Smart Energy

Integrating district heating potentials into European energy system modelling: An assessment of cost advantages of renewable and excess heat

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Abstract:	Achieving climate neutrality by 2050 requires rapid progress in decarbonising the heating sector and rendering energy demand and supply more efficient. Reducing heat demand in line with the energy efficiency first principle is crucial. A promising option for an efficient heat supply is the deployment of district heating with large-scale heat pumps. Hence, instead of looking only at the heating sector, an integrated perspective is needed that takes into account additional sectors, such as the electricity sector through the electrification of heating. In addition, renewable and excess heat sources could complement the electrification of district heating. This paper takes a novel modelling approach by considering high-resolution heat generation potentials for district heating and examining their impact on the district heating technology mix and the overall energy system. A modelling analysis of the European energy system, including district heating and electricity supply, is conducted. Thereby, the high-resolution potentials allow for a detailed cost comparison of different possible future technology mixes in district heating. The paper finds that the utilisation of geothermal and excess heat can provide cost advantages for district heating and the overall energy system.
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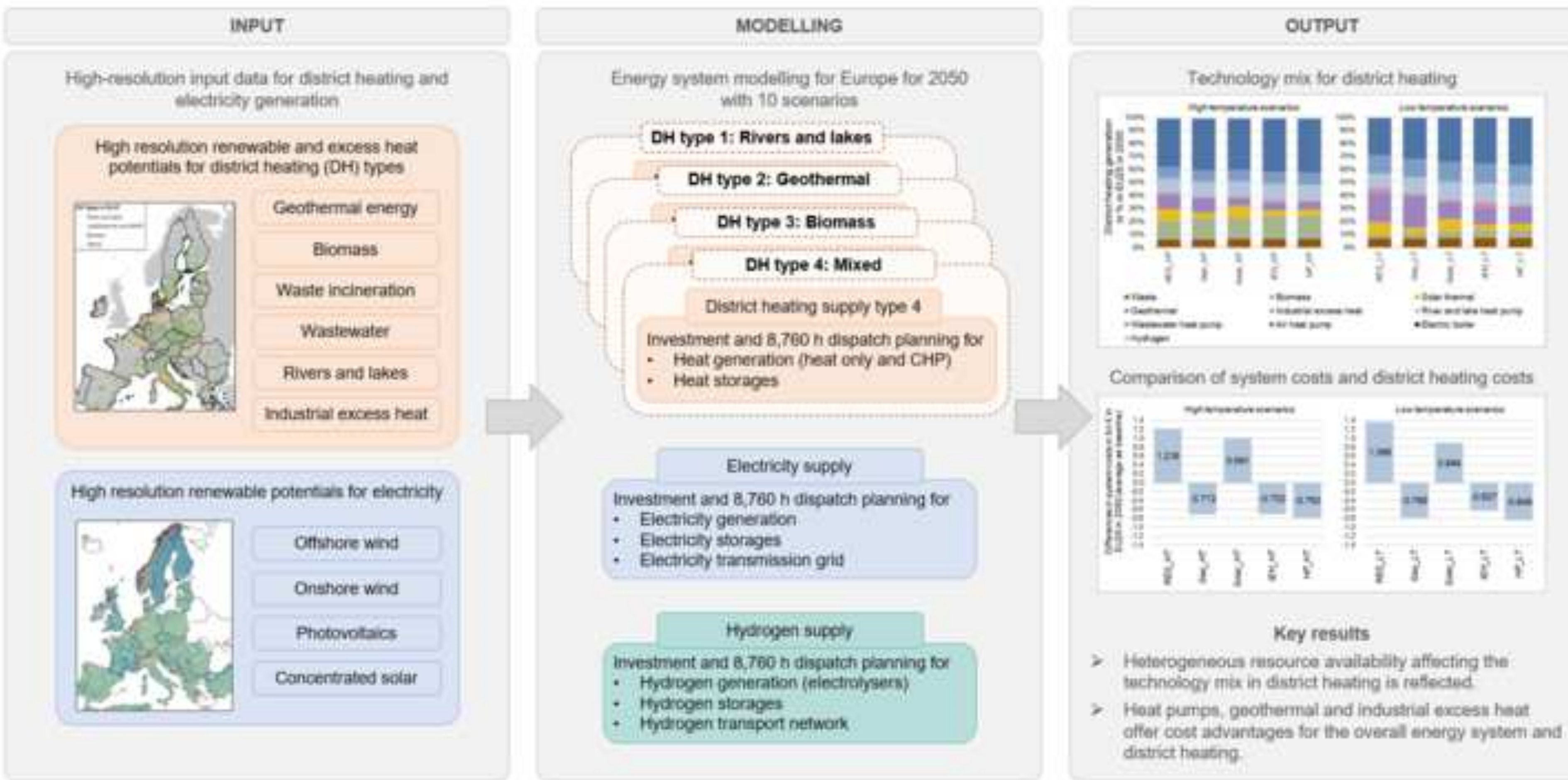
Graphical Abstract



Integrating district heating potentials into European energy system modelling: An assessment of cost advantages of renewable and excess heat

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Highlights

- This paper presents scenarios for a climate-neutral European energy system in 2050
- It pursues a novel approach to model district heating (DH) at high resolution
- The heterogeneous resource availability in DH is reflected by the novel approach
- The modelling results show multivalent DH networks dominated by heat pumps
- Heat pumps, geothermal and industrial excess heat provide cost advantages for DH

Abstract

Achieving climate neutrality by 2050 requires rapid progress in decarbonising the heating sector and rendering energy demand and supply more efficient. Reducing heat demand in line with the energy efficiency first principle is crucial. A promising option for an efficient heat supply is the deployment of district heating with large-scale heat pumps. Hence, instead of looking only at the heating sector, an integrated perspective is needed that takes into account additional sectors, such as the electricity sector through the electrification of heating. In addition, renewable and excess heat sources could complement the electrification of district heating. This paper takes a novel modelling approach by considering high-resolution heat generation potentials for district heating and examining their impact on the district heating technology mix and the overall energy system. A modelling analysis of the European energy system, including district heating and electricity supply, is conducted. Thereby, the high-resolution potentials allow for a detailed cost comparison of different possible future technology mixes in district heating. The paper finds that the utilisation of geothermal and excess heat can provide cost advantages for district heating and the overall energy system.

Keywords

district heating, energy systems modelling, heat pump, optimisation, renewable and excess heat

1 Introduction

Achieving the European Union's (EU) target of climate neutrality by 2050 [1] requires rapid progress in decarbonising the energy sector and in rendering energy demand and supply more efficient and interlinked. To this end, several studies have modelled different scenarios or pathways for future energy systems and discussed in detail the feasibility of achieving this target (see overview in [2]). The existing literature shows that an integrated, holistic perspective is required, taking into account several sectors, as discussed within the concept of smart energy systems [3–5].

The key to reaching a climate-neutral energy system is to phase out fossil fuels, rapidly expand renewable electricity generation and electrify the other sectors (e.g. heating, transport) as far as possible [2,6]. Moreover, reducing energy demand and supplying energy more efficiently, in line with the energy efficiency first principle (EE1st) plays an important role [7]. As the heating and cooling sector accounts for around half of European energy demand [8], energy savings in this sector are vital. Efficiency measures in buildings can reduce fuel needs, running costs and the needed investment for (new) heating systems [9]. In the case of district heating, heat savings from buildings allow operators to reduce the temperature level of their grid, making it easier to integrate (low temperature) renewables and excess heat sources (i.e. 4th and 5th generation district heating, e.g. [10–15]). Thereby, the compatibility of district heating with building refurbishment as a competing or synergetic strategy is still being explored [16]. Even with heat savings, the remaining district heating demand still needs to be climate neutral and efficient. As mentioned above, electrification via heat pumps appears to be a promising option [6,17–19].

However, renewables such as geothermal and solar thermal energy, and waste or excess heat sources in district heating can also make a significant contribution to a climate-neutral and efficient heat supply but are not yet addressed in detail in energy system analyses. District heating networks are very heterogeneous and at the same time, renewable and excess heat potentials are unevenly distributed [20,21]. Therefore, district heating is usually modelled in a simplified way in integrated energy system models covering Europe. There are only very few integrated energy system analyses focusing on district heating technology mixes and covering all of Europe (e.g. [5,23,24]). These studies model district heating based on a limited resolution or do not cover a wide range of renewable and excess heat potentials. This paper addresses this research gap by pursuing a novel approach to model the technology mix in district heating based on high-resolution heat potentials while simultaneously using an integrated perspective by modelling the whole European energy system (i.e. district heating and the power sector). With this holistic modelling approach, we aim to answer the research question: Can local renewable and excess heat sources offer cost advantages for district heating and the overall energy system?

To address this question, 10 scenarios for the year 2050 for Europe are modelled using the energy system model ENERTILE. The analysis builds on preliminary work by Manz et al. [20], which provides the needed high-resolution renewable and excess heat potentials for district heating. A model extension integrates the potentials into the optimisation problem for the present paper. Subsequently, each modelled scenario sets a different rate of potential utilisation to account for differences in the exploitation of renewable and excess heat potentials. Thereby, two scenario groups are analysed, focusing on (1) high and (2) low temperatures in district heating. Lowering temperatures in district heating recognises that improvements in energy efficiency can significantly contribute to achieving climate neutrality (i.e. EE1st).

The paper is structured as follows: Section 2 describes the methodology and data. Section 3 presents the main results, i.e. the modelling output for district heating and electricity generation as well as the overall system costs and cost for district heating. Section 4 discusses key results, and section 5 provides conclusions and policy implications.

2 Methodology and data

2.1 Overview of the modelling approach

Regionally heterogeneous resource availability substantially influences the prospects for different technologies in district heating. For example, the availability of geothermal energy depends on the geological situation and industrial excess heat is only available in some areas [20,22]. This necessitates an approach that assesses the contribution of renewable and excess heat technologies based on high spatial resolution data. Besides a high level of detail regarding district heating, interaction with the remaining energy system, e.g. through heat pumps, needs to be considered. Therefore, this paper takes a novel approach to model the technology mix in district heating based on high-resolution heat potentials in an integrated energy system model. The analysis uses heat potentials for district heating generation from [20], aggregated into four district heating types. The district heating types represent multivalent district heating networks, where specific resources are abundantly available [20]. For example, in *DH Type 2: Geothermal*, a significant part of the demand could be covered by geothermal energy due to its favourable geological situation. The types are integrated into the energy system model ENERTILE as separate regions. Figure 1 provides an overview of the modelling approach. Section 2.2 provides a general overview of the model ENERTILE and section 2.3 describes the model extension.

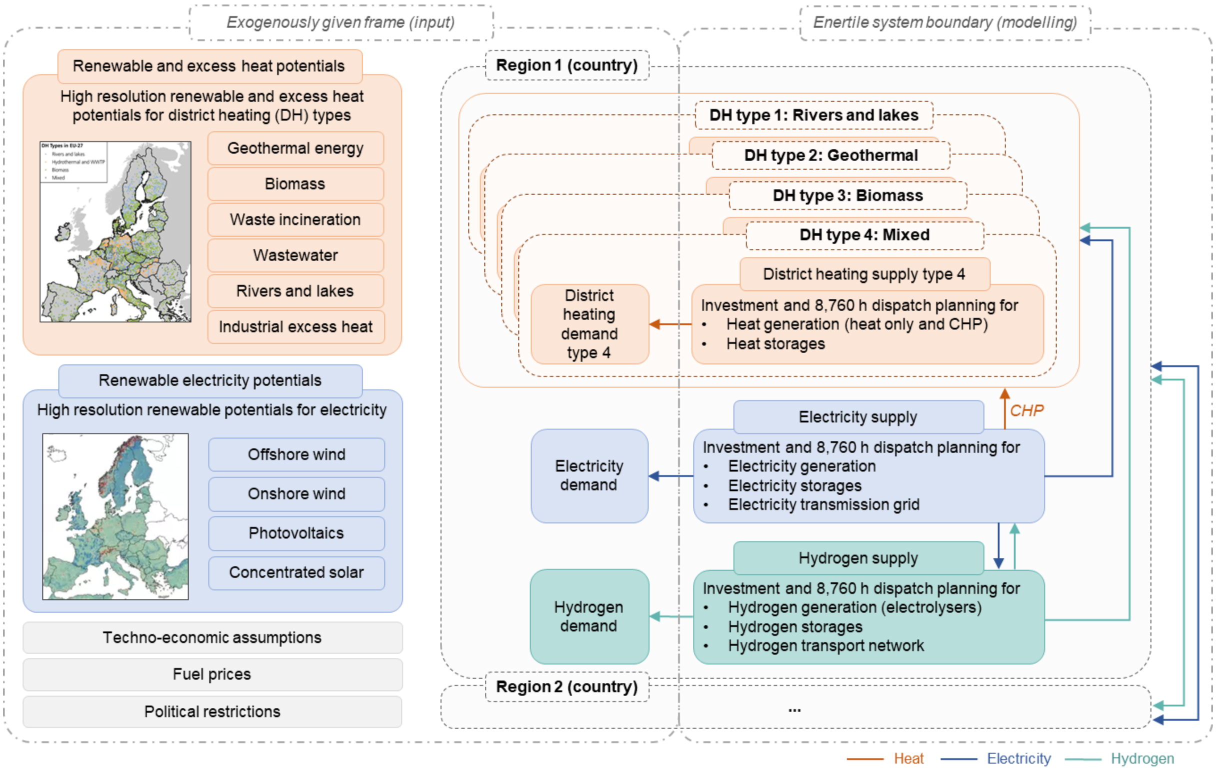

Figure 1: Schematic representation of the quantities, interactions, and boundary conditions in the model ENERTILE

2.2 The energy system model ENERTILE

For the scenario analysis, the model ENERTILE is used. ENERTILE is a bottom-up techno-economic optimisation model for energy systems, which minimises the costs of energy generation, transmission and storage (compare Figure 1 and [23]). ENERTILE covers the supply of electricity, district heating, and synthetic fuels and gases (i.e. hydrogen). The model simultaneously optimises capacity expansion and hourly generation of all system components based on the exogenously specified demand for electricity, district heating and hydrogen. It covers conventional and renewable power plants, combined heat and power (CHP) plants, conventional and renewable heating technologies in district heating networks, cross-border electricity transmission capacities, energy storage technologies, hydrogen generation technologies and infrastructures. Furthermore, the model considers demand-side flexibility from decentralised heat pumps in buildings and electric mobility in the transport sector.

The key constraints of the model ensure that the demand for electricity, district heat and hydrogen is met in every region and hour. In this paper, ENERTILE'S geographical coverage comprises 25 Member States (MS) of the EU[1]. ENERTILE can model several years in a row and has a high temporal resolution with 8,760 hours in each year analysed. However, in this paper, we use a green field approach and model only the year 2050, as investment in new generation capacities is required by 2050, and the research question in the paper relates to the cost advantages in the year 2050.

The heat supply in district heating and the associated capacity expansion of generation technologies is modelled endogenously in ENERTILE based on exogenously predetermined heat demand for each region (i.e. district heating types per country) and year. ENERTILE scales the annual demand down to hourly demand, using daily district heating time series that incorporate average daily outdoor temperature. Different technologies are available, including electric boilers, large-scale heat pumps, geothermal energy and solar thermal plants, biomass boilers and CHP, waste CHP, hydrogen boilers and CHP, and heat storage. A description of the modelling of renewables and heat pumps is provided in section 2.3. Further methodology details of ENERTILE are published in [24–28].

2.3 District heating types and heating technologies in ENERTILE

As stated in section 2.1, heat potential data, aggregated into so-called district heating types, is used and integrated into ENERTILE. The four types are based on a clustering analysis where 5815 district heating areas in Europe in 2050 are clustered according to the available heat potentials [2]. Thereby, the cluster analysis has shown that these four district heating types adequately represent the diversity and heterogeneity of the potentials [2].

The types represent multivalent district heating networks with several sources: (1) ambient heat from rivers and lakes used with heat pumps, (2) ambient heat from wastewater treatment plants used with heat pumps, (3) direct use of industrial excess heat, (4) direct use of (deep) geothermal energy (hydrothermal and petrothermal), (5) biomass and biogas and (6) waste incineration. Thereby, one or two potential sources could cover a large part of the demand, giving the type its specific name. All of the

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1 Malta and Cyprus do not have a district heating infrastructure and it is assumed that they will not start investing.

described potentials are integrated into the model, except petrothermal potentials due to their low probability of exploitation, high costs and lower specific potentials. Furthermore, solar thermal potentials are not provided by [2], as it is assumed that the technical potentials are not limited by spatial proximity. Potentials for other types of heat pumps, e.g. air source heat pumps, are not considered for similar reasons. Solar thermal energy and air source heat pumps are, however, included as available technologies in the modelling (compare below and section 2.4).

Following [20], two different temperature settings for district heating grids are analysed: Higher grid temperatures (flow around 80 °C) and lower grid temperatures (flow around 65 °C). With the lower temperatures, a higher share of heat potentials can be utilised. Both temperature settings are used in this paper, leading to two scenario groups: Group (1) includes the potentials for high grid temperatures and group (2) the potentials for low grid temperatures. Figure 2 illustrates the four district heating types on the Europan level by showing the aggregated mix of potentials for the two scenario groups.

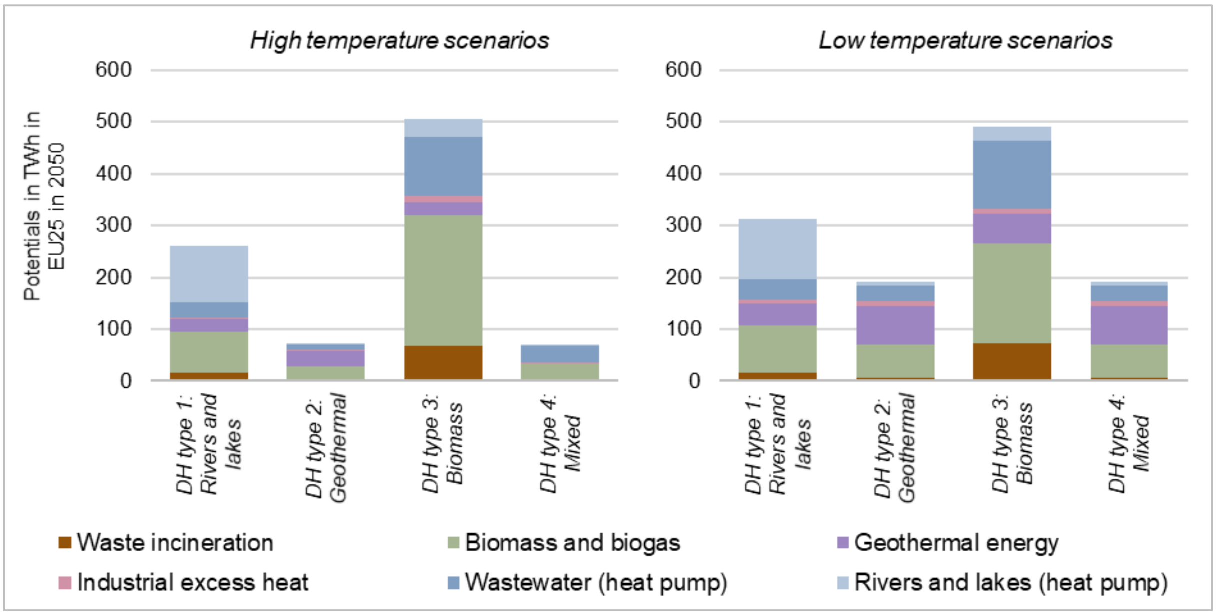

Figure 2: Potentials per district heating types (own illustration, based on data from [20])

The four types are integrated into ENERTILE on the MS level, i.e. for each MS, four types of district heating grids are implemented (compare Figure 1). As stated, the integrated types represent all district heating areas with their available heat generation potentials. Thus, the detail of the technical potentials is maintained. Previously, district heating was modelled in a simplified manner with only one grid for each MS. Thus, the model extension strongly improves the representation of district heating in the model.

Furthermore, several technologies are updated or newly included in ENERTILE to cover the technological varieties linked to the wide variety of potentials.

(i) Geothermal and solar thermal plants

The use of deep geothermal and solar thermal energy for heat generation in district heating is associated with comparatively high investments and their use is often additionally influenced by political preferences. Therefore, the generation of district heating with deep geothermal and solar thermal energy is not subject to the cost optimisation procedure in ENERTILE, but is included as an exogenous assumption (compare [29]). Heat generation from these sources is predefined per country and year. However, different utilisation rates and related costs of the two technologies are explored within the scenarios design by varying the share of the predefined heat generation from these sources (see section 2.4). Since these renewable heat sources are quasi-inexhaustible, it is assumed that the predefined annual values directly correspond to the heat production in the heat grids. To achieve this required heat production, only the heat flow taken from the water reservoir or the solar collector area and the overall system configuration must be adjusted accordingly. Furthermore, a geothermal plant is usually operated as a base load so that constant hourly production is assumed during the year. In contrast, solar thermal generation varies considerably due to the diurnal and seasonal variation of solar radiation. Therefore, an hourly solar irradiance profile is used to derive hourly generation profiles.

(ii) Direct use of industrial excess heat

For this paper, the use of industrial excess heat in district heating is integrated into ENERTILE. This technology is modelled methodically analogous to geothermal energy. Consequently, the annual heat generation quantities are predefined, included in the scenarios, and converted to a constant hourly generation profile. Again, different utilisation rates and related costs are explored within the scenarios design (see section 2.4).

(iii) Large-scale heat pumps

Usually, all large-scale heat pumps in ENERTILE are simplified and modelled as air-source heat pumps. For this paper, the representation of large-scale heat pumps is amplified by integrating additional heat sources like water from rivers and lakes or wastewater. A methodological challenge in modelling heat pumps is representing the variable efficiency as realistically as possible. Since the coefficient of performance (COP) of heat pumps strongly depends on the variable temperature of the heat source, the COP is determined in the model in hourly resolution using a piecewise linear approximation function depending on the temperature of the heat source. Based on the assumptions of inlet and outlet temperatures of the heat source and sink, respectively, and the use of estimated Lorenz efficiencies of large heat pumps in district heating in Denmark [30], different linear approximation functions for the COP of the heat pumps are derived. Furthermore, two versions of linear functions are used in this analysis to reflect the two different temperature flow settings for district heating grids (high temperature vs. low temperature scenarios). For the heat source air, hourly average temperatures per country are used. Similarly, hourly average water temperatures per country based on [20] are used for rivers and lakes. Furthermore, it is assumed that rivers and lakes can only be used at a water temperature of 3°C and higher. As wastewater has a relatively stable temperature throughout the year, a constant COP for this type of heat pump is derived. To incorporate the upper limit of potentials for heat pumps with wastewater and rivers or lakes, additional capacity restrictions for these technologies are included in the linear optimisation with ENERTILE.

(ii) Biomass and waste

The use of biomass for district heating is limited according to the derived potential for each district heating type. Therefore, maximum generation restrictions limit the possible use of biomass for district heating. The same applies to heat from waste incineration.

2.4 Scenario design

The objective of this paper is to analyse the impact of varying shares of renewables and excess heat potentials in district heating on the system and district heating costs (compare section 1). Therefore, an explorative scenario-based approach including different scenarios for Europe for the year 2050 is chosen, scanning a broad solution space. In line, 10 scenarios are designed by varying the share of renewable and excess heat in district heating. In particular, in each scenario, the utilisation of geothermal energy, industrial excess heat and solar thermal energy is set to different levels with equal restrictions in the optimisation problem. Thus, a certain share of the district heating generation mix is fixed, and only the remaining supply to meet the demand is freely optimised with the remaining technologies (i.e. heat pumps, biomass and hydrogen boilers and CHP and waste CHP). This approach makes it possible to analyse the impact of different technology shares on the system and district heating costs.

To fix the levels of geothermal energy, industrial excess heat and solar thermal energy, the potential data provided per district heating type by [20] is used (compare section 2.3). In detail, in the scenarios, the utilisation rates of the technically available geothermal and industrial excess heat potentials are varied from 50% to 100%. As stated, solar thermal potentials are not provided by [20]. However, solar thermal plants can be utilised (almost) everywhere, as radiation is high enough in all European countries [31]. Therefore, solar thermal energy is included with a share expressed as coverage of the demand. In line with the literature [31], this share ranges from 5% to 10% in the different scenarios. In contrast, the potentials of rivers and lakes, wastewater, biomass and waste incineration provided by [20] are used as upper limits, and their contribution is freely optimised.

Table 1 provides an overview of the scenarios. The first scenario *RES* focuses on a generally high deployment of renewables and excess heat. Thus, the utilisation rates of geothermal and industrial excess heat potentials are set to 100%. Solar thermal is set to a maximal contribution of 10% of the district heating demand. In the second scenario *Geo*, geothermal potentials are set to 100% utilisation of the technical potentials, while industrial excess heat and solar thermal are reduced to half of their maximal contribution. Similarly, in the scenario *Solar,* a focus lies on solar thermal energy. Thus, solar is set to its maximal contribution of 10% of the demand, and the other potentials are reduced to 50%. In line, in the *IEH* scenario, industrial excess heat is set to 100% utilisation of the potentials and the two other sources are reduced to half of their contribution. Finally, the scenario *HP* focuses on a (potentially) high deployment of large-scale heat pumps. Therefore, geothermal, solar and industrial excess heat are reduced to half of their maximal contribution in order to have a high residual demand that is freely optimised. This overall scenario design is used for the high temperature (*HT*) scenario group and the low temperature (*LT*) scenario group, resulting in 10 different scenarios. Figure 3 provides a graphical illustration of the 10 designed scenarios.

All of the modelled scenarios achieve climate neutrality in the modelled year 2050. Assumptions in the other sectors, i.e. all sectors except the district heating supply mix, remain constant in the scenarios (e.g. assumptions for transport or industry). This means that effects caused by changes in the district heating supply mix can be identified, quantified and interpreted.

Table 1: Overview of the modelled scenarios

Scenario name	Utilisation rate of geothermal potential	Utilisation rate of industrial excess heat potential	Contribution of solar thermal as a share of demand
RES	100%	100%	10%
Geo	100%	50%	5%
Solar	50%	50%	10%
IEH	50%	100%	5%
HP	50%	50%	5%

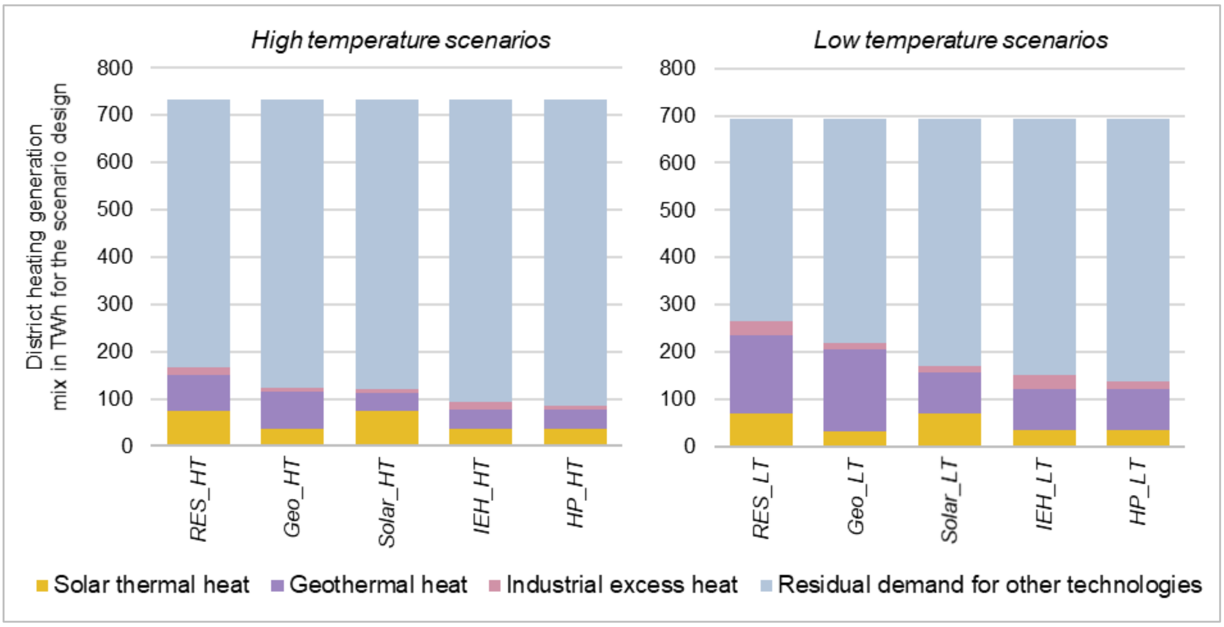

Figure 3: Overview of renewables and excess heat contributions in the scenarios

2.5 Data and assumptions

The future district heating demand in 2050 and heat potentials to cover this demand form the basis of the modelling analysis. The district heating demand for 2050 is based on [20] (building on [32]) and represents an increase of current district heating demand to 732 TWh in the *HT* scenarios and 695 TWh in the *LT* scenarios. Compared to current levels of around 445 TWh [21], this means an increase of at least 250 TWh (+50%). This ambitious deployment of district heating is overall in line with other energy system scenarios that foresee 400 to 800 TWh for district heating in Europe in 2050 (compare e.g. [2,9,17,33]). The district heating demand, covering all 5815 district heating areas in Europe in 2050, is used together with potential data [20], representing the technical renewable and excess heat potentials with high-spatial resolution that are spatially matched to the identified district heating areas (compare section 2.3). For spatial matching, maximum distances are assumed between the different heat sources and district heating areas [20]. Datasets related to [20] can be found in an online data repository.[2]

Besides the district heating demand, the scenario runs require demand data for all other sectors (e.g. electricity for appliances in households or for processes in the industry). The primary source for this

2 Fordatis - Research Data Repository of Fraunhofer-Gesellschaft; http://dx.doi.org/10.24406/fordatis/280

demand data set is the project 'Potentials and levels for the electrification of space heating in buildings' (ENER C1 2019-481) and, thereby, the *Elec_60* scenario [34]. The electricity demand from heat pumps and auxiliary energy demand are used as input for ENERTILE and were provided by the model INVERT in the named project. Details on the model INVERT can be found e.g. in [17,33]. Furthermore, hourly load profiles for decentralised electric direct heaters are integrated into ENERTILE. Losses incurred within energy distribution grids are accounted for (5.5% for electricity, and 10% to 16% for district heating, depending on the temperature level).

Renewable electricity generation is endogenously optimised (compare Figure 1). Thereby, lower limits are defined based on the current electricity generation in the countries [35]. In addition, upper limits for wind and solar are defined based on calculated generation potential (see methodology in [23,26] and compare Figure 1). For electricity generation from hydro and geothermal energy, it is assumed that their current production remains constant until 2050 [35].

Lastly, the optimal investment and operation of different technologies (in heating and electricity) depend strongly on the assumed energy carrier prices and techno-economic parameters of the technologies. In all scenarios, a very high CO_2 price of 500 €/t in 2050 is assumed in order to achieve a climate-neutral energy system. Furthermore, an interest rate of 2% is assumed for all technologies in all scenarios, representing a social discount rate. The techno-economic parameters of the technologies comprise specific investments, variable and fixed operating and maintenance costs, efficiency, lifetime, etc., and are presented in Table A1 in the appendix.

3 Results

3.1 District heating generation

The district heating generation to meet the given demand is one of the main outputs of ENERTILE. In line with the input demand data, the district heating generation is, in general, higher in the *HT* scenarios with up to 767 TWh than in the *LT* scenarios with up to 743 TWh (compare demand data in section 2.5). Furthermore, the scenario groups and the scenarios have different technology mixes. Figure 4 shows the modelled district heating technology mixes on the European level in 2050 in the different scenarios.

The technology mixes in the scenarios **Error! Reference source not found.**show that heat pumps (air, rivers and lakes, wastewater) provide the majority of the heat in all scenarios. In line with the scenario design, the highest contribution of heat pumps occurs in the *HP_HT* scenario with 62% (459 TWh) and the *HP_LT* scenario with 66% (468 TWh). In terms of capacities, this relates to 209 GW in the *HP_HT* scenario and 219 GW of capacities for heat pumps in the *HP_LT* scenario. The lowest contribution of heat pumps occurs in the *RES_HT* scenario with 55% (420 TWh) and the *RES_LT* scenario with 54% (399 TWh). Hence, even in scenarios with a very high share of renewables and industrial excess heat, large-scale heat pumps cover more than half of the heat generation.

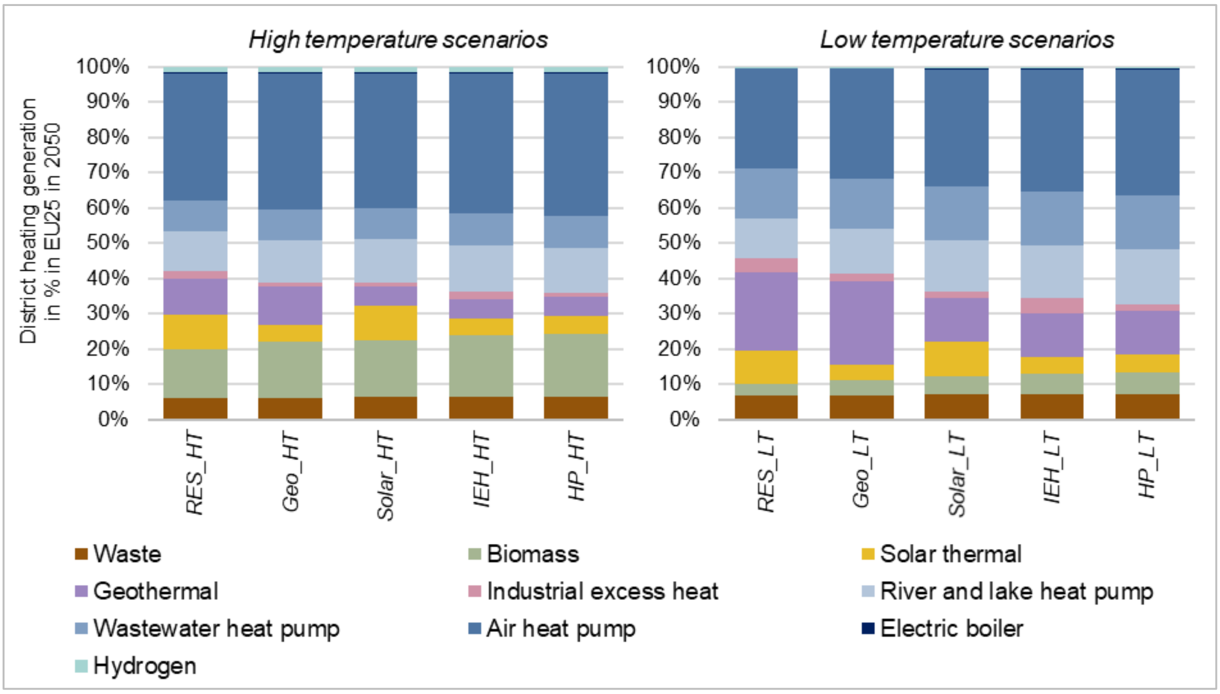

Figure 4: District heating generation mix in the scenarios in Europe in 2050

The results in Figure 4 show further that river and lake heat pumps and wastewater heat pumps significantly contribute to the share of heat pumps. River and lake heat pumps reach up to 13% (95 TWh) in the *HP_HT* scenario and up to 15% (108 TWh) in the *HP_LT* scenario. Wastewater heat pumps reach up to 9% (67 TWh) in the *HP_HT* and up to 15% (109 TWh) in the *HP_LT* scenarios. With the novel modelling approach, both technologies are freely optimised with an upper limit according to their potential (compare section 2). The results show that on average, river and lake heat pumps are utilised to around half of their limit, i.e. almost 60% of the potential is exploited. However, in several district heating types, the river and lake potentials are exploited to 100%. Wastewater heat pumps are on average utilised to their upper limit, i.e. around 95% to 99% of the potential is exploited.

As by scenario design, geothermal heat generation is highest in the *Geo* and *RES* scenarios, with up to 11% (80 TWh) in the *Geo_HT* scenario and 24% (174 GWh) in the *Geo_LT* scenario. Similarly, solar thermal and industrial excess heat enter the mix in line with the assumptions and the scenario design (compare section 2.4). In contrast, biomass is freely optimised in the scenarios with an upper limit. However, biomass shows only slight variations in the scenario groups. In the *HT* scenarios, biomass reaches a maximum of 18% (132 TWh) in the *HP_HT* scenario and a minimum of 13% (103 TWh) in the *RES_HT* scenario. In the *LT* scenarios, contribution reaches 3% (25 TWh) in the *RES_LT* scenario to 6% (45 TWh) in the *HP_LT* scenario. Overall, the biomass results show that less biomass is needed in the *LT* scenarios due to higher potentials in general and higher heat pump efficiencies. Furthermore, in both scenario groups, the biomass shares are slightly higher in the *HP* scenarios compared to the other scenarios, as less renewable and excess heat potentials are available.

The heat from waste incineration is more or less constant in the scenario groups, with 6% (46 TWh) in the *HT* scenarios and 7% (50 TWh) in the *LT* scenarios. Electric heaters only have very low shares in the generation mix in both scenario groups, mainly because of lower efficiency compared to heat pumps.

Lastly, hydrogen-based heat generation technologies have only a small contribution of around 2% in the *HT* scenarios and 1% in the *LT* scenarios. Hydrogen-based technologies show low generation but higher capacities. They have a backup role for district heating in times of electricity shortages as well as shortages of renewable and excess heat.

Figure 5 shows the district heating generation mix in 2050 in the scenarios per district heating type. In line with the definition of the types, Figure 5 displays multivalent district heating networks where one or two sources cover a large part of the demand, depending on the type.

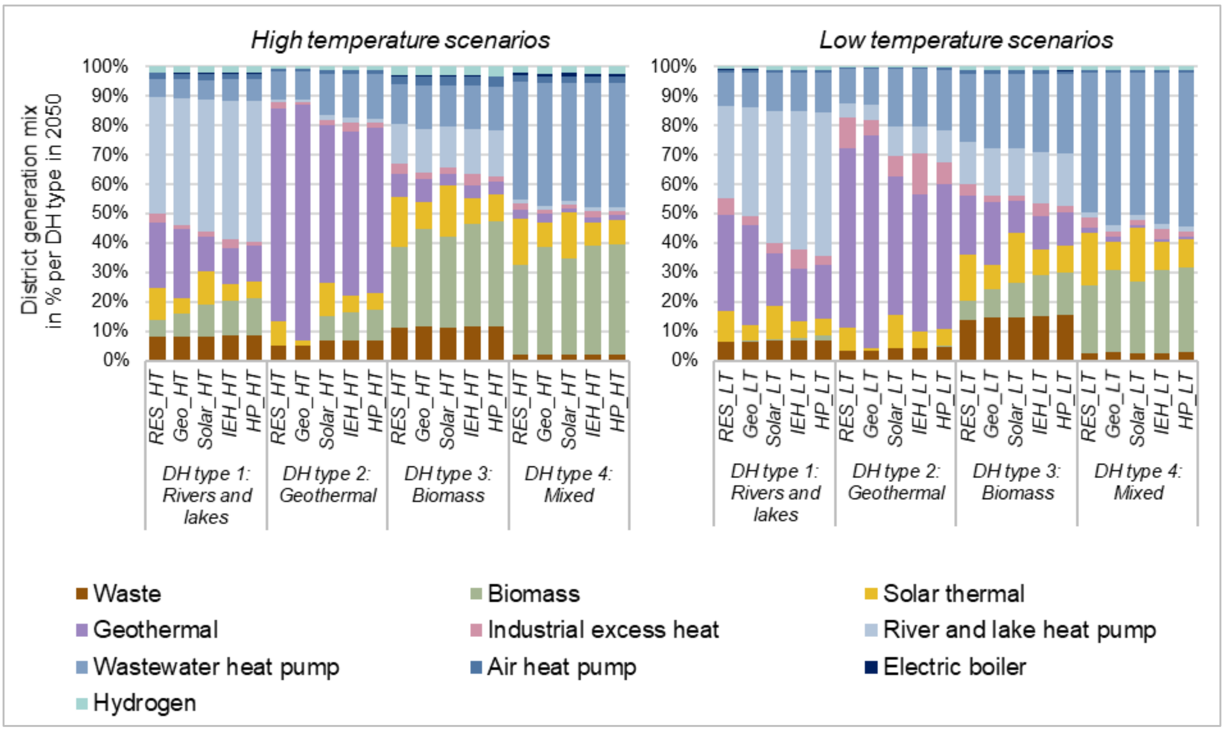

Figure 5: District heating generation mix in the scenarios per DH type in 2050

The technology mixes in Figure 5 show that in the *HT* scenarios, in *DH type 1*, river and lake heat pumps provide up to 50% (48 TWh) of the generation. *DH type 2* shows a very high share of up to 80% (30 TWh) of geothermal energy. In *DH type 3*, up to 36% (54 TWh) is covered by biomass. Finally, *DH type 4* shows a generation profile with up to 38% (10 TWh) biomass and up to 42% (11 TWh) wastewater heat pumps. Similarly, in the *LT* scenarios, in *DH type 1,* river and lake heat pumps can provide up to 49% (55 TWh) of the generation. In line, *DH type 2* shows a very high share of up to 72% (75 TWh) of geothermal energy. In *DH type 3*, around 15% (36 TWh) is covered by biomass. Again, *DH type 4* shows a generation profile with up to 29% (6 TWh) biomass and up to 52% (11 TWh) wastewater heat pumps. Notably, there are district heating types without the need for biomass, because other sources are available. In particular, in the *LT* scenarios, *DH type 1* and *DH type 2* have (almost) no biomass.

Overall, the results show that the district heating types capture the diversity and heterogeneity of the potentials. Hence, the resolution of district heating generation is greatly increased and the heterogeneous resource availability affecting the technology mix in district heating is more adequately reflected by the model extension.

3.2 Electricity generation

This section focuses on electricity generation to assess further differences between the scenarios. Figure 6 shows the modelled electricity generation mix in the scenarios in Europe in 2050.

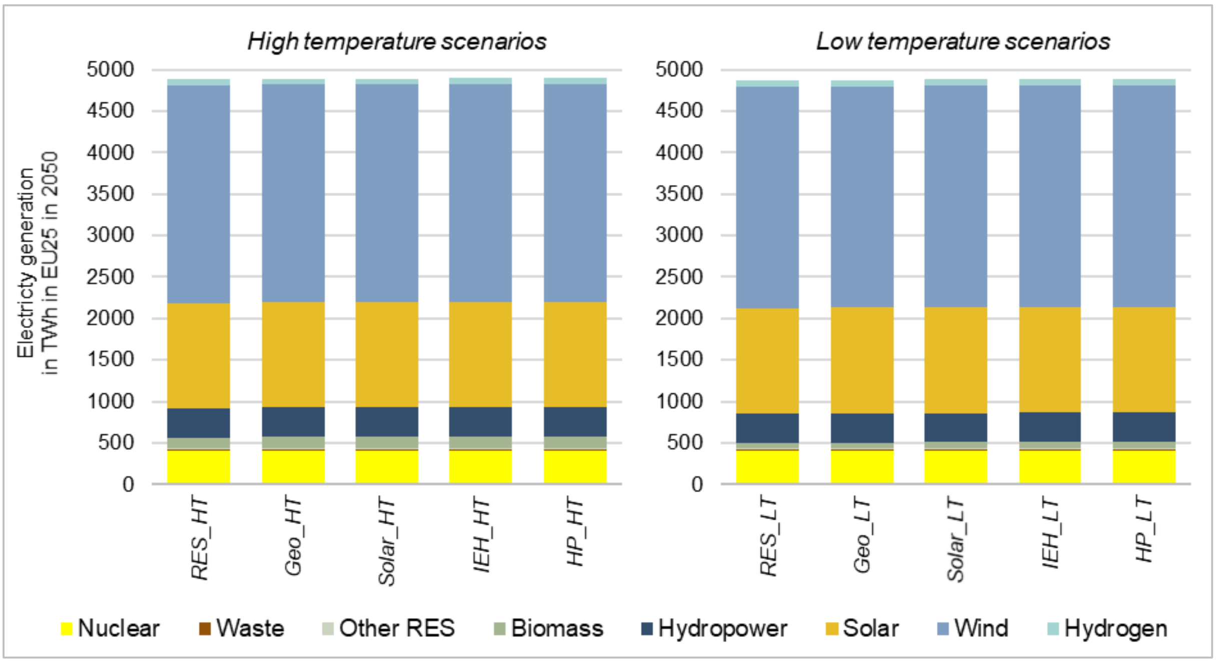

Figure 6: Electricity generation mix in the scenarios in Europe in 2050

One might assume that a higher share of heat pumps in district heating would lead to higher electricity generation, however, the differences between the scenarios are negligible. Overall, in the *HT* scenarios, electricity generation reaches from 4,895 TWh in the *RES_HT* scenario to 4,885 TWh in the *HP_HT* scenario. Thus, the difference is only 0.19%. Similarly, in the *LT* scenarios, generation reaches from 4,883 TWh in the *RES_LT* to 4,866 TWh in the *HP_LT* scenario, i.e. 0.35% difference. The maximal generation difference of heat pumps reaches 70 TWh heat (difference between *HP_LT* and *RES_LT*). This relates to 20 TWh difference in electricity needs, which illustrates why the differences in electricity generation are not visible.

Also, regarding the technology mix, there are no relevant differences. In all scenarios, electricity generation is vastly dominated by wind and solar. The need for flexibility to balance the energy system increases because of the high share of fluctuating renewable electricity. Energy storage, international trading and demand-side flexibility, electric mobility as well as hydrogen production provide the necessary flexibility in this future electricity system.

3.3 System and district heating costs

This last result section focuses on (i) overall system costs and (ii) district heating costs. The objective is to identify the lowest cost scenario, i.e. to analyse whether renewables and excess heat in district heating provide cost advantages. Thereby it is important to emphasise that the costs between the *HT* and *LT* scenarios should not be compared. For the *LT* scenarios, additional investments (e.g. in infrastructure and on the building side) and, thus, capital costs would be necessary in order to reduce the temperatures in the grids. District heating grid costs (e.g. for pipes) and costs on the building side are not in the scope of the ENERTILE modelling. Hence, a comparison of the costs between the scenario groups is not reasonable.

(i) System costs

The system costs (in billion (bn) €) are an output of ENERTILE. They represent the annualised cost of the energy system, covering all fixed and variable costs of the supply side as a whole. Figure 7 shows the differences between the system costs in the scenarios in Europe in 2050. Thereby the average of the system costs per scenario group serves as a baseline for the comparison. Thus, only the differences to this baseline are displayed. For example, the system costs in the *RES_HT* scenario are € 1.22 bn higher than the average costs of all *HT* scenarios.

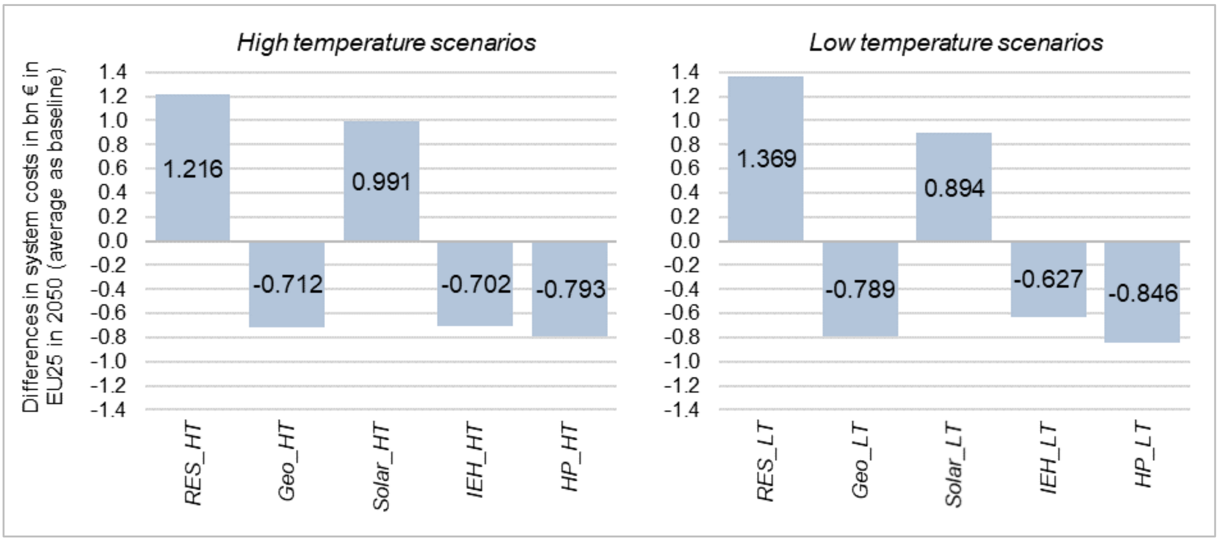

Figure 7: Difference in system costs between the scenarios in Europe in 2050

Comparing the system costs of the scenarios per scenario group shows a similar picture. In both groups, the *HP* scenario is the cheapest scenario, closely followed by the *Geo* scenario. Besides, in both groups, the *IEH* scenario shows lower system costs than the average of the scenarios. In contrast, the *RES* and the *Solar* scenario show higher costs than the average. Thus, independent of temperature levels, higher shares of heat pumps, geothermal and industrial excess heat in district heating seem to be cost-efficient for the energy system. The system cost comparison shows, however, that the differences between the scenarios are very small. In the *HT* scenarios, the differences are € 2.0 bn, which relates to only 0.7% of the total system costs. Similarly, in the *LT* scenarios, the differences are € 2.2 bn, i.e. 0.8% of the total system costs. Hence, the district heating generation mix has only a minimal impact on the overall European energy system costs.

Moreover, sensitivity calculations show that the system costs are very sensitive to the underlining cost assumptions. At the same time, costs for renewable and excess heat projects are still little explored. Geothermal investment, in particular, is highly uncertain. In the scenarios, the investment for geothermal is set to 1300 €/kW [30] (compare Table A1 in the appendix). If the investment could be reduced by more than 15%, the overall picture would change, and the *Geo* scenarios would become the cheapest scenarios as shown in Figure 8.

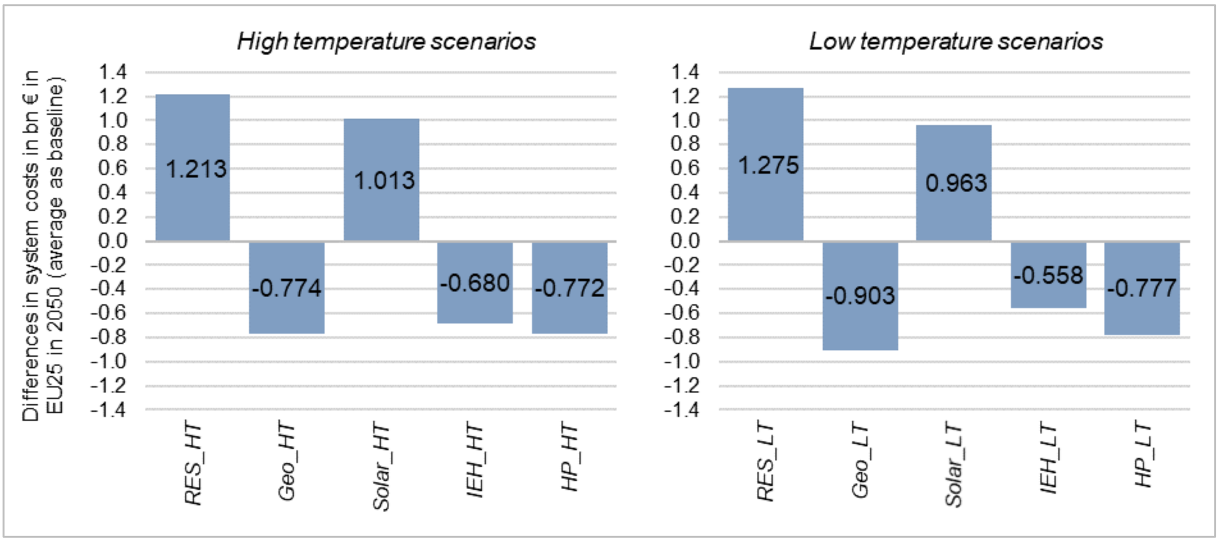

Figure 8: Difference in system costs between scenarios in Europe in 2050 with 15% reduced investment in geothermal energy (sensitivity calculation)

(i) District heating costs

The district heating costs (in €/MWh) represent the cost of district heating divided by the district heating generation. Thus, these costs reflect the fixed and variable costs of the total district heating generation. Figure 9 shows the differences between the district heating costs in the scenarios in Europe in 2050. Again, the average of the costs per scenario group serves as a baseline for the comparison. Thus, only the differences to this baseline are displayed. For example, the district heating costs in the *RES_HT* scenario are 1.24 €/MWh higher than the average costs of all *HT* scenarios.

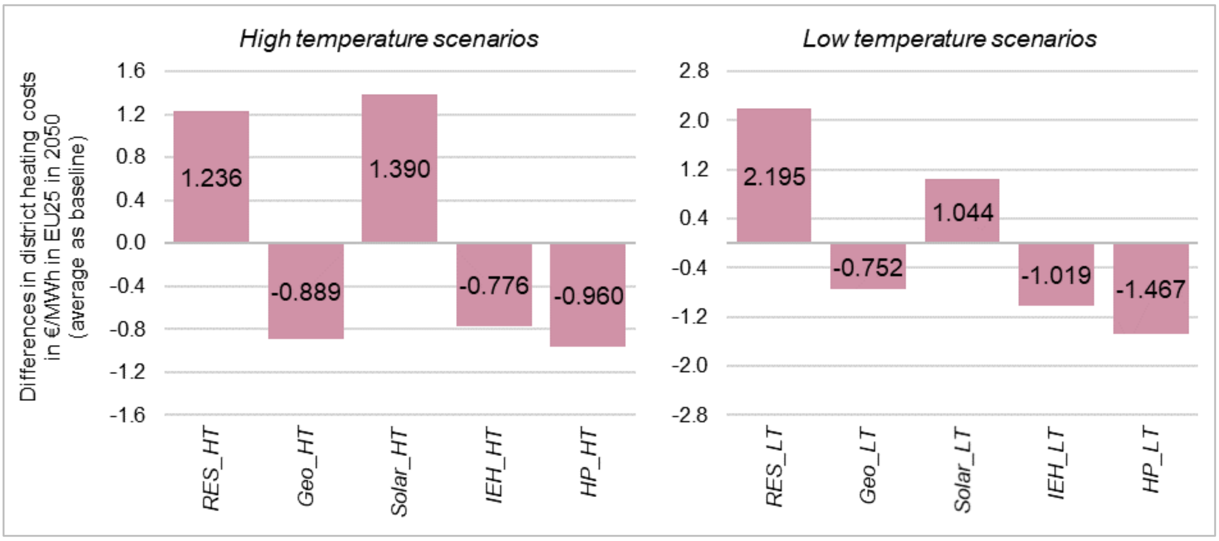

Figure 9: Difference in the district heating costs between the scenarios in Europe in 2050

The comparison of the district heating costs between the scenarios shows a similar picture to the comparison of the system costs. In both scenario groups, the *Geo*, *IEH* and *HP* scenarios are below average, while the other two scenarios are above average. Thus, in particular, high shares of heat pumps, geothermal energy and industrial excess heat seem to offer cost advantages for district heating. In both scenario groups, the lowest cost scenario is the *HP* scenario. Overall, the district heating generation mix has a greater impact on district heating costs than on total energy system costs. The differences reach up to 2.20 €/MWh (14%) in the *HT* scenarios and even up to 3.66 €/MWh (24%) in the *LT* scenarios.

4 Discussion

The optimisation results show that in all scenarios heat pumps reach high shares in the district heating generation mix in Europe in 2050. Even in the scenarios focussing more on renewable and industrial excess heat, heat pumps cover more than half of the demand. The main reason for this is the cost efficiency of heat pumps compared to the alternative technologies (i.e. biomass or hydrogen boilers and CHP etc.). Besides their economic advantage, heat pumps additionally offer valuable flexibility for the electricity system (see e.g. [26]).

The high shares of heat pumps are in line with results from other scenario analyses [2,17,34,36]. Compared to these existing studies, our results provide more technological detail and a more subtle view, showing that river and lake heat pumps and wastewater heat pumps can make a significant contribution to the district heating generation mix in 2050 (up to 15% each). These heat pumps are more efficient than air-source heat pumps, and their deployment should be focused on in further research. Furthermore, additional sources for heat pumps (e.g. near-surface geothermal energy and excess heat from data centres, shopping malls, metro stations and electrolysers) should be explored in future research.

According to the results, other generation technologies also have relevant contributions to an efficient district heating generation mix. Geothermal, solar thermal, and industrial excess heat enter the mix in line with the scenario design and assumptions. Biomass shows a higher generation share in the high temperature (*HT)* scenarios than in the low temperature (*LT)* scenarios. This is mainly because of lower geothermal and industrial excess heat potentials and lower efficiencies of heat pumps in the *HT* scenarios. Sensitivity analyses show, however, that heat generation from biomass is very cost sensitive. With a higher price (i.e. more than 13 €/MWh), even less biomass would be used and vice versa. Hence, the role of (sustainable) biomass and the various uncertainties regarding biomass prices should be analysed in future research.

Regarding the power sector, the results show negligible variation in electricity generation between the scenarios. The electricity demand increase in scenarios with a higher share of heat pumps is less than 1%. This is mainly reasoned by the high efficiency of heat pumps.

Similarly, the differences in the overall system cost between the scenarios are very low with less than 0.8%. Thus, the developments in the district heating mix seem to have only a very limited impact on the overall system costs. Nevertheless, the results show that higher shares of heat pumps, geothermal and industrial excess heat in district heating are cost-efficient for the energy system. In particular, the scenarios with higher shares of heat pumps reach the lowest system costs. This can be explained by their comparatively low (levelised) costs of heating and by their flexible contribution to the power system, helping to integrate a high share of fluctuating renewable electricity. However, the system cost comparison is very sensitive. The scenario with higher geothermal contribution could become the most cost-efficient one if the investment in geothermal plants could be reduced by more than 15%. Apart from cost advantages, geothermal energy could reduce the pressure on the electricity system, resulting from the overall increase in electricity demand.

In contrast, there are greater differences in district heating costs between the scenarios reaching 14% in the *HT* and 24% in the *LT* scenarios. Thereby, the overall picture is similar to the system cost comparison and shows that higher shares of heat pumps, geothermal energy and industrial excess heat offer cost advantages for district heating. Higher shares of solar thermal energy cannot provide cost advantages for district heating. This is most likely reasoned by the fact that the profile of solar thermal energy is less suited to the demand curve. However, it is important to note that the modelling analysis does not include seasonal storage[3], which could overcome this disadvantage of solar. Further research with seasonal storage should be carried out to analyse the optimal contribution of solar thermal energy.

5 Conclusions

A reduction in energy demand for heating buildings, in line with the energy efficiency first principle, is needed, while the remaining supply requires the use of climate-neutral and energy-efficient technologies. Electrification of heating is seen as the main solution for the supply side and involves a stronger integration of the heating and the power sector (compare section 1). The increased deployment of district heating plays a major role in decarbonising the heating sector. Besides the use of large-scale heat pumps, the optimal contribution of other climate-neutral heating technologies such as geothermal and solar thermal energy, and excess heat sources used directly or in combination with heat pumps, is not yet explored in detail in European energy system modelling analyses.

To fill this gap, this paper takes a novel approach and models different technology mixes in district heating for 2050 in Europe taking into account interaction with and impacts on the power sector while simultaneously using high-resolution renewable and excess heat potentials for district heating generation. Therefore, the analysis uses heat potentials, aggregated into district heating types, and integrates them into the existing energy system model ENERTILE. Accordingly, the representation of district heating is significantly improved.

A set of 10 scenarios is used to analyse different rates of potential exploitation and the impact on the overall energy system and district heating costs. Thereby, one set of scenarios focuses on high temperatures and one on low temperatures in district heating networks. Overall, the results show that the district heating types capture the diversity and heterogeneity of the potentials. Hence, the regionally heterogeneous resource availability affecting the technology mix in district heating is more accurately reflected by the novel modelling approach. Still, future research is needed on the required resolution of district heating in integrated energy system models.

3 In the district heating networks, water storage tanks that can store heat for several days are modelled, but no seasonal storages are included so far.

The optimisation results show that at the European level, high shares of heat pumps are achieved in all scenarios. Besides air-source heat pumps, river and lake and wastewater heat pumps can significantly contribute to the future generation mix (with up to 15% each). The advantages of lower grid temperatures are an increase in potentials, improved efficiencies for heat pumps and a reduced need for biomass. Nevertheless, (some) disadvantages, such as the need for investment in infrastructure and buildings to heat homes at lower temperatures, must be considered. Future research should focus on optimal grid temperature levels, e.g. with different temperature types.

With regard to system costs, the results indicate that the developments in the district heating mix have only a very limited impact on the overall European energy system costs. Nevertheless, higher shares of heat pumps, geothermal and industrial excess heat in district heating are cost-efficient for the overall energy system. Scenarios with the highest share of heat pumps are the cheapest, probably due to low generation costs and their contribution to flexibility in the power sector. However, the system costs are very sensitive to the cost assumptions. Hence, further research on costs for renewable and excess heat is needed.

When looking at district heating costs, the results show that a higher share of heat pumps, geothermal energy and industrial excess heat are cost-efficient for district heating. Hence, the research question of the paper can be answered to the extent that local renewable and excess heat sources indeed offer cost advantages for district heating and the overall energy system. In particular, high shares of heat pumps (utilising different sources such as air, river and lakes and wastewater), geothermal and industrial excess heat could offer cost advantages. In addition, they can contribute to the diversification of the generation mix for district heating. Future research should focus on the deployment of these technologies and sources in district heating to achieve a rapid market uptake and a climate-neutral energy system in 2050.

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Author contributions

Anna Billerbeck: Conceptualization; Methodology; Software; Formal analysis; Investigation; Resources; Data curation; Visualization; Writing - original draft

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Appendix

Table A1: Techno-economic parameters of investment options in ENERTILE IN 2050 [30,37]

Technology		Lifetime	Investment in €/kW	Fixed O&M in €/kW	Variable O&M in €/MWh	Efficiency el (chp)	Efficiency heat
Electricity	Battery storage	10	204	5.5	0.0	95%	
	Combined cycle hydrogen turbine	30	750	11.3	3.0	61%	
	Hydrogen turbine	30	400	7.5	1.5	41%	
CHP	Biomass CHP	25	2900	103	2.1	30% (71%)	
	Waste to energy CHP	25	6460	148	23.6	24% (80%)	
	Hydrogen CHP	30	950	30	3	48% (88%)	
District heating	Biomass boiler	25	750	42.9	0.7		103%
	Electric boiler	20	60	0.9	0.4		99%
	Air source heat pump	25	760	2.0	1.7		variable
	River and lake heat pump	25	380	4.0	1.7		variable
	Wastewater heat pump	25	570	2.0	1.7		variable
	Geothermal	30	1300	18.8	2		-
	Solar thermal	30	310	60	0		-
	Industrial excess heat	25	1500	80	5.6		-
	Heat storage	20	22	0.0	0.0		99%
	Hydrogen boiler	25	50	1.7	0.9		104%

Cover letter

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Prof. Brian Vad Mathiesen, PhD
Editor-in-Chief Smart Energy

Special Issue "Supply Chain Effects of the Energy Efficiency First Principle"

Smart Energy Editorial Office
Elsevier B.V.

Karlsruhe, 01.08.2023

Dear Prof. Vad Mathiesen,

we herewith submit a full-length research article entitled *"Integrating district heating potentials into European energy system modelling: An assessment of cost advantages of renewable and excess heat"* for consideration as an article in Smart Energy in the Special Issue *"Supply Chain Effects of the Energy Efficiency First Principle"*. We firmly believe that the article falls within the scope of the journal and addresses a timely and relevant topic of potentially large interest to the journal's readership.

In the article, we analyse scenarios for a climate-neutral and energy-efficient European energy system in 2050. The article pursues a novel approach to model the technology mix in district heating based on high-resolution heat potentials while simultaneously using an integrated perspective by modelling the whole European energy system (i.e., district heating and the power sector). District heating networks are very heterogeneous and at the same time, renewable and excess heat potentials are unevenly distributed, which justifies the novel modelling approach.

The results show that the heterogeneous resource availability affecting the technology mix in district heating is more adequately reflected by the model extension. Moreover, the high-resolution potentials allow for a detailed cost comparison of different possible future technology mixes in district heating. The article finds that the utilisation of heat pumps, geothermal energy and industrial excess heat can provide cost advantages for district heating and the overall energy system. Therefore, the article not only addresses a highly relevant research issue, which has not been adequatly analysed so far but also develops potentially highly relevant insights for policy making in the short and medium term.

We believe that the research article is appropriate for publication by Smart Energy because it presents novel research in the areas of optimization of district heating and smart energy systems. The article contributes to a better understanding of different technology mixe for district heating, related costs and their impact on the power system.

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We have no conflicts of interest to disclose. Thank you for your consideration of this manuscript.

Best regards,

Anna Billerbeck, Christiane Bernath, Pia Manz, Gerda Deac, Anne Held, Jenny Winkler, Ali Kök, Mario Ragwitz

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: