an evolving heating sector. Does the heating solution for new housing depend on how the DH system can evolve or do individual heating solutions improve sufficiently so that DH is not an economical option in any case? Without considering both sides simultaneously, the acquired heating solution may not represent how heating systems can evolve economically for both the demand and supply sides.

Therefore, this thesis aims to provide insights into how the cost-efficient heating solution for expanding cities can look in the future, by considering the supply and demand sides simultaneously, which has not been done before. The case study is Gothenburg, an expanding city in Sweden that has a DH system in place with a diverse array of DH supply plants. The diversity of the supply options enables the system to use whichever option is best-suited to different situations. This means that it is possible to determine which technologies are utilized at different times. With a long-term modeling approach, it can be investigated whether the existing system benefits from having a diverse supply option set or if such diversity will decrease in the future.

As computer models are commonly used in this type of investigation, this thesis also aims to provide insights in how the model formulation itself affects the acquired heating solution. As it is impossible to incorporate all aspects of these systems into a single model, it is of high importance to understand how the solution is affected by the model formulation.

4. Method, modeling, and case

In this chapter, the method, modeling, and case used in this thesis to address the research aims are addressed.

In this thesis, an approach in which both the supply and demand sides of a heating system are considered simultaneously and in combination over a long time period is developed and used. If considering only one side at a time, the full dynamics and interdependencies of the considered system are not taken into account, which has been the case in most of the previous studies. The dynamic systems approach used in this thesis enables an investigation of what happens on both the supply and demand sides when they are affecting each other at the same time. As the heating solution for new housing is a central theme of this thesis, the cost of connecting the new housing to the DH grid is evaluated and included in the model, as are the costs for other heating technologies.

As this thesis investigates the development of a heating system over several decades and takes both the supply and demand sides into consideration, the study becomes data-intensive. The research questions have, for this reason, been investigated using bottom-up, cost-optimizing, dynamic energy system modeling. The city of Gothenburg on the west coast of Sweden is used as the modeling case. Gothenburg has a DH system that has been in use since the 1950's and is also an expanding city in which new housing is built every year. The DH system of Gothenburg is a diverse system with various types of supply plants, including: industrial EH recovery, MSW incineration, CHP, HOB, HPs and electric boilers.

A techno-economic perspective is used in this thesis. This perspective is used because technical and economic considerations are often central to the decision-making of actors in the heating sector, such as city planners, DH utilities and customers. For this reason, it is important to assess the costs of using different heating solutions, as the cost-optimal solution can be different for different kinds of housing.

As there are many outside factors that can affect the cost-efficient development of a heating sector, the papers included in this thesis have different focal areas, and different factors are in focus in the different papers (for details, see Table 1 in Chapter 2).

4.1. The dynamic systems approach

A dynamic systems approach is used in all the papers included in this thesis. In this approach, the supply and demand sides are connected to each other ('system') and the development trajectories ('dynamic') of both sides are considered, both together and simultaneously, over the entire period. The setup of this approach is shown in Figure 1, where an existing heating system is in place but develops over time. Even though the focal points of the papers are somewhat different, both the supply and demand sides are considered simultaneously in all the papers.

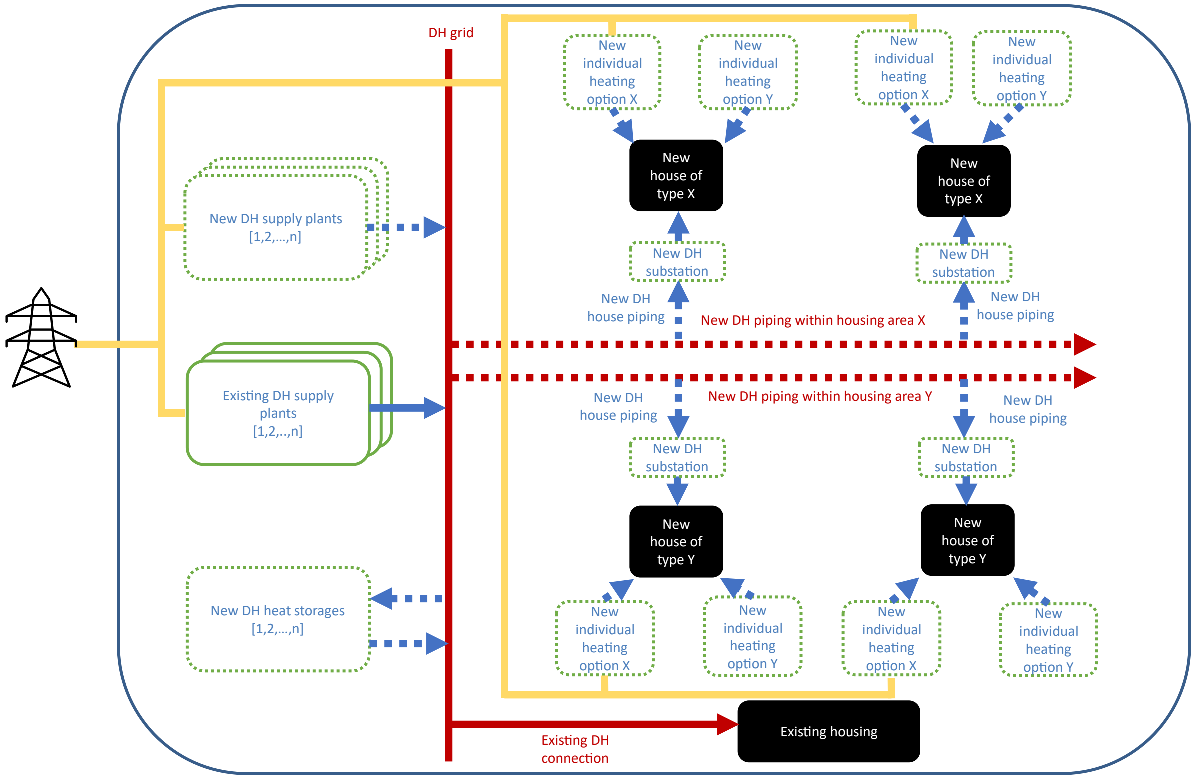

Figure 1. Schematic overview of the heating system. Figure adapted from Paper V. Heat storages are only included in Papers IV and V. In addition, in Papers I–III, the piping within a specific housing area is not distinguished from the piping going into a specific house.

4.2. Heating solutions, opportunities and challenges

4.2.1. District heating

Several opportunities are identified in the different papers that could influence the role of DH systems in the future. Although there are some large-scale heat storage units in some DH systems, they are still relatively uncommon. Thus, the potential roles of TES in the DH system are investigated in **Papers IV** and **V**. In **Paper IV**, different forms of TES are presented that are used in systems at different locations. As the cost of building new TES may be strongly influenced by the local conditions and as few existing systems have large-scale seasonal TES in place, several levels of investment cost are investigated in **Paper IV**. The possibility to make investments in TES is also present in **Paper V**, as the results in **Paper IV** show that TES is economically beneficial for the DH system.

The focus of **Paper IV** is seasonal TES that can be discharged during colder periods. Using biogas in HOBs is, however, also a potential solution for peak production during colder periods. Therefore, the ways in which good availability of biogas can affect the heating solution are included, as biogas could also meet the peak power demand due to the low investment costs for this technology.

The focus of **Paper V** is on investigating whether changes in how the DH system is run affect DH system operation, and also whether this affects the heating solution for new housing. A phase out of biomass for heating purposes is investigated, as this could have a severe negative effect on the DH system owing to the high share of biomass currently used for energy purposes. Regarding DH systems, two opportunities are identified and investigated: 1) to utilize a low-grade heat source from an industry; and 2) to lower the DH temperature.

As with all HPs, there is a need for a heat source, and DH HPs are no exception. How this heat source is managed is different in the different papers. In **Papers I** and **II**, there is no limit on the heat source, and in **Paper III**, the scenarios are compared whether or not there is a limit. In **Paper IV**, the heat source is limited to the current maximum output. In **Paper V**, three sources with different corresponding COPs are available, where only the one with the lowest COP is treated as being unlimited.

Assessing the cost of connecting housing to the DH system is of central importance when investigating how the heating system can develop economically. In **Papers I** and **II**, the costs for burying piping and installing a substation are considered as a single cost item, although they are different for different types of housing. This approach is modified in **Paper III**, where the piping and substation are separated into two different investments. In **Papers IV** and **V**, the piping is separated into two parts, one in which the piping is buried in the new housing area, and the other in which the piping is to an individual building in the area. This is done because the building density is higher for apartment buildings than for single-family housing, so it is captured through the separation of the two types of piping. Thus, **Paper III** represents new housing that is built in close proximity to existing DH grids, while **Papers IV** and **V** represent the situation in which a whole new area is constructed with one specific type of housing and in the absence of a DH grid within that area.

4.2.2. Individual heating solutions

One of the main developments in the last few decades is the continuous increase in the use of HPs as individual heating solutions for new housing. While ground-source HPs are a mature and common technology, the installation of air-to-water HPs has also been steadily increasing.

Installation of air-to-water HPs is relatively straightforward, as the suitability of this technology is not dependent upon the characteristics of the ground and no drilling is required. However, one of the main drawbacks is that the COP of air-to-water HPs is dependent upon the ambient temperature. As the heating demand is higher when it is cold outside the building, this means that the COP is lowest when the demand is highest. This characteristic must be captured when different heating solutions are to be compared with each other. This is, therefore, implemented in **Paper III** and used also in **Papers IV** and **V**.

Due to economies of scale, all individual heating options have a lower specific cost (in €/kW) for apartment buildings compared to single-family housing units. Future economic and technical improvements to the different technologies are also included in the modeling.

4.3. Existing and new housing

Cities consist of many different types of housing, and the housing units built in the future will also be heterogeneous. The demand side of the heating system is considered by having several types of housing in the system, and as this thesis aims to investigate the heating system in the long-term perspective, new housing units of different types are added annually. Owing to the heterogeneity of the available housing stock, the added housing exhibits differences in characteristics, such as size, heat demands, and the costs for installing and using different kinds of heating solutions. Thus, the heating demands from these housing types form the total heating demand. Differentiation between the housing types enables investigations into how the heating solutions for the different types of housing differ depending on the ways in which external factors, such as the electricity price, develop in the future.

In total, seven different types of housing are considered in this thesis:

- The existing housing units that currently use DH;
- Two apartment building types of different sizes with the same heat demand per m^2;
- Two single-family housing types of different sizes with high heat demand per m^2; and
- Two single-family housing types of different sizes with low heat demand per m^2.

All seven types of housing are considered in **Papers I** and **II**, whereas in **Papers III–V**, single-family housing units with low heat demands are not included. The latter are excluded as the results in **Papers I** and **II** show that the resulting heating options are always individual heating solutions. As **Papers III–V** have a much higher resolution on the demand side, the computational burden is significantly increased and single-family housing with low heat demands is, therefore, omitted to decrease the computational time.

All the papers reflect upon an existing heating system that evolves over time. For this reason, the already existing housing is also included. Nevertheless, it is assumed that the existing housing units that use DH as the heating solution will continue to do so also in the future, and that the existing housing units that apply individual heating solutions will also continue to do so in the future.

In **Papers I** and **II**, it is allowed to mix investments in new technologies to whatever extent that is most cost-effective. Although mixes of several technologies are not 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. In **Paper III**, the impact of this assumption is assessed by examining the differences in the results and the computational burden, by either allowing for a mixing of technologies, having a fixed minimum installation cost when installing a technology of any size, or requiring that the installed technology be installed at such a size that it can always provide the full heating demand. The results from **Paper III** show that there are differences, and consequently, in **Papers IV** and **V**, it is mandated that an installed heating solution should be able to provide the full heat demand, as it is relatively rare to mix different heating solutions within the same building.

4.4. Modeling case and scenarios

4.4.1. Electricity price

Due to the close connections between the heating sector and the electricity sector, the ways in which different electricity price projections affect the development of the investigated system have been investigated in all the papers, given that the electricity price affects different technologies in different ways. Assessing future electricity prices accurately is difficult for many reasons, such as a steadily increasing level of intermittent electricity production or rapid changes in fuel pricing. Therefore, the investigations apply different future electricity price scenarios. In **Paper I**, two future electricity prices are considered: one in which the price increases for all months; and one where the price decreases for all months. In **Paper II**, the same profiles as in **Paper I** are used, and a third, more-variable price profile is considered in which the prices decrease in summertime and increase during the colder months. For **Papers III–V**, the price during the first modeling year is set significantly higher than the prices in **Papers I** and **II**, in order to reflect the drastic price increase that occurred during the winter of 2022 following the Russian invasion of Ukraine. The different price cases investigated in **Papers III–V** are for this reason set at a high level in the starting year but decrease in subsequent years to different extents, depending on the specific scenario. In **Paper III** and **Paper V**, three different price cases are investigated, while in **Paper IV**, four cases are investigated.

4.4.2. Bioenergy for heating purposes

As described in Chapter 3.1, the availability of bioenergy for heating purposes can become severely limited due to competition for available biomass, as well as for reasons linked to the transition to a circular economy. As a large part of the total energy input into the heating sector in the Nordic countries comes from bioenergy, the impact on the heating sector of differences in bioenergy availability is investigated.

In **Papers I–IV**, there is no limit attached to the availability of bioenergy in the form of woodchips derived from forest residues, although the cost is increasing in future years. **Paper V** looks at how a phase out of the biomass used in the DH system affects the future heating system.

In **Paper IV**, the focus is on seasonal TES, which can store heat in the summertime to be used during the colder periods. As the investment cost of biogas HOBs is relatively low but there is a relatively high fuel cost, this technology is well-suited to peak heat production, which means that it could compete with TES as a fossil free heating solution during colder periods. How the availability of biogas affects the heating system development is investigated in **Paper IV**. Biogas production is limited in the real energy system of today, and for this reason it is explored in **Paper IV** how the heating system develops depending on whether biogas availability is high, compared to whether it is not available for use in the heating system.

4.4.3. Decreased DH temperature

Lower DH temperatures confer several benefits on different parts of the DH system, as described in Chapter 3.1. These benefits include decreased distribution losses, increased electricity production in CHP plants, and higher COP values for DH HPs [33].

In **Paper V**, it is investigated how the heating system development is affected by decreasing the temperature of the DH grid from that used in 3rd generation DH to levels commonly used in 4th generation DH systems.

4.4.4. Excess heat as heat source

Several processes produce EH that can be utilized for heating purposes, as described in Chapter 3.1. Reuse of the EH internally within industrial processes is common, although there is often EH that cannot be used and must be dissipated by cooling. EH for use in DH can be divided into high-grade EH and low-grade EH. High-grade EH is heat that is at a suitable temperature to be utilized directly in the DH grid. The temperature of low-grade EH is too low to be used directly but it can be upgraded using HPs. As the COP of HPs is dependent upon the input and output temperatures, with smaller differences between the input and output temperatures resulting in higher COPs, low-grade EH sources can be utilized more easily when the DH grid temperature is lower.

In **Papers II** and **V**, changes in the availability of EH are investigated. In **Paper II**, the EH is assumed to come from a change in the production processes of refineries, such that the EH is high-grade. In **Paper V**, the EH is instead from a new industry that is assumed to be built, whereby the EH is low-grade.

4.4.5. Seasonal thermal energy storage

TES units have been built in several DH systems, but only a few have large-scale seasonal TES. How the heating system is affected by whether or not it is allowed to make investments in TES is the focus of **Paper IV**, and this topic is also included in **Paper V**.

4.4.6. Modeling case

In all the appended papers, Gothenburg has been used as the modeling case. DH has been used as a heating solution in Gothenburg since the 1950's and supplies slightly more than 3 TWh annually, which is almost 90% of the heat demand of Gothenburg. The DH system of Gothenburg is a diverse system with many different types of supply plants, including industrial EH, MSW incineration, CHP plants, HOBs, and sewage water HPs. The diversity of the studied system enables the heating system to adapt its production, ensuring flexibility according to various internal and external factors. Most of the technologies will, however, reach their respective end of technical lifetime within the studied period, and must therefore be replaced. Whether it is more cost-efficient to replace a certain plant with a similar type or to change the plant type in the future can be studied using this type of diverse heating system.

4.5. Heat load profile

A heat load profile is used to represent the variation in the heat demand throughout the year. Measurements from a new housing area [74] are used as the basis for constructing the heat load profiles used in the different papers. The heat demand consists of both a demand for space heating and a demand for hot tap-water. In **Papers III–V**, the space heating demand is also used to compute the COP of air-to-water HPs in the different time periods, owing to the close relationship between the outside temperature and the resulting COP.

4.6. Modeling

As stated at the beginning of this chapter, using a cost-optimizing model to investigate the heating system is a data-intensive process. In addition, due to the interconnection between the supply and demand sides over several decades, the problem has become increasingly complex. Using an energy systems optimization model (ESOM), it is possible to study this problem using the computational power of a computer. As cost considerations are central to the investigated system, a cost-optimizing model that considers the investment costs, running costs, fuel costs, taxes, etc., can compute the optimal investments and dispatch levels of the different available technologies. By adding constraints, such as disallowing the use of fossil fuels, the pathways through which the heating can develop in a cost-optimal fashion can be uncovered.

In all the papers of this thesis, The Integrated MARKAL-EFOM System (TIMES) energy modeling framework has been used. TIMES is a cost-optimizing framework, developed by the International Energy Agency Energy Technology Systems Analysis Program (IEA-ETSAP) [71], which uses a bottom-up modeling approach in which technical and economic data are provided to the model.

The model uses perfect foresight, which means that there is no uncertainty regarding future prices, demands etc. This makes it possible for the model to plan for future years without any uncertainty. The model is solved to find the lowest-cost solution that fulfills all the demands while still respecting all the constraints applied to the model. The objective function that is minimized in TIMES is as follows [75]:

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

- *NPV*, the 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 thesis, only one region is included.

As the framework considers new investments with technical lifetimes, a 'salvage value' is considered for the technologies that have some lifetime remaining at the end of the modeling period. This makes it economically feasible to also make investments close to the end of the modeled period.

In **Papers I** and **II**, the modeling period is 2018–2050, while in **Papers III–V**, the period is 2023–2050.

TIMES is mainly formulated using linear programming (LP). This programming method is commonly used in large-scale energy models because the computational time required can be kept reasonably short. Furthermore, it can be mathematically proven that the found solution is the global optimum for the specific problem. The downside is that many physical behaviors cannot be implemented at a detailed level but have to be linearized in order to be considered in such models. Moreover, linear models cannot take minimum investments into account, which is of importance when taking economies of scale into account. In TIMES, it is however possible to use lumpy investments, thus adding binary variables, which transforms the model into a mixed integer linear programming (MILP) model.

In this thesis, **Papers I** and **II** use an almost fully linear model formulation. In **Paper III**, it is investigated to what extent the results are affected by having an almost fully linear model, as compared to a model that utilizes the features of MILP much more extensively, with the focus on how heating solutions can be installed in new housing. In **Papers IV** and **V**, the model is formulated with a much higher number of binary variables compared to **Papers I** and **II**.

In **Papers III–V**, the granularity of the demand side is increased significantly compared to **Papers I** and **II**. Instead of having seven demands as in **Papers I** and **II**, six new demands are added for each modeling year in **Paper III**, while in **Papers IV** and **V**, four new demands are added each year. This separates each housing type according to the year in which it is built, resulting in each new housing area being separated from the other areas.

In **Paper III**, it is investigated how adding minimum investment costs or sizes affect the resulting heating solution. This feature is of importance as it is uncommon to mix several individual heating solutions within the same building. Thus, how the results differ between using a fully linear model, which encourages mixing, and using a model that defines either a minimum investment cost or requires that the installed solution covers the full heat demand during all periods of the year, is investigated. The results show that there are indeed differences, and for this reason it is mandated in **Papers IV** and **V** that if an individual heating technology is installed, it has to be of sufficient size to cover the total heating demand during the entire year, with the exception of ventilation HPs, which can only cover part of the full heating demand and therefore have to be combined with some other technology.

5. Main results and discussion of the results and method

In this chapter, the main results regarding the heating solution for new housing (Section 5.1), DH supply (Section 5.2), and effect of seasonal TES (Section 5.3) are presented. This is followed by the impact arising from requiring minimum sizes or installation costs for new installations on the demand side (Section 5.4). Finally, the results (Section 5.5) and method used (Section 5.6) are discussed.

5.1. Heating solution for new housing in the future

The modeling results for the heating solution for new housing stock differ significantly between **Papers I** and **II** and **Papers III–V**. This is attributable to two major differences in the modeling setups used in the studies. First, the granularity of the new housing areas is increased significantly in the latter papers. Second, in the latter papers, the possibility to use air-to-water HPs is added as an available heating solution.

Parts of the results from **Papers II** and **V** are presented in Figure 2. In Figure 2, it can clearly be seen that in **Paper II**, DH takes a dominant role as the heating solution for new housing, while in **Paper V**, individual solutions assume a larger role than in **Paper II**. In **Paper V**, the individual heating solution for the first years is ground-source HPs, while in the latter years it is air-to-water HPs.

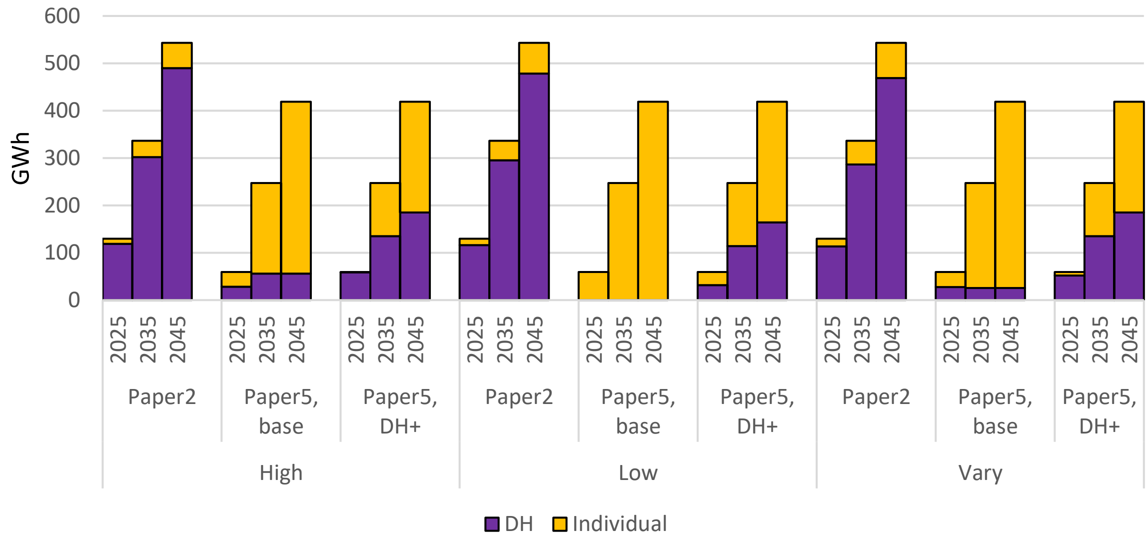

Figure 2. DH heat production levels (in GWh) from DH and individual heating sources for the new housing added to the heating system for different electricity price cases and years. Values are adapted from Papers II and V. The values acquired from Paper V are for the base scenario (base), and in which the circumstances for DH are favorable (DH+), i.e., a decrease in the DH temperature and the addition of a new low-grade industrial EH source, but without TES. The lower total heat demand in Paper V, as compared to Paper II, is due to the later starting year in Paper V compared to Paper II.

The development of the electricity price in the future does exert an effect on the resulting heating solution. A high or varying electricity price entails greater use of DH compared to the low electricity price cases. This stems from the fact that it is HPs (the individual heating solution) that are competing with DH.

5.2. Development of the DH supply

In all the papers, the results show that the DH supply side undergoes development that is heavily influenced by the electricity price development. The results show that even for the high electricity price cases, HPs play a prominent role in the DH system (see Figure 3).

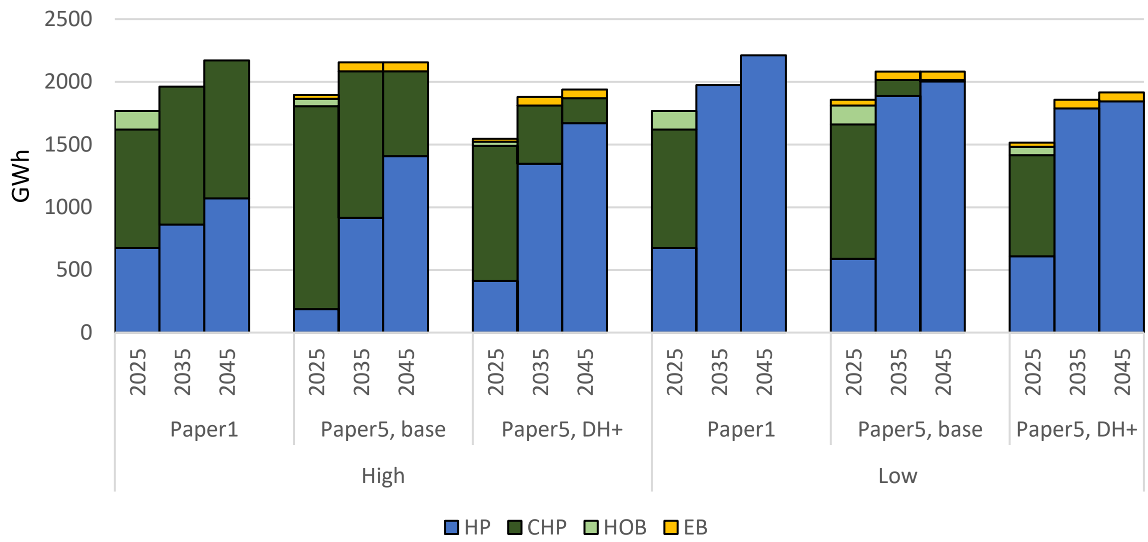

Figure 3. DH heat production levels (in GWh) from the different sources (HP, bio CHP, bio HOB and EB) for different electricity price cases and years. Values adapted from Papers I and V. Paper 5 DH+ indicates a scenario in which there is a decrease in the DH temperature and there is addition of a new low-grade industrial EH source, but there is no TES. For all the presented graphs, the EH and MSW incineration values have been omitted to improve readability.

The results in **Paper V** show that low-grade industrial EH is utilized to its maximum extent for all the electricity price cases. Sewage water HPs are also used to a large extent in the high electricity price cases, but even more so in the low- and varying-price cases. In addition, if the DH grid temperature is decreased, HPs assume an even more-prominent role. This shows that there is a potentially large benefit associated with using HPs as one of the primary technologies in future heating systems, even if the electricity price is high. This can by itself have the effect of decreasing the use of biomass without any changes to the surrounding system. A decreased availability of biomass or a total phase out of biomass may, therefore, pose a less-serious challenge than was initially presumed. However, as HPs need some kind of heat source, for systems in which there is no readily available heat source, the economics of using DH in such systems faces a severe challenge in terms of competition from individual HPs as the future heating solution.

5.3. Impact of seasonal thermal energy storage

The results in **Papers IV** and **V** show that investments in TES are often economically desirable. In both of these papers, the results show that new TES investments are economically beneficial for already existing systems, whereas there are also large investments at the point when old plants are dismantled due to reaching their respective end of technical lifetimes. If there are investments in seasonal TES, the sizes of other supply plants are lower compared to if there are no investments in TES.

For all the electricity price cases, it is the DH HPs that are utilized to a greater extent to charge the TES during the warmer periods (Figure 4), for which the results for one of the investigated electricity prices in **Paper IV** are presented. For all the investigated electricity price cases, the same dynamic is present, whereby electric boilers are replaced completely by TES and the biomass HOBs and CHPs are affected to different extents depending on the electricity price. The utilization of DH HPs increases for all the electricity price cases.

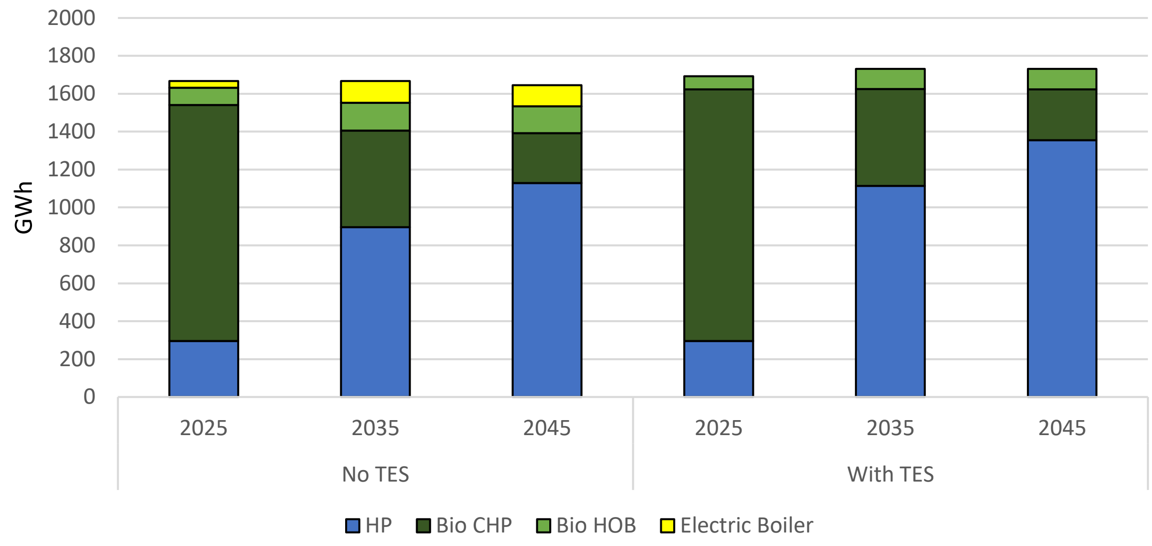

Figure 4. Annual DH production levels of heat in the High2030 electricity price scenario in Paper IV. The values for EH and MSW incineration have been omitted to improve readability.

The total electricity demand for electricity from the heating sector increases annually due to the increased utilization of the DH HPs. The results in **Paper IV** do, however, show that the need to import electricity decreases dramatically during the colder periods when TES are available, as there are no investments in or utilization of electric boilers (Figure 5). However, if biogas is available the level of imported electricity decreases to the same extent as with TES.

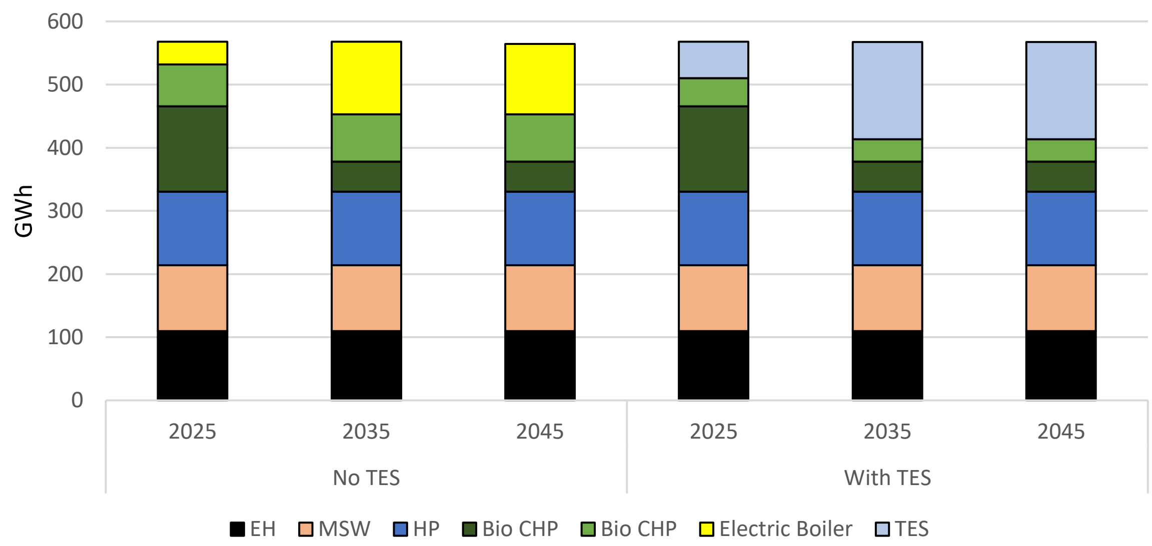

Figure 5. DH heat output for the different sources in the coldest month of the selected years for the High2030 electricity price case in Paper IV.

The modeled system does not place any limits on the importation or export of electricity from the heating system, and there is no price elasticity for electricity depending on the demand. In reality, this assumption is of concern and has to be addressed accordingly. Nonetheless, as the results indicate, if there is some aspect that imposes a limit on electricity imports during colder periods, both biogas and TES can alleviate this potential problem. Moreover, since biogas is a limited resource, TES seems to be a viable and economical option to mitigate this problem.

The effect on the heating solution of new housing is, however, relatively limited. In **Paper IV**, allowing for investments in seasonal TES increases slightly the use of DH for new housing, but only if biogas is not available for use at peak power supply. In **Paper V**, a slight increase can also be seen for some electricity price cases, but the effect is rather small.

5.4. Impacts of linear or mixed integer formulation for new installations

Requiring installations of new technologies to be of sufficient size to cover the whole heat demand or encouraging technology mixing by allowing technologies to be installed at whatever size is desirable, influences the resulting heating solution. In Figure 6, the resulting heating solution for these two cases are shown for large apartment buildings built in Year 2020. As shown in Figure 6, encouraging mixing increases the usage of individual heating solutions, in this case air-to-water HPs, and decreases the use of DH as the heating solution. The *linear* cases are formulated using linear variables, while the *all-or-nothing* cases use a more mixed-integer approach, and consequently use many more binary variables. Due to the higher numbers of binary variables in the *all-or-nothing* cases, the modeling of these cases requires much more computational power and time to be solved.

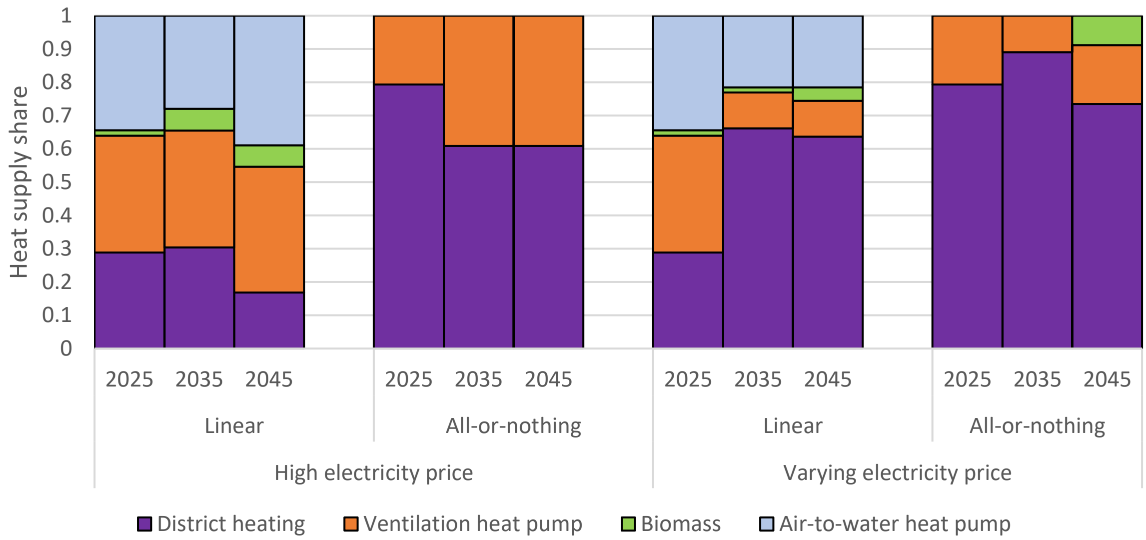

Figure 6. Heating solutions for new large apartments buildings constructed in 2020, for different electricity price cases. The figure is adapted from Paper III. The linear category indicates where there is no minimum investment cost and that the cost of installing a certain technology increases linearly with the installed capacity. The all-or-nothing categories indicate where new installations have to be of sufficient size to cover the full heat demand during all time periods. The ventilation HPs can, however, cover part of the heat demand.

5.5. Discussion of the results

One of the core results of the papers included in this thesis is that the use of DH HPs is often prominent. One of the important implications of this outcome is that the heating sector is likely to become increasingly electricity-dependent. For all the papers, it has been assumed that there is no limit as to the electricity grid connection capacity, and that there is always electricity available with no price elasticity. There are, however, often limits to the electricity grid capacities of cities, such that the representation of the grid between local energy systems and central electricity systems affects the resulting solution [41]. Installation of CHP plants within city borders can, therefore, be an economically viable solution due to the grid limitation issue [42]. From a policy perspective, this highlights the need to assess potential economic benefits of having CHP plants within city borders due to electricity concerns, compared to assessing CHP plants only from an economic perspective for the heating system.

As the modeling is carried out on an existing system with a high degree of diversity in terms of DH supply technologies, translation into general rules for future heating systems can be problematic. Nevertheless, the results show that the existing system evolves into a system that is more heavily reliant on electricity as the main energy source for use in HPs. These results indicate that for heating systems that have the opportunity to recover heat from, for example, nearby industrial sources or sewage water, it can often be economical to incorporate these types of sources into the DH systems. The results also indicate that individual HPs are economical for many types of housing and scenarios. These results further indicate that it can be economically beneficial for the heating system to undergo electrification. As a consequence, existing systems with a diverse set of supply units may become more reliant on using electricity as their energy source. This can prove to be a challenge for systems, often the small systems, which are reliant upon single or few production units that use biomass as their energy source. Having different types of production units within the same system enables greater flexibility, although it also requires investments in units that may have relatively low utilization factors. The customers in such systems may find that it makes more sense economically to make investments in individual HPs than to continue using communal solutions.

Furthermore, as the availability of biomass in future heating systems is mainly affected by factors outside the heating sector, the actors involved in heating systems need to consider the risk associated with decreased availability of biomass for heating purposes (i.e., not stemming from cost reasons). In contrast to the future of biomass in heating systems, the technological development and implementation of 4th generation DH is driven by internal factors that emerge from decisions made by the DH grid owner. The utilization of EH is, meanwhile, driven by both internal and external factors. Whether or not DH companies find it economical to make investments in DH HPs depends on the electricity price and on the willingness of the EH producers to provide EH even though that is not their main business. It is clear that technical or economic factors are not always determining why more EH is not harnessed; instead, other barriers are hindering the utilization of more EH [56]. The risks affecting the DH systems if the use of biomass is phased out, either for internal or external reasons, can therefore be mitigated by the actors within DH systems by transforming the DH systems of today into 4th generation DH or by increasing efforts to harness EH from different available sources. This highlights the importance of having a policy to assess the local potential for using EH, and also to incentivize actors to provide EH to the DH system.

5.6. Discussion of the method and modeling

Cost-optimizing models are often used in techno-economic investigations of energy systems. However, there are certain limitations associated with how such models can be used and how the modeling results can be translated into investment and operational decisions.

One of the core limitations of this modeling method is linked to the combination of optimization and perfect foresight. This combination enables the model to see the future without any uncertainties. In the absence of uncertainty, there is no need for any spare capacity within the system, which is something that is required in real-life systems. Unplanned failures in supply plants also require that there is spare capacity available. How to cope with this limitation is not a simple task. Simply adding a requirement that a certain amount of spare capacity must always be available will result in that the solution to the model is to add the capacity of the technology with the lowest investment cost on top of the other technologies. However, such a solution would hardly give any additional insights.

The results in **Paper IV** show that the seasonal TES is built to a size that enables the heat output capacity (in MW) to be much larger than the heat demand during the coldest time period. Therefore, it appears that with seasonal TES, the resulting system has spare capacity even though this is not an explicit requirement. Thus, short-term heat demand peaks may be covered by utilizing the output capacity of the TES unit.

In addition, the modeling approach used in the papers optimizes the investment and production costs of heat in the system as a whole, without explicitly considering the actors within the system. It is, therefore, not the house owners who make investments in DH connections or individual heating solutions. The production and distribution costs of heat can differ significantly from the heat price to the customer, meaning that the identified heating solution that which is most economical for the heating system, whereas the heating solution for customers may differ. The price of purchasing electricity for individual houseowners is not only the price on the spot market, but also includes taxes and, often, grid fees, so the cheapest heating solution for houseowners may be different to the cheapest solution for the system as a whole, as using HPs is the dominant individual heating solution.

One of the goals of **Paper III** is to investigate how different assumptions regarding investments made on the demand side affect the resulting heating solution. In addition, in **Paper III**, the granularity of the heating system is increased significantly compared to **Papers I** and **II**. The results do in some ways differ from those of **Papers I** and **II**. Mixes of different heating technologies within the same building are relatively rare, which means that having a fully linear model runs the risk of generating results that are not feasible in real-life systems. Furthermore, the increased granularity, which makes it possible to differentiate the heating solution of new housing depending on when it is built, also affects the results. It is important to note that the input data for the technology costs and fuel costs are updated between the papers. The computational power and time needed to solve a model with additional binary variables and higher granularity are significantly greater.

That the results in **Paper III** are somewhat different from those in **Papers I** and **II** shows that it is important to consider carefully the granularity of this kind of modeling when creating the model, as well as the simplifications/linearization that can be made. A too-coarse resolution may result in solutions that might be unviable in real systems. It is also important to consider these aspects for local systems because smaller systems can be more-severely affected by single investment decisions, as compared to larger systems. Furthermore, as air-to-water HPs are shown to be an economic solution for many cases, their economic and technological properties are important to consider in this type of modeling.

6. Main contributions and conclusions

At the beginning of this thesis, it was pointed out that there is a lack of studies regarding how the supply and demand sides of an evolving heating system affect each other. One of the aims of this thesis has thus been to provide insights into how this can be modeled, and how the heating solution for new housing depends on the development of the supply side, and vice versa. A summary of how the different parts of future heating systems are affected in future scenarios is presented in Table 3.

That DH or individual heating solutions are the most economical to use for new housing depends on the housing type and the development of the DH supply side, may seem intuitive. DH solutions are often cost-competitive for apartment buildings, but also for some single-family housing units. The results do, however, indicate that it is economically beneficial for heating systems, both for DH supply and individual heating options, to undergo electrification. The utilization of low-grade industrial EH, upgraded by HPs, is economical, and a decreased DH distribution temperature can also increase the economic viability of DH solutions in the future, while an eventual phase out of biomass could affect the viability in a negative way. In the case in which the circumstances are least-favorable for DH, there is no expansion of DH into any new future housing. As the future of biomass for energy purposes is called into question, electrification may even be required for DH systems to remain competitive. The main competitor for DH systems as a heating solution for new housing is individual HPs, and as they also use electricity as the energy input, this can also increase the electrification of the heating system.

His thesis also contributes to the research field with the inclusion of two specific technologies that have not been included previously in long-term modeling of heating systems, namely seasonal TES and individual air-to-water HPs, and both are shown to affect the development of heating systems. Seasonal TES units are economically viable for the heating system and can reduce the need for electricity imports during colder periods, although the impact on the heating solution for new housing is rather low. Individual air-to-water HPs are shown to be a prominent heating solution for future housing, and it is thus crucially important to incorporate their economic and technical properties into the long-term modeling of heating systems.

In addition, this thesis contributes to an understanding in how the economical heating solution for new housing is affected by whether mixes of technologies are allowed, which is usually a property of fully linear models. As mixes of technologies within the same building are rare, this is important to consider when exploring how new housing can be heated economically. Furthermore, the results are affected by the granularity of the investigated new housing areas.

Table 3. Summary of how different parts of the heating system (rows) are affected in different scenarios (columns) compared to the existing heating system.

	HIGH ELECTRICITY PRICE	**LOW ELECTRICITY PRICE**	**VARYING ELECTRICITY PRICE**	**TES INVESTMENTS ALLOWED**	**NO BIOMASS AVAILABILITY FOR DH**	**LOWER DH TEMPERATURE**	**ADDITION OF LOW-GRADE EH SOURCE**	**BIOGAS READILY AVAILABLE TO A LOW COST**
Connection of future new housing to DH	Similar to varying, higher than low	Lower than high and varying	Similar to high, higher than low	Mostly no effect, small increase in some cases	Decrease	Increase	Increase	Slight increase if TES not available
Usage of DH HPs	Increase in the future	Dominating technology in the future	Dominating technology in the future	Increase	Dominating technology	Increase	Increase	Unaffected
Usage of Biomass CHP	Decrease in the future	Significant decrease in the future	Significant decrease in the future	Slight decrease	Unavailable due to scenario	Decrease	Decrease	Unaffected
Usage of Electric boilers	Increase in the future	Increase in the future	Increase in the future	Total phase out	Unaffected	Unaffected	Unaffected	Total phase out
Electricity imports during wintertime	Increase in the future	Increase in the future	Increase in the future	Significant decrease	Increase	Slight decrease	Slight increase	Significant decrease
TES size	Significant increase in the future	Significant increase in the future	Significant increase in the future	Required by scenario	Slight increase for varying electricity price case, no effects for high- and low-price cases	Unaffected	Unaffected	Slight decrease for varying electricity price case, decrease for high- and low-price cases

7. Future work

One of the conclusions of this work is that it is economically beneficial for heating systems to undergo electrification, although this assumes that the electricity system is able to provide sufficient levels of electricity when needed. How the full energy system of today would be affected by electrification of the heating system, which currently is a net electricity producer, is something that is of importance to consider when investigating how the full energy system can undergo decarbonization.

One of the aspects that has been investigated extensively in recent times is how intermittent renewable energy sources can be integrated into electricity systems that need to be cost-efficient, reliable and sustainable. Heating systems could provide system services that would help to balance such electricity systems in various ways. Heating systems do not need to balance supply and demand in the same rapid manner that electricity systems must be able to achieve. In addition, heating systems can simulate electricity storage in a way that is potentially much cheaper than utilizing batteries for direct electricity storage. By using TES, heating systems can absorb excess electricity, and during low-level intermittent electricity production periods, the production from HPs can be decreased. An alternative strategy is to increase the electricity output and decrease the heat production of CHP plants during such periods, and to discharge the TES. In this way, the electricity is stored within the heating system, and this would be cheaper due to the lower cost of TES compared to batteries.

As the results indicate, the use of CHP plants may be decreased for economic reasons when considering only heating systems. Nonetheless, CHP plants can have benefits for interconnected energy systems that are difficult to assess when only looking at heating systems. Analyzing CHP plants from only the heating system perspective may, therefore, be too-narrow an approach. That CHP plants can have higher value for the system level compared to the city level, has been shown previously [76]. In the case of a limited electricity import capacity, investments in CHP plants can be economically beneficial at the city level [42]. However, as CHP plants are often built by heating companies to provide heat, it is important to see whether there are other opportunities for CHP plants to render economic benefits, and thereby also contribute on the system level, as compared to the city level exclusively.

There are services that the DH system, and CHP plants, could provide that do not directly belong to the heating systems and that could affect the economics of DH and CHPs plants. Among these are balancing of the electricity system [77,78] and the production of biofuels [79–81] or biochar [82]. Carbon capture and storage (CCS) is also possible within CHP plants [83,84]. While other industries have a lower cost for capturing the CO_2 [85,86], the cost of transporting the CO_2 to the end storage is a significant part of the total cost of CCS [87]. This implies that CHP plants located close to transport hubs could be cost-competitive for CCS. There are also synergies associated with combining DH with district cooling [88] through the utilization of, for example, EH [89] or using heated return water from the cooling system as a heat source for HPs [1].

As heating systems are local in nature, they are often dependent upon a low number of units within the system. When analyzing large energy systems, i.e., at the national and international levels, simplifications are often made, where the details of the smaller system are difficult to address. There is a need to understand when the details of the small systems affect larger systems, to avoid the problem that the solution for larger systems suggests solutions that are not viable for small systems.

Although the utilization of EH seems to make economic sense, it is not only technological barriers that hinder the increased use of this heat source [56,57]. As large-scale, seasonal TES units are also uncommon in existing heating systems, it is probable that there are also barriers that hinder the deployment of this solution.

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