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Influence of heat pumps on renewable electricity integration: Germany in a European context

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ABSTRACT

Reducing CO_2 emissions, as targeted by the European Union, requires the substitution of fossil fuels with renewable energies. This reduces the CO_2 intensity of electricity generation and this low carbon electricity can then be used in other sectors, e.g. to decarbonize heating. Besides contributing to emission savings, this so-called sector coupling provides additional flexibility in the electricity sector and fosters the integration of renewable energies. We assess how heat pumps in district heating grids contribute to renewable electricity integration. We analyze different scenarios using the Enertile model, which optimizes capacities and dispatch of electricity and heat generation simultaneously. The results show that, the higher the achieved levels of decarbonization and renewable electricity, the more competitive heat pumps become in heating grids.

1. Introduction

The 2015 Paris Agreement aims to limit global warming to well below 2 °C by reducing global greenhouse gas (GHG) emissions [1]. In this context, the European Union intends to reduce GHG emissions by at least 80% by 2050 relative to 1990 levels. The majority of GHG emissions originate from the combustion of fossil fuels. In order to achieve climate targets, these energy-induced GHG emissions must be substantially reduced by substituting fossil fuels with renewable energy sources (RES). Due to the ongoing expansion of wind and solar power, the CO_2 intensity of electricity generation continues to decline. There is broad consensus that this low carbon electricity can therefore be used to decarbonize other sectors, e.g. the heating sector. This approach is referred to as sector coupling and plays an increasingly prominent role in public debate among politicians and researchers. Besides contributing to emission savings, sector coupling can also provide flexibility in the electricity sector and foster the integration of renewable energies [2].

Almost 90% of the final energy consumption in German households in 2016 was attributable to the provision of useful heat [3]. Heat supply in the building sector is still primarily based on fossil fuels such as natural gas and heating oil, while renewable energies currently account for only 13% of the final energy consumption in the heating sector [3,4]. Similar conditions prevail in other European countries. Sector coupling is therefore a promising concept to reduce the emission intensity of heat supply. Decarbonizing the heating sector can make an essential contribution to meeting climate targets. In this context, we define sector coupling as the use of renewable electricity for heat generation, also denoted as power-to-heat.

Heat is supplied either by decentralized systems located close to the point of use or by centralized systems using heating grid to transport the heat generated by large plants to the consumer. Various centralized and decentralized power-to-heat options exist for the residential sector [5]. Electric heat pumps, for example, can provide heat at low temperature with high efficiency and can generate heat in both buildings and in heating grids. Heat pumps have recently become more important in the building sector, whereas large heat pumps are not yet common in district heating grids [6]. However, heating grids will become much more relevant for the decarbonization of the heating sector, especially given the ambitious climate targets set for the year 2050. Heating grids enable the use of systems with higher efficiency, the use of waste heat or renewable heat technologies [7]. Furthermore, the use of multivalent heat generation and heat storage in district heating grids offers considerable system flexibility during times of high RES production [8,9].

The intensified use of sector coupling options leads to an increase in electricity demand [10]. Consequently, sector coupling can only be beneficial to climate protection if primarily renewable energies are used to cover the additional electricity demand [11]. Furthermore, the increasing use of electricity has an impact on the power sector's infrastructure and system operation. This situation requires an integrated optimization of the energy system, which takes into account the interdependencies between heating and electricity generation.

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Numerous existing power system and market models have been extended and new models have been developed to assess the impact of power-to-heat technologies (a comprehensive review can be found in Ref. [5]). The majority of these assessments are based on simulations or cost minimization of the overall system costs of operation with hourly resolution. Some of them also optimize investments. Numerous assessments have been done for Europe, most of which focus on Denmark and other Nordic countries, but some on Germany [12–21]. These assessments investigated the cost effectiveness, and system integration of renewable energy sources and the decarbonization of the energy system. Most papers found evidence that residential power-to-heat options have the potential to contribute to the system integration of variable RES. This integration is achieved through better utilization of existing assets and additional renewable capacity expansion, particularly when district heating systems can be used, but also for the system-optimal use of decentralized heat pumps [13,14,22,23]. Mathiesen and Lund [24] as well as Ostergaard [25,26] even conclude that centralized heat pumps are by far the most suitable technology to save non-renewable primary fuels by 2030. Other comparative analyses of sector coupling also conclude that coupling the electricity and heating sectors is the most cost-efficient option [24,27]. Most assessments see a multivalent district heating supply with a central role for heat pumps, while the contribution of the direct use of electricity in electric boilers is ambitious. The majority of studies are long-term scenario studies considering the years 2030 and 2050, which allows the analysis of the impacts of increasing shares of renewable energies in the energy system. Therefore, many studies assume a RES share of 40–60% and a few examine the electricity system with shares up to 100% [18,25,28–30]. Only some studies consider other sectors in addition to electricity and heat. Some model the mobility sector [24–27,29] or the cooling sector [25,29].

In general, there are three different perspectives of energy system models to analyze the benefits and challenges of power-to-heat options in power systems. On the one hand, there are models that are limited to mostly individual heating grids and in which, for example, the use of combined heat and power (CHP) generation or electricity-based heat generators are investigated. A certain fixed share of renewable energies in electricity generation is often defined for this purpose. In this model perspective, the connection of the heating grid modeling to the electricity system is often weak. On the other hand, there are electricity system models that consider the new exogenously defined electricity demand through power-to-heat technologies, e.g. of heat pumps or electric boilers, as temporarily flexible load profiles. In this model perspective, competition with other heat generation technologies is often not part of the model. In particular, heating grids with multivalent generation options are often not adequately depicted. In the third case of the energy system models, both electricity and the heating sector are at least partially modeled and the associated interdependencies between heat and electricity generation are explicitly considered. These models are often more complex, which can make the evaluation of the results more challenging. The influence of heat pumps on renewable electricity integration can therefore be examined with these three approaches. Either the influence on the use of heat pumps is analyzed under the assumption of a certain share of renewable energies in electricity generation. Alternatively, the impact of renewable electricity generation is analyzed by assuming a high share of heat pumps. However, assuming too many renewables or too many heat pumps may not be the most cost-effective solution from an overall system point of view. Iterative approaches of both mentioned procedures can improve the quality of the solution. Nevertheless, analyzing both parameters directly together in adequate level of detail in one single step, leads to a cost-efficient solution for the overall energy system. The expansion of renewable energies and the use of heat pumps are mutually influential and therefore it is necessary to model their interdependencies when analyzing sector coupling.

The aim of the present paper is to examine the contribution of heat pumps in district heating grids to integrate renewable electricity in Germany. We consider the interdependencies of sector coupling for the electricity and heating sectors by using the *Enertile* optimization model. This integrated modeling approach optimizes investment and dispatch of heating technologies in heating grids as well as conventional and renewable electricity generation in one single cost minimization problem. The model provides a detailed picture of the potential of solar and wind energies based on a geographic information system (GIS) model in high spatial resolution. The generation profiles of these renewable energies are based on detailed regional weather data and their expansion is endogenously optimized within the model. This integrated cost optimization approach including CHP, electric boilers and heat pumps in heating grids and the detailed future development of RES is, to the best of our knowledge, not found elsewhere in the literature. The use of this new approach can thus not only confirm existing findings but also provide detailed and new insights concerning the interaction between the electricity sector and district heating grids. Our scenario analysis examines Germany's energy system in a European context in 2050. We focus on the role of heat pumps in district heating grids and their impact on renewable electricity generation. Furthermore, we demonstrate the influence of national and European modeling on the results by considering Germany within an integrated European electricity market.

This paper is structured as follows. Section 2 introduces our modeling approach and relevant input data for the scenarios. Section 3 presents and discusses the results of our model-based scenario analysis. The final section draws conclusions from our findings and makes suggestions for further research.

2. Methodology

It is necessary to consider the interdependencies between heating and electricity generation when analyzing sector coupling. Therefore, we use the energy optimization model *Enertile*, which applies an integrated modeling approach to the electricity and heating sectors. Section 2.1 introduces the main features of the *Enertile* model and the representation of the heating sector. Section 2.2 summarizes our input data and assumptions for the scenario analysis.

2.1. Energy system model Enertile

Enertile is an energy system model focusing on the electricity sector developed at the Fraunhofer Institute for Systems and Innovation Research [31–33]. *Enertile* is used for long-term scenario studies and designed to depict challenges and opportunities of increasing shares of renewable electricity in the energy system. The model also considers interdependencies with other sectors such as the heating and transport sector as well as the hydrogen economy [34].

2.1.1. Enertile modeling approach

Enertile is a techno-economic optimization model that minimizes the costs of generation, transmission and storage of electricity for Europe and beyond. *Enertile* simultaneously optimizes the expansion of generation and grid infrastructures as well as their hourly operation based on the demand for electricity, heating, and hydrogen. The objective function contains all costs incurred by the major infrastructures. These infrastructures include conventional power plants, renewable energy technologies, combined heat and power, cross-border transmission capacities, storage technologies, and centralized heating technologies in heating grids. The most important constraints dictate that the demand for electricity, heating, and hydrogen in every region is met at all times. The temporal resolution is of great importance for analyses of energy systems with a high proportion of fluctuating renewable energies. *Enertile* has an hourly resolution and models every 8760 h of each analyzed year. Hereby, for example, extreme weather events like long calm periods or weak wind phases are considered. The electricity sector is in the focus of the modeling, but other demand areas such as electric mobility, decentralized heat pumps, and production of hydrogen are also represented in more detail. Furthermore, *Enertile* models large district heating grids with multivalent heating in hourly resolution.

The expansion of wind and solar energy is based on a potential analysis with a GIS model in a high spatial resolution [34,35]. The potential calculation is performed on a model grid with a tile length of about 7 km in Germany. The necessary geographical information and meteorological data are transferred to this model grid. The potential calculation for renewable energies takes place in several steps. The first step is to determine the usable area in each tile. Therefore, areas unsuitable for use, such as nature reserves and areas with very steep slopes are cut out. In addition, information on the type of land use (e.g. forest, wetland or cultivation area) and the weather time series are stored in the model grid. To calculate the potentials, hourly time series of solar radiation, wind speed and temperature are used. The long-term output potential for each technology is calculated based on weather data from 2007 to 2012. To calculate the technology-specific potentials, the installable capacity, the possible output and the specific generation costs for individual expansion steps are determined. Subsequently, the potentials within a country are aggregated and presented in the form of cost potential curves, which are integrated into the optimization problem. Electricity capacity and generation from other RES like biomass, hydro, and geothermal energy are exogenously predefined and based on constant or monthly profiles.

The modeled regions include all member states of the European Union, plus Norway and Switzerland, and countries in North Africa and the Middle East. Since network restrictions within regions are not considered, an unlimited electricity exchange is possible within a region. In power system modeling, this form of representation is referred to as a “copper plate”. Options for transnational balancing are considered via electricity trading between regions using a model of net transfer capacities (NTC). The decision to expand cross-border transmission capacities is part of the optimization problem considering the specific investments required. These grid expansion costs depend on the cost for different technologies, especially cables and overhead lines, and the linear distance between the centers of the regions. Furthermore, average transmission grid losses are considered and the default transmission costs for transporting electricity are 0.5 €/MWh. The resulting capacities including expansion are part of the solution. Existing conventional power plants are aggregated by fuel and efficiency category. Due to this aggregation procedure and the hourly resolution, part-load efficiencies or start-up costs are not modeled.

2.1.2. Modeling of heating in Enertile

The modeling of heating in *Enertile* comprises decentralized heat pump systems on the one hand, and district heating grids with multivalent heating on the other.

2.1.2.1. Decentralized heat pump systems. Each modeled heat pump system in *Enertile* consists of a building with a defined heat demand, a heat pump, and a heat storage. The building type, the insulation standard, and the architecture specify the building's annual heat demand. Hourly demand is calculated based on outside temperature, specific transmission, and ventilation losses as well as internal and solar gains. The efficiency of heat pumps depends on the heat source and its temperature as well as the flow temperature of the heating system. The heat storage has a capacity of two full load hours of maximum heat demand.

2.1.2.2. District heating grids. The heat supply in large district heating grids is modeled in *Enertile*. The annual heat demand is given exogenously for each region and year. The model scales this annual demand down to hourly demand as follows. First, the daily heat demand for district heating grids with mostly residential consumers is calculated based on district heating time series [36]. This calculation incorporates the daily average outdoor temperature. Finally, the hourly heat demand is determined using type-days. To meet this calculated heat demand, different generation options are available including CHP, gas boilers, electric boilers, large heat pumps, and heat storages. The decisions about investments in and the dispatch of heating technologies to meet heat demand are directly integrated into the system optimization [37].

The annual demand for district heat is usually derived from results of demand-side models, which model the costs of different heating technologies in buildings. This district heat demand is an exogenous input and *Enertile* optimizes the supply side. Costs for the network infrastructure of heating grids or the grid connection to buildings are not modeled. This means network expansion and densification are not explicitly considered in the model. Furthermore, gas distribution costs and mark-ups or takes on electricity used in the heating sector are not included.

2.1.2.3. Modeling of large heat pumps in district heating. Large electric heat pumps use environmental heat at a low temperature and electrical energy to generate useful heat at a higher temperature. Various heat sources like water, soil, waste heat or air are possible. The availability of these sources depends largely on local conditions. Furthermore, the costs of heat pumps vary considerably depending on type and heat source. In general, heat pump systems require high investments, but offer low heat generation costs [38]. The efficiency of heat pumps, indicated by the COP,[1] is highly dependent on the operating point. The smaller the temperature difference between heat source and heating system, the higher the COP. Large heat pumps typically reach COPs between 2 and 5, while maximum values up to 7 are possible [39]. The maximum flow temperatures are 80–100 °C for high-temperature heat pumps [38].

The large heat pump is modeled in *Enertile* as an air-based heat pump using ambient air as heat source since it is independent of local conditions, in contrast to other heat sources like waste heat from industry. When modeling heat pumps, one methodological challenge is to determine the variable efficiency. Since the efficiency of an air heat pump is strongly dependent on the variable temperature of the outside air, the COP in the model is determined with a piecewise linear approximation function and the ambient temperature in hourly resolution. The COP is calculated according to Equation (1) based on temperatures in 2010, T_A(h), and four parameters (COP_{a1}^{air}, COP_{a2}^{air}, COP_{b1}^{air}, and COP_{b2}^{air}) considering the type of heat pump.

$$COP(T_A,\ h) = \begin{cases} COP_{a1}^{air} \cdot T_A(h) + COP_{a2}^{air}, & T_A \leq 3°C \\ COP_{b1}^{air} \cdot T_A(h) + COP_{b2}^{air}, & T_A > 3°C \end{cases} \tag{1}$$

2.1.3. Formulation of the linear optimization problem

This section gives an excerpt and simplified version of the objective function and constraints of the linear optimization model. For reasons of space and clearness, only formulas and variables for the focus of this study on sector coupling of electricity and heat sectors are shown. A more detailed description and extended set of formulas of the electricity system model is found in Pfluger [32]. All scenarios in this paper are designed solely for a single year, but *Enertile* can also be used to determine development paths for multiple years, which are optimized together in a single model run. For this purpose, an additional index for the set of scenario years is integrated in the problem formulation given in this paper.

A linear problem is formulated taking into account all the input data. A complete nomenclature is given in Appendix A. This linear problem is defined for all hours of the year $h \in H$ and regions $r \in R$

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[1] The coefficient of performance (COP) is used to state the efficiency of heat pumps. It is defined by the ratio of heat generated to electrical power used by the heat pump.

considered in the scenario setting. The objective is cost minimization of all system components, including all technologies of the electricity sector $i \in I$ and heating technologies $ht \in HT$ in heating grids $hg \in HG$. The technology set I contains conventional power plants, renewable energy technologies, electricity storage plants, and cross-border transmission capacities. The set of heating technologies HT contains CHP, gas boilers, electric boilers, large heat pumps, and heat storages.

The objective is to minimize all the monetary costs linked to the decision variables for electricity generation x^{el}, heat generation x^{heat} and installed capacity X^{el} or X^{heat}. Costs comprise (i) the discounted (discounting factor δ) annualized fixed costs for expansion and (ii) the variable costs for generation. Fixed costs include costs for investment plus fixed operating and maintenance costs, together denoted as C^{fix}, multiplied by the respective capacity X^{el} or X^{heat}. Variable costs are fuel costs and variable operating costs c^{var} for the electricity or heat generation (x^{el} or x^{heat}). The objective function displayed in Equation (2) contains five components:

1. Total fixed cost of the capacity expansion in the electricity sector for all technologies i
2. Total variable cost of electricity generation for all technologies i and hours h
3. Total fixed cost of the capacity expansion in all heating grids hg for all heating technologies ht
4. Total variable cost of heat generation in all heating grids hg for all heating technologies ht in all hours h
5. Total variable cost of CHP electricity generation in all heating grids hg for all heating technologies ht and hours h

$$
\begin{aligned}
&minimize_{\vec{x},\vec{X}} \sum_{r\in R}\left(\sum_{i\in I}\left(\underbrace{\delta_i(C_i^{fix}\cdot X_{r,i}^{el})}_{expansion\ in\ electricity\ sector} + \underbrace{\sum_{h\in H} c_i^{var}\cdot x_{r,i,h}^{el}}_{electricity\ generation}\right)\right.\\
&\left. + \sum_{hg\in HG}\sum_{ht\in HT}\left(\underbrace{\delta_{ht}(C_{ht}^{fix}\cdot X_{r,hg,ht}^{heat})}_{expansion\ in\ heating\ grids} + \underbrace{\sum_{h\in H} c_{ht}^{var}\cdot x_{r,hg,ht,h}^{heat}}_{heat\ generation} + \underbrace{\sum_{h\in H} c_{ht}^{var}\cdot x_{r,hg,ht,h}^{el,chp}}_{chp\ electricity\ generation}\right)\right)
\end{aligned}
\tag{2}
$$

Key constraints of the model include hourly demand supply equations, which ensure that the exogenous electricity and heat demand in each individual region are met for every hour of the year. Equation (3) shows the demand supply equation for heating grids. Heat production $x_{r,hg,ht,h}^{heat}$ of all heat generation technologies ht minus the heat saved in the heat storage $x_{r,hg,h}^{Sheat,in}$ plus the heat withdrawn from the heat storage $x_{r,hg,h}^{Sheat,out}$ must correspond to the heat demand $D_{r,hg,h}^{heat}$ in every hour. A similar equation controls the heat demand and heat supply for decentralized heat pump systems.

$$
[DS_{hg}]\ \sum_{ht\in HT}(x_{r,hg,ht,h}^{heat}) - x_{r,hg,h}^{Sheat,in} + x_{r,hg,h}^{Sheat,out} = D_{r,hg,h}^{heat} \quad \forall\ r,\ hg,\ h \tag{3}
$$

Equation (4) gives the demand supply equation for electricity. Electricity generation $x_{r,i,h}^{el}$ of all technologies i plus CHP electricity generation $x_{r,hg,ht,h}^{el,chp}$ in all heating grids hg minus all technologies consuming electricity must match the electricity demand $D_{r,h}^{el}$. Electricity consuming technologies include electric boilers eb and large heat pumps hpg in heating grids and all decentralized heat pumps $hp \in HP$ in all buildings $b \in B$.

$$
\begin{aligned}
[DS_{el}]\ &\sum_{i\in I} x_{r,i,h}^{el} + \sum_{hg\in HG}\left(\sum_{ht\in HT}(x_{r,hg,ht,h}^{el,chp}) - x_{r,hg,h}^{el,eb} - x_{r,hg,h}^{el,hpg}\right) - \sum_{b\in B}\sum_{hp\in HP} x_{r,b,hp,h}^{el}\\
&= D_{r,h}^{el} \quad \forall\ r,\ h
\end{aligned}
\tag{4}
$$

In this representation, the electricity generation variable $x_{r,i,h}^{el}$ in Equation (4) summarizes several variables of different system components of the electricity sector. Variables that lead to an increase in the quantity of electricity have a positive sign, while variables that lead to a decrease in the quantity of electricity have a negative sign. Generation from conventional and renewable power plants, electricity imports from other regions, and electricity withdrawn from storages like pumped storages operating in generation mode are positive. Electricity exports to other regions, curtailment of excess renewable electricity, and electricity saved in storages like pumped storages operating in pumping mode are negative.

Several other constraints control that:

- Hourly generation of a production unit does not exceed its installed capacity.
- Electrical energy required by heating technologies is derived from the amount of heat produced and the efficiency of the conversion process of the technology.
- Current transmission flows between considered regions do not exceed the maximum transmission capacity of the respective grid connections.
- Heat and electricity storages only operate within the limits of their technical configuration.

2.2. Scenarios and assumptions

2.2.1. Definition of scenarios

We want to analyze the use of large heat pumps in district heating grids in Germany and the interdependencies with the electricity sector. In order to do this, we provide a model-based long-term scenario analysis using the *Enertile* model. We examine three main scenarios for the year 2050. By using a Greenfield approach neglecting existing power plants, the optimal solution indicates the most cost-efficient electricity and heating system for the given parameter settings. The linear optimization problem is constructed solely for the year 2050 and the minimum cost solution is determined. In the scenarios, electricity and heat generation are integrated in a single linear optimization problem. Therefore, we can analyze the effects of sector coupling on the electricity sector taking into account district heating grids and decentralized heat pumps. The analysis focuses on the role of heat pumps in district heating grids and the underlying electricity mix. In this study, industrial heating grids are not considered and we disregard coupling with other sectors like transport or industry. We explicitly excluded the other modeled demand areas such as electric mobility and hydrogen production in order to see the maximum possible effect of the heating sector. A mixture of several sector coupling options makes the identification of impacts and mechanisms much more complex or impossible. It is not the aim of this paper to compare different options for integrating fluctuating renewables into the electricity sector.

In the first scenario, we model Germany without considering its neighboring countries (GERMANY scenario). In the second scenario, we analyze Germany in a European context by extending the modeled region (EUROPE scenario). In this study, Europe comprises all the European Union member states as well as Norway and Switzerland. A third scenario introduces restrictions on network expansion for cross-border transmission capacities (EUROPE LIMITED scenario). Since price assumptions have a strong impact on results, we conduct a sensitivity analysis by systematically varying the prices for CO_2 and gas. We reduce and increase both prices by 50% and calculate a scenario for each price combination. The other settings remain unchanged based on EUROPE LIMITED scenario. Table 1 lists the scenarios and sensitivities as well as underlying key assumptions.

2.2.2. Data and assumptions

This section describes data and assumptions used for the previously defined scenarios. We show data for Germany and for Europe as aggregate to reduce complexity. Many data sets and assumptions are based on data from the SET-Nav Project [40]. There are four categories of input data required for the model.

Table 1
Overview of calculated scenarios and sensitivities.

Scenario	Region	Gas price (€/MWh)	CO_2 price (€/t)	Description
GERMANY	Germany	Medium	Medium	Scenario for Germany only
EUROPE	EU 28 + 2			Scenario with extended model region
EUROPE LIMITED				Scenario with limited expansion of electricity transmission capacities
Sensitivity 1		Low	Low	Sensitivities for CO_2 and gas prices
Sensitivity 2			Medium	
Sensitivity 3			High	
Sensitivity 4		Medium	Low	
Sensitivity 5			Medium	
Sensitivity 6			High	
Sensitivity 7		High	Low	
Sensitivity 8			Medium	
Sensitivity 9			High	

2.2.2.1. General input data. The first category comprises general input data like the interest rate for discounting, fuel and CO_2 prices. We assume a constant interest rate of 7.0% for different technologies and sectors in order to achieve fair competition between the technologies among each other. Furthermore, we assume a CO_2 price of 100 €/t in 2050. The fossil fuel prices in 2050 are a trend projection of the prices in the IEA 450 scenario [41]. We also conduct sensitivity analyses for price variations of CO_2 and gas (see Section 2.2.1). The medium gas price is 30 €/MWh as shown in Table 2. In the sensitivity analysis we use a gas price of 15 €/MWh for the lower end and 45 €/MWh for the higher end of the price range. The same applies to the CO_2 price variations with a low price of 50 €/t, a medium price of 100 €/t and high price of 150 €/t.

2.2.2.2. Demand for electricity and heating. The second category of input data covers the demand for electricity and heating. The electricity demand is based on the Primes Reference Scenario 2016 for the year 2050 [42]. The heat demands for district heating grids and for decentralized heat pump systems are taken from the ambitious policy scenario of the SET-Nav case study on "Energy demand and supply in buildings and the role for RES market integration" [43]. As Norway and Switzerland are not included in these two studies, their electricity and heating demand in 2050 is estimated with demographic data. In the ambitious policy scenario, district heating increases its market share, although total energy demand from district heating decreases slightly. Redensification existing and development of new district heating grids mainly compensate the decreasing useful energy demand due to thermal refurbishment. Table 3 shows the annual demand for electricity and heating in Germany and Europe. For data by individual country, see Table B1 in Appendix B.

2.2.2.3. Representation of renewable energy technologies. The third category of input data concerns the representation of renewable energy technologies. As previously described, the electricity generation potentials for wind and solar technologies are determined before the optimization with a GIS model. The outcomes are regionally defined cost potential curves comprising the potential capacity, annual specific cost and full load hours for individual expansion steps. For solar energy, a distinction is made between PV (utility scale and rooftop) and concentrating solar power (CSP). Wind energy is classified into onshore and offshore. The following figures show the aggregated cost potential curves for electricity generation from renewable energies in Germany (Fig. 1) and in Europe (Fig. 2).

Table 2
Assumed fuel and CO_2 prices in 2050.

CO_2 price (€/t)	Fuel prices (€/MWh)		
	Natural gas	Hard coal	Oil
100	30.0	6.2	42.5

Table 3
Annual demand for electricity and heating in 2050.

		Germany	Europe
Electricity (TWh_{el})		579.7	3797.9
Heat (TWh_{th})	District heating grids	60.0	382.7
	Decentralized heat pump systems	22.9	336.0

2.2.2.4. Other system components. The fourth category of input data covers the techno-economic characteristics of other system components like generation plants, cross-border transmission capacities, and storage technologies. All system components are depicted using techno-economic parameters including specific investments, variable and fixed operating and maintenance costs, efficiency, technical availability, running time, self-consumption and the utilized energy carrier. For cost assumptions on system components see Tables C2, C3 and C4 in Appendix C. The COP of large heat pumps in district heating grids is modeled using the parameters given in Table 4 (see Equation (1)).

We assume that as a minimum for the cross-border transmission capacities in 2050 the reference grid in 2027 of the current Ten Year Network Development Plan of ENTSO-E in 2018 is implemented [44]. We additionally define maximum limits for each transmission capacity in the scenario with restricted expansion and assume an increase of 50% as further electricity network expansion can be expected. For existing and maximum cross-border transmission capacities see Table D5 in Appendix D.

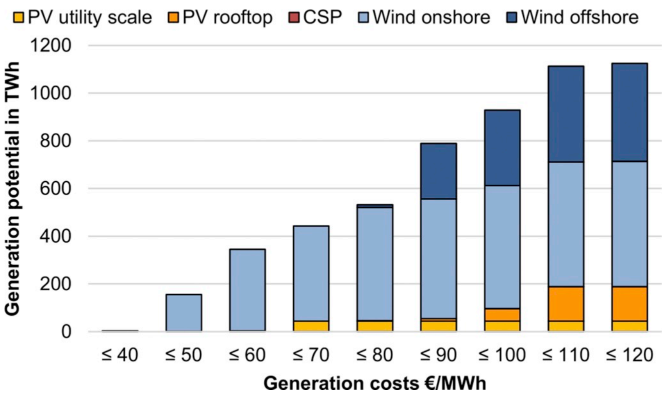

Fig. 1. Generation potentials of renewable energies in Germany in 2050.

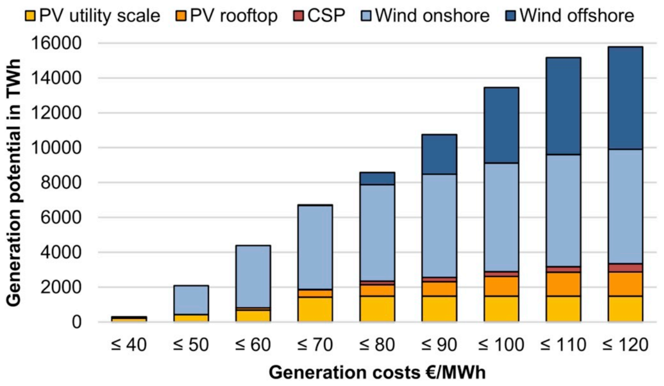

Fig. 2. Generation potentials of renewable energies in Europe in 2050.

Table 4
Parameters for modeling the COP of large heat pumps (see Equation 1).

Parameter	COP_{a1}^{air}	COP_{a2}^{air}	COP_{b1}^{air}	COP_{b2}^{air}
Value	0.02	1.8	0.063	1.65

3. Results and discussion

3.1. Results of the main scenarios

In the following, we present the aggregated results for the electricity sector and the heating grids in the three main scenarios. Fig. 3 shows the electricity generation in TWh and the heat generation mix in district heating grids in percent. We show results for Germany and for all countries in Europe including Germany in the scenarios GERMANY, EUROPE and EUROPE LIMITED. Electricity trading amounts are displayed as import and export for Germany, or as transmission losses when considering the entire modeled region. Table 5 lists curtailment and RES shares in the scenarios.

3.1.1. Results for Germany

Germany is the only modeled region and considered completely isolated from its neighbors in the GERMANY scenario. This limits the flexibility of the entire system as balancing electricity supply and demand across national borders is not possible.

Electricity production from wind energy (300 TWh) meets about half the electricity demand. In addition, a large solar energy capacity generates around 45 TWh of electricity. Renewable energies account for 66% of total electricity consumption. There is still a considerable proportion of conventional gas-based electricity generation (159 TWh) necessary to cover residual and peak loads. Gas-based CHP produces an additional 44 TWh of electricity and covers heat demand in the heating grid. Gas CHP dominates **heat generation** (61%). Electric and gas boilers each account for about half of the remaining heat demand. In this scenario, there are no heat pumps installed in district heating grids.

Overall, in the GERMANY scenario, it is not cost-efficient to operate large heat pumps in district heating grids. One reason is the limited flexibility in the electricity system. Curtailment, as an indicator of system inflexibility, equals 2% (8.7 TWh) of electricity production from renewable energies (see Table 5). This indicates that balancing supply and demand within Germany is impeded. In reality, Germany is well connected and integrated into the European electricity market. Therefore, the next scenario considers the energy system at European level.

3.1.2. Results for Europe

The EUROPE scenario optimizes the Europe-wide system of the electricity sector and heating grids. Supply and demand is balanced between different countries and cross-border flows are based on the transmission capacities.

Fig. 3 compares the **electricity generation** of Germany and Europe in 2050. Germany imports most of its electricity from other countries (319 TWh). It is more cost-efficient to import electricity than to build more power plants within Germany. The imports are primarily from Denmark, France and Poland. Electricity generation in France is based on wind and solar energy as well as nuclear power. Denmark and Poland have large wind capacities and export wind energy to Germany as well. Wind energy within Germany is another main source of electricity (300 TWh) to cover domestic demand. Solar energy produces 13 TWh. Renewable energies account for 62% of total electricity consumption. Electricity generation from fossil fuels is negligible. Nevertheless, 32 GW of gas turbines cover peak loads during a few hours of the year in Germany reaching 203 full load hours.

In contrast to Germany, other European countries still use nuclear power in 2050 to produce around 435 TWh of electricity. Apart from nuclear power, electricity production in Europe is almost completely based on renewable energies. Wind energy produces 2147 TWh and solar energy 639 TWh. The optimized solution for Europe leads to a total RES share in Europe of 90%. The majority of Europe's wind capacity is located in the UK, France, Poland and Denmark, while solar energy is located predominantly in Spain, Italy and France. Fluctuating generation of wind and solar capacities is balanced by the exchange of large quantities of electricity between countries, which is associated with transmission losses of 55 TWh.

In this scenario, the **heat generation mix** in heating grids in Germany and in Europe is highly comparable. Gas-based CHP has only a small share in the heat generation mix, which is also apparent in the electricity mix. Heat pumps are the main source of heat generation and provide around 50% of the heat in Germany and Europe. Gas boilers also cover a considerable proportion of the heat demand in heating grids, while electric boilers play only a minor role.

The high share of heat pumps in heating grids indicates that their operation is cost-efficient in the EUROPE scenario. Electricity trading appears to be an important supportive factor for the use of heat pumps. However, expanding the transmission capacities drastically is likely to be difficult to implement in reality because of long project times, planning uncertainties and local opposition. Therefore, the next scenario addresses this topic.

3.1.3. Results for Europe with limited expansion of electricity transmission capacities

In the EUROPE LIMITED scenario, the expansion of the transmission grid is restricted by defining upper bounds for the maximum capacity of electricity transfer between countries. This decreases the transnational electricity exchange compared to the EUROPE scenario.

The result for Germany is between the previous two scenarios. Again, wind energy is the most important source of electricity generation (352 TWh) and electricity imports from neighboring countries contribute 190 TWh. Solar energy and gas CHP each produce around 40 TWh, while gas-fired electricity generation only contributes 13 TWh. For Europe, the electricity generation with restricted grid expansion resembles the unrestricted case in the EUROPE scenario. The biggest differences are less electricity trading and less wind energy. Around 160 TWh less wind energy is produced, since not all regional energy surpluses can be exported and transmission losses are reduced to 42 TWh. Gas CHP makes a small contribution to electricity generation and the heat generated at the same time is consumed in heating grids. Moreover, some gas-based conventional electricity generation is available to supply peak loads. The RES shares are 77% in Germany and 87% in Europe.

In the EUROPE LIMITED scenario, the resulting **heat generation mix** in heating grids in Germany and in Europe differs substantially. Gas CHP is the main heat generation source in Germany. Heat pumps in Germany meet 23% of district heating demand. Electric boilers have a

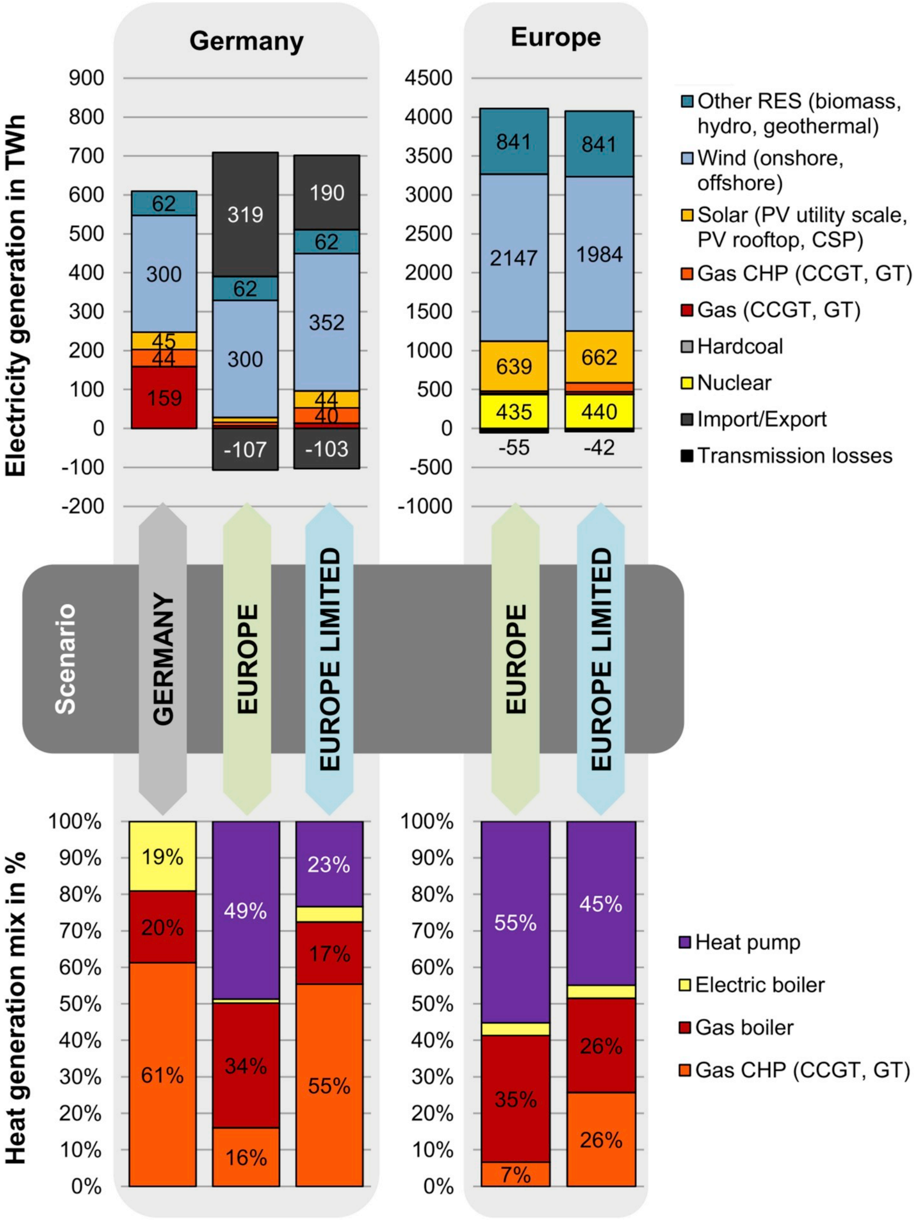

Fig. 3. Electricity generation and heat generation mix in district heating grids for Germany and Europe in 2050 for the scenarios GERMANY, EUROPE and EUROPE LIMITED.

rather small share and a utilization of 760 full load hours. In Europe, heat pumps cover 45% of the heat demand, while the shares of gas boilers and gas CHP are much lower.

In the EUROPE LIMITED scenario, operating heat pumps in district heating is cost-efficient. There are bigger differences between Germany and Europe because transnational electricity trading is limited and balancing supply and demand takes place more intensively within the borders of each country. The country's electricity mix determines how many heat pumps are used.

3.2. Comparison of the main scenarios

3.2.1. Utilization of heat generation technologies

We use an integrated modeling approach, which simultaneously

Table 5
Curtailment and RES shares for Germany and Europe in 2050 for the scenarios GERMANY, EUROPE and EUROPE LIMITED.

Scenario	Curtailment in TWh and % of RES production				RES share of total electricity consumption	
	Germany		Europe		Germany	Europe
GERMANY	8.7 TWh	2.1%			66%	
EUROPE	0.0 TWh	0.0%	31.5 TWh	0.9%	62%	90%
EUROPE LIMITED	0.3 TWh	0.1%	27.2 TWh	0.8%	77%	87%

optimizes electricity generation in the electricity sector and heat generation in district heating grids. The demand supply equations for electricity and heat are directly linked to each other by the corresponding generation variables (see section 2.1.3). Therefore, the current situation in the electricity sector has a decisive influence on the use of various heating technologies in heating grids.

Due to its high total efficiency, **gas CHP** is the preferred option at times with positive residual load in the electricity sector. This is mainly the case in the GERMANY and EUROPE LIMITED scenarios in Germany. CHP technologies can lead to fuel savings as they supply heat and electricity at the same time. The market potential of CHP technologies in the electricity sector is limited in the other scenarios, as CHP has to compete with low cost and low carbon generation technologies based on renewable electricity. This applies to the EUROPE scenario, in which large amounts of electricity based on RES is imported. This is also apparent in the heat supply mix, where CHP has only a small share in heat generation.

Gas boilers cover heat demand at times when the residual load is close to zero as no additional electricity generation is required. In all scenarios and regions, gas boilers account for a considerable proportion in the heating mix (17–35%). Higher shares correlate with lower shares of CHP generation and higher shares of heat pumps. This applies to the EUROPE scenario for both Germany and Europe.

Furthermore, **electricity-based technologies** like electric boilers or heat pumps are used during hours with negative residual load. In these times, renewable electricity production exceeds electricity demand and the surplus is either curtailed or used to produce heat in heating grids. Whether electric boilers or heat pumps are used depends not only on the current situation in the electricity sector but also on the long-term cost efficiency of these technologies. Parameters like fixed cost, efficiency and utilization rate predominantly determine this cost efficiency. The duration, frequency and quantity of RES surpluses influence the achievable full load hours. In our scenarios, investments in heat pumps are six times higher than in electric boilers. Heat pumps require much less electricity than electric boilers to produce the same amount of heat since the COP of heat pumps is substantially higher than the efficiency of electric boilers. In our scenarios, we assume an efficiency of 0.95 for electric boilers and the annual COP[2] of the modeled heat pumps is around 3.2 in the results. Consequently, heat pumps are preferred for longer, more frequent and lower RES surpluses, while electric boilers are preferred for shorter, rarer and higher RES surpluses.

The electric boiler has the largest share in the heating mix in the GERMANY scenario (19%). There are only few hours with negative residual load in this scenario, and the electric boilers have around 1100 full load hours. In this case, it is not cost-efficient to install heat pumps compared to electric boilers. In contrast to this, heat pumps are preferred to electric boilers in the EUROPE and EUROPE LIMITED scenarios. Investing in heat pumps is cost-efficient due to the high utilization possible as there are high amounts of either renewable electricity produced within the country or imports of renewable electricity from neighboring countries. In the EUROPE LIMITED scenario, the share of electric boilers rises to 4% compared to 1% in the EUROPE scenario. The combination of both technologies can increase the flexibility in the electricity sector and thereby foster the integration of renewable electricity.

3.2.2. *Heat pumps, renewable electricity and electricity trading*

We want to analyze the influence of heat pumps on renewable electricity integration in our scenarios. At the same time, it is necessary to consider the availability of transnational electricity trading. On the one hand trading increases the flexibility of the electricity system and on the other hand, flexibility is an important influencing factor for both renewable electricity and heat pumps. Our scenarios reflect the availability of electricity trading in two different forms. First, the choice of modeling at national or European level affects the general availability of electricity balancing with neighboring countries. Modeling one country, e.g. Germany, completely isolated from its neighbors, represents an extreme scenario without electricity trading. Second, the assumptions on cross-border transmission capacities control the extent of transnational electricity trading.

In general, a system with limited transmission capacities can lead to high fluctuation in electricity generation and therefore a higher utilization of heat pumps in heating grids. Similarly, a system with higher transmission capacities and the same amount of RES leads to less fluctuation and a decreasing utilization of heat pumps. In our scenarios, however, the share of renewable energies and the share of heat pumps are both results of optimization and mutually influence each other. Therefore, the simple correlations described above no longer apply in our scenario analysis.

In the GERMANY scenario, there is no possibility of electricity trading, which leads to a RES share of 66% but no utilization of heat pumps. The lack of flexibility in this scenario seems to inhibit the cost-efficient use of heat pumps. In the EUROPE scenario, transnational electricity balancing of supply and demand is possible and large quantities of electricity are exchanged within the European electricity system. The RES share in Germany lowers to 62% but the share of heat pumps rises substantially to 49%. At the same time, the optimal RES share in Europe is 90% and heat pumps have a share of 55% in heating grids. In spite of the high RES share, less than 1% of the renewable electricity production is curtailed (see Table 5). The availability of the transmission grid and its unlimited expansion allows the construction of renewable generation capacities at the most suitable and cost-efficient locations. Electricity trading according to demand at all times allows balancing their fluctuating generation. Including these primarily renewable electricity imports, the RES share in Germany would be substantially higher. The conditions in this scenario are advantageous for the operation of heat pumps in heating grids.

In the EUROPE LIMITED scenario, transnational electricity exchange decreases due to restrictions on cross-border transmission capacities. Even though, electricity generation from wind and solar energy in Germany rises from 313 TWh in the EUROPE scenario to 396 TWh in EUROPE LIMITED, the imports decrease substantially from 319 TWh to 190 TWh. In this process, the RES share in Germany rises to 77% but the share of heat pumps lowers to 23%. Including the primarily renewable electricity imports would increase the RES share in Germany, but compared to the EUROPE scenario, the sum of imports, wind and solar energy is lower. Furthermore, the possible utilization of heat pumps in heating grids is limited, as the CHP generation in the electricity sector supplies part of the heat demand. Considering Europe, the RES share lowers to 87% and heat pumps account for 45% of heat demand in heating grids. Here, less renewable electricity leads to less heat pumps. Despite the still high share of renewable electricity and the limited electricity trading, only a small amount of electricity is curtailed (less than 1%). In this scenario, the heat generation mix in the individual European countries varies considerably. Balancing supply and demand takes place more intensely within each country and the availability of cost-efficient renewables determines the country's electricity mix.

The availability of transnational electricity trading is a crucial parameter for the utilization of heat pumps in heating grids. When limiting the modeled region or the grid expansion, the availability of low cost and low carbon generation technologies in the electricity sector of each country determines the heat generation mix in the respective country. In general, we observe an interdependency between the share of heat pumps in heating grids and the share of renewables in the electricity sector. High shares of renewables entail high shares of heat pumps and low shares of CHP.

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[2] The annual COP is defined by the ratio of the heat generated to the electrical energy consumed in one year.

Table 6

Comparison of total system costs and CO_2 emissions in 2050 for the three main scenarios.

Scenario	Total system costs in billion €[a]		Total system emissions in Mt. CO_2	
	Germany	Europe	Germany	Europe
GERMANY	44.0		74.0	
EUROPE	23.7	176.3	12.0	49.4
EUROPE LIMITED	32.1	180.7	24.4	83.5

[a] The total system costs do not include the capital costs for nuclear capacity.

3.2.3. Total system costs and CO_2 emissions

The scenario results reveal least-cost electricity and heating systems for the given framework conditions. Table 6 compares the total costs and CO_2 emissions for the energy system separately for Germany only and for Europe including Germany.

For Germany, the total system costs and the CO_2 emissions in the GERMANY scenario are the highest. Due to its restricted flexibility, large gas-fired capacities are necessary to meet the electricity and heating demand. These gas capacities have high costs and high emissions. The lowest costs and emissions for Germany emerge in the EUROPE scenario because Germany is able to import large amounts of low-cost electricity from abroad and thus requires fewer power plant capacities within its borders. Since wind is the main source for electricity generation, wind energy accounts for the main cost share. CO_2 emissions are very low because there are only small gas capacities within Germany. The system costs and CO_2 emissions increase under the limited electricity trading in the EUROPE LIMITED scenario. Limiting electricity trading implies the need for larger power plant capacities of conventional and renewable technologies within Germany.

Considering costs in the European context, there are only minor differences between the unlimited and limited trading scenarios. In the EUROPE scenario, total system costs are 2% lower than in EUROPE LIMITED. Furthermore, CO_2 emissions are much lower in EUROPE than EUROPE LIMITED, which is attributable to the higher share of renewable energies in the former. The limited network expansion in the EUROPE LIMITED scenario results in a similar level of costs but substantially higher CO_2 emissions for Europe.

Overall, the comparison reveals that the EUROPE scenario has the lowest costs as well as the lowest emissions for Germany and Europe. The comparison indicates that electricity grid expansion and electricity trading are important requirements for cost-efficient emission reduction. Isolated electricity systems on a national basis have higher costs and emissions. Thus, international cooperation appears to be crucial to achieving climate protection targets in a cost-efficient way. Countries with high potentials for solar and wind energy should fully exploit these resources. Countries with lower renewable electricity potentials should import renewable electricity rather than relying on conventional domestic power plants. Increased system flexibility due to electricity trading can reduce the overall costs and CO_2 emissions within Europe. Greater flexibility in the electricity system also supports more heat pumps in heating grids that contribute to cost-efficient CO_2 emission reduction.

3.3. Sensitivities to gas and CO_2 price variation

To test the influence of price assumptions on the results and findings, we systematically vary the prices for CO_2 and gas by reducing or increasing both prices by 50% for each price combination. The sensitivity analysis is based on the EUROPE LIMITED scenario and all other parameters remain the same. Table 7 gives an overview of the assumed prices for the nine sensitivity scenarios. Sensitivity scenario 5 is equivalent to the EUROPE LIMITED scenario with medium gas and CO_2 prices. The results are evaluated for Germany only.

Table 7

Overview of assumed gas and CO_2 prices in the sensitivities.

Sensitivity	S1	S2	S3	S4	S5	S6	S7	S8	S9
Gas price in €/MWh	15	15	15	30	**30**	30	45	45	45
CO_2 price in €/t	50	100	150	50	**100**	150	50	100	150

Fig. 4 illustrates the electricity generation in Germany in the nine scenarios of the sensitivity analysis. As expected, with increasing CO_2 prices conventional electricity generation decreases and the share of renewable energies and electricity trading increases. Wind power is the most important generation technology in almost all scenarios. Electricity imports also play a major role in the German electricity sector. Sensitivity 1, with a lower CO_2 price and lower gas price, has more than 300 TWh of gas-fired electricity generation, but only 39% renewables. Gas generation is competitive and cost-efficient compared to renewable electricity generation at this low price combination. If the CO_2 price increases to 100 €/t, gas-fired electricity generation is still competitive, but the RES share rises to 64% (Sensitivity 2). As the coal price is very low, coal-based electricity replaces gas-fired generation in the scenarios with a low CO_2 price (Sensitivities 4 and 7). As long as the CO_2 price is very low and there are no severe sanctions for the comparatively high emissions from coal-fired power generation, coal is preferred to gas in the case of higher gas prices. The RES shares in these two scenarios (Sensitivities 4 and 7) are only 62% or 63%. In the remaining scenarios, the RES share is higher because of the large proportion of wind (at least 325 TWh) and solar energy (around 45 TWh). The contribution of gas CHP to electricity generation varies considerably within the scenarios; this is also apparent for heat generation.

Fig. 5 shows the heat generation mix in Germany in the scenarios. Heat pumps have shares of up to 64% in heating grids in Germany. They only cannot compete with gas CHP and boilers if there are low gas prices combined with low or medium CO_2 prices. With rising gas and CO_2 prices and subsequently rising shares of renewable electricity, heat generation based on natural gas is gradually replaced by electricity-based heating technologies. Sensitivities 4 and 7 with low CO_2 prices stand out on the heat generation side, as they have a comparatively high proportion of heat pumps. Electricity generation from coal is more cost-efficient than natural gas with these price constellations (see Fig. 4). Heat pumps are a more favorable generation option for heat generation than gas CHP as they can use the electricity generated by coal power plants. This leads to low shares of gas CHP in heating grids. Gas-fired boilers cover the remaining heat demand.

The sensitivity analysis shows that heat pumps are a relevant and cost-efficient generation technology in heating grids for most of the analyzed price constellations. Price assumptions for fossil fuels, specifically natural gas, and for CO_2 influence the operating costs of competing technologies in heating grids. CHP plants can save fuel compared to generating heat and electricity separately based on fossil fuels. At low CO_2 prices, these fuel savings result in cost savings. Rising CO_2 prices lead to increasing shares of renewable energies. Consequently, CHP electricity generation has to compete with renewable electricity in more situations. High CO_2 prices cause high shares of renewable electricity produced at low cost and with low CO_2 emissions. Heat pumps can then use this electricity to produce heat. In general, the CO_2 price determines the share of renewable electricity and the overall decarbonization of the energy system. The higher the level of decarbonization, the more advantageous heat pumps become in heating grids.

4. Conclusions

In this paper, we assess how heat pumps in district heating grids contribute to renewable electricity integration. We use the energy

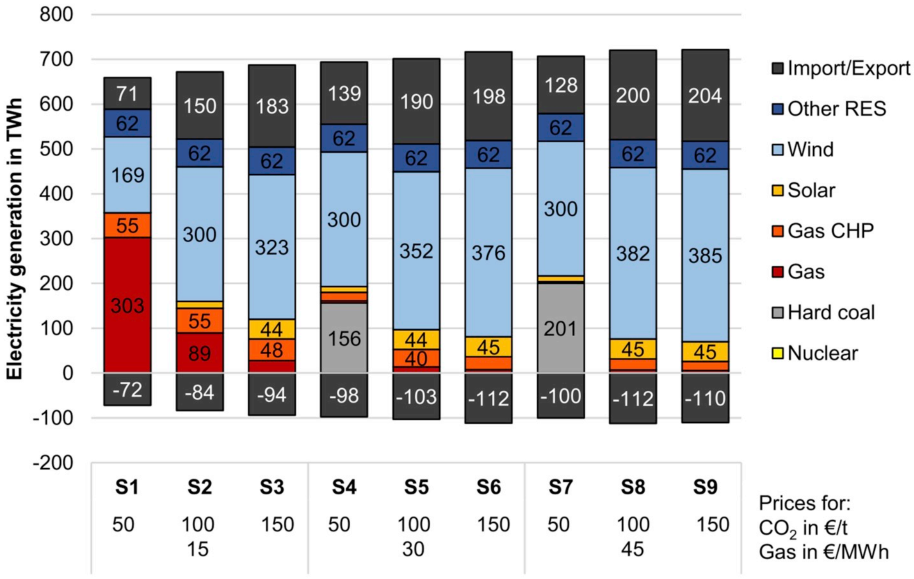

Fig. 4. Electricity generation in Germany in 2050 in the sensitivity scenarios.

system model *Enertile*, which applies an integrated cost-optimization of investment and dispatch to district heating and electricity generation. We examine the energy system in Germany in a European context for the year 2050 in three scenarios. The first scenario, GERMANY, models Germany in isolation without considering its neighbors. The EUROPE scenario analyzes Germany in a European context by extending the modeled region. The EUROPE LIMITED scenario restricts network expansion for cross-border transmission capacities. A sensitivity analysis of CO_2 and gas prices complements our analysis.

Our analysis shows that heat pumps play a major role in the investigated range of fuel and CO_2 price developments. Nevertheless, resulting shares of heat pumps in heating grids depend strongly on the framework conditions, such as CO_2 price, gas price and the flexibility provided by the European transmission grid. When limiting the modeled region or the grid expansion, the share of heat pumps decreases as it becomes more difficult to exploit the potential of low cost renewables and the appropriate utilization of heat pumps. The expansion of renewable energies in the electricity sector correlates with the selection of heating technologies in heating grids. The results show that the higher the achieved levels of decarbonization and renewable electricity, the more competitive heat pumps become in heating grids.

Our analysis focuses on the flexibility provided by district heating grids excluding other demand areas like industrial heating grids, electric mobility and hydrogen production. Considering further flexibility options could reduce the particular contribution of heat pumps to the integration of renewable energies [45]. However, integrating industrial heating grids could further enhance the use of heat pumps, as these offer high potential for heat pump applications [46]. The modeled heat pumps are using ambient air as heat source since it is independent of local conditions. Additional heat sources like industrial waste heat or underground sources could be superior alternatives for the application of heat pumps. Availability of these sources at European level requires further research. This also applies to the integration of renewable heating technologies like geothermal and solar thermal energy, which are competing technologies to heat pumps but depend heavily on the local environment.

Our analysis shows that integrated modeling of the electricity sector and heating grids can provide valuable insights for future decarbonization strategies. In particular, using a model with high temporal resolution makes it possible to consider fluctuating renewable

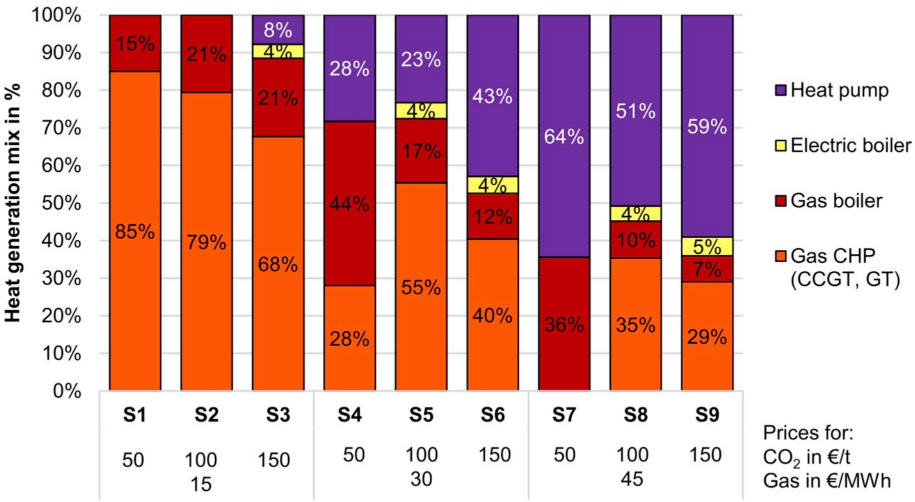

Fig. 5. Heat generation mix in district heating grids for Germany in 2050 in the sensitivity scenarios.

electricity generation and the time-varying efficiency of heat pumps more accurately. Consequently, research that focuses on improving the technological resolution of heat supply in such models can be particularly beneficial. An extension of the scope to include other sectors also subject to decarbonization could provide supplementary evidence.

Acknowledgements

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Appendix A. Nomenclature

Indices

h	Hour of the year index
r	Region index
i	Technology index
b	Building type index
hp	Heat pump in buildings index
hg	Heating grid index
ht	Heating technology index
chp	Combined heat and power (part of the heating technologies)
eb	Electric boiler (part of the heating technologies)
hpg	Heat pump in heating grid (part of the heating technologies)

Index sets

H	Set of hours of the year
R	Set of scenario regions
I	Set of technologies of the electricity sector
B	Set of building types
HP	Set of heat pumps in building
HG	Set of heating grids
HT	Set of heating technologies

Parameters

$D^{el}_{r,h}$	Electricity demand in country r in hour h in $\mathrm{MWh_{el}}$
$D^{heat}_{r,hg,h}$	Heat demand in country r in heating grid hg in hour h in $\mathrm{MWh_{th}}$
δ_i	Discounting factor for costs of technology i
δ_{ht}	Discounting factor for costs of heating technology ht
C^{fix}_i	Annualized specific fixed cost of technology i in €/$\mathrm{MW_{el}}$
c^{var}_i	Specific variable cost of technology i in €/$\mathrm{MWh_{el}}$
C^{fix}_{ht}	Annualized specific fixed cost of heating technology ht in €/$\mathrm{MW_{th}}$
c^{var}_{ht}	Specific variable cost of heating technology ht in €/$\mathrm{MWh_{th}}$

Variables

$X^{el}_{r,i}$	Capacity of technology i in region r in $\mathrm{MW_{el}}$
x^{el}	Unit of electricity produced in $\mathrm{MWh_{el}}$
$x^{el}_{r,i,h}$	Unit of electricity produced by technology i in region r in hour h in $\mathrm{MWh_{el}}$
$x^{el,chp}_{r,hg,ht,h}$	Unit of CHP electricity produced by technology ht in region r in heating grid hg in hour h in $\mathrm{MWh_{el}}$
$x^{el,eb}_{r,hg,h}$	Unit of electricity consumed by electric boilers in heating grid hg in region r in hour h in $\mathrm{MWh_{el}}$
$x^{el,hpg}_{r,hg,h}$	Unit of electricity consumed by heat pumps in heating grid hg in region r in hour h in $\mathrm{MWh_{el}}$
$x^{el}_{r,b,hp,h}$	Unit of electricity consumed by heat pump hp in region r in building b in hour h in $\mathrm{MWh_{el}}$
$X^{heat}_{r,hg,ht}$	Capacity of heating technology ht in region r in heating grid hg in $\mathrm{MW_{th}}$
x^{heat}	Unit of heat produced in $\mathrm{MWh_{th}}$
$x^{heat}_{r,hg,ht,h}$	Unit of heat produced by technology ht in region r in heating grid hg in hour h in $\mathrm{MWh_{th}}$
$x^{S_{heat,in}}_{r,hg,h}$	Unit of heat stored in region r in heating grid hg in hour h (inflow) in $\mathrm{MWh_{th}}$
$x^{S_{heat,out}}_{r,hg,h}$	Unit of heat stored in region r in heating grid hg in hour h (outflow) in $\mathrm{MWh_{th}}$

Appendix B. Demand for electricity and heating

Table B1
Annual demand for electricity and heating in 2050 [42,43].

Country	Electricity (TWh_{el})	Heat (TWh_{th})	
		District heating grids	Decentralized heat pump systems
Austria	82.8	13.7	9.1
Belgium	108.1	6.7	6.2
Bulgaria	35.6	1.5	4.7
Croatia	20.5	2.0	1.2
Cyprus	6.8	0.0	1.9
Czech Republic	79.1	13.8	6.3
Denmark	44.5	23.0	1.4
Estonia	9.8	2.7	0.1
Finland	96.1	32.4	21.7
France	547.5	21.6	114.6
Germany	579.7	60.0	22.9
Greece	56.4	0.6	8.3
Hungary	47.2	7.8	3.6
Ireland	33.9	1.6	2.9
Italy	394.8	7.6	34.2
Latvia	9.9	2.5	0.0
Lithuania	11.7	3.1	0.0
Luxembourg	12.0	1.2	0.4
Malta	3.1	0.0	0.2
Netherlands	132.8	12.3	9.1
Norway	148.0	18.4	6.4
Poland	202.3	12.1	13.2
Portugal	51.0	0.0	3.2
Romania	62.3	2.1	0.8
Slovakia	34.2	4.9	6.9
Slovenia	17.2	2.0	0.6
Spain	290.9	0.2	14.0
Sweden	165.8	34.9	12.2
Switzerland	76.1	13.1	8.7
United Kingdom	437.9	80.9	21.2
Europe 28 + 2	3797.9	382.7	336.0

Appendix C. Cost assumptions

The tables below show the costs assumed in the analysis for the year 2050. These include the costs for central power plants (Table C2), central CHP plants (Table C3) and heating technologies and storage (Table C4). The capacity expansion of nuclear plants is set exogenously for each modeled country. Therefore, no costs are given for nuclear power in Table C2.

Table C2
Overview of central power plant parameters (own assumptions)

Technology	Efficiency	Lifetime (a)	Investment (€/kW)	Fixed O&M (€/kW)	Var. O&M (€/MWh)
Coal steam plant	49%	40	1700	42.5	1.5
Combined cycle gas turbine (CCGT)	61%	30	950	11.3	3.0
Gas turbine (GT)	40%	30	450	7.5	2.7
Pumped storage	91%	40	1000	10.0	0.5

Table C3
Overview of central CHP plant parameters (own assumptions)

Technology	Electric capacity (MW)	Investment (€/kW)	Lifetime (a)	Power to heat ratio	Efficiency CHP	Electrical efficiency	Fixed O&M (€/kW)	Var. O&M (€/MWh)
Gas turbine CHP	90	730	30	0.63	85%	33%	30	1.5
Combined cycle gas turbine CHP	100	950	30	1.19	88%	48%	30	3.0

Table C4
Overview of central parameters for heating technologies and storage (own assumptions)

Technology	Thermal capacity (MW)	Investment (€/kW)	Lifetime (a)	Efficiency	Fix O&M (€/kW)
Gas boiler	5	50	20	94%	1.98
Electric boiler	10	100	20	95%	5.54
Large heat pump	10	600	20	variable	2.40
Heat storage	4.5	22	20	99%	0.00

Appendix D. Cross-border transmission grid capacities

Table D5
Cross-border transmission grid capacities in 2050 (Existing capacities based on [44])

From	To	Existing capacity (MW)	Maximum capacity (MW)
AT	CH	1700	2550
AT	CZ	1200	1800
AT	DE	7500	11250
AT	HU	1200	1800
AT	IT	1050	1575
AT	SI	1200	1800
BE	DE	1000	1500
BE	FR	4300	6450
BE	LU	680	1020
BE	NL	3400	5100
BE	UK	1000	1500
BG	GR	1350	2025
BG	RO	1500	2250
CH	DE	5600	8400
CH	FR	3700	5550
CH	IT	6000	9000
CY	GR	0	0
CZ	DE	2600	3900
CZ	PL	1200	1800
CZ	SK	1800	2700
DE	DK	4000	6000
DE	FR	4500	6750
DE	LU	2300	3450
DE	NL	5000	7500
DE	NO	1400	2100
DE	PL	5000	7500
DE	SE	1315	1973
DE	UK	1400	2100
DK	NL	700	1050
DK	NO	1700	2550
DK	PL	0	0
DK	SE	2440	3660
DK	UK	1400	2100
EE	FI	1016	1524
EE	LV	1379	2069
ES	FR	5000	7500
ES	PT	4200	6300
FI	NO	0	0
FI	SE	3200	4800
FR	IE	0	0
FR	IT	4550	6825
FR	LU	380	570
FR	UK	6900	10350
GR	IT	500	750
HR	HU	2000	3000
HR	SI	2000	3000
HU	RO	1400	2100
HU	SI	1200	1800
HU	SK	2000	3000
IE	UK	500	750
IT	MT	200	300
IT	SI	1895	2843
LT	LV	1500	2250
LT	PL	1000	1500
LT	SE	700	1050
NL	NO	700	1050
NL	UK	1000	1500
NO	SE	4145	6218
NO	UK	2800	4200
PL	SE	600	900
PL	SK	1980	2970

Appendix E. Abbreviations

CCGT	Combined cycle gas turbine
CHP	Combined heat and power
COP	Coefficient of performance
CSP	Concentrating solar power
DE	Germany
EU	European Union including Norway and Switzerland
GHG	Greenhouse gas
GIS	Geographic information system
GT	Gas turbine
NTC	Net transfer capacity
O&M	Operating and maintenance
PV	Photovoltaics
RES	Renewable energy sources

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