# Policy implications of challenges and opportunities for district heating – The case for a Nordic heating system



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# Policy implications of challenges and opportunities for district heating – The case for a Nordic heating system

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ABSTRACT

District heating (DH) is an efficient urban heating solution. Numerous external factors (energy efficiency, fuel-price increases, heat -pump competition and policy changes) are challenging. It is relevant to explore long-term cost-competitiveness of DH. A model has been developed testing three, future DH pathways: (i) phase out of biomass (aligned to the cascading principle of the EU Taxonomy), (ii) including waste heat in the fuel supply mix (aligned to the updated Energy Efficiency Directive) and (iii) lower system temperatures (aligned to the idea of more renewables and waste heat).

The model considers the long-term development of the supply and demand sides together and simultaneously. This allows the model to determine the most cost-efficient heating solution for different building types in different points in time.

The results confirm that a phaseout of biomass would erode -but that developments rendering lower system temperatures and increased waste heat utilization would strengthen-the DH business case. Additionally, it is confirmed that heat pumps constitute the main competition to DH. Hence, to remain a cost-efficient heating alternative in the future, DH systems need to revisit the tradition of centralized heat supply resorting to combustion for decentralized heat supply resorting to heat supply on demand.

## 1. Introduction

Approximately half of the final energy use in the EU is used for heating and cooling purposes in buildings, and around 40 % of the $CO_2$ emissions of the EU stems from this part of the energy sector [1]. The use of district heating (DH) is seen as an important and cost efficient part of the decarbonization of the European energy system [1,2]. DH covers around 12 % of the total heat demand of EU today, but the share vary greatly between countries in the EU [3]. One of the advantages of DH is that it can use many types of fuels, meaning that fossil fuels can be phased out in favor of renewable fuels or by heat recovery from many kinds of sources.

### 1.1. District heating fuel supply characteristics

Fossil fuels dominate as energy source for DH in the EU, while biomass provides 22 % of the energy [3]. The share is however varying greatly between countries. Biomass provides over 40 % of the DH energy in all of the Nordic and Baltic countries, while for some countries, the biomass share is almost neglectable [3]. That a decarbonization of the DH sector can be achieved with a combination of biomass, excess heat (EH) utilization and electrification is shown in Ref. [4]. Although biomass use previously has been regarded as carbon neutral, biomass combustion leads to $CO_2$ emissions and due to expected, increased competition for limited biomass resources it is doubtful if bioenergy should be considered to be carbon neutral. The EU taxonomy, for example, promotes the reuse and recycling of resources and demotes incineration according to the cascading principle.

To efficiently decarbonize all sectors, not only the energy sector, it may be more desirable and economical to use the available biomass in hard to abate-sectors. The support for usage of biomass in the energy sector differs between the EU countries [5]. It is pointed out that the increased production of biofuels can affect the DH sector negatively [6,7]. The biomass available for the heating sector may thus decrease and competition cause a price increase, which in turn could decrease the economics of DH, thus negatively affecting the DH business case. The

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urgency of action upon the business side of DH is concluded in Ref. [8].

Although the shares of biomass as energy source in the DH in some countries are significant, this has not always been the case. For the example of Sweden, the DH sector was dominated by oil in the 70's, but has been able to phase out the oil use almost completely [9]. This phase out followed the oil crises of 1970 when the price of oil increased dramatically. Policies were therefore implemented to increase the energy security by the use of indigenous resources, but also to promote the use of sustainable and renewable energy sources. The introduction of a carbon tax in the early 90's and a ban on landfills for combustible and organic material in the 00's has also contributed to the use of combustion of biomass and municipal solid waste (MSW) in Swedish DH systems [9]. Although the direct use of fossil fuels has been mostly phased out for heating purposes in Sweden, there are still fossil parts left in the incineration of MSW. The fossil parts of MSW consist of a large share of plastic which have not been recycled for different reasons. The incineration does therefore provide a service for the waste handling sector. But if a circular economy is to be achieved, it cannot be the responsibility of the waste handling sector to handle the phase out of fossil content [10]. One of the abilities of DH which individual heat solutions lack is the possibility to use recycled heat from different actors, such as industries and MSW. The utilization of such recycled heat is seen as an important factor for increasing energy efficiency at the system level as this solution can reduce the need for primary energy for heating purposes [11]. Since this EH is a product with low or no value for the industries it can normally be purchased at a low price. Although if the EH could be utilized more extensively within a certain industry, the environmental performance may be affected [11].

Except for combustion of biomass and MSW, the DH supply also utilizes several kinds of other sources and technologies, such as industrial EH, MSW incineration, heat pumps (HPs) and electric boilers. The updated (2023) Energy Efficiency Directive (EED) for the first time equals waste heat recovery to renewable energy. There is an ongoing trend of decreasing temperatures of DH grids [12], which implies benefits for DH systems, including an increased ability to recover waste heat from different sources. That recovery of heat from waste water can be economical is shown in Ref. [13].

### 1.2. Competition to district heating

DH is not the only heating solution available for fulfilling the heating demands of buildings. Individual solutions are solutions in which each individual building has its own heating solution which can only supply heat to that specific building. DH has generally been used as the main heating solution in cities while individual heating solutions are more prominent in less dense areas. In the Nordic and Baltic countries, around 50 % of the total space and water heating demand is supplied by DH systems [3], while in cities in Sweden, 90 % of the heating demand in cities is supplied by DH.

In the recent decades, the use of HPs as individual heating solution has increased dramatically in both Sweden [14] and the EU [15]. Ground source HPs as well as air source HPs have seen increases in their coefficient of performance (COP) as well as decreases in the unit and installation costs. Although DH can have a large role in future sustainable and reliable heating systems, the question whether DH or individual solutions is most well suited for new housing may differ in future compared to how it has been viewed historically. Previous studies have shown that whether it is more economical to use DH or individual solutions depends on several factors, such as the future electricity price and type of housing [16,17]. Historically, oil boilers and direct electric heating was the main competitor to DH, but in the last decades, HPs have been, and still are, the main competitors [18,19].

### 1.3. New buildings are energy efficient and low temperature DH can be a future solution

New buildings are generally more energy efficient than older buildings. With a lower need of heat required for new buildings, the economics of DH can be affected negatively due to the investment costs of extending DH grids into new housing areas with low heat demand. Also, the efficiency of individual heating solutions is steadily increasing, and installations costs are decreasing, especially for HPs. These aspects may have the effect that it is not economical to connect new housing to the DH grid. The need for taking into account recent developments on both the supply and demand sides of heating systems is stated in Ref. [20]. Further, the revised EU Energy Performance of Buildings Directive has recently entered into force, which will decrease the heating demands of existing buildings.

There are however several possible aspects which can increase the economic viability of using DH also in future housing. The concept of 4th generation DH includes many aspects as: closer interaction between producer and consumer, lower DH distribution temperatures, and increased integration of EH from industries and other actors supporting the decarbonization of heat supply [21,22]. Important to note is that DH grids are often natural monopolies, while DH companies can be both privately and publicly owned. For this reason, there are regulations affecting how price setting schemes can be constructed to prevent misuse of monopoly situations [23]. The business model of future DH needs to differ compared to todays' for DH companies to stay competitive [1]. Reductions in the CHP production capacity can also contribute to a need of developments of business models for DH companies [4].

In the concept of 4th generation, DH utilization of EH from different kinds of heat sources is relevant. Utilization of high temperature EH has been performed for a long time, both by direct use and upgrading the heat by HPs [24]. This energy recovery it often highly profitable [24], even in the case of long distances to the EH source [25], and can contribute to fuel savings [26,27] and decarbonization [28]. Although there is a lack of decision support tools available industrial actors to address all benefits and issues regarding the utilization of EH [29]. The utilization of low temperature EH is less common even though a decrease of DH distribution temperatures has several benefits, such as decreasing the distribution losses, increasing the COP of HPs, allowing for new kinds of piping to be used for distribution as well as allowing for more efficient CHP plants [12]. It is required that the equipment used at the end customer is suited for the specific distribution temperature used, meaning that simply reducing the temperature of existing DH grids could come with issues.

### 1.4. Research questions

Due to the uncertainties involved in the development of energy systems, there are large risks, but also opportunities present which can severely affect how heating systems of today may evolve in the future. The research for the use of biomass for energy purposes is an active field [30], but there is a lack of studies investigating how the EU taxonomy and the updated EED can affect the cost-competitiveness of DH in future housing.

In this study, three future DH pathways presented previously in this chapter which can severely affect DH systems are investigated: a phase out of biomass use in the DH system, addition of a new low-grade heat source, and a decreased distribution temperature. The aim of this paper is to investigate how the cost optimal operation of DH systems and the cost-competitiveness of DH as heating solution for new, future housing are affected. The research questions investigated in this paper are thus:

How cost efficient is district heating for new housing.

- If biomass is phased out?
- With the addition of a low-grade EH source?
- At a decrease in the DH temperature?

A cost-optimizing model developed in previous studies for investigating the cost-efficient development of a local heating system is used in this study. The model is adapted in this study for investigating the research questions by creation of multiple scenarios which are used as input to the model.

## 2. Method and scenarios

Section 2.1 presents the system setup and the connections between the different parts of the system. The identified DH system pathways presented in the introduction are used in this study to investigate how the system can develop under future DH scenarios; the pathways and scenarios are presented in Section 2.2. The DH scenarios are put into combination with different electricity price assumptions and heat storage options, which are all presented in Section 2.3. Lastly, Section 2.4 presents details about the modeling framework used.

### 2.1. System setup

In this study, the supply and demand for heat are connected and therefore develop together over several decades. The system setup used is shown in Fig. 1. It is based on a methodology previously used [16,17,31,32]. Specifically, the same input data as in Ref. [17] for both the supply and demand of heat are used, but the heat source available for DH HPs is separated into three different sources, industrial EH, sewage water and other heat sources, with different corresponding COP and different maximum output power limits.

In the starting year, the heating system consists of DH supply plants, a DH grid and existing housing which use DH as their heating solution. The existing housing which does not use DH as heating solutions is assumed to continue to use individual heating options also in the future and is therefore not considered further in this study. The heating system is also connected to an outside electricity system. Housing areas of different types are added to the system annually. These require heating, either by a DH grid expansion, an individual heating option or a mix of them. Important to note is that a systems perspective is used in this study, implying a single agent which operates the full heating system and make investments into new installations, both DH supply plants and individual solutions, and into DH grid expansion.

Supply plants reach their respective end of technical lifetime at different years and need to be replaced. There is therefore a need to make investments in new DH units at some point. Investments in DH supply plants, and thermal energy storage (TES) systems are allowed to be made at any point, not only when old plants are dismantled. Decreased costs and increased efficiencies due to technological improvements are considered for DH plants as well as for individual solutions.

It is assumed that there is no direct use of fossil fuels from 2025 onwards except for plastic incineration in MSW incineration, which is phased out in 2030. This phase-out indicates a transition into a more sustainable and circular economy.

The technologies in which investments can be made are summarized in Table 1.

**Table 1**
Available heating technologies.

| | Notes |
|---|---|
| **DH plants** | |
| Biomass CHP | Not available in certain scenarios |
| Biomass heat-only-boilers (HOBs) | Not available in certain scenarios |
| Electric boiler | |
| Industrial EH HP | Only available in certain scenarios. |
| Sewage water HP | Has a maximum power limit |
| Other HP | No maximum power limit |
| **Individual solutions** | |
| Ground source HP | Same COP in all seasons |
| Air-to-water HP | Seasonally dependent COP |
| Ventilation HP | Cannot supply the full heat demand |
| Electric boiler | |
| Pellets boiler | |

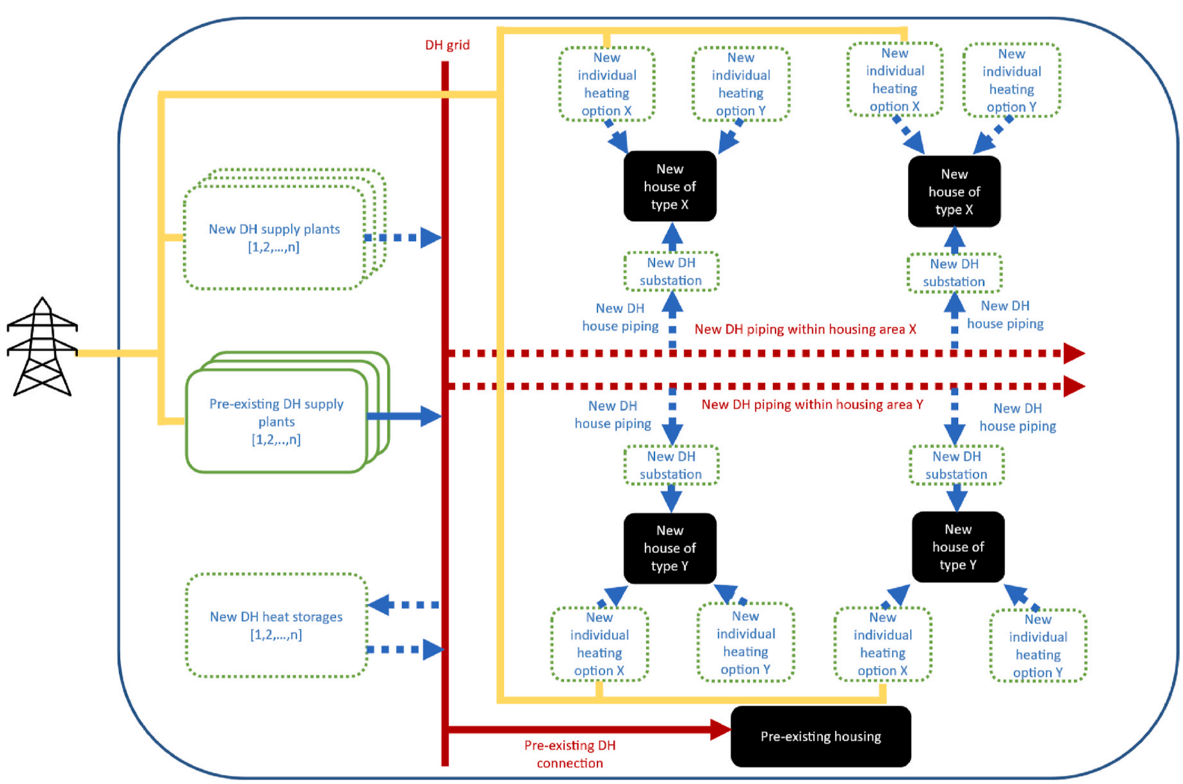



**Fig. 1.** Heating system setup.

### 2.2. DH pathways and scenarios

#### 2.2.1. No biomass usage in DH system

Biomass is a renewable resource which is utilized in many sectors for different purposes. The availability of sustainable biomass is however limited. The heating sector mainly uses residues from the forest industry, a biomass fraction which is hard to use for other sectors. The availability of such biomass residues can be restricted for the heating sector when other sectors, e.g. renewable airline fuel, with higher willingness to pay would start to use these residues.

The use of biomass for heating purposes has also been put into question due to the transformation into a circular economy which promotes reuse and recycling of products as more desirable than incineration according to the cascading principle.

#### 2.2.2. New industrial EH source available

Using low-grade EH sources, such as industries or grocery stores, as DH system supply can contribute to reductions in the primary energy use, and has therefore been identified as a contributor to reducing the greenhouse gas emissions [33]. The temperature of these sources is not sufficiently high to be used directly for DH, thus HPs are required to raise the temperature. The temperature of the EH provided by the sources is different depending on the source activity, and the corresponding COP is therefore also dependent on the EH source.

The addition of a new industrial EH source corresponds to the addition of a low-grade heat source, and the temperature of this source is higher than for sewage water and other heat sources, and therefore has a higher COP. There is however a limit on the capacity of this heat source.

#### 2.2.3. Decreased DH distribution temperature

A decrease in the DH grid temperature is one of the defining characteristics between DH generations. A lower temperature in the DH grid would have several economic benefits for the different parts of the DH system [12,34]. Nine benefits are listed in Ref. [12], and in this study these three are included:

- Distribution losses can be decreased.
- The electrical output of CHP can be increased without decreasing heat output.
- The COP of HPs can be increased.

The other benefits listed in Ref. [12] which are not included in this study are: more heat that can be obtained from geothermal, waste, solar and flue gas condensation, higher heat storage capacities and the ability to use plastic pipes instead of steel. Other possible benefits or difficulties of having a lower DH temperature are also not considered in this study.

As long as the supply and return temperatures are decreased by the same amount, the existing pipes can distribute the same amount of heat [27]. For this reason, conversion or replacements costs of existing equipment which may be needed are also not considered in this study.

#### 2.2.4. Scenarios

Six DH scenarios are constructed based on the three DH pathways as:

1. Base scenario
2. No biomass usage in DH
3. New industrial EH source
4. Decreased DH grid temperature
5. New industrial EH source + decreased DH grid temperature
6. New industrial EH source + decreased DH grid temperature + no biomass usage in DH

The six DH scenarios are presented in Table 2.

**Table 2**
Summary of DH scenarios.

| | No biomass usage in DH | New industrial EH source | Decreased DH grid temperature |
|---|---|---|---|
| Base | | | |
| NoBio | X | | |
| HeatSource | | X | |
| LowTemp | | | X |
| SourceTemp | | X | X |
| BioSourceTemp | X | X | X |

### 2.3. Investigated combinations

In addition to the DH scenarios, two other parameters are included in the analysis: the electricity price and if it is possible for investments into seasonal TES systems. The investigation covers every combination of the six DH scenarios, three electricity price assumptions and two storage options, thus resulting in 36 combinations, summarized in Table 3.

How the electricity price will evolve in the future is uncertain. As the electricity price affects different parts of the heating system differently, three different electricity price cases are therefore included:

- *High2030*, where the electricity price is high until 2030 after which it drops annually. The price is flat throughout the whole year.
- *Low2030*, where the price drops annually until 2030 after which the price is constant. The price is flat throughout the year.
- *Vary2030*, where the price becomes increasingly varying within the years as the price drops annually during summer and spring/autumn until 2030. After 2030 there is no price change compared to previous years.

Investments in TES systems have previously been shown to be economical for the heating sector. The use of large-scale TES systems is, however, still mostly not utilized. For this reason, how the results are affected by investments into TES systems are investigated.

### 2.4. Modeling

The cost-optimizing TIMES modelling framework has been used in this study. The TIMES framework is a well-known framework which has been used has been in numerous previous studies on long-term energy systems evolutions in various countries [35,36]. The specific model used in this study has been developed over several years and has been used in several previous papers with different focuses for investigations of cost-efficient development of local heating systems [16,17,31,32]. The results of these studies have been validated through discussions with actors involved in different parts of heating systems. The model has previously been used to investigate the impact of specific additions or restrictions to the heating system or the programming methods of the model itself. Whereas in this study, the model has been adapted to be able to investigate the research questions by combining them into multiple scenarios.

The cost-optimality implies the total lowest system cost over the entire modeled period including all operational costs, fuel costs and investment costs for the whole system. Thus, the results present not only

**Table 3**
Summary of the 36 investigated combinations.

| DH scenarios | Electricity price cases | DH TES investments possible |
|---|---|---|
| Base | High2030 | Yes |
| NoBio | Low2030 | No |
| HeatSource | Vary2030 | |
| LowTemp | | |
| SourceTemp | | |
| BioSourceTemp | | |

cost-optimal investments but also how different technologies are utilized over the modelling period.

## 3. Data and assumptions

This section presents data and assumptions used: in Section 3.1 the DH supply; in Section 3.2 details about the treatment of new housing added to the system, and in Section 3.3 data used for the pathways and cases are presented.

### 3.1. DH supply

The modeled DH supply system is based on the system of Gothenburg which consists of a large variety of supply plants: waste heat from industries, waste incineration, CHP plants, HPs and heat-only boilers. Most of the plants reach their end of technical lifetime in the modeled period, and therefore must be replaced. The model is free to make investments into new plants at any time point.

#### 3.1.1. Waste incineration

The fuel for the MSW incineration consists of both organic and plastic material. It is assumed that around 40 % of the energy content of the MSW comes from the plastic fraction. The capacity of the MSW is therefore reduced by 40 % when the plastic fraction of the waste is phased out, as it is assumed that the fuel is not stored but is incinerated evenly throughout the year. It is also assumed that there will be no major difficulties in incinerating the plastic-free waste fuel, which could potentially arise due to e.g. changes in fuel moisture content.

#### 3.1.2. DH HPs

The DH HPs of the Gothenburg heating system of today use sewage water as their heat source. It is assumed that this source will continue to be available and that the maximum capacity will remain at 160 MW. It is also assumed that other heat sources are available which could be utilized by HPs. No maximum capacity limit is imposed on these kinds of HPs, but the COP is lower compared to sewage water HPs.

### 3.2. New housing

The heating system develops over time as new housing of different types is added. It is assumed that these additions happen annually. The heating solution for the different types of housing is not determined beforehand but can be either connections to the DH system or individual solutions. Four different new housing types are included: two apartment buildings of different sizes, and two single-family housing of different sizes.

The cost of connecting the new housing to the DH system or installing individual heating solutions is based on [17]. The cost for connecting new housing to the DH is based on both the burying of distribution pipes and installation of a DH substation within each house.

It is assumed that the size of investments in technologies should be sufficient to cover the demands at all times, with the exception of ventilation HPs which can only cover the demand for hot tap water.

### 3.3. Pathways and cases

#### 3.3.1. New industrial EH source

A new industrial EH source is added with 80 MW capacity. The cost for the HPs needed to utilize this heat source is set to be the same as for the other DH HPs. The COP is high, between 5.0 and 5.4 depending on the investment year. If the DH temperature is also decreased, the COP is between 6.5 and 6.9 depending on the investment year. The availability of sewage water and other heat sources remains unchanged.

#### 3.3.2. Decreased DH distribution temperature

This implies decreased distribution losses for all seasons. The numbers used are based on a DH temperature decrease of around 20 °C.

The electrical efficiency of CHPs depend on the type of turbine [12], and it is assumed that the total electrical efficiency of CHPs increases by 10 % with a decreased DH temperature. The heat production efficiency is unchanged.

The COP of DH HPs increases with decreased distribution temperature. For Sewage HPs, the COP increases from 4.15 to 4.45 up to 5.0–5.4, depending on the investment year. For the other HPs, the COP increases from 3.25 to 3.75 up to 3.75–4.25, depending on the investment year.

Possible costs of decreasing the DH temperature are not considered in this study. Also, there may be difficulties for older housing to cover their heating demand due to installed equipment not being dimensioned for lower DH temperatures but the possible cost of replacing the installed equipment with suitable equipment is not considered.

#### 3.3.3. Electricity price cases

There is a high uncertainty in how the electricity price will develop in the future. Three different future electricity price cases are therefore investigated in this study. Due to the Russian invasion of Ukraine, the electricity price of Sweden was historically high in 2022 and 2023, and the starting point for this study is therefore that the price in 2023 starts at a high level, approximately the average price in 2022–2023 in the price region where Gothenburg is located. In one case, the high electricity price continues, while in the other two cases, the electricity price decrease toward the average price during 2018–2020.

The three investigated electricity price cases start at a flat electricity price of 100 €/MWh, constant throughout the year 2023, but then develops differently:

- *High2030*: the price remains at 100 €/MWh up until 2030, from where it starts to decrease annually until it reached a flat price of 45 €/MWh in 2050.
- *Low2030*: the price starts decreasing after 2023 until 2030 in which the price is 45 €/MWh throughout the whole year. The price remains flat after 2030 until 2050 at 45 €/MWh.
- *Vary2030*, the price during summer and spring/autumn decreases annually until 2030 in which the price for these seasons reaches 45 €/MWh. The price during summer and spring/autumn remains at 45 €/MWh after 2030 up until 2050. The price during the winter month remains at 100 €/MWh throughout the whole investigated period.

For the cases where the price is changed, the price changes annually with the same amount each year.

#### 3.3.4. TES systems investment cost

The investment cost of building large scale TES systems is uncertain and is geographically dependent. In Ref. [17], three different investment costs are stated for underground TES systems. In this study, the mid cost is used, between 1.16 M€/GWh and 0.94 M€/GWh, depending on investment year, based on the fact that new excavations are needed.

### 3.4. Other costs and assumptions

Fuel costs, investments costs, taxes as well as and other technical data are based on [17].

Electricity grid fees are not included in this study. These fees are often separated into a fixed cost independent of electricity use and a running cost, paid per energy unit used. The ratio between these two is highly dependent not only on usage, but also on geographical location and on grid owner. In this study, it is assumed that there is no extra fixed cost if a technology using electricity is used as heating solution as all housing will be connected to the electricity grid regardless of heating solution. It is also assumed that there is no need for a larger fuse for the new housing, which would come with an increased grid fee cost.

## 4. Results

In this section, the modeling results are presented: in section 4.1, the heating solution of new housing; in section 4.2, the DH supply; and in section 4.3, the role of HPs in the DH system is presented more in detail as this type of technology takes a large role in the results for future DH systems.

### 4.1. Heating solution of new housing

The heating solution for new housing for the six scenarios and for each of the three electricity price cases are shown in Fig. 2.

The *LowTemp* and *HeatSource* scenarios lead for all electricity price cases to an increased DH grid expansion into new housing, with a more profound impact for *LowTemp* than for *HeatSource*.

If investments can be made into TES systems, the *SourceTemp* scenario leads to a larger DH grid expansion than the *LowTemp* for the High2030 price case while for the Low2030 and Vary2030 price cases, there is no difference between the two scenarios. In general, if TES systems can be built, this leads to a slight positive effect on the DH grid expansion, but it also depends on the electricity price.

There is no DH grid expansion if biomass becomes unavailable after 2030 (*NoBio*) for any of the electricity price cases. However, if both the temperature is decreased and the industrial EH source is added, the DH grid is expanded even if biomass becomes unavailable (*BioSourceTemp*). In *BioSourceTemp* for the Vary2030 case, the DH grid is expanded more if TES systems can be built but has no, or very low, effect on the High2030 and Low2030 price cases.

For the High2030 case (Fig. 2a), TES systems increase the DH grid expansion if the industrial EH source is added (*HeatSource*, *SourceTemp*).

For the Low2030 case (Fig. 2b), TES systems increase the DH grid expansion if there is a decrease of the DH temperature (*LowTemp*, *SourceTemp*).

For the Vary2030 case (Fig. 2c), the TES systems increase the DH grid expansion for the combination of no biomass available together with a temperature increase as well as the addition of the industrial EH source (*BioSourceTemp*). An increase can also be found for the scenario in which only the industrial EH source is added (*HeatSource*).

For all electricity price cases, the individual heating solution used is HPs. In the early years, it is mostly ground source HPs which are installed, while after around 2030, it is mostly air-to-water HPs which are installed. Ventilation HPs are also common in apartment buildings, although this technology cannot supply the whole heating demand.

### 4.2. DH supply

The DH supply for the different electricity price cases is presented in Fig. 3. Note that the figure presents the heat output from the different plants and does not include DH grid distribution losses or losses within the TES system.

The results show that for all electricity price cases, the system which is present in the beginning of the modeled period evolves into systems which utilize DH HPs to a larger extent. This result indicates that it is economical for the heating system to undergo electrification. There is still some production of heat, and thereby also electricity, from CHP plants in the High2030 and Vary2030 electricity price cases unless biomass is phased out, but the production is significantly lower from 2035 onwards compared to in 2025.

It can also be seen that investments into TES systems increase the production from HPs in most scenarios. For all scenarios, investments in TES systems remove the use of EBs (and decrease the biomass HOB in the Vary2030 *LowTemp* scenario). It is in most scenarios the production of HPs which is increased to compensate for this. In some scenarios (High2030 *LowTemp*, Vary2030 *Base*, Vary2030 *SourceTemp*), the production from CHPs is also decreased by investments into TES systems.

### 4.3. The role of HPs in the DH supply

For all scenarios and electricity price cases, the industrial EH source is utilized to its full extent, or very close to, after 2030 if it is available. Also, the sewage water HPs are installed to the maximum possible capacity. Without a lower DH temperature or the addition of the industrial EH source, the sewage water HPs are used to their full extent. However, with the addition of the industrial EH source, the utilization factor of the sewage water HPs decreases, but the sum of the production from industrial EH and sewage water HPs is still increased by the addition of the industrial EH source. The addition of TES systems does however increase the utilization factor of the sewage water HPs in all electricity price cases.

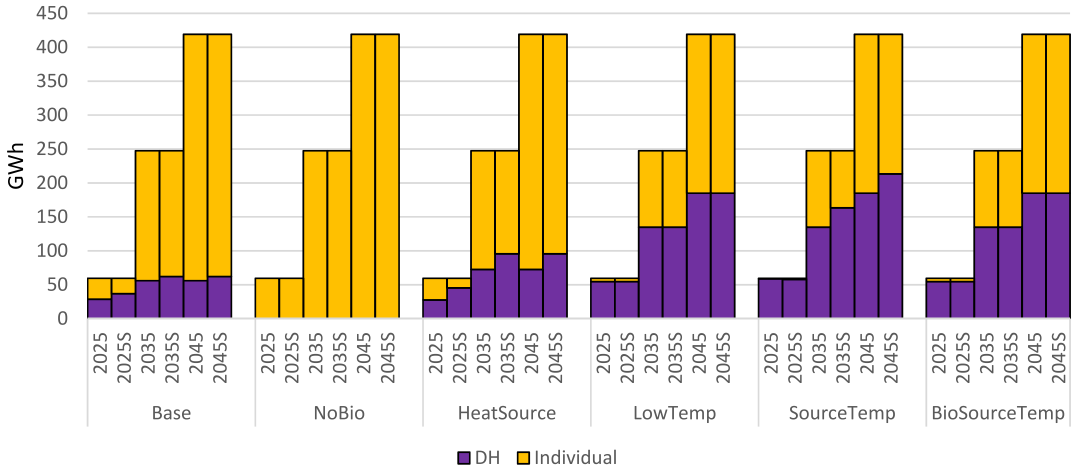
There are investments into other HPs after 2030 which do use neither sewage water nor industrial EH as their heat source. These HPs do not produce heat during summer, except for the *NoBio* and *BioSourceTemp* scenarios, regardless of if TES systems are built or not. They are thereby used as mid load and not for storing the heat.

## 5. Analysis and discussion

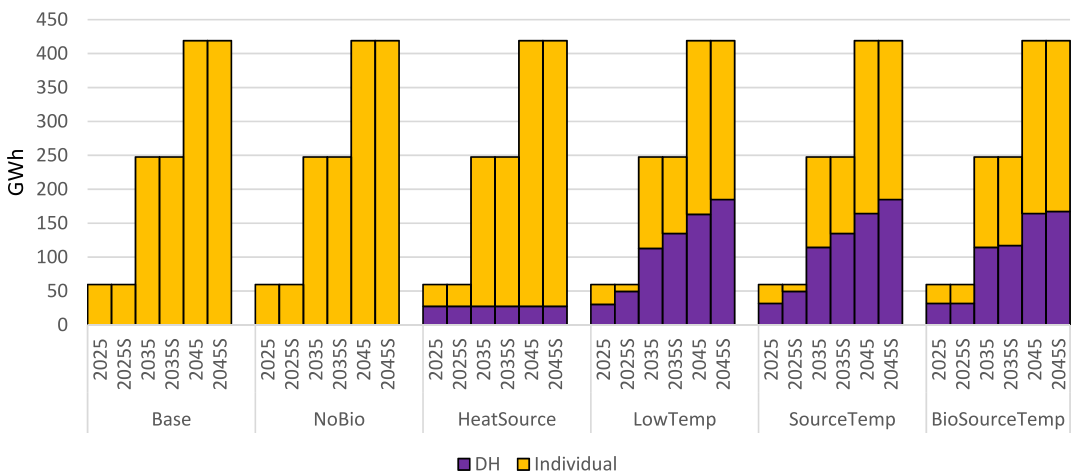
A complete phase-out of biomass usage in the heating system decreases DH competitiveness, and without a DH distribution temperature decrease or addition of new low-grade EH, there is no DH grid expansion into new housing at all if biomass is phased out. This further suggest that a fully electrified heating system may consist of both DH and individual solutions, but individual solutions may become totally dominant in new housing unless DH systems decrease their distribution temperature or harness low-grade industrial EH. Given that HPs are currently advocated as an important, decarbonizing technology across the EU, a future development with no biomass usage is likely one of HP dominance. All scenarios investigated in this study show that it seems cost-efficient to electrify heating systems with the use of HPs, implying that the cost of heating can become increasingly correlated with the electricity price. However, predicting future electricity price levels is hard, and it would therefore be of interest for future studies to investigate how heating systems may develop applying other methods for predictions of future electricity prices. Depending on the probability and length of low-price periods, the most cost-efficient heating system would depend on how the system can react to, for example, fast variations in the electricity price. More frequent low-cost periods would benefit the use of HP, possibly even more with the use of TES systems.

Whether biomass incineration should be treated as carbon neutral is a highly debated topic. The use of biomass for DH started to increase in the 1970's in Sweden as biomass was seen as a sustainable fuel in particular in comparison with fossil fuels [9]. The view of the sustainability of using biomass for heating purposes is however changing as other sectors, such as the industrial and transport sectors, can use biomass for other purposes than heat generation. The transition of the current economy into a circular economy is ongoing in the EU. Circularity principles promote the use of biomass for reuse and recycling before incineration (according to the cascading principle). This resembles the waste hierarchy but for biomass, in which incineration is the second last step. Indeed, the EU advocates that biomass shall be used where it has the highest economic and environmental benefit, which promotes the use of long-lived products. Since it is mostly residue products (from forestry and industrial processes) that are incinerated for heating purposes, this means that if different stakeholders reduce biomass residues, the heating sector may find it hard to find biomass for heating purposes at a competitive market price.

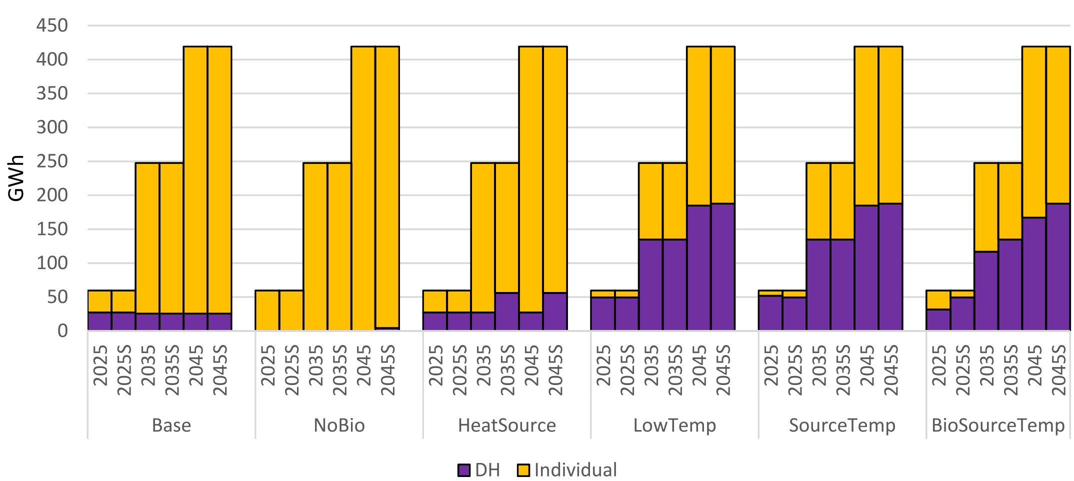
In sum, when biomass is phased out the current configuration of DH systems in Sweden is not efficient. The temperature in the current infrastructure is too high, generating too high distribution losses and too low COP of large-scale DH HPs. The current solutions will be outcompeted by individual ground source and air to water HPs. High temperature CHPs exist across Europe (mainly fueled by gas), when they




*(a) High2030 electricity price case.*

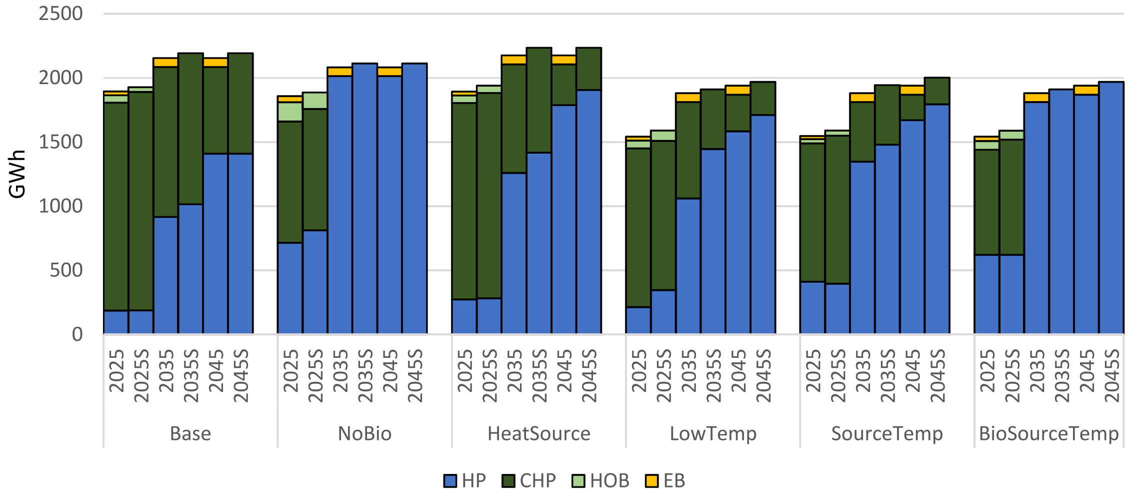



*(b) Low2030 electricity price case.*

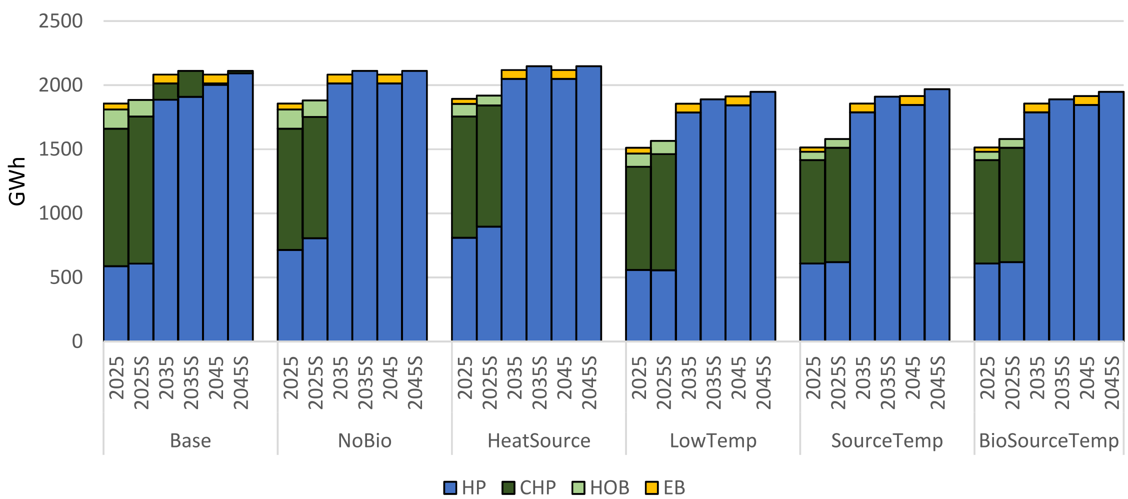



*(c) Vary2030 electricity price case.*

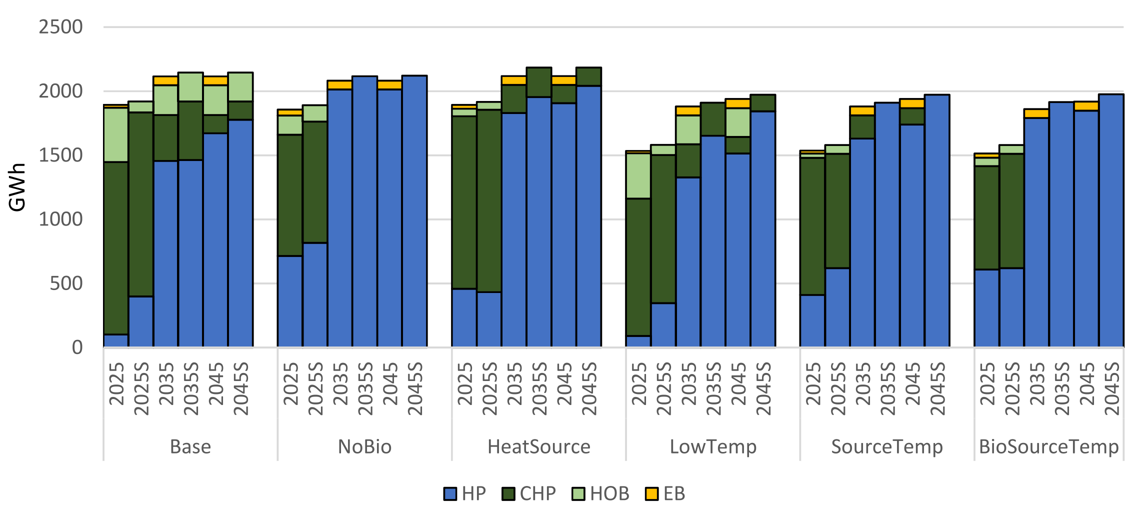
**Fig. 2.** Heating solution for all new housing in the different electricity price cases. A "S" after a specific year indicates that investments into TES systems can be made.




*(a) High2030 electricity price case.*




*(b) Low2030 electricity price case.*




*(c) Vary2030 electricity price case.*

**Fig. 3.** DH supply in the different electricity price cases. A "S" after a specific year indicates that investments into TES systems can be made. Waste incineration and high-grade industrial EH have been left out to improve readability.

are refurbished their heat supply is often shifted to biomass (seen in countries like France, Spain, Germany and former eastern European states). The heating sector is different from the electricity sector in that it is based on local conditions resulting in different, national legislations that have not yet been harmonized and as a result, the pace of and focus of the heat supply transition differs (away from gas to biomass in refurbishment or growing markets contrasted to away from biomass in mature markets). Given the current discussion about biomass in the context of the EU Taxonomy and the identified need amongst Swedish DH companies to shift to other heating supplies, it seems as if an EU level approach to CHP units is needed. What is the desirable, green heat supply desired to reach the objective of Europe being a climate neutral continent 2050?

In the context of DH and phaseout of biomass, the role of electricity must be addressed. An HP dominance would, in turn, create an increasing need for electricity, which is already a scarce asset in many countries during peak load hours. It would lead to an increasing dependency on local electricity production or imports. However, local electricity generation, e.g. in CHP plants, can alleviate this potential problem. Heating companies in the Nordic countries mainly make investments into CHP plants for heating purposes. Doing so, electricity is generated that alleviates the capacity problem in the electricity sector. Indeed, CHPs can serve as a flexibility agent in the energy systems as a whole. An energy future that is sector coupled is likely. In such a context, the added values for the system as a whole that CHPs bring need to be accounted for. Indeed, there appears to be a gap in energy policies not allowing system gains to be identified and thereby not incentivized. It is, for example, shown in Ref. [37] that on a city level, it can be more economical to make investments into HOBs or HPs compared to CHPs, while CHPs have a higher value for a larger energy system.

Both a decrease in the DH distribution temperature as well as utilization of low-grade EH from industrial heat sources increases the competitiveness of DH to such extent that the most cost-efficient heating solution for new housing is DH. As the use of DH is increased for both of these pathways, regardless of whether biomass is phased out or not, this suggest that utilization of low-grade EH and a decrease of the DH temperature should be considered by heating utilities for either continued cost-competitiveness, in the pathway of no biomass availability, and for increased cost-competitiveness if biomass is available. As pointed out in Ref. [24], it is often not technical or economical limitations which are the main barriers hindering collaboration between DH systems and industries providing EH. Rather, it is about new ways of stakeholder interactions. This applies to the whole value chain from architectural design of buildings to investors in green energy. Without changes in the policies concerning the use of EH, the potential of utilizing EH may remain untapped, thus resulting in a decreased viability for using DH as heating solution for new housing. It is concluded in Ref. [38] that few firms in Sweden has investigated the possibility to provide EH to the DH grids. Of the firms which have investigated this possibility, half of them were rejected. Third party access would increase the use of EH in DH systems, but third party access can come with risks of decreasing the economic incentives for investments into DH infrastructure [38]. The lack of policies encouraging the use of EH is concluded in Ref. [33], pointing out that waste heat recovery analysis should be made mandatory in the planning phase of all new buildings and in public procurement. As a starting point, mandatory heat recovery analysis can be initiated in the context of public sector buildings and then, when proven efficient, made an EU standard across both the construction and energy sectors.

Further, due to the long lifetimes of DH grids, starting the conversion of current generation DH into future generation is urgent. As different parts of DH systems built in the near future will stay around for a long time, they have to be prepared for a decreased DH temperature. DH grid operators may therefore need to implement solutions that ensure that equipment installed today, whether it is supply plants, piping or substations within individual buildings, is able to function with decreased DH temperatures. As technical and economic improvements of individual heating solutions will continue in the future, DH systems need to adapt to stay competitive to these kinds of solutions. Decreased heating demands in new buildings due to improvements in energy efficiency, as well as the decreases in the heat demand in existing buildings due to the EU Energy Performance of Buildings Directive can also affect the economic viability of DH due to the usually higher investment costs of DH compared to individual solutions. Failing to take opportunities and technological developments into consideration can have severe consequences for future DH systems, especially if biomass becomes unavailable for the heating system or the price is increased due to competition for this resource. Indeed, the consequences of inaction in DH systems can have severe and negative impacts on the continued activity of this sector. It is thus a field of study that merits further research.

In sum, the results show that district heating systems characterized by using low temperature heat sources and lower system temperatures are a cost-efficient alternative to provide new buildings with heat. In the context of low temperature DH and EH recovery, there appears to be a lag in supporting EU level incentives. For increased deployment, policies targeting construction of new buildings are needed. National building codes need to be upgraded with mandatory reviews of available EH sources in the foreseen area. A feasibility investigation of EH inclusion for heating and cooling purposes could initially be made mandatory in the construction and refurbishment of all public buildings. Once the feasibility has been proven, EH recovery for heating and cooling purposes of buildings should become an EU standard.

## 6. Conclusions

Returning to the first part of the question of research, *How cost efficient is district heating for new housing if biomass is phased out?* In this study, it is concluded that if biomass becomes unavailable, district heating is not a cost competitive alternative for heating new buildings. There is no DH grid expansion into new housing at all if no low-grade industrial EH is added or the DH temperature is not decreased. Even with integration of EH and a decreased DH temperature, without biomass, the DH grid expansion into new housing is lower compared to if biomass is available. Investments into TES can however contribute to somewhat higher DH grid expansion in this particular scenario. In terms of policy, we identify a need for DH utilities to be aware of the potential strong impact on the cost-efficiency of their district heating operations as a consequence of likely future changes of biomass availability and prices.

Returning to the second and third parts of the question of research, *How cost efficient is district heating for new housing with the addition of a low-grade EH source or at a decrease in the DH temperature?* This study concludes that such systems are a cost competitive alternative for heating new buildings. The DH supply is affected, and the integration of low-grade industrial EH for use in DH HPs is economical for all electricity price cases and benefits the DH grid expansion into new housing. Also, a lower DH temperature also contributes to the DH grid expansion. In combination, more low-grade industrial EH together with lower DH temperature leads to even higher DH grid expansion.

A final conclusion is that the heat supply in the future will be different from what it is today. EH in combination with HP solutions appears to be a viable option and directly reflects a strong sector coupling between heat and electricity. Sector coupling has been identified as a next development step in the EU, but many pieces of policymaking are still missing. To couple sectors, the silos that they currently operate within need to be opened up and synergies across activities need to be identified, in this process policies that support CHP providers to contribute with added values at the system level are recommended. At an overall national policy level, it is of importance to see district heating not only as a local concern but as an interlinked part of a national smart and efficient electricity-heating system and to understand that the investigated pathways could have a strong effect on the economic viability of district heating in particular its expansion into new buildings.

## CRediT authorship contribution statement

**Karl Vilén:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Conceptualization. **Kristina Lygnerud:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Erik O. Ahlgren:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

## Declaration of competing interest

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

## Data availability

Data will be made available on request.

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## References

[1] Lygnerud K, Popovic T, Schultze S, Støchkel HK. District heating in the future - thoughts on the business model. Energy 2023;278. https://doi.org/10.1016/j.energy.2023.127714.
[2] Connolly D, Lund H, Mathiesen BV, Werner S, Möller B, Persson U, et al. Heat roadmap Europe: combining district heating with heat savings to decarbonise the EU energy system. Energy Pol 2014;65:475–89. https://doi.org/10.1016/j.enpol.2013.10.035.
[3] European Commission, Directorate-General for Energy, Bagheri M, Mandel T, Fleiter T, et al. Renewable space heating under the revised Renewable Energy Directive – ENER/C1/2018-494 – description of the heat supply sectors of EU member states space heating market summary 2017. Publications Office of the European Union; 2022.
[4] Siddique MB, Nielsen PS, Rosendal MB, Jensen IG, Keles D. Impacts of earlier natural gas phase-out & heat-saving policies on district heating and the energy system. Energy Pol 2023;174:113441. https://doi.org/10.1016/j.enpol.2023.113441.
[5] Banja M, Sikkema R, Jégard M, Motola V, Dallemand JF. Biomass for energy in the EU – the support framework. Energy Pol 2019;131:215–28. https://doi.org/10.1016/j.enpol.2019.04.038.
[6] Riekkola AK, Wetterlund E, Sandberg E, Biomassa Energiforsk. Systemmodeller och målkonflikter. 2017.
[7] Börjesson M, Athanassiadis D, Lundmark R, Ahlgren EO. Bioenergy futures in Sweden - system effects of CO2 reduction and fossil fuel phase-out policies. GCB Bioenergy 2015;7:1118–35. https://doi.org/10.1111/gcbb.12225.
[8] IVL. Passivitet i klimatfrågan. Fjärrvärmesektorns exponering mot en utvecklad bioekonomi och ett förändrat klimat. 2021.
[9] Di Lucia L, Ericsson K. Low-carbon district heating in Sweden - examining a successful energy transition. Energy Res Social Sci 2014;4:10–20. https://doi.org/10.1016/j.erss.2014.08.005.
[10] Djuric Ilic D, Eriksson O, Ödlund (former Trygg L, Åberg M. No zero burden assumption in a circular economy. J Clean Prod 2018;182:352–62. https://doi.org/10.1016/j.jclepro.2018.02.031.
[11] Pettersson K, Axelsson E, Eriksson L, Svensson E, Berntsson T, Harvey S. Holistic methodological framework for assessing the benefits of delivering industrial excess heat to a district heating network. Int J Energy Res 2020;44:2634–51. https://doi.org/10.1002/er.5005.
[12] Averfalk H, Benakopoulus T, Best I, Dammel F, Engel C, Geyer R, et al. Low-temperature district heating implementation guidebook. 2021.
[13] Ziemele J, Volkova A, Latõšov E, Murauskaitė L, Džiuvė V. Comparative assessment of heat recovery from treated wastewater in the district heating systems of the three capitals of the Baltic countries. Energy 2023;280:1–11. https://doi.org/10.1016/j.energy.2023.128132.
[14] Svenska Kyl & Värmepumpföreningen. Värmepumpsförsäljning. 2022. https://skvp.se/statistik/varmepumpsforsaljning. [Accessed 27 September 2022].
[15] Statista. Annual amount of heat pumps in operation in the European Union (EU) from 2013 to 2020. 2022. https://www.statista.com/statistics/739745/heat-pumps-in-operation-eu/. [Accessed 14 November 2022].
[16] 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;10:100097. https://doi.org/10.1016/j.segy.2023.100097.
[17] Vilén K, Ahlgren EO. Seasonal Large-Scale Thermal Energy Storage in an Evolving District Heating System – Long-term Modeling of Interconnected Supply and Demand. Unpubl Results n.d..
[18] Werner S. District heating and cooling in Sweden. Energy 2017;126:419–29. https://doi.org/10.1016/j.energy.2017.03.052.
[19] Johansen K, Werner S. Something is sustainable in the state of Denmark: a review of the Danish district heating sector. Renew Sustain Energy Rev 2022;158:112117. https://doi.org/10.1016/j.rser.2022.112117.
[20] Sernhed K, Lygnerud K, Werner S. Synthesis of recent Swedish district heating research. Energy 2018;151:126–32. https://doi.org/10.1016/j.energy.2018.03.028.
[21] Lund H, Duic N, Østergaard PA, Mathiesen BV. Future district heating systems and technologies: on the role of smart energy systems and 4th generation district heating. Energy 2018;165:614–9. https://doi.org/10.1016/j.energy.2018.09.115.
[22] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. https://doi.org/10.1016/j.energy.2014.02.089.
[23] Odgaard O, Djørup S. Review of price regulation regimes for district heating. Int J Sustain Energy Plan Manag 2020;29:127–40. https://doi.org/10.5278/ijsepm.3824.
[24] Lygnerud K, Werner S. Risk assessment of industrial excess heat recovery in district heating systems. Energy 2018;151:430–41. https://doi.org/10.1016/j.energy.2018.03.047.
[25] Sandvall AF, Ahlgren EO, Ekvall T. System profitability of excess heat utilisation - a case-based modelling analysis. Energy 2016;97:424–34. https://doi.org/10.1016/j.energy.2015.12.037.
[26] Bühler F, Petrović S, Karlsson K, Elmegaard B. Industrial excess heat for district heating in Denmark. Appl Energy 2017;205:991–1001. https://doi.org/10.1016/j.apenergy.2017.08.032.
[27] Lund H, Østergaard PA, Chang M, Werner S, Svendsen S, Sorknæs P, et al. The status of 4th generation district heating: research and results. Energy 2018;164:147–59. https://doi.org/10.1016/j.energy.2018.08.206.
[28] Ziemele J, Dace E. An analytical framework for assessing the integration of the waste heat into a district heating system: case of the city of Riga. Energy 2022;254:124285. https://doi.org/10.1016/j.energy.2022.124285.
[29] Kumar S, Thakur J, Gardumi F. Techno-economic modelling and optimisation of excess heat and cold recovery for industries: a review. Renew Sustain Energy Rev 2022;168:112811. https://doi.org/10.1016/j.rser.2022.112811.
[30] Guzović Z, Duic N, Piacentino A, Markovska N, Mathiesen BV, Lund H. Recent advances in methods, policies and technologies at sustainable energy systems development. Energy 2022;245. https://doi.org/10.1016/j.energy.2022.123276.
[31] 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.
[32] Vilén K, Ahlgren EO. Linear or mixed integer programming in long-term energy systems modeling – a comparative analysis for a local expanding heating system. Energy 2023;283:129056. https://doi.org/10.1016/j.energy.2023.129056.
[33] Lygnerud K, Federizzi R, Wynn HP, Corscadden J, Lucas P, Scotton S, et al. Low temperature waste heat recovery could combat climate emergency - policy recommendations. Euro Heat Power Mag 2022;4:6–11.
[34] Averfalk H, Werner S. Economic benefits of fourth generation district heating. Energy 2020;193:116727. https://doi.org/10.1016/j.energy.2019.116727.
[35] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87:1059–82. https://doi.org/10.1016/j.apenergy.2009.09.026.
[36] ETSAP. Energy technology systems analysis program n.d. https://iea-etsap.org/index.php/etsap-tools/model-generators/times. [Accessed 10 October 2023].
[37] Lindroos TJ, Mäki E, Koponen K, Hannula I, Kiviluoma J, Raitila J. Replacing fossil fuels with bioenergy in district heating – comparison of technology options. Energy 2021;231. https://doi.org/10.1016/j.energy.2021.120799.
[38] Broberg S, Backlund S, Karlsson M, Thollander P. Industrial excess heat deliveries to Swedish district heating networks: drop it like it's hot. Energy Pol 2012;51:332–9. https://doi.org/10.1016/j.enpol.2012.08.031.