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Hybrid energy networks and electrification of district heating under different energy system conditions

Peter Sorknæs

Department of Planning, Aalborg University, Rendsburggade 14, DK-9000, Aalborg, Denmark

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Abstract

As electricity systems world-wide are transitioning into increasing levels of variable renewable electricity sources, such as wind power and photovoltaics, increased electrification of other energy sectors has shown to be important for allowing a resource- and cost-efficient integration of these sources. Research has found electrification of district heating to be one of the more promising energy sectors for electrification in relation to integrating variable renewable electricity sources, as district heating allows for the utilization of varied use of different energy conversion technologies and low-cost energy storage solutions. Historically, district heating has mainly been interconnected to the electricity system via combined heat and power units, though research have found that with increasing levels of variable renewable electricity sources the need for electricity consuming conversion units, such as heat pumps, are becoming more important. In this, the national energy system effects of electrification of the district heating sector are investigated. Two future energy system scenarios for two different countries, being Austria and Denmark are made: one with a high degree of district heating utilization and one with a lower degree of district heating utilization. Both countries are expected to utilize increasing levels of variable renewable electricity sources, though the level and type of variable renewables are different due to differences of e.g. in availability hydro power solutions within the countries and the wind and solar resources available. As such, these two countries provide different perspectives on how electrification can be understood under different conditions.

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Keywords: Hybrid energy networks; District heating; Electrification; EnergyPLAN

E-mail address: sorknaes@plan.aau.dk.

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Nomenclature

AT	Austria
CEEP	Critical excess electricity production
CHP	Combined heat and power
COP	Coefficient of performance
DH	District heating
DK	Denmark
HP	Heat pump
HRE	Heat Roadmap Europe
PV	Photovoltaics
RES	Renewable energy sources

1. Introduction

World-wide increasing levels of variable renewable energy sources (RES) are being installed in energy systems to reduce costs of and greenhouse gas emissions from the energy system. It is especially in the electricity system that variable RES is being implemented [1]. However, large-scale introduction of variable RES also means that the energy system, and especially the electricity system, needs to change to facilitate these new variable sources, which contrast more traditional dispatchable sources [2]. Mathiesen et al. [3] argue that such a change in the energy system should be addressed in a holistic way as to best identify synergies between the different energy sectors that all needs to go towards lower emissions of greenhouse gases, and as such, all needs to be changed radically. Henrik Lund [2] refer to such a holistic approach as Smart Energy System, which is defined "*as an approach in which smart electricity, thermal, and gas grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system*". Similar concepts have emerged in research, such as the Hybrid Energy Networks approach, which is a local optimized connection of different energy grids.

One of the sectors that is seen as a potential low-cost solution for integration of variable RES is the heat sector [2]. In many countries heating makes up a substantiable part of the energy demand, e.g. in the European Union heating is estimated to account for about 48% of the final energy demand [4]. Within the heating sector, especially district heating (DH) is often found to be important to facilitate low-cost and energy system efficient integration of variable RES through electrification, as it e.g. allows for low-cost heat storage options [5], flexible operation of different energy conversion technologies, and utilization of otherwise discarded excess heat [2]. DH is currently going towards what is referred to as 4th generation, where lower temperatures in the DH grid would allow for increased efficiency of the DH grid itself, but also increases the efficiency of the conversion technologies that is utilized and allow for more excess heat sources to be utilized cost-efficiently [6,7]. This shift allows for increased potential for electrification of DH, as e.g. heat pumps (HP) could achieve a higher Coefficient of performance (COP). Electrification of DH can be divided into two categories, being direct electrification, such as electric-driven HP and electric boilers, and indirect electrification, such as excess heat from electric-driven industrial process and excess heat from electrofuel production [8].

In this paper it is investigated how direct electrification affects different energy system scenarios. The scenarios used utilize different levels and types of RES in their energy system and have different levels of DH. The purpose is to quantify the effect of direct DH electrification on the entire energy system under different circumstances. To quantify these effects a holistic energy system analyses tool and existing national energy system scenarios are used.

2. Methods

Here the methods utilized are presented. First the energy system analyses tool used is presented, and then the energy system scenarios are described.

2.1. EnergyPLAN

EnergyPLAN is a holistic energy system analyses tool developed for simulation of hourly energy flows across all energy sectors, being electricity, heating, cooling, industry, and transport. EnergyPLAN is primarily designed for simulation of national and regional energy systems and has been used for a range of different energy system analyses in research. EnergyPLAN is developed around the concept of Smart Energy System, where all energy demands are included in the energy system alongside possible coupling points between the energy sectors [9].

An overview of the energy demands, energy conversion units, energy storages and energy sources used in EnergyPLAN can be seen in Fig. 1.

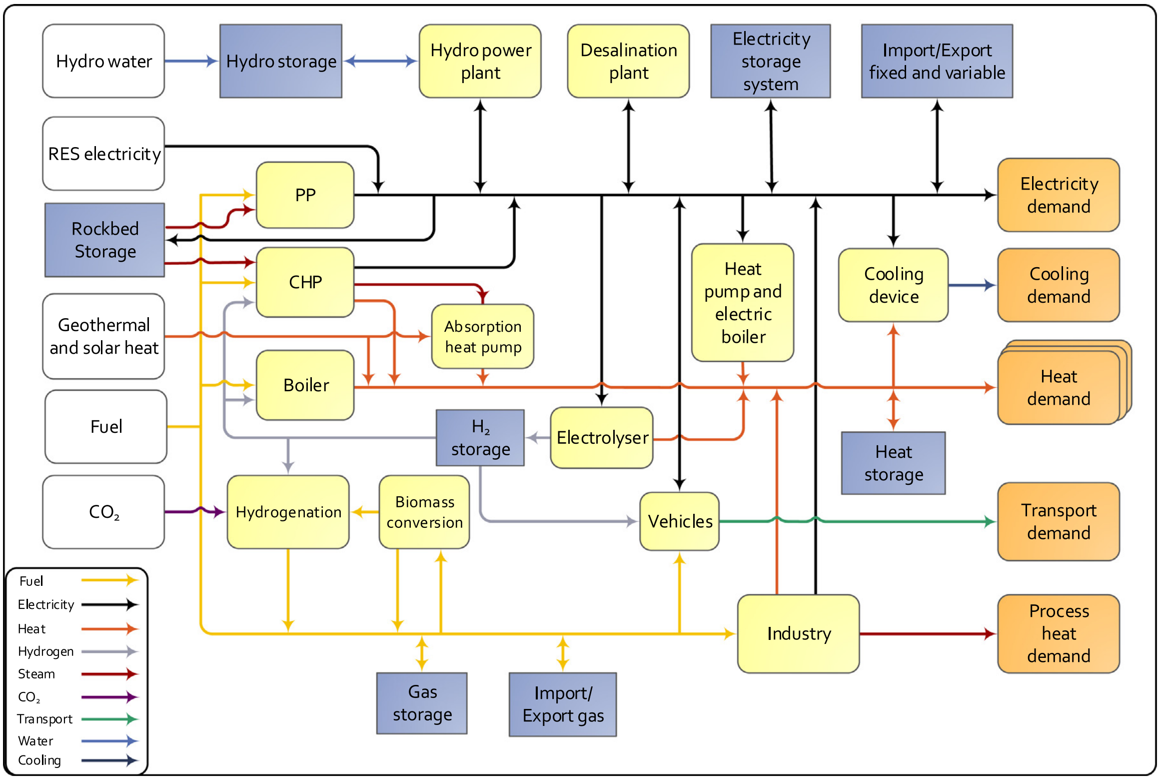

Fig. 1. Overview of EnergyPLAN technologies and cross-sector integration [10].

EnergyPLAN simulates the operation of each type of technology shown in Fig. 1based on different simulation strategies that can be chosen by the user. The simulation includes the possibility to utilize flexibility using energy storages and coupling points between different energy sectors. The two overall simulation strategies are Technical simulation, where the aim is to reduce the fuel consumption of the energy system, and Market Economic simulation, where aim is to operate each unit to reduce the short-term marginal costs of their operation to maximize the units' profit. The Market Economic simulation is based on the Uniform price principle that is dominant in day-ahead electricity markets in continental Europe. All scenario results presented in this paper are made using the Technical Simulation strategy.

2.2. Energy system scenarios

As to understand how direct electrification of DH affects different energy systems scenarios depending on RES potentials, two different countries are used, being Austria and Denmark. Both countries have existing DH systems, however, based on 2015-numbers the DH market share in Austria is around 28% compared to around 58% in Denmark [11]. Previous studies have found that both countries have the potential to increase DHs market share while reducing energy system costs and fuel consumption, also when including potentials for energy savings in buildings. For Austria the DH market share has been found to be most energy system feasible around 45%–54% [12] and for Denmark it has been found to be around 66% [13]. The two countries also have very different options for implementation of non-fuel RES in the electricity system. Austria has existing hydro power facilities with the potential to expand this capacity, and likewise have potential for geothermal electricity, onshore wind power and PV [12]. Denmark has no significant potential for hydro power or geothermal electricity, instead mostly having a potential for offshore wind power, onshore wind power, and PV [13]. As such, it is expected that the future Danish energy system to a larger extend that the future Austrian energy system will rely on electricity supply from variable RES. Based on these differences Austria and Denmark represent two different current and future energy system situations, that can show how direct electrification of DH affects different energy systems.

Instead of developing new energy system scenarios, existing energy system scenarios are used for Austria and Denmark. Three different scenarios are used for each country, being: a reference model for 2015, a low DH market share scenario for 2050, and a high DH market share scenario for 2050. The 2050 scenarios being energy systems relying primarily on RES.

For Austria, scenarios from the study "Heat Roadmap Europe 4" [14] are used, where the 2050 HRE scenario represents the high DH market share with a DH market share of approx. 50%. The "Heat Roadmap Europe 4" also includes a 2015 model for Austria which will be used as the 2015 reference scenario. EnergyPLAN was utilized in the study, and the technical setup of the Austrian EnergyPLAN HRE and 2015 scenarios remain mostly unchanged compared to their original setup in that study. However, in this study the HRE scenario is changed so that the DH fuel boiler capacity is increased to be able to cover 120% of peak DH demand, as to allow for it to work as backup and peak load capacity, and DH grid loss changed from 15% to 10%, as the 10% is what was found for this DH level in the analyses in the Heat Roadmap Europe 4 study [14]. The HRE scenario is used as a base for making an Austrian low DH market share scenario in 2050, where the DH market share is decreased from 50% to 42% while maintaining the same total heat demand, and as such, the heat demand supplied by individual heating solutions are instead increased by the reduced DH heat demand (excl. DH grid loss), keeping the same share of different individual heating solutions of the total individual heating demand. More specifically the following changes are made to the HRE scenario to create a low DH market share 2050 scenario for Austria:

- Reduced the DH demand to deliver 42% of end-use consumption (down from approx. 50%), meaning a reduction from 25.03 to 21.43 TWh/year. The lower DH market share is equal to the Decarbonization scenario for Austria from the Heat Roadmap Europe 4 study [14].
- Individual HP electricity demand increased from 25.5 to 29.1 TWh/year.
- Annual costs of DH grids reduced from 700 M EUR to 420 M EUR.
- DH fuel boiler capacity set to cover 120% of peak demand, reduced from 10.45 GW to 8.95 GW.
- The seasonal storage for solar DH and industrial excess heat is reduced from 73.71 to 63.11 GWh
- DH HP capacity reduced from 1,200 to 1,027 MW_e.
- Electric boiler capacity for DH production reduced from 1,200 to 1,027 MW_e.
- Industrial excess heat utilized for DH reduced from 2.48 to 2.13 TWh/year.
- Geothermal heat for DH reduced 0.21 to 0.18 TWh/year.
- It is assumed that DH from waste incineration and excess heat from electrofuel production remains unchanged. As these productions remain unchanged and act as baseload in the DH system, it is assumed that other baseload units should be reduced as to not produce too high levels of non-usable heat in the low heat demand season. It is therefore chosen to first reduce the geothermal heat capacity until the level of non-usable heat is the same as with high DH demand in percentage of the total DH demand. If more reductions are needed to reach this, then reductions are made to the solar thermal DH capacity. Based on this method, the DH geothermal heat capacity is reduced from 0.21 to 0 TWh/year, and as this is not sufficient to reach the same level of non-usable heat, the solar thermal DH capacity is reduced from 0.74 to 0.2 TWh/year.

In case nothing else is indicated in the list above, each change is made based on the percentage reduction in yearly DH production.

For Denmark, the IDA2050 scenario from the study "IDA's Energy Vision 2050" [13], where a 100% RES based Danish energy system is proposed, is used as the high DH market share scenario, alongside the 2015 energy system model described by Sorknæs, et al. [15]. The IDA2050 scenario has a DH market share of 66%. IDA2050 is used as a base for making a Danish low DH market share scenario in 2050, where the DH market share is decreased from 66% to 50% while maintaining the same total heat demand, and as such, the heat demand supplied by individual heating solutions are instead increased by the reduced DH heat demand (excl. DH grid loss), keeping the same share of different individual heating solutions of the total individual heating demand. More specifically the following changes are made to the IDA2050 scenario to create the low DH market share 2050 scenario for Denmark:

- Reduced DH demand to deliver 50% of end-use consumption. 75% of these DH demand reductions are made in smaller DH areas (reduced from 10.35 to 5.68 TWh/year) and 25% in larger DH areas (reduced from 17.84 to 15.67 TWh/year).
- Individual biomass boilers fuel demand increased from 1.59 to 2.33 TWh/year.
- Individual HP electricity demand increased from 13.07 to 19.24 TWh/year.
- Individual solar thermal increased from 0.25 to 0.37 TWh/year for buildings supplied by biomass boilers and from 2 to 2.94 TWh/year for buildings supplied by HP.
- Annual costs of DH grids reduced from 1,236 M EUR to 879 M EUR based on [16].
- DH fuel boiler capacity set to cover 120% of peak demand, reduced from 12 GW to 9 GW.
- Solar thermal DH capacity reduced from 2.35 to 1.49 TWh/year, and related solar storage is reduced from 30 to 16.46 GWh
- DH HP capacity reduced from 700 to 516 MW_e.
- Electric boiler capacity for DH production reduced from 900 to 692 MW_e.
- Industrial excess heat utilized for DH reduced from 5.28 to 4.23 TWh/year.
- As waste incineration and excess heat from electrofuel production are not expected to occur due to DH demand, it is assumed that these remain unchanged. As these acts as baseload units in the DH system, it is assumed that other baseload units should be reduced as to not produce too high levels of non-usable heat in the low heat demand season. As such, geothermal heat capacity is reduced until the DH production of non-usable heat is the same as with high DH demand in percentage of the total DH demand. As such, the DH geothermal heat capacity is reduced from 4.64 to 2.06 TWh/year.

In case nothing else is indicated in the list above, each change is made based on the percentage reduction in yearly DH production.

Changes to DH grid loss and electric grid costs are not considered for both low DH 2050 scenarios. Here especially the change in electric grid costs, caused by an increased amount of individual HP, could be significant. Henrik Lund [17] estimates that the fixed costs of expanding the electric distribution grid in Denmark could be in the range of 5 and 10 Billion EUR/MW.

All the chosen scenarios have been developed in EnergyPLAN. The 2050 scenarios used for Denmark were originally created using v12.4 [13], however, has in previous work been updated to work in v15.1 [18], and the 2015 scenario for Denmark was developed in v13.1 [15]. The models used for Austria were originally developed in v14.2 [14]. Using different versions of EnergyPLAN would result in different outcomes, and therefore to make the results comparable, all scenarios presented in this paper are instead simulated in EnergyPLAN v16 [10]. Also, where the Austrian models and IDA2050 were developed using the Technical Simulation strategy, the 2015 Danish model was developed using the Market Economic simulation strategy. As the focus of this paper is the technical connections between different types of technologies, the Technical simulation strategy is utilized for all scenarios.

As to emphasize the energy system effects of different changes to the energy system scenarios, it is chosen to remove all electric interconnections to other countries from the scenarios, as this will more clearly show any potential change in energy system operation. The Austrian scenarios were all developed using this approach, however, all the Danish scenarios include transmission capacity to surrounding countries. Therefore, the transmission capacity is removed from the Danish energy system scenarios, and instead additional power plant capacity is installed as to allow the model to balance the electricity system.

All technology costs have been updated using technology data from the Danish Energy Agency [19] (accessed December 2020). To convert these numbers from Danish costs to Austrian costs the method described by Guddat et al. [20] has been used. For costs associated with hydro power, geothermal electricity and industrial excess heat, the original Heat Roadmap Europe 4 costs have been maintained. The costs used for Denmark are similar to those described in Sorknæs et al. [18], which is also based on Danish Energy Agency [19], though as the cost data in this source has been updated for DH fuel boilers, electric boilers, solar thermal, seasonal solar storage, and individual fuel boilers, these costs have been updated accordingly.

The IDA2050 scenario is based on the principle that on a yearly basis the domestic production of gas must equal the gas consumed in Denmark. This scenario principle is maintained for the two versions of IDA2050 and for any adjustment of these two. For simplicity, the yearly balance of gas is maintained by only adjusting the capacity and biomass input to the biomass gasification plants, as this has been shown to be the lowest cost gas production solution [21].

The primary energy supply of the entire energy system of each updated scenario can be seen in Fig. 2, and the DH supply can be seen in Fig. 3.

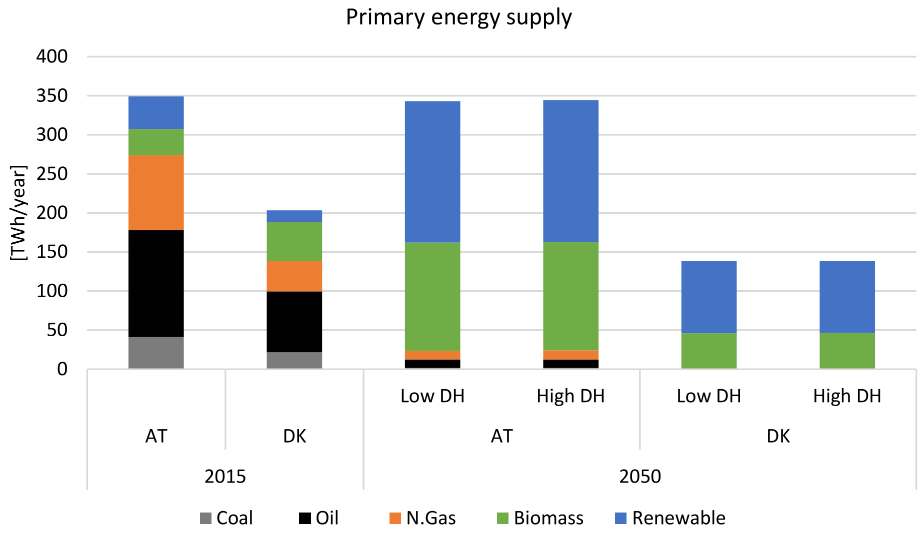

Fig. 2. Primary energy supply per fuel type of each scenario.

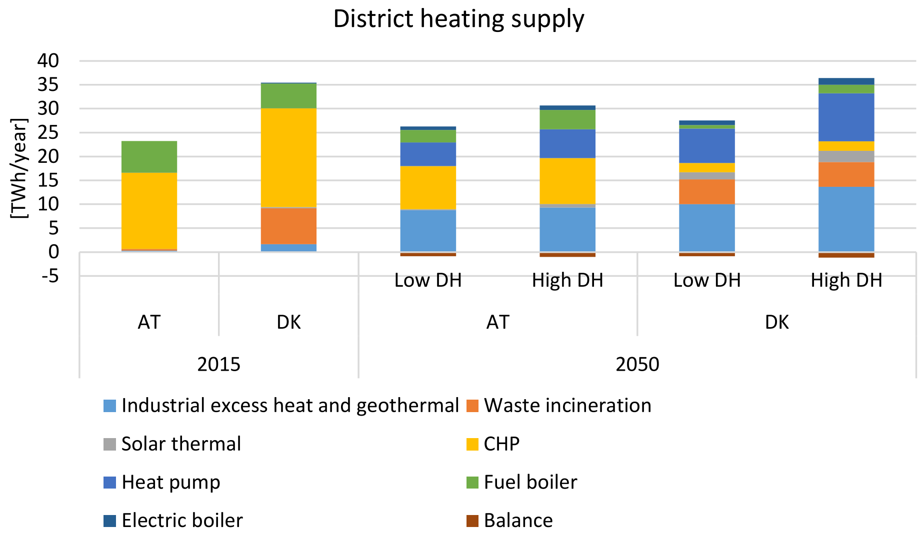

Fig. 3. District heating supply for each scenario.

In the analysis, each scenario will be changed to have different levels of direct electrification in the DH supply, meaning that the capacities of electric boilers and HPs will be changed. The capacities of these vary greatly from scenario to scenario. As to make the results easier to compare, the ranges of capacities are set as 0%–200% of the existing capacities in the 2050 high DH market share scenarios for each country. For Austria this means that 100% correspond to 1.2 GW_e HP capacity and 1.2 GW electric boiler capacity, respectively. For Denmark, the 100% correspond to 0.7 GW_e HP capacity and 0.9 GW electric boiler capacity, respectively. The DH HP technology and resulting COP is unchanged compared with the original scenarios, where in the 2015 scenarios the COP is 3 for both countries, and in the 2050 scenarios the COP for Austria is 4 and for Denmark it is 3.5, with the difference being related to differences in heat sources utilized and the expected lower DH grid temperatures in 2050. The efficiency of the electric boilers is assumed to be 100%. Table 1 shows the capacities of the DH based electric boilers and HPs in each of the six scenarios.

Table 1. Electric boiler and HP in DH capacity in the different scenarios.

Scenario	Electric boiler [MW_e]	HP [MW_e]
AT2015	0	0.7
AT-Low DH	1,027	1,027
AT-High DH	1,200	1,200
DK2015	522	3.8
DK-Low DH	692	516
DK-High DH	900	700

Changes to the electrification of DH will make it possible to utilize different amounts of variable RES compared to what was originally installed in the energy system scenarios. As to account for this, the installed capacity of the technology that can be seen as the marginal variable RES will be adjusted when making changes to the technologies. This change will be done based on the yearly critical excess electricity production (CEEP), being electricity produced that cannot be utilized in the energy system. In a real-world situation this production would either be exported or result in reduced production from variable RES units. So, in case that a change in technology results in lower CEEP, then the capacity of the marginal variable RES capacity is increased until the yearly CEEP value is kept unchanged, and vice versa with a higher CEEP. For Austria it is assumed the marginal variable RES technology is PV, and for Denmark it is assumed to be offshore wind power, as the technical potential for offshore wind power capacity in Danish waters could be up towards 40 GW [22], and the IDA2050 scenario makes use of 14 GW offshore wind power. Table 2 shows the capacities of the marginal variable RES technology and starting CEEP value in each scenario.

Table 2. Marginal variable RES capacity and CEEP in the different scenarios. For AT scenarios the marginal is PV and for DK scenarios it is offshore wind power.

Scenario	Marginal variable RES capacity [MW]	CEEP [TWh/year]
AT2015	103	0
AT-Low DH	47,000	7.73
AT-High DH	47,000	7.72
DK2015	1,271	0.04
DK-Low DH	14,000	5.74
DK-High DH	14,000	5.59

3. Scenario results

Here the results for changing the DH electric boiler capacity and DH HP capacity are shown and discussed. The focus is on the change in the marginal variable RES production, the DH production of the electrification technologies, the energy systems biomass consumption, and the total annual costs of the entire energy system.

3.1. Change to DH electric boiler capacity

In this section the electric boiler capacity that is connected to DH is changed from 0% to 200% of the initial installed capacity in the 2050 high DH scenario for each country, and the DH HP capacity is kept unchanged. For

Austria this means that 100% correspond to 1.2 GW electric boiler capacity, and for Denmark 100% correspond to 0.9 GW electric boiler capacity.

The change in the marginal variable RES production needed to maintain same CEEP value as shown in Table 2 are shown in Fig. 4. The change in marginal variable RES production is relative to the production in the original scenario, and the different levels of electric boiler capacity are relative to the original high DH market share scenario shown in Table 1.

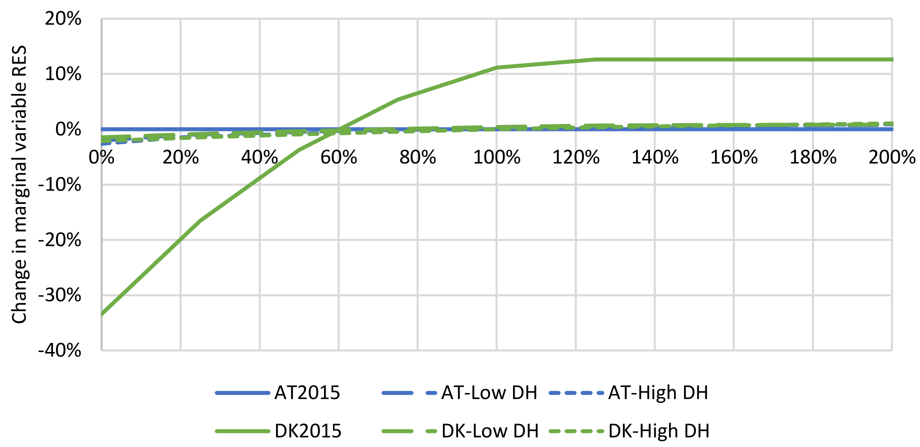

Fig. 4. Change in marginal variable RES production at different levels of electric boiler capacity relative to the original high DH market share scenario of the country.

More electric boiler capacity allows for more marginal variable RES capacity in all scenarios, except for the AT2015 scenario, as in this scenario other technologies are included that already allow for the full utilization of the variable RES, meaning that the CEEP value is zero, as shown in Table 2. For 2050 the high DH market share scenarios allow for more potential integration than their low DH market share counterparts. The change in DH electric boiler capacity especially affect the relative capacity in DK2015, as few other flexibility options exist in this scenario, removing or reducing the existing capacity reduces the relative capacity of offshore wind power, where the current installed electric boiler capacity being around the 60% mark on Fig. 4. It is important to note that the offshore wind power production is lower in the 2015 scenario than in the 2050 scenarios. More electric boiler capacity allows for further integration of offshore wind power, but only up to a certain capacity, which is due to the production of electric boiler evens out, as can be seen in Fig. 5 that shows the heat production of electric boilers and HPs at different levels of electric boiler capacity relative to the original high DH market share scenario of the country.

It can be seen in Fig. 5 that changing the electric boiler capacity mostly affects the production of heat on the electric boiler, which mostly replaces the fuel boilers installed in the DH systems. The reason being that in EnergyPLAN the HP is utilized before the electric boiler, due to the higher efficiency of the HP, and the changes that can be observed in the HP operation are caused by the electric boiler using the DH storage systems, as the heat produced by the electric boiler can be stored if it cannot be utilized at time of production. It can also be seen that the higher DH market share scenarios allow for more production on the electric boiler.

Fig. 6 shows the change in the energy systems' total biomass consumption and total annual costs at different levels of electric boiler capacity. As such, these include biomass consumption and costs for all energy sectors. The change in biomass consumption and total annual costs are relative to the original scenario, and the different levels of electric boiler capacity are relative to the original high DH market share scenario shown in Table 1.

As shown in Fig. 6, in all scenarios increasing the capacity of electric boilers decrease the biomass consumption of the energy system, as it both allows for integration of increased capacities of variable RES, as shown in Fig. 4, but also reduces the biomass consumption for DH fuel boilers.

The effect on the total annual cost of the entire energy system shown in Fig. 6 seems to increase with higher levels of electric boiler capacity in the Danish, which is related to the increase in marginal variable RES capacity, as especially can be seen for the development of the DK2015 scenario, as it has relatively large increase in costs

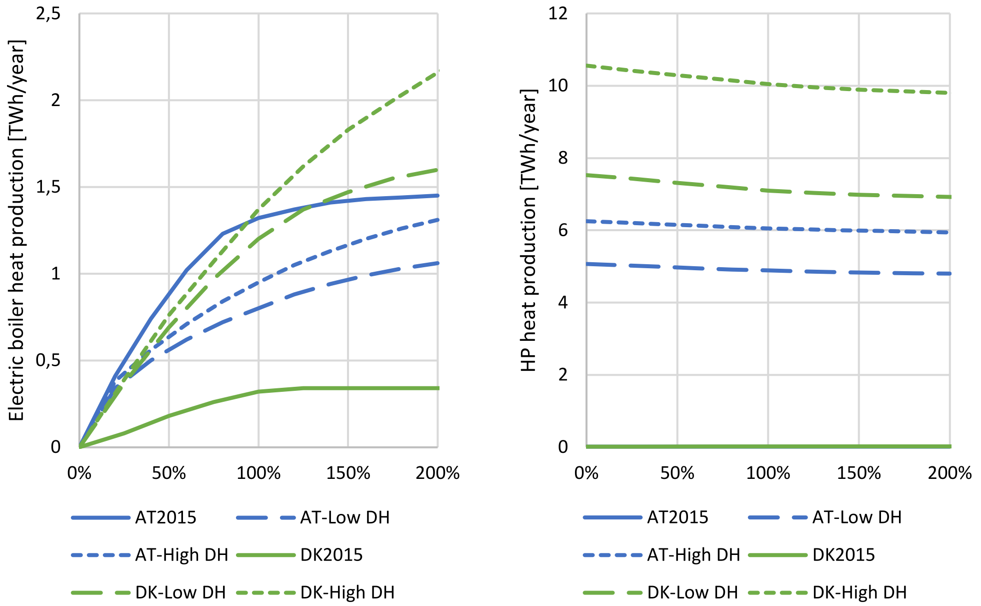

Fig. 5. Heat production of electric boilers and HPs at different levels of electric boiler capacity relative to the original high DH market share scenario of the country.

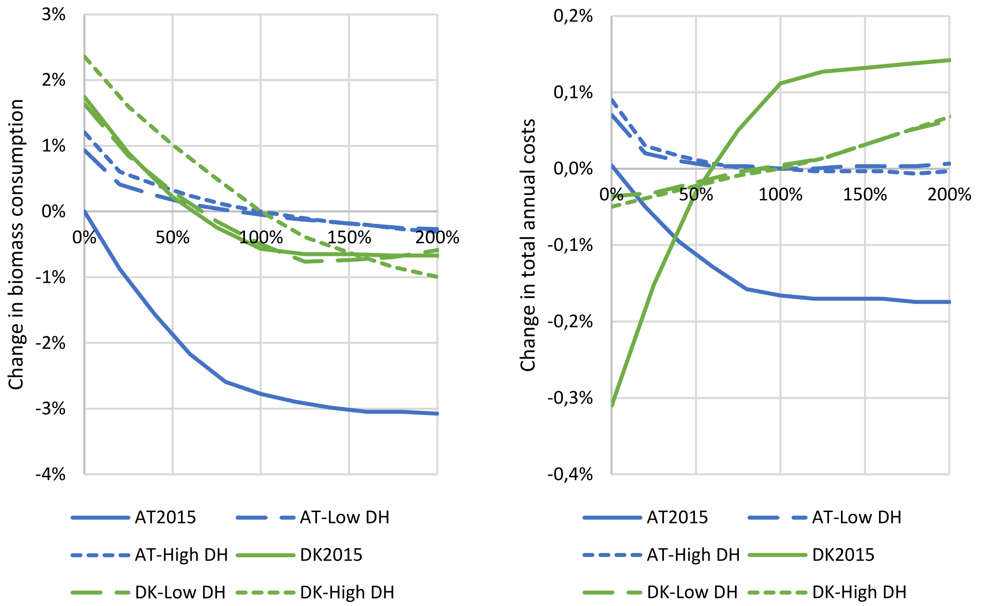

Fig. 6. Change in the energy system's total biomass consumption and total annual costs at different levels of electric boiler capacity relative to the original high DH market share scenario of the country.

until around 100%, which correspond to the development shown in Fig. 4. The opposite effect can be seen for the Austria scenarios, where increased electric boiler capacity result in reduced total annual costs, until the increased in electric boiler capacity does not allow for more integration of the marginal variable RES technology, being PV for Austria. This indicates that for the electric boiler capacity it is related to the marginal variable RES technology of the energy system. Though, the change in total annual costs is relatively low compared with the total cost of the entire energy system, as this also includes costs for the transport sector, etc.

3.2. Change to DH HP capacity

In this section the HP capacity that is connected to DH is changed from 0% to 200% of the initial installed capacity in the 2050 high DH scenario for each country, and the DH electric boiler capacity is kept unchanged. For Austria this means that 100% correspond to 1.2 GW_e HP capacity, and for Denmark 100% correspond to 0.7 GW_e HP capacity.

The change in the marginal variable RES production needed to maintain the same CEEP value as shown in Table 2 are shown in Fig. 7. The change in marginal variable RES production is relative to the production in the original scenario, and the different levels of HP capacity are relative to the original high DH market share scenario shown in Table 1.

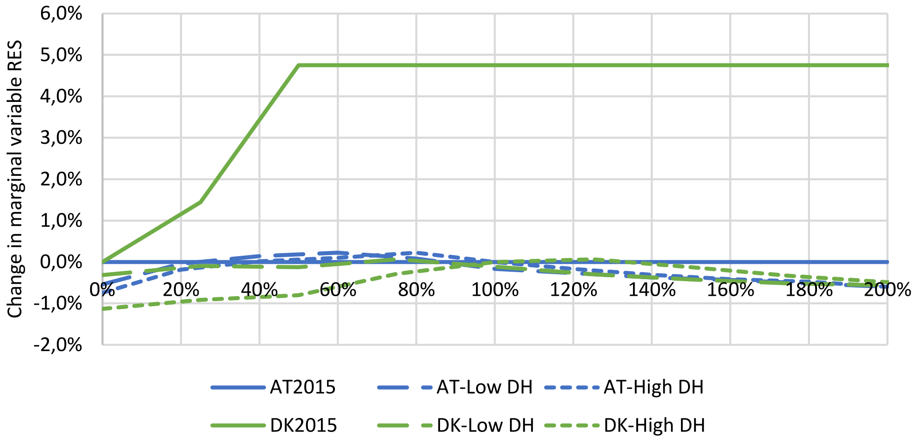

Fig. 7. Change in marginal variable RES at different levels of HP capacity relative to the original high DH market share scenario of the country.

Generally, change to the HP capacity shown in Fig. 7 allows for less integration of more marginal variable RES than when changing the electric boiler capacity, due to the lower efficiency of the electric boiler, as the HP thereby to a larger extend is limited by the DH demand available.

The change in HP capacity especially affects the capacity in DK2015, as few other flexibility options exist in this scenario, like what was shown in Fig. 4 for electric boiler capacity. Though as this scenario starts with a DH HP capacity of 3.8 MW_e all variations above 0% adds more DH HP than the starting point of the scenario and adding more DH HP capacity allows for increased integration of offshore wind power in the energy system, though only up until around 50% where the HP production reaches it maximum heat production potential, as shown in Fig. 8. Compared with the change to electric boilers, the change in marginal variable RES when changing DH HP capacity is significant lower for the DK2015 scenario, which is partly due to the electric boiler capacity of 522 MW that is also present in this scenario allowing for CEEP regulation, where in the case of changing electric boiler capacity, only 3.8 MW_e HP capacity was in the system. It is important to note that the offshore wind power production is lower in the 2015 scenario than in the 2050 scenarios.

Fig. 8 shows the heat production of electric boilers and HPs at different levels of HP capacity relative to the original high DH market share scenario of the country.

It can be seen in Fig. 8 that changing the HP capacity affects both the production of heat on the HP and the electric boiler with increasing levels of HP decreasing the electric boiler production, except for AT2015 that has no electric boiler capacity. The higher DH market share scenarios allow for more production on the HP and therefore allow for a higher capacity to be installed before the heat production levels out.

Fig. 9 shows the change in the energy system's total biomass consumption and total annual costs at different levels of HP capacity. The change in biomass consumption and total annual costs are relative to the original scenario, and the different levels of HP capacity are relative to the original high DH market share scenario shown in Table 1.

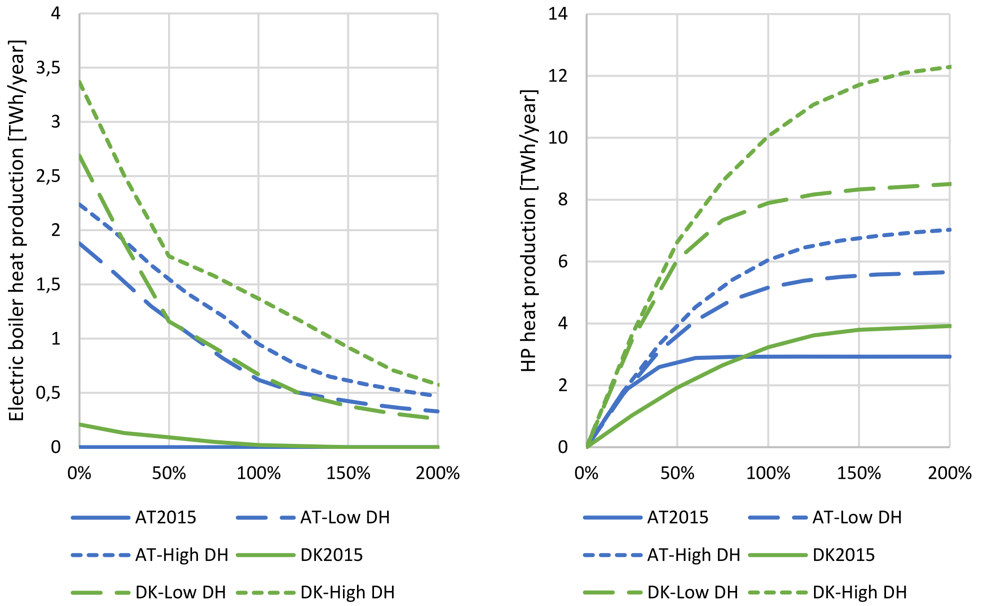

Fig. 8. Heat production of electric boilers and HPs at different levels of HP capacity relative to the original high DH market share scenario of the country.

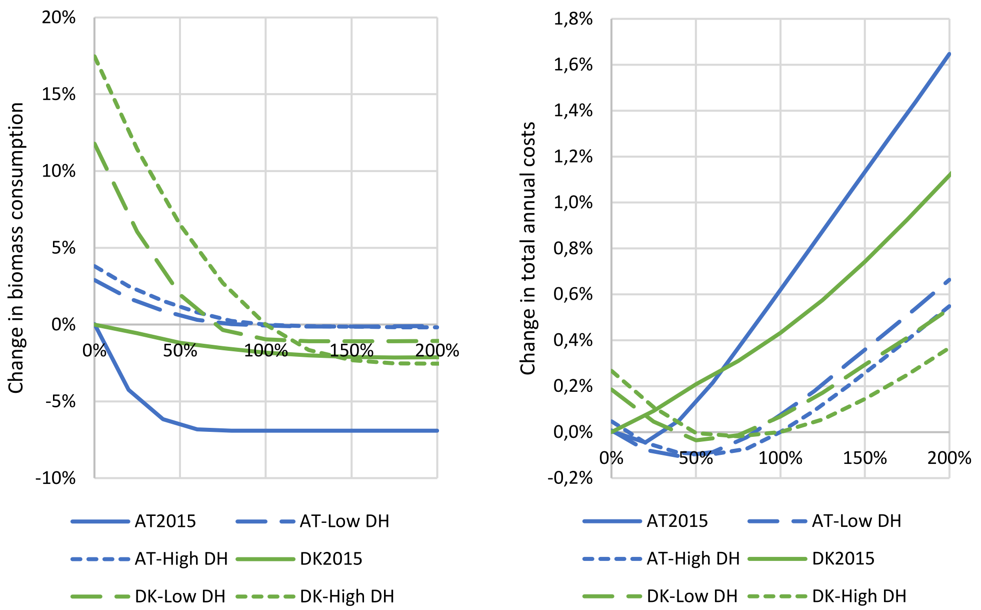

Fig. 9. Change in the energy system's total biomass consumption and total annual costs at different levels of HP capacity relative to the original high DH market share scenario of the country.

As shown in Fig. 9 the biomass consumption is reduced by larger HP capacities, though only until the HP production levels out, as shown in Fig. 8. The drop in biomass consumption is larger for HP than was found for change to electric boiler capacity shown in Fig. 6. The biomass consumption of the high DH market share 2050 scenarios is relatively more affected by the change in HP capacity than their lower DH market share counterparts. The Danish 2050 scenarios are generally more affected by the change in HP capacity, which is directly related to the change in marginal variable RES shown in Fig. 7, where the Danish 2050 scenarios also see a larger effect on the installed marginal variable RES, than the Austrian scenarios, which especially is due to the more flexibility options in the Austria electricity supply.

Cost-wise it is clear from Fig. 9 that having some capacity of DH HP in the energy system allows for reduced energy system costs, but only to an extent, whereafter the costs increase due, which is directly related to the utilization of the installed capacity of HP, as shown by the production level outs in Fig. 8. The effect for HP is more significant than for electric boilers, as the investment cost of HPs is significantly higher than for electric boilers, e.g. in the 2050 Danish scenarios the HP investment cost is set to 2.66 M EUR/MW_e (0.76 M EUR/MW_{th}) compared to 0.06 M EUR/MW_e for electric boilers. The energy system costs for the 2015 scenarios are relatively more affected by this, due to lower HP COP alongside higher costs for HPs and the marginal variable RES technology used, compared with the 2050 scenarios.

3.3. Change to DH HP capacity with electric boiler capacity as replacement

In this section the HP capacity that is connected to DH is changed from 0% to 200% of the initial installed capacity in the 2050 high DH scenario for each country, like the previous section, though here the DH electric boiler capacity is also changed according to the change in HP electric capacity. Meaning that when the HP electric capacity is reduced then the electric boiler capacity is increased by the same capacity, and vice versa. The electric boiler capacity is limited to zero in capacity, as at high levels of HP capacity the increase in HP capacity in some scenarios is larger than the starting capacity for electric boilers, as shown in Table 1.

The change in the marginal variable RES production needed to maintain the same CEEP value as shown in Table 2 are shown in Fig. 10. The change in marginal variable RES production is relative to the production in the original scenario, and the different levels of HP capacity are relative to the original high DH market share scenario shown in Table 1.

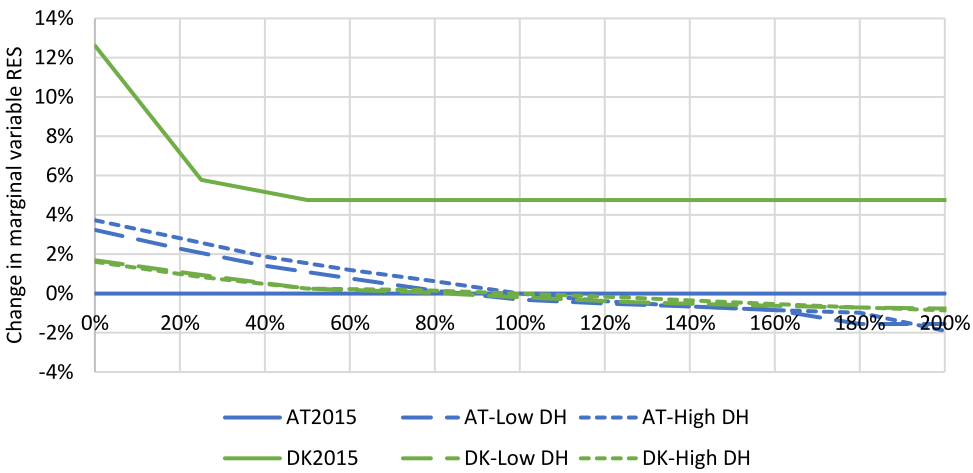

Fig. 10. Change in marginal variable RES at different levels of HP capacity relative to the original high DH market share scenario of the country. Electric boiler capacity is used as replacement technology based on MW_e.

As shown in Fig. 10, increasing the HP capacity, and thereby also reducing the electric boiler capacity, results in reduced potential to integrate the marginal variable RES, which confirms what was found in the previous sections, that electric boiler capacity generally allow for a larger integration of the variable RES, due to its lower efficiency. The effect is most significant in the Austria scenarios, which is likely due to the larger share of DH HP compared with the DH demand, as shown in Table 1 and Fig. 3, meaning that the capacity difference between 0% and 200% is larger, both in absolute and relative terms.

Fig. 11 shows the heat production of electric boilers and HPs at different levels of HP capacity relative to the original high DH market share scenario of the country with electric boiler replacement.

Fig. 11 shows similar effects as was shown in Fig. 8, where only the HP capacity was changed, though here the effects are a little more significant as e.g., at higher levels of HP capacity, here the electric boiler capacity is either completely removed or significantly reduced, allowing more heat produced via HPs.

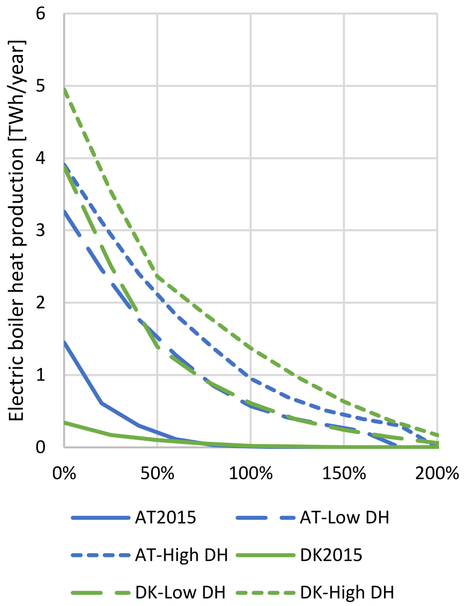

Fig. 11. Heat production of electric boilers and HPs at different levels of HP capacity relative to the original high DH market share scenario of the country. Electric boiler capacity is used as replacement technology based on MW_e.

Fig. 12 shows the change in the energy system's total biomass consumption and total annual costs at different levels of HP capacity. The change in biomass consumption and total annual costs are relative to the original scenario, and the different levels of HP capacity are relative to the original high DH market share scenario shown in Table 1. Fig. 12 shows results like those in Fig. 9, where only the HP was changed, indicating that the largest effect on these is the implementation of the HP capacity, with the electric boilers having a significantly lesser effect.

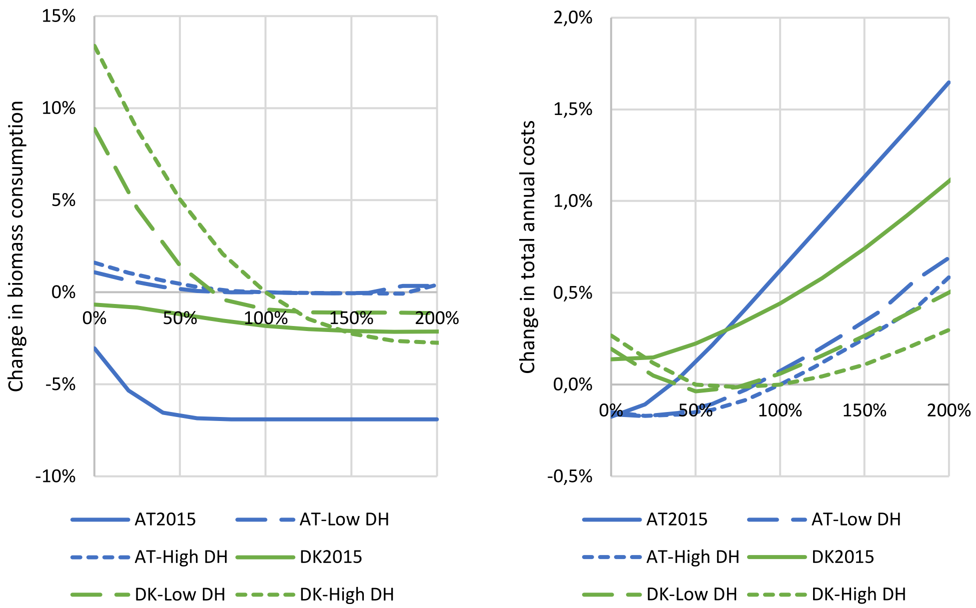

Fig. 12. Change in the energy system's total biomass consumption and total annual costs at different levels of HP capacity relative to the original high DH market share scenario of the country. Electric boiler capacity is used as replacement technology based on MW_e.

4. Conclusion

In this paper energy system scenarios for two different countries, being Austria and Denmark, are used to identify the energy system effects of the two most prominent technologies for direct electrification of DH. Three scenarios are used for each country, a 2015 scenario, a 2050 scenario with low DH market share, and a 2050 scenario with high DH market share.

The results show that DH based electric boiler capacity to a greater extent than HPs allow for larger integration of variable RES into the energy system without creating increased levels of unusable electricity production. This is due to the electric boilers less efficiently converting the electricity to heat, meaning that they are less bound by the heat demand in their operation.

Looking at the change in biomass consumption, it is found that DH HP have a larger potential to reduce the biomass consumption of the energy system compared with electric boilers, even when accounting for the potential to integrate more variable RES with electric boilers. Though, the integration of either is found to reduce biomass consumption, but only until the operation of these units are being limited by the DH demand, which occurs at higher capacities for high DH market share scenarios, and at lower capacities for HPs. The biomass reduction is especially in relation to reduced use of biomass-fired DH boilers.

The total annual costs of the energy system are also mostly affected by the capacity of HPs, compared with the electric boilers. For electric boilers, the effect on the total annual costs is mostly related to the potential to integrate more variable RES into the energy system. Though, for both the change in total annual costs is relatively low compared with the total cost of the entire energy system, as this also includes costs for the transport sector, etc, with the tested electric boiler capacities affecting it up to around 0.1–0.5% and the tested HP capacities affecting it up to around 0.4%–17%, depending on scenario. The DH demand affects the most suitable level of capacity.

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.

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