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The Impact of Local Climate Policy on District Heating Development in a Nordic city – a Dynamic Approach

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ABSTRACT

On a national level, Sweden has announced plans to have no net emissions of greenhouse gases in 2045. Furthermore, Gothenburg, a city in southwestern Sweden, has plans to phase out the use of fossil fuels in its heat and electricity production by 2030. Given that the development of a district heating (DH) system under dynamic and different climate policies and climate goals is a nontrivial problem, this study investigates two different policies of phasing out fossil fuels, either by introducing a fossil fuel ban, or by increasing the carbon tax to phase out the fossil fuel use in 2030 or 2045. The effects of the different phase out strategies on the future development of the existing DH system in Gothenburg has been investigated. The study is based on a system-wide approach covering both the supply and demand side developments. A TIMES cost optimizing energy system model representing the DH system of Gothenburg was developed and applied for calculations. The results show that the total amount of heat supplied by the DH system is unaffected by the phase out policies. The amount of natural gas used to supply the DH system is however dependent on what kind of phase out policy is implemented. A yearly increasing carbon tax policy introduced in 2021 phases out fossil fuel use earlier than the target year, while a ban phases out the fossil fuel only from the actual target year.

Keywords

Local climate policy;
District heating;
Heating system;
Energy system modelling;
TIMES;
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1. Introduction

Sweden has formulated goals for greenhouse gas emission reduction where the goal for 2045 is to have zero net emissions [1]. Apart from national goals, there are cities which have their own goals as to how much the emissions should be reduced.

The combination of an almost entirely fossil free power grid and a decreasing share of fossil fuels used in the district heating (DH) sector has resulted in CO_2 emissions from electricity and DH accounting for only about 8% of the annual emissions in Sweden. In the 70's, the DH was an oil dependent heat source, but today is mainly a low carbon heat source [2]. Between 1990 and 2018 the production of DH has increased by 50% while simultaneously the use of fossil fuels in DH and electricity production has decreased by 69% [3].

Even though emissions from heat and electricity are relatively low in Sweden compared to other countries, if the climate goals are to be achieved, the heating sector needs to continue its decrease of emissions in the future. Energy efficiency measures have a role to play in reaching 100% renewable energy and DH systems have an important role to play in increasing the energy efficiency [4]. Thus, exploring impacts of climate goals on future development of DH is essential.

In a recent study published by IRENA [5], it is found that most countries do not have climate policies to address the transition to a sustainable and climate

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Abbreviations

CHP	Combined heat and power
DH	District heating
EH	Excess heat
EU-ETS	European Union Emission Trade Scheme
HOB	Heat-only boiler
HP	Heat pump
MSW	Municipal solid waste
NG	Natural gas
O&M	Operation and maintenance
TIMES	The Integrated MARKAL-EFOM System

neutral heating system. Of the countries which do have climate policies, the majority are in the EU. Policies supporting biomass use in the EU are investigated in [6], where it was found that there are several different support schemes in place promoting biomass use, but the schemes implemented are not similar across the EU countries. Ref [5] also finds that some local climate policies are more ambitious than national climate policies.

In [7], it is investigated how renewable energy incentive policies diffuse between countries. There has been a large increase of number of policies between 2005 and 2015 for many policy types, and the average number of policies in countries of all income levels has increased. The authors showed that international socialization, as well as learning, showed positive effects on policy adoption. They also found that domestic factors, such as energy security and interest groups, also play an important role.

Climate policies for the heating sector can be generally divided as financial/economic policies and regulatory policies. Financial/economic policies include investment subsidies, grants, rebates, tax credits, tax deductions and exemptions, and loans. Regulatory policies include solar heat obligations, technology-neutral renewable heat obligations, renewable heat feed-in tariffs, and bans on the use of fossil fuels for heating and cooling at the national or local level [5]. Carbon tax on emissions is an example of an economic policy which punishes the use of fossil fuels. This type of policy has been used in Sweden since the 90's, and the tax level has increased severalfold since its introduction [8].

The European Union Emissions Trade Scheme (EU-ETS), introduced in the 00's, is an example of a regulatory policy which does not directly punish carbon emissions economically, but instead it steadily decreases the emission allowed within the EU and this gives a shadow price of CO_2 emissions set by the market. When the allowances reach zero, no emissions of CO2 are allowed, effectively banning CO_2 emissions in the EU.

Despite the understanding that climate policies are critical for the transition to a climate neutral heating system, there is scarce literature investigating the impact of introduction of climate policies aimed at reaching specific emission goals, and on the development of urban heating systems. Studies usually do not have binding climate goals as requirements for analyzing their impact on the heating system. See for example [9], where the authors study the carbon emissions impact from low energy buildings where it is shown that individual heating options increase biomass and electricity usage, which in turn can increase carbon emissions in a broad systems perspective.

The authors of [10] investigate the energy and environmental efficiency of the policies of the countries in the EU. The results show that there are large differences between countries. This indicates that different kinds of policies aimed at reaching the same emission goal could have different consequences depending on what kind of policy is introduced.

Future DH systems, usually named 4th generation DH, involves utilization of a more diverse mix of energy sources, but also increased integration of other energy sectors and integration of new housing with more energy efficient standards. The challenges and motivation for integrating more sectors together with new energy sources and efficient buildings are discussed in [4]. One of the motivations for 4th generation DH systems put forward is society's transition to a sustainable energy system where DH will be based on fossil free energy. It is stated that the operation of DH supply plants in 4th generation DH system may be severely affected by the fluctuation of renewable energy sources.

In a study [11] investigating the potential of 4th generation DH grids in Norway with a high degree of electrification, it is shown that DH can increase the total system efficiency of the energy system. The authors of [12] show that integrating electricity and heating sectors can be economically beneficial on a system level.

The concept of smart thermal grids, defined in [4], implies efficiency gains by smart thermal management, e.g. decreased supply and return temperatures to minimize losses and decentralized control and metering. According to [13], existing DH grids can deliver the same amount of heat while reducing losses if both the supply and return temperatures are decreased. In [14], it is demonstrated that decreasing the DH temperature to very low levels may be economically beneficial.

The authors of [15] show that DH systems combined with energy savings can contribute to emission reductions in the EU with a lower cost compared to other alternatives. The authors also argue that DH is seldom disregarded in local and national studies but are, on the other hand, seldom the focus. Also, the authors of [16] argue that energy system models are often designed for the electricity sector, which means that the role of the heating sector may be overlooked.

In [17], the authors investigate the cost efficiency of different heating options for hypothetical low energy building areas. The general result is that large heat network options have lower system cost compared to individual heating options. This study compared scenarios when the whole area chooses the same heating option, but it could be of interest to investigate if it would be more cost effective to allow for different heating options within the same area, as well.

The cost effectiveness of different heating solutions is also investigated in [18] where the authors investigated if DH is more economically viable compared to individual house-heating options by different means. The authors showed that in some areas, expansion of DH is not economical while in others it is. For the example of Copenhagen given in the paper, it is shown that for large parts it is economical to expand DH from a socio-economic point of view while DH is not the cheapest option from a consumer economic point of view. This shows that answering whether it is economical to expand DH into new areas is not a simple or trivial problem.

Heating systems are closely connected to the electricity system since heating systems can both produce and consume electricity by use of different technologies such as co-generation and heat pumps (HPs). This implies that future development of cost efficient heating systems could strongly depend on the future development of the electricity system. This has been shown to influence how heat is produced in DH systems.

In [19], the authors analyzed how different electricity prices affect the future DH system in Uppsala. This study included analysis of new multi-family buildings being added to the building stock, but also decreasing heat demand of existing multi-family housing due to energy efficiency measures. The authors showed that the use of HPs is promoted with low overall prices with low seasonal variations in electricity price, while high winter prices increases heat and electricity production in combined heat and power (CHP) plants.

In [20] the fluctuations in electricity price is investigated and it is shown that increasing price fluctuations can change the merit order of HPs and CHP plants, and it is therefore of interest to investigate how different future electricity price profiles impact the heating system.

There is however a lack of studies of policy impacts on future heating and a lack of studies taking a dynamic systems approach, simultaneously addressing both supply and demand side developments. Thus, the aim of this study is to investigate impacts of climate policies on the cost efficient future development of an urban heating system by posing the following questions:

- Does an introduction of a local climate policy in the form of a fossil fuel ban or an increasing carbon tax policy impact the development of an urban heating system?
- If it does, how do the different climate policies aimed at reaching climate goals in different years impact the development in terms of system cost, emissions reduction cost, heat production and heat production capacity?

2. Method

Since this study is aiming at investigating future developments of cost efficient urban heating, a dynamic system approach is adopted implying a representation of the inter-related developments of both supply and demand sides of the heating system. This dynamic approach addresses the cost efficient optimum for the whole system, as opposed to studying either the supply or demand sides since these are inter-related. The study is focusing on the impacts of two different types of climate policies on system cost, heat production and capacity mix changes.

In order to be able to simultaneously address both supply and demand side dynamics over the studied time horizon and answer the research questions, a cost optimizing energy system model was developed and applied.

The city of Gothenburg in south-west Sweden was chosen as the case to be studied since the city is strongly expanding and its current DH system covers most of the city's heat demand. The city has also adopted climate goals.

Data were collected for the construction of the urban heating optimization model. The impact of different climate policies on the system cost, heat production and capacity of different technologies under various scenarios is carried out assisted by the constructed model.

2.1. Climate policies

Two climate goals target years are assumed and investigated; zero CO_2 emissions in 2030 and 2045, respectively. The results are compared to when no climate goal is present. The 2030 CO_2 emission phase out year is based on the climate plan of Gothenburg, expressing an aim to phase out fossil usage fully for its heat and electricity production in 2030 [21]. The year of 2045 is based on Sweden's national goal of having net zero emissions in 2045 [1].

Two different kinds of climate policy aimed at achieving the two climate goals explained above are investigated; a fossil fuel ban and a linearly increasing carbon tax starting from 2021.

The carbon tax required to phase out the use of fossil fuels is not known beforehand and thus needs to be calculated. To calculate it, an iterative method is used as shown in Figure 1.

The carbon tax level is first set to remain constant throughout the whole modelling time period to see if that carbon tax is high enough. If not, the carbon tax is increased each year with an equal annual increase for all years, thus giving a linear tax increase. The increase of the carbon tax is not halted at the climate target year but continues to increase up until 2050. The model is rerun with this increased carbon tax to see if the climate goal is reached.

If the goal still has not been reached, the annual carbon tax increase is increased by 1/3 €/ton CO_2, and the model is rerun again. This iterative procedure is performed until the climate goal has been reached. In this way the lowest carbon tax required to fulfill the climate goal is found.

In both the fossil fuel ban scenario and the scenario with no climate policy, the tax on carbon emissions is set to 100 €/ton CO_2, which is approximately the carbon tax today in Sweden, and remains unchanged until 2050, see. In the carbon tax scenarios, the carbon tax begins at the same level as in the other scenarios and increases from 2021 to 2050.

Table 1 Policy pricing used in the model for the no policy-scenarios and fossil fuel ban scenarios. In the case of carbon tax scenarios, the carbon tax remains at the same level in 2019 and 2020 and is then increased by the same amount each year to 2050.

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

* Heating plants in Sweden pay carbon tax at a reduced level since they must buy permits from the EU-ETS. The value of 100 €/ton CO_2 is approximately the sum of the emission permits and the reduced carbon tax.
**Only paid by electricity users.
***Only paid to electricity from renewable sources. Revenue set to 0 from 2030 onwards due to the proposal that no new plants can be added to the certificate system from the end of 2030 [22].

2.2. CO_2 emissions assumptions

In this paper, electricity use, biomass use, municipal solid waste (MSW) incineration and the use of industrial excess heat (EH) is assumed to be carbon neutral.

Although the Swedish electricity system is not an isolated system and electricity, which may be of fossil origin, is regularly imported from other countries, in this paper it is assumed that use of electricity is carbon neutral since the generation mix consists mainly of hydro,

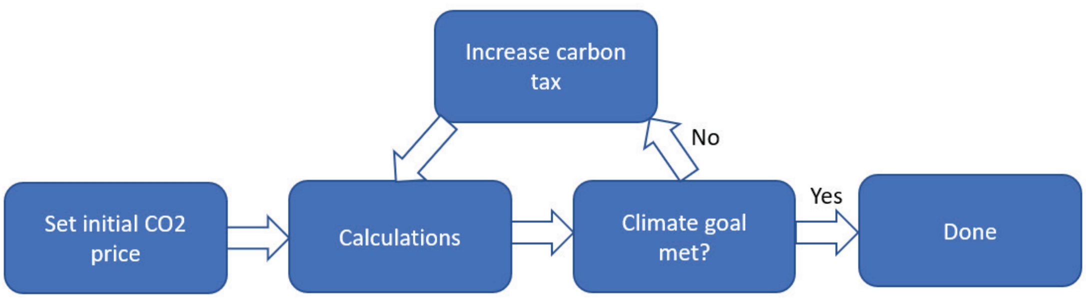


Figure 1. Iterative method for determining carbon tax required to phase out fossil fuel use at a specific year when using an increasing carbon tax policy

nuclear and wind power and Sweden is a net electricity exporter [23].

The carbon neutrality of biomass use is questioned but in this study we assume biomass to be renewable and carbon neutral referring to its large mitigation potential [24] despite that others, e.g. [25], stress that the biomass potential is constrained and, thus, it should not be considered carbon neutral.

CO2 is emitted due to waste incineration but since the incineration is primarily a part of the waste handling when recycling is not deemed as an option, these emissions are entirely allocated to the waste management [26].

Further, CO2 emissions from fossil fuels used to produce both heat and electricity in CHP plants are allocated to the heating sector according to the power to heat-ratio. The electricity produced is also assumed not to substitute any other electricity production, potentially decreasing total CO2 emissions by substituting other fossil production in the electricity sector.

2.3. Model

Using an energy systems optimization model enables the investigation of the evolving heating system of Gothenburg, given that even at present, traditional cost-benefit analyses underpins the decision of investment and heating choice.

In this study, the TIMES energy modelling framework has been used. This is a cost optimizing modelling framework finding the lowest total system cost over the chosen time horizon, from 2019 to 2050. The model is run for 9 time periods with shorter lengths in the beginning years. First there are two one-year periods for 2019 and 2020 which are followed by one two-year period for 2021-2022. From 2023 onwards the period length is 5 years. Each year is divided into 12 time slices, one month in length each, to represent the seasonally varying heat demands.

The TIMES (The Integrated MARKAL-EFOM System) model framework was developed by the International Energy Agency (IEA) [27]. Costs, such as fuel costs and operation and maintenance (O&M) costs, and characteristics, such as technical lifetime and efficiency, for different kinds of technologies, both present and possible future investments are given by the modelers, and the model computes the optimal solution in terms of lowest total system cost.

The model is driven by exogenously given heat demands which it must fulfill by supplying enough heat to meet all heat demands for all buildings. This forces the model to always be able to produce enough heat and have enough distribution capacity available. Since the goal function of the model is to minimize the total system cost for the whole modelling period, the model is computing when to run which technologies and decide when it is cost optimal to invest in new production capacity as old technologies are dismantled when reaching their end of technical lifetime.

The TIMES model is based on perfect foresight and is implemented using mixed integer programming. The perfect foresight means that the model knows the exact heat demand and costs for everything at any specific time. The perfect foresight together with the dynamic approach makes it possible for the model to make optimal decisions regarding dispatch and investments in new technology since it knows the exact demands for all time periods.

The mixed integer programming is based on linear programming but allows better representation of economies of scale by only allowing discrete investment levels into new heat production capacity. The discrete investment level aspect is of importance for the model, especially when considering investment in new CHP plants since CHP plants with a high power-to-heat ratio are generally required to be larger in size compared to CHP plants with a low power-to-heat ratio. Investments into new CHP plants could therefore be affected by restricting new plants to certain minimum plant sizes.

The TIMES model developed in this study treats existing energy power plants as sunk costs and may at any time invest in new heating technology. All heat demands and prices for all time periods are exogenously given and there is no price elasticity for the heat demands or on the resource availability. This means that the price for each resource is independent of how much of it that is used and the heat demands are independent of the supply cost.

Except for electricity, there are no seasonal price variations, but the future price changes are assumed for several resources, see Appendix A for details.

The demand side development is represented by an annual addition of new housing to the system. The model is always required to meet the heat demand for all housing and a heating option must be chosen for each new housing type. In the model, two options are available for the heat supply to the new housing; DH (connection to existing DH including distribution piping and heat exchanger) or an individual heating option. Also, a mix of both is allowed.

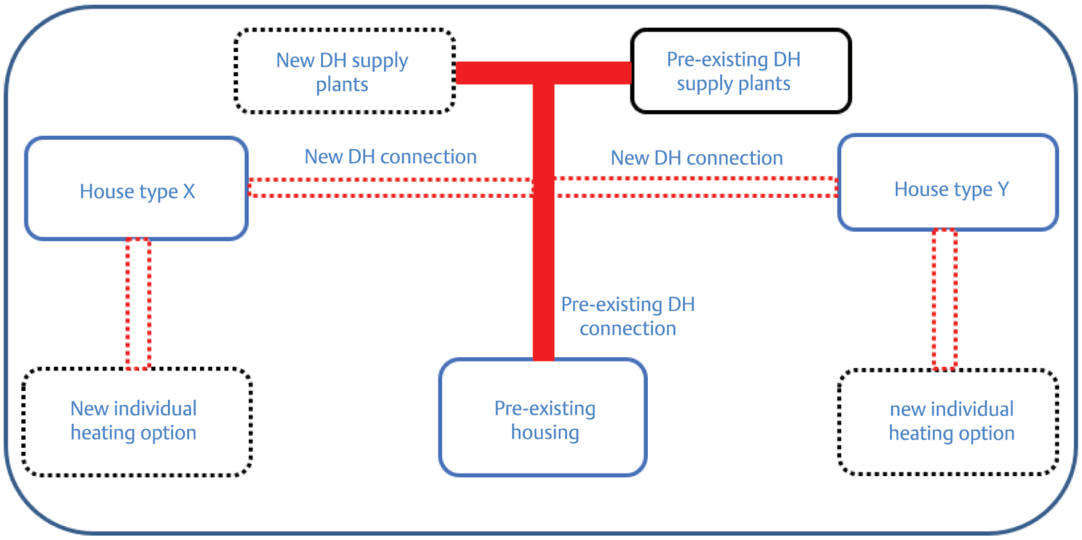


Figure 2. Schematic representation of the model setup for determining the cost optimal heating solution with different types of new housing.

The setup of this dynamic approach where the model simultaneously treats both the supply and demand side developments is shown in Figure 2.

Existing housing already connected to the DH system is assumed to continue to use only DH, and the heat demand of the existing housing is assumed not to change.

2.4. Case data and assumptions

Input data used for the model is presented in this subchapter. The modelling case of Gothenburg is presented first. This is followed by assumptions for the new housing and the heat demand profile used.

2.4.1. Modelling case

This study is carried out by constructing a model representing the present and assumed future heating demands of Gothenburg, Sweden's second largest and populous city, situated on the western coast.

Gothenburg began using DH in the 1950's as one of the first cities in Sweden. Today, almost 90% of the housing heat demand in Gothenburg is supplied by DH and the annual DH production exceeds 3 TWh.

The DH system in Gothenburg uses a mix of several technologies to produce the required heat. This mix includes MSW incineration, industrial EH, sewage water HPs, CHP plants and heat-only boilers (HOBs). The available heat capacity is presented in Table 2.

Table 2 Existing heat production capacity in Gothenburg. Values acquired from [9].

	Heat production capacity, MW
MSW incineration	143
EH	150
HP	160
Bio CHP	120
NG CHP	411
Bio HOB	107
NG HOB	325
Oil HOB	629
Electric HOB	8

2.4.2. Housing data

Assumptions for the new housing is based on historical data and it is assumed that the same number of houses is built annually in the future and that this number is roughly the same as in recent years.

The new housing of Gothenburg is made up of different types of housing, such as apartment buildings of different sizes, and single-family houses of different sizes and energy demands. The data for the new housing built in Gothenburg is presented in Table A.2 in the appendix.

It is assumed that the investment cost, in terms of k€/MW, for individual heating options are the same for all housing types, see Table A.1 in the appendix. This assumption comes from that individual heating options of different sizes and costs are widely available on the market.

However, the investment cost for new DH connections are assumed not to be the same for all housing types. This stems from that a new DH connection for a building requires both a new piping connection to the existing DH grid and a substation to be installed. The absolute cost for installing piping and a substation for a single-family house are assumed to be the same for all single-family housing types, while the absolute cost for an apartment building is somewhat larger. See Table A.2 in the appendix for the calculated installation cost in terms of k€/MW.

2.4.3. Heating profile

For all housing types, the annual heat demand is exogenously given and distributed according to the heating demand profile presented in Figure 3.

The same profile is used for all types of housing. The demand profile is acquired from real measurements from a housing area consisting of both single family and multi-family housing built between 2011 and 2014.

2.5. Sensitivity analysis

A sensitivity analysis is carried out to investigate the robustness of the results with respect to different electricity price developments. Since the DH system includes CHP technologies, the electricity price and its development may have a major impact on the heating system development, and it is essential to investigate its potential impact.

Therefore, two electricity price cases are investigated: one where the price increases and one where it decreases.

The increasing price case assumes that a fossil fuel power source sets the short-term marginal electricity price which, apart from giving high electricity prices all year, results in a relatively flat electricity price profile.

The decreasing price case is based on a future where there are large investments into intermittent renewable electricity sources resulting in low electricity prices and a price profile with large seasonal variations. Both electricity prices are presented in Appendix B.

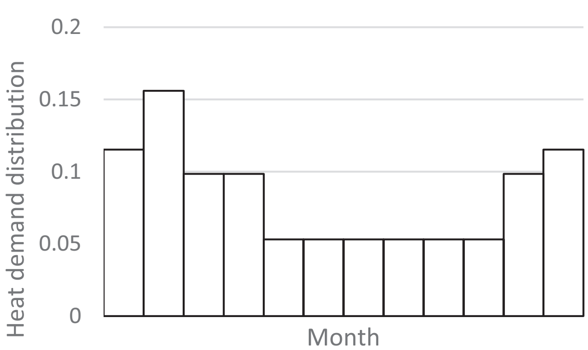


Figure 3 Heat demand distribution throughout the year. Values acquired from [28]

2.6. Modelling the development of an urban heating system

The research questions formulated guiding this study are focusing on two different types of climate policies and how they would impact cost efficient heating choices and the development of an urban DH system. The energy system model is used to investigate the impact on the development of an urban heating system by introduction a local climate policy in the form of either a ban or an increasing carbon tax.

There is an important distinction between the two policies: while the fossil fuel ban will ban the use of fossil fuels from a certain year, in our study, the carbon tax should be just sufficient to result in a phase out of all fossil fuel in the DH system at the fossil phase out target year.

As explained above, the required carbon tax is not known beforehand and thus has to be calculated by the energy system model. The carbon tax does not only depend on the fossil phase out target year but also on the future electricity price level and must therefore be calculated for both electricity price cases.

Thus, after determining the carbon tax required to reach the climate goals, in order to enable comparisons of the impact of the different climate policies, the model is used to calculate the DH system heat production and the DH system capacity mix for the different policy scenarios and electricity price cases. The overall system cost and the total CO_2 emissions are important system impacts and calculated by the model.

In summary, to answer the research questions, the model is used for the following calculations:

- Required carbon tax needed for fossil phase out.
- Total system cost and total emissions.
- DH system heat production for future years.
- Capacity mix of installed heating technologies.

3. Results and Analysis

The modelling results (required carbon tax, heat production from different technologies, heat production capacity and the impact on the system cost and CO_2 emissions by the different policies) are presented in the following subsections.

3.1. Carbon tax

The carbon tax required to phase out CO_2 emissions obtained from the model is presented in Table 3. For both target years it was found that a higher electricity price requires a higher carbon tax to reach the fossil fuel phase out target since, in both electricity price cases, natural gas (NG) HOBs substitute HPs, and the required carbon tax is therefore higher at high electricity prices.

Table 3 Carbon tax, in €/ton CO_2, required to phase out fossil fuel use at target year. * highlights the climate goal target year

	2020	2030	2045	Carbon tax increase per year
Tax policy 2030, low electricity price	100	223*	408	12.3
Tax policy 2045, low electricity price	100	150	225*	5
Tax policy 2030, high electricity price	100	263*	508	16.3
Tax policy 2045, high electricity price	100	187	317*	8.7

3.2. Heat production

The DH system heat production for the different policy scenarios is presented in Figure 4 Heat production by DH plants. The EH and MSW incineration remain unchanged and have been left out in the figures to improve readability.

A fossil ban has an effect only from the actual year when it is introduced (for both electricity cases) while in the carbon tax scenarios, all fossil fuel use is phased out by 2025 for both electricity prices for the phase out target year 2030 (while for the phase out target year 2045 the actual fossil phase out depends on the electricity price.

In the high electricity price case, the fossil fuel use is phased out already in 2025, but in the low electricity price case there is some use of NG HOBs up until 2030.

Regardless of whether a climate policy is introduced or not, almost no difference in the amount of heat that is produced by DH is found. Introduction of either climate policy substitutes production from NG HOBs by increasing the production from HPs after 2030 (for both electricity price cases).

3.3. Heat capacity

In the case of a fossil fuel ban in 2045, investments in new capacity are made into NG HOBs up until 2045 which is used for peak power during winter, see Figure 5. Due to a lack of non-fossil alternative peak power technologies in the model, investments into NG HOBs are made since the total system cost decreases even though they have not reached their end of technical lifetime in 2045.

For both electricity price cases, the new NG HOB substitutes HP capacity. In the carbon tax scenarios, there is no investment into fossil fuel capacity regardless of the target year, but the capacity mix differs depending on the electricity price. With a low electricity price, there is only investments into HPs, while in the high electricity price case, there is a mix of biomass CHP plants and HPs.

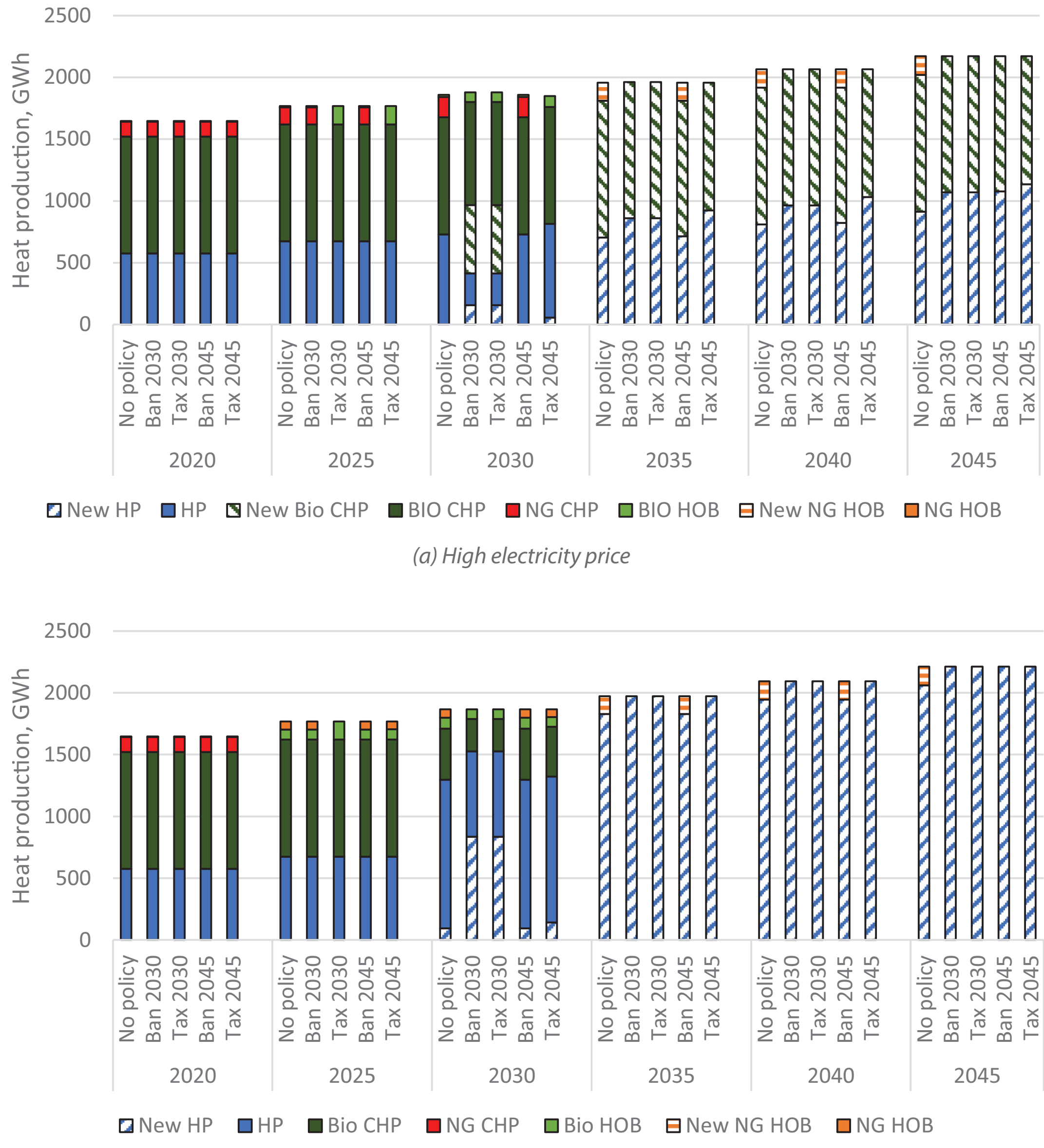
For all policy scenarios, there is a large drop in total heat capacity after 2030, see Figure 5, with no corresponding drop in the heat production, see Figure 4 Heat production by DH plants. The EH and MSW incineration remain unchanged and have been left out in the figures to improve readability.

This result stems from that the modelled system is based on the real heating system which exists in Gothenburg today which includes a large reserve capacity but reserve capacity is something which the model does not consider, as investments into unused capacity would be an economic burden due to the exogenously given heat demand and perfect foresight of the model.

3.4. System cost and cumulative CO_2 emissions impact of climate policies

The total system cost increase together with the cumulative CO_2 emissions for the whole modelling period is presented in Figure 6. On the primary (left) Y axis the cumulative CO_2 emissions, allocated to the heating system, is presented, while on the secondary (right) Y axis the total system cost increase, compared to when no climate policies are implemented, is presented.

For both electricity price cases, the carbon tax scenarios have higher cost increases compared to the ban scenarios for the same year. For both climate policies, the cost



(a) High electricity price

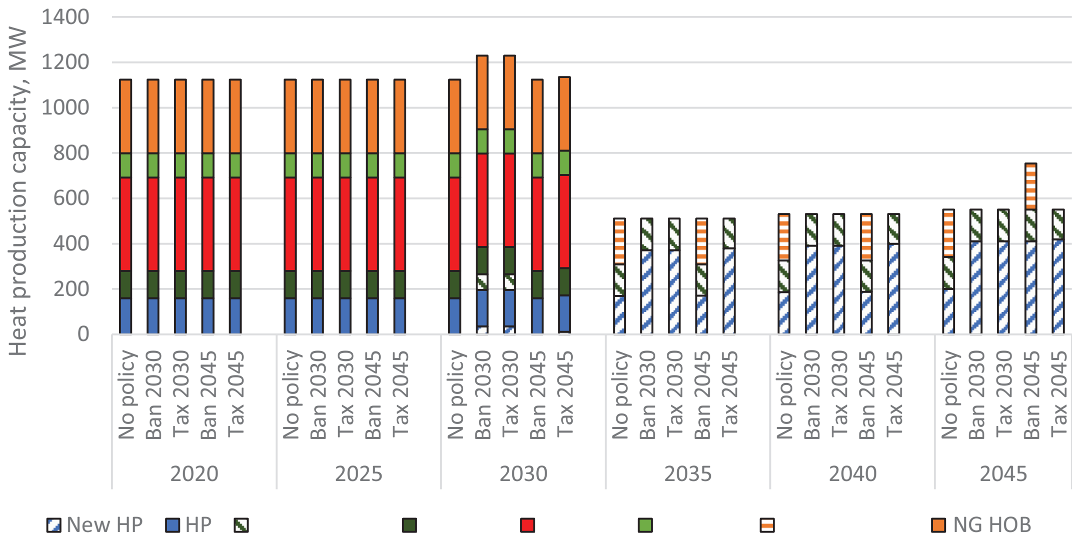
(b) Low electricity price

Figure 4 Heat production by DH plants. The EH and MSW incineration remain unchanged and have been left out in the figures to improve readability.

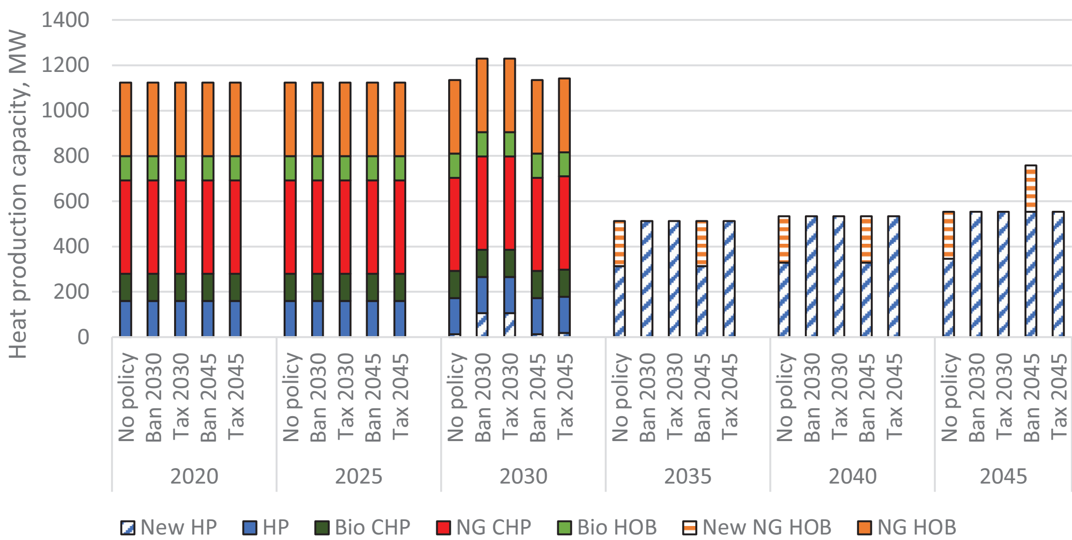
increase is higher in the high electricity price case than in the low electricity price case. The reason for this is similar as with the required carbon tax in the previous subsection; NG HOBs substitute HPs in both resulting in fossil fuel use is more competitive at high electricity prices.

For both electricity price cases, the system cost increase is significantly lower in the fossil ban 2045 scenarios compared to the carbon tax scenarios. Even though there are investments into new NG HOBs which are not used to their full technical life time in the fossil ban 2045 scenarios, the total system cost is decreased by using these for less than their technical life time. The CO_2 emissions are however significantly larger compared to the other climate policy scenarios.

It is important to note that due to a lack of alternative CO_2 free peak power investment options and no heat storage, the computed system cost increases for the different scenarios are likely overestimates.



(a) High electricity price



(b) Low electricity price

Figure 5 Capacity of DH supply plants. EH and MSW incineration remain unchanged and have been left out in the figures to improve readability. Also, oil HOB and electric HOB available from the starting year but are never utilized are left out to improve readability.

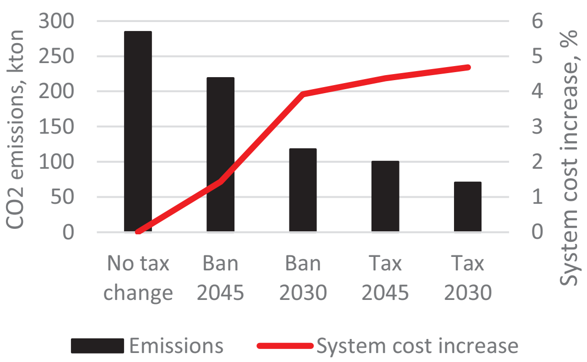
3.5. Summary

In summary, the climate policy goals affect the investment choices of heating supply technologies, but the amount of produced heat in the DH system is unaffected. Furthermore, the climate policy target year also affect when different investments are made.

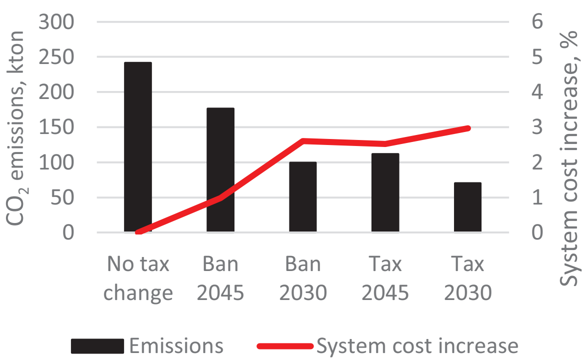
A fossil fuel ban only completely forsakes fossil fuels in the DH system from the year of the ban, while a carbon tax induces a forsaking of fossil fuels in the earlier years. Given these results, a tax on carbon emissions is more effective in divesting investments from fossil fuels than a ban on fossil fuel use but do have a somewhat higher increase of the total system cost.

4. Discussion

The modelling results shows that there is a small, if any, impact of the tested climate policies on how much of the heating demand, including new housing, that is supplied by DH when the total system cost is minimized.



(a) High electricity price



(b) Low electricity price

Figure 6 Increase of total system cost and CO2 emissions for the local heating system for entire modelling period by introduction of different climate policies.

Introduction of a climate policy does, however, impact how the DH supply system evolves in the model.

Depending on what type of climate policy that is introduced, the year in which fossil fuel usage in the DH system is phased out is affected, but without a climate policy, use of fossil fuels is not phased out. A carbon tax policy does phase out the use earlier than the target year, while a fossil fuel ban only has an effect from the target year onwards. This implies that different climate policies do have different consequences even though they are aimed at phasing out the use of fossil fuels at the same year.

Important to note is that the applied model has perfect foresight which enables it to take costs and prices into account for all years without any uncertainty to find the most cost optimal system. Further, the model does not include the possibility of recovery of scrap value before the modelling end year due to dismantling plants before their end of technical lifetime.

The system cost does increase when implementing a climate policy, with taxation leading to a higher increase than a fossil fuel ban. However, while the tax is taken out of the heating system it could be regarded as an additional income for the local authority, the municipality. Further, the system cost increase is larger at higher electricity prices.

The system cost increase when implementing a climate policy is however relatively small. The increase is below 5% for all scenarios at high electricity prices and below 3% for all scenarios at low electricity prices. Important to note here is that the cost increases likely are overestimated, as neither heat storage nor renewable gas are included as alternatives in the model for CO_2 free peak power production.

The results also show a large drop in DH capacity after 2030, but no corresponding drop in heat production. This effect is due to the optimizing nature combined with the perfect foresight of the model. The reserve capacity present in any real system, to deal with unforeseen events and relative fuel and electricity price changes, is also present in the existing modelled DH system, and it remains in the modelled system until its technical lifetime has been reached. Though, as the model knows the exact future heat demand, it does not have any need for any reserve capacity and therefore there are no reserve capacity investments.

The development of the heating system due to changing future electricity prices could have a severe impact on how an interconnected energy system where other energy sectors are integrated, such as the electricity and transport systems, develops. As the results show, a future with low electricity prices benefits investment into HPs while for a high electricity price, the model results that a system with both CHP plants and HPs. Further, the results show that an implementation of a fossil phase out policy increases the capacity and production of heat from HPs, but no significant changes in CHP capacity or production, in both the high and low electricity price cases.

As stated in [4], further interconnections with other energy sectors, especially the electricity sector, is of great interest as large scale introduction of intermittent renewable electricity sources could have a large impact on the development of local heating systems as CHP and large scale HPs could have a role in balancing in such an energy system. Whether the local heating system is dominated by HPs or if there is a mix of HPs and CHP plants would affect the local heating systems' ability to shift between consumption and production of electricity.

The heating profile used was acquired from real measurements from a newly built housing area with low energy demands and was used for every kind of housing in this study. This gave a relatively flat heat demand profile compared to e.g. [29] based on DH heat load in the past in Gothenburg. A heat distribution profile with a more pronounced winter demand would require more peak heat production. NG HOBs are found in this study to fulfill that role when permitted to do so, but it was also found that when fossil fuels are phased out, there were no significant changes in the amount of heat produced by and distributed by DH. Also, in both electricity price cases, NG HOBs are replaced by HPs in the case of fossil fuel phase out. This indicates that a less flat heat demand profile would not have a significant impact on the results presented in this study.

Further studies using the dynamic approach, simultaneously addressing both supply and demand side developments, used in this paper could be of great interest. As studies using a dynamic approach on local heating systems are scarce, there are several aspects which is of interest to investigate at a local level.

The role of both long term and short term thermal and electricity storages could give insights into how an interconnected energy system can be achieved in a cost efficient way where the characteristics of both the local heating and electricity sectors are utilized. The authors of [12,29] investigated impacts of thermal energy storages and found that it can be economically beneficial, but not by using a dynamic approach. It would therefore be of interest to investigate the combination of using a dynamic approach, possibility of thermal storage and interconnected electricity and local heating systems, to see how new housing can be heated cost efficiently.

5. Conclusions

In this study the impact of introduction of two types of local climate policies, a CO_2 tax and a fossil fuel ban, on the future development of an urban heating system is investigated. It is found that the two types of investigated climate policies do have an impact on the production of heat in a future heating system and what kind of policy is introduced does affect the development of the heating system, but no significant changes in the amount of heat produced by DH is found.

If no climate policy is introduced, the heating system invests in new capacity of DH NG HOBs to cover the peak demand during winter. This indicates that the use of fossil fuels is economically beneficial for the system, but the system cost increase of phasing out fossil fuels by introduction of a climate policy is found to be relatively low. This is regardless of electricity prices since this is occurring for both high and low electricity prices.

The introduction of a fossil fuel ban only influences the heating system from the actual year of its introduction, while an increasing carbon tax phases out fossil fuel use earlier than the target year. This result holds for both high and low future electricity prices.

Regardless of high or low future electricity prices, an introduction of a climate policy increases the investments and usage of large-scale HPs while investments into other technologies are unaffected.

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Appendices

Appendix A

Table A.1 Cost of Individual heating options for new housing. Acquired from [31]

	Efficiency 2019/2030/2050	Investment cost (k€/MW_heat) 2019/2030/2050	O&M fixed (k€/MW_heat) 2019/2030/2050	Lifetime (years)	Fuel
Biomass boiler	0.82/0.86/0.88	697/665/603	41/39/35	20	Pellets
HP	3.45/3.6/3.75	2750/2500/2250	68/61/56	20	Electricity
Electric boiler	1/1/1	967/933/833	8/7.7/7	30	Electricity

Table A.2 Data for new housing used in the model including calculated investment cost for installing DH in new housing. Efficiencies and lifetime acquired from [9]. Energy use of housing and annually built is based on [32,33].

	Investment cost for connecting to the DH network (k€/MW_heat)	Distribution efficiencies Summer/spring & autumn/winter/ cold winter	Energy use, kWh/(m2*year)	House size (m2)	Built annually	DH connection lifetime
Apartment large	477	0.63/0.85/0.9/0.915	70	2800	40	50
Apartment small	955	0.63/0.85/0.9/0.915	70	1400	80	50
Single family large	2393	0.63/0.85/0.9/0.915	95	175	200	50
Single family large passive	4785	0.63/0.85/0.9/0.915	47.5	175	20	50
Single family small	3987	0.63/0.85/0.9/0.915	95	105	150	50
Single family small passive	7975	0.63/0.85/0.9/0.915	47.5	105	15	50

Table A.3 Cost of new DH technology which has heat as only output. Based on [34]

	Total efficiency	Inv cost (k€/ MW_heat)	O&M cost fixed (k€/ MW_heat)	O&M variable (k€/GWh_heat)	Lifetime (years)	Size (MW_heat)	Fuel
Bio HOB	1.15	700	33	1	25	-	Biomass (Woodchips)
HP Small/ large	3.5	700/600	2	3.3/0.9	25	4-12/12-500	Electricity
NG HOB	1.03	60	2	1.1	25	-	NG

Table A.4 Cost of new CHP plants. Based on [34]

	Total efficiency (Electrical)	Inv cost (k€/MW_el)	O&M cost fixed (k€/MW_el)	O&M variable (k€/GWh_el)	Lifetime (years)	Size	Fuel
Bio CHP Small/ medium/ large	1.12(0.14)/ 1.09(0.27)/ 1.10(0.28)	6700/3700/ 3500	293/158/101	7.8/3.8/3.8	25	2.9-23/ 23-177/ 177-500	Biomass (woodchips)
NG CC CHP	0.90(0.55)	900	30	4.5	25	-	NG
NG GT CHP	0.90(0.47)	1300	30	4.5	25	-	NG

Table A.5 Cost, in terms of k€/GWh, for different fuels available. Costs for bio oil, EH and MSW are based on [17], biomass and pellets price is based on [35] together with own calculations. NG price is based on [36] together with own calculations.

	2019	**2030**	**2050**
Biomass (wood chips)	25	30	40
Pellets	40	45	55
Bio oil	42	50	60
NG	18.4	26.5	41.2
EH	0.56	0.56	0.56
MSW	-14,5	-14,5	-14,5

Appendix B

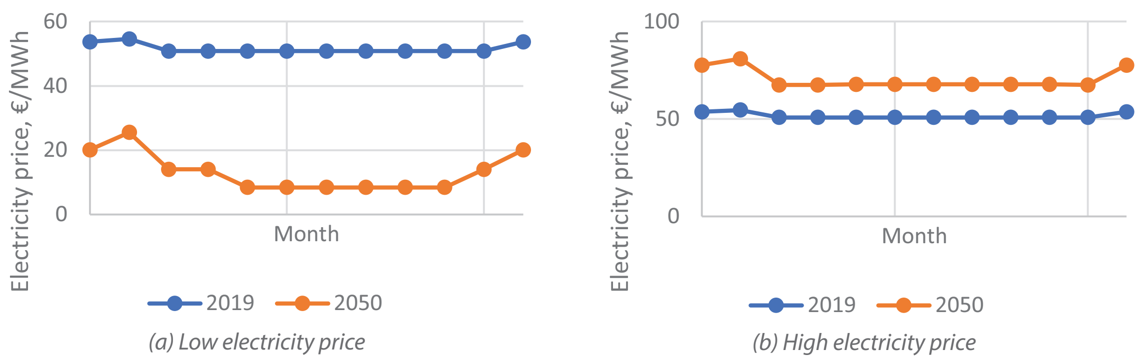

Figure B Electricity price cases. The prices per month for each year in between 2019 and 2050 are linearly interpolated from the 2019 and 2050 monthly price levels.