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The role and costs of large-scale heat pumps in decarbonising existing district heating networks – A case study for the city of Herten in Germany

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ABSTRACT

This paper discusses different decarbonisation scenarios for an existing district heating (DH) network supplied by coal-fired combined heat and power plants in Germany. Integrating higher shares of renewable heat is indispensable in reaching the climate goal and CO_2 emission reduction targets. The study analyses the technical and economic aspects of integrating various technologies such as solar thermal, biomass boilers, waste incineration plant and heat pumps into the existing DH network, with the main focus on large-scale heat pumps. The approach consists of two main steps. First, we forecast future heat demand and the potential to extend the DH system by simulating the evolution and energy consumption of the city's building stock. Second, we use a supply dispatch model with hourly resolution to calculate alternative scenarios and sensitivities for the supply mix with a focus on heat pumps.

Our results show that, under the current regulatory and economic framework, large-scale heat pumps are not cost competitive with the existing coal-fired CHP units. However, redesigning the regulatory framework and optimising heat pump design and operation could achieve cost parity. The CO_2 price induced by the EU emissions trading scheme will most likely not be a sufficient incentive in short and medium term.

1. Introduction

1.1. Background and objectives

In order to mitigate climate change impacts, Germany aims to reduce its GHG emissions by 80–95% compared to 1990 emissions [1]. Space heating and hot water heat demand in buildings were responsible for about 150 Mt CO_2 or around 17% of Germany's total GHG emissions in 2015 [2].

In this context, a successful energy transition without decarbonising the heating sector is hardly feasible. The starting points to reduce heat consumption in buildings are energetic refurbishments of older buildings and the construction of new energy-efficient ones. Based on the German government's climate protection report [3], around 1/3 of the anticipated GHG reductions in buildings until 2030 should come from decreased energy demand due to building refurbishments. The remaining 2/3 GHG reductions shall be provided by efficient and renewable heat supply. This means that the share of RES heat supply in the German heating sector must be significantly increased in order to achieve the GHG emission reduction targets. DH is a possible supply solution that enables the efficient integration of large-scale RES like solar thermal or biomass and the utilisation of various forms of excess heat [4–6]. It could also provide flexibility on the electricity market via power-to-heat (PtH) solutions with either direct electric heating or large-scale HP [7]. These benefits are recognized by the German government [8] and programmes are currently being developed to increase the share of DH networks, foster the transition to 4GDH, and bring a higher market share of PtH solutions. In one of these programmes [9], a DH is considered 4th generation if at least 50% of its heat input comes from RES (and maximum half of this from

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Abbreviations

CAPEX	Capital expenditure
CHP	Combined heat and power
COP	Coefficient of performance
CF	Capacity factor
DH	District heating
DHW	Domestic hot water
EEG	Erneuerbare-Energien-Gesetz (German Renewable Energy Sources Act)
FED	Final energy demand
GHG	Greenhouse gas
HP	Heat pump
LCOH	Levelized cost of heat
MFH	Multi-family house
O&M	Operation and maintenance
OPEX	Operational expenditure
PtH	Power-to-heat
Ren	Renovation
RES	Renewable energy source
RES-H&C	Renewable energy source for heating and cooling
SDH	Solar district heating
SFH	Single-family house
SH	Space heating
ST	Solar thermal
TES	Thermal energy storage
UESM	Urban energy system model
VAT	Value added tax
4GDH	Fourth generation district heating

biomass), it has a maximum supply temperature of 95 °C and comparable costs to fossil heating networks. On the other hand, DH also faces challenges like decreasing heat densities and the high upfront costs of infrastructure expansion. Further, integrating RES in an efficient way requires lowered supply temperatures (see discussion about 4GDH [10]).

The results of several studies [11,12], indicate that DH energy systems are more efficient when compared to individual heating and cooling solutions. Based on the case of Denmark, the optimal DH market share in a future 100% renewables-based energy system is between 55 and 65% of heat demand [13,14] despite the forecasted heat savings. The current heat supply mix in Germany consists mainly of natural gas and oil, whereas the DH networks are mostly supplied by gas or coal-fired CHP plants (Fig. 1). DH accounts for about 14% of the heat supply in buildings. In 2016, around 83% of the DH demand was supplied by CHP units, 15% by heat-only boilers and the remaining 2% by industrial excess heat [15]. Large-scale HP can play a crucial role in the transition from 3rd to 4th generation DH networks. Sweden is an internationally unique example of a country using PtH solutions in DH networks with a large-scale heat pump capacity of around 1500 MW and almost continuous operation for more than 30 years [16]. Until now, the major heat sources for large-scale HP have been sewage water, ambient water resources and industrial excess heat [17].

It is not yet clear what role DH will play in Germany's energy system, although most scenarios expect an increase in its share. Current scenarios for the future evolution of Germany's DH system range from a share of 20% [19] to 50% [20] in building heat supply, with a RES supply share of up to 88% in 2050 [21]. All the scenarios expect a high demand reduction of at least 40% due to improved building insulation.

Herten is representative for many cities in Germany: It has a large-scale DH system (the share of DH for residential heating and hot water was 28% in 2014), predominantly supplied by coal-fired CHP plants with some natural gas and oil back-up capacity. It is operated at high temperatures and faces the risk of decreasing heat demand due to building refurbishments. It does not yet include RES, but the city is committed to boosting the share of RES in DH supply. As the German government is planning to shut down all the coal-fired power plants until 2038[†] (many of which are scheduled earlier), this provides a window of opportunity for many utilities to invest in own heat generation capacities. This paper aims to answer two central questions:

i. What role does the existing DH network play in reaching Herten's climate protection targets?
ii. Are large-scale HP a cost-competitive DH supply option?

1.2. Literature survey

To be able to answer the questions raised before, we chose to use an urban energy system model (UESM) to answer these questions. Keirstead at al [22] identified the growing interest in urban energy consumption and the importance of UESM as a key tool in assessing better designs, new policies and related technologies based on a review of 219 papers dealing with urban energy systems. Allegrini at al [23] pointed out that no single tool provides the best combination of all the desired factors and the need for different tools to address planning, design and operation issues. Due to tightly restricted access to measured energy consumption in buildings and generally insufficient knowledge about the thermal properties of buildings, one of the largest remaining uncertainties for UESM simulations is data reliability of the analysed building stock [24].

We chose an approach combining building stock modelling, optimisation of energy supply dispatch and scenarios to construct a representative UESM for the city of Herten that will be able to answer the above-mentioned questions. A similar approach to assessing UESM for a different set of conditions has been taken in case studies in southern Europe [25], eastern Europe [26], and for other northern European cities [27].

In other studies, Van Leeuwen et al. [28] developed a computer model for energy priority scheduling and optimisation of renewable energy systems for a case study in Meppel, the Netherlands. Three different renewable energy concepts are evaluated and compared to a case reference in relation to costs, environmental concerns and applicability within the Dutch governance context. From the results it is observed that the reference case is financially more attractive than the renewables concepts and much higher CO2 prices are required to make the renewable concepts feasible. Andric et al. [29] analysed the influence of a future reduced heat demand caused by global warming and building renovation triggered by new building energy efficiency policies for a case study in Nantes, France. The results indicate a sharp demand reduction by 52% compared to reference level which decreases the DH linear heat density below the profitability minimum for a traditional DH network. Volkova et al. 25 [30]by using a large-scale DH network for a case study in Tallinn, Estonia have reviewed the barriers faced by existing DH systems in their process to transitioning to 4GDH. Based on the results the highest potential for improvement and

[†] Bundesnetzagentur - Power plant closure notification.

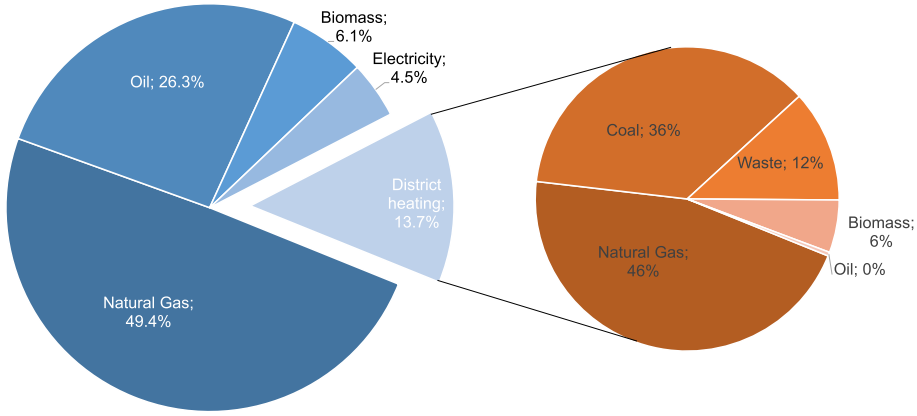

Fig. 1. Energy supply mix for SH and hot water in Germany (2015) (own representation based upon [15,18]).

notable impact exists with the supply and return temperatures, share of renewable energy and network conditions. Ziemele et al. [31] analyse the indicators that describe the overall efficiency of the DH system and restrictions for its transitions towards a 4GDH by using a case study in Jelgava, Latvia. By analysing possible 4GDH scenarios it was concluded that bio-scenarios can provide sustainable future of the DH systems. By using a case study in Trondheim, Norway Nord et al. [32] analysed the barriers in transition to low-temperature DH networks. From the results it is observed that the competitiveness of the DH network decreases for the heat densities lower than 1 MWh/m. Knies [33] has developed a framework for performing integrated energy planning for local area based on current German conditions. By using fuzzy logic and spatial mapping the study shows a way to analyse heat demand data which can contribute to more consistent and transparent urban planning process.

1.3. Previous work

This paper is an extension of a previous work [34] where the need for additional evaluation of the competitiveness of large-scale HP was identified. In the previous paper a similar methodology was used by constructing a detailed building stock model and using a DH dispatch simulation model in order to analyse four different scenarios. The first two scenarios represent the business-as-usual case with and without building renovation, and the other two scenarios with high share of RES in the DH network, with and without DH expansion. By constructing a detailed building stock we can explicitly consider its future changes and heat demand that has a direct influence on the cost-competitiveness of the DH network. Furthermore, by using a DH dispatch simulation model with hourly resolution individual units can be modelled and their influence on the overall DH costs can be assessed. As identified in the previous work, the introduction of heat pumps into the DH supply mix leads to much higher supply costs and have a negative influence on the competitiveness of the network. Hence, the focus of this study is on the role of large-scale HP. For this reason, three additional scenarios were simulated in order to analyse the most influencing factors of the competitiveness of large-scale HP and its interconnection with the other RES in the DH network as well. For the most cost-competitive scenario we conduct sensitivity analyses to identify the individual impact of several factors such as electricity price, investment costs, capacity factor, COP and DH supply temperatures. By focusing on each individual factor, we are able to construct two cases where the HP is cost-competitive with the coal-fired CHP and to provide further recommendations which can have a direct influence on the share of large-scale HP in the current and future DH networks.

After a short introduction to the modelled area, we describe the methods and data used. Based on this, we present the results for the examined scenarios. This is followed by a sensitivity analysis examining the cost-effectiveness of large-scale HP. The final part of the paper discusses the results and draws conclusions.

2. Herten case study and modelled area

The municipality of Herten is located in the Ruhr Area in Germany. It covers an area of 37 km^2 with around 60 000 inhabitants and 30 000 households [35]. The combined CO2 emissions in the municipality were approximately 419 thousand metric tons in 2011 [36]. Private households accounted for around 32% of this for SH and DHW. The total demand for heat in the residential sector in 2011 was around 470 GWh, supplied by natural gas (47%), DH (28%), heating oil (16%), coal (5%) and electricity (4%).

The DH network is divided into two parts (north and south) with limited interconnection and several island networks as presented in Fig. 2. Additional information concerning the current state of the DH network can be found in the annex.

3. Methodology and data

A five-step methodology was used in this study. Fig. 3 shows a flow chart of the applied methodology with the obtained results.

1. A detailed residential **building stock model** was constructed for Herten. This was done so that a realistic heat demand forecast can be made based on building stock data.
2. A **bottom-up building stock simulation model** was used to calculate the heat demand in buildings in order to forecast demand up to 2050. This can simulate possible new heat generation technologies, not only for the current heat demand, but also for future demand in line with transformation pathways to decarbonise the building sector.
3. **Hourly heat demand profiles** were generated. These are necessary so that the simulation of possible new DH generation technologies also considers weather-dependent influencing factors.
4. The **DH dispatch model** was constructed using the simulation software energyPRO by combining the results from the foregoing steps with techno-economic data on large-scale HP.

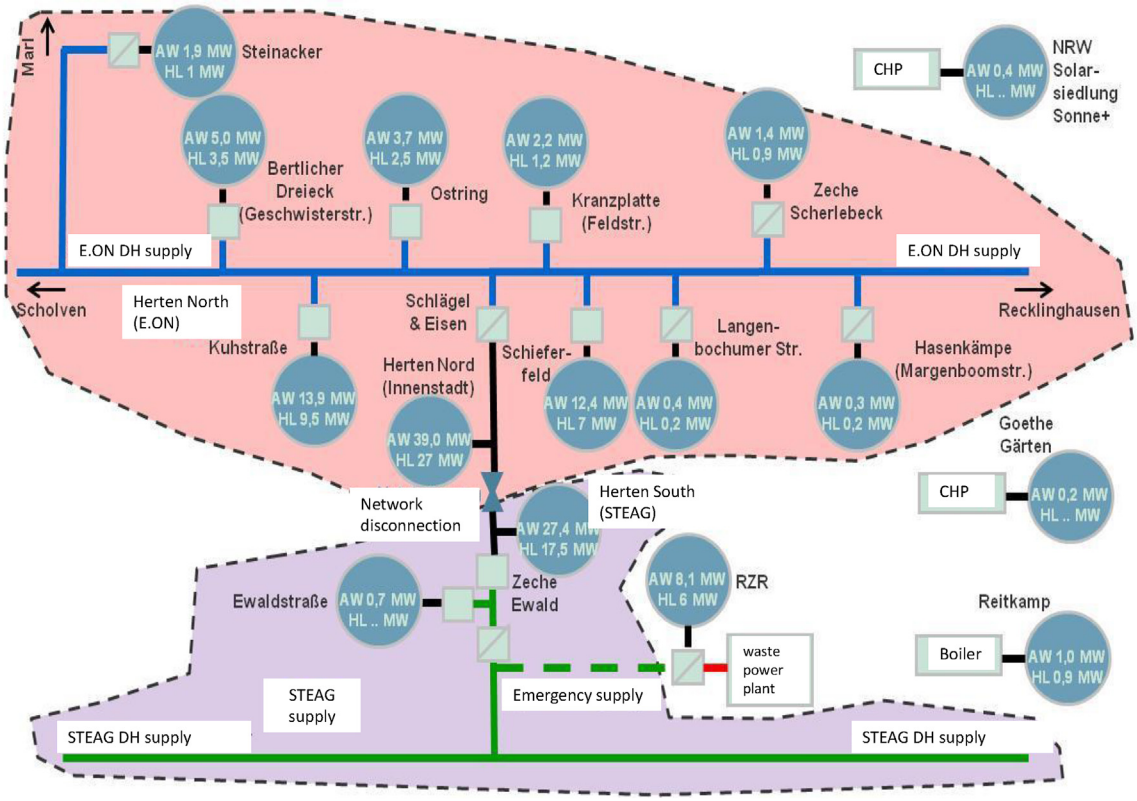

Fig. 2. Existing DH network in Herten [37] (AW-Connected load; HL- Peak load at −12 °C).

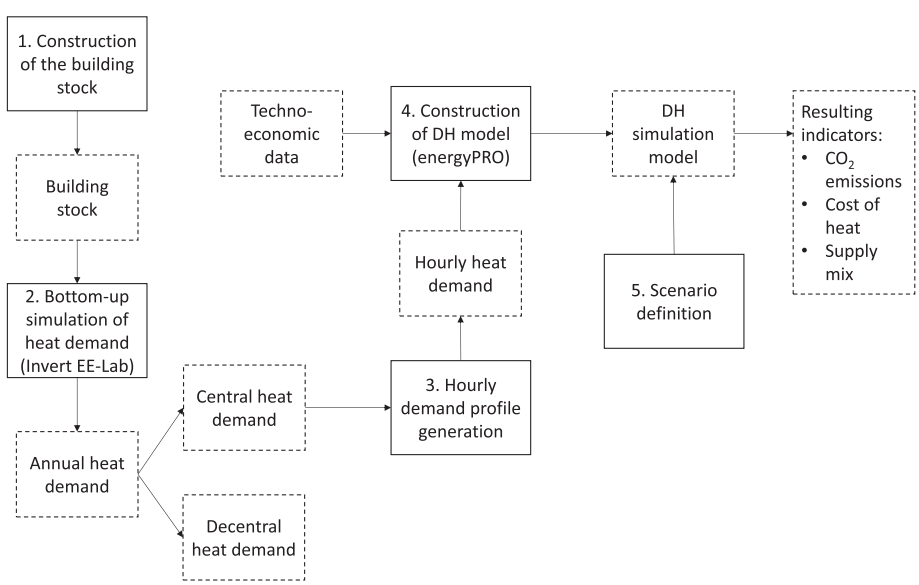

Fig. 3. Overview of the applied methodology and results.

5. **Scenarios** for a change of the supply mix in the DH were defined that incorporate large-scale HPs and assessed using the DH dispatch model.

3.1. Construction of the building stock model.

This section summarizes the construction of Herten's residential building stock model. Numerous publicly available sources, mainly maps, were used as the basis. The maps were used to generate a discrete building stock using a combination of remote sensing and on-site inspection methods.

A central source was the map of the so-called energetic urban space types [38]. In this map, the city of Herten is grouped into more or less homogeneous areas of house blocks. This map was combined with a map of building floor areas in Herten [39]. With the help of standard parameter sets for building types [40], the information on the energetic urban space types and building floor

areas was used to construct a building stock that is differentiated by location, building type, living space area and building age class. An essential step here was to redefine areas in the map of energetic urban space types more finely by remote sensing, since the existing structure was too crude. An exemplary sequence of the steps used for redefining one area is provided in Fig. 4.

In the final step, the total living space provided by the constructed building stock was compared and calibrated with official statistical surveys for Herten. In addition, selective on-site inspections were carried out to check the plausibility of the allocation of buildings to sites. A more detailed construction of the building stock is described in Refs. [34,41]. The summary of the resulting building stock differentiated by building types is given in Table 1.

3.2. Bottom-up simulation of heat demand

The current heat demand of the building stock differentiated by building type was calculated based on local utility data. The local utility evaluated the energy demand of the buildings in the city by analysing the demand for natural gas and DH at the customer delivery points. Based on this heat demand and the constructed building stock, projections are made until 2050 using the simulation model INVERT/EE-Lab 4 [42]. This model makes it possible to simulate the impact of current building standards, renovation on the evolution of the future building stock and the resulting energy demand. The projection is based on a target policy scenario for Germany that includes higher building renovation rates than the current ones [43]. Energy-related investments are simulated based on a combination of approaches from decision theory as well as diffusion theory [44,45]. The simulation model anticipates an average yearly rate of renovation of 1.5% (currently around 1.1% [46]) for the period between 2014 and 2050. This means that the annual renovation rates for a period of 15 years (e.g. 2020–2035) are higher than the current ones for SFH (2.4%) and a bit lower for MFH (1.1%). The current renovation rates in Germany are around 1% for SFH and 1.3 for MFH [46].

The model predicts a substantial decrease in heat demand from about 460 GWh in 2014 to around 220 GWh in 2050. The resulting demand reduction of around 52% lies somewhere in-between the reference scenario (38%) and the maximum achievable trend scenario (64%) [3]. The corresponding annual specific heat demand for SH and DHW is given in Table 2.

3.3. Hourly demand profile generation

The hourly demand profile was generated by splitting the annual demand of the DH network into hourly demand values. 80% of the DH demand was modelled as linear dependent on ambient temperatures to account for SH. This used a threshold ambient temperature value of 15 °C. It was assumed that there is no demand for space heat above this threshold. The residual 20% of DH demand is modelled independent of ambient temperatures based on the assumption that this mainly consists of residential hot water demand.

In order to compare whether this approach reflects real systems, the normalised profile applied has been compared with relative figures from measured data analysed in Conrad et al. [47]where the hourly demand profiles of DH networks in Germany and Austria are presented. Conrad et al. analysed the hourly demand profiles of DH networks in Germany and Austria. They derived a function using statistical analysis to predict the relative load of DH networks dependent on the ambient temperature. Fig. 5 shows the comparison of the two approaches. An average difference (mean bias error) of around 14% is observed possibly due to the aggregated number of networks considered in Conrad et al.

Fig. 4. Approach to redefine areas.

Table 1
Estimated stock and gross floor area for residential buildings in Herten.

Building type	Number of buildings [1000]	Plot area [km^2]	Gross floor area [million m^2]
Detached house	8.5	0.85	1.07
Terraced house	1.8	0.14	0.26
Apartment building	5.0	0.75	1.5
Large apartment build.	0.1	0.02	0.11
Total	**5.4**	**1.76**	**2.94**

Table 2
Estimated average annual FED for SH and DHW in kWh/m^2 per building type.

Building type	2014	2030	2050
Detached house	185	115	89
Terraced house	150	97	81
Apartment building	150	85	64
Large apartment buildings	83	64	54

3.4. Construction of the DH model.

The fourth step constructs the DH model using the energy modelling software energyPRO. First, RES heat generation technologies were chosen that are technically suitable and able to decarbonise the DH network in Herten. Secondly, techno-economic data were researched and assigned to technologies for modelling purposes. Finally, an initial system design was defined for the technologies (capacities, etc.).

3.4.1. RES supply units

In principle, large-scale solar thermal fields and HP seem to be the most (technically) viable options to increase RES in the DH in Herten in the long term. Thus, for the potential new mix of RES heat generation technologies, a SDH system together with a large-scale HP was chosen.

Biomass based solutions in the long term were only considered as option to cover peak loads. There are three main reasons why. First, a recent study developed pathways for the transition of the energy system that are compatible with the Paris Agreement and indicates that biomass- and/or biogas-based fuels might become scarce in the future [48]. Second, from an exergy point of view, HP are better for residential heating than biomass fuels, especially in a world with high shares of renewable electricity generation, which is Germany's goal. Third, Herten and its neighbouring cities have favourable conditions for large-scale HP as they are former coal mining areas. A local mining company annually pumps over 100 million cubic metres of water to the surface in the region to guarantee ground stability and safe drinking water. This pit water has a temperature of around 20 °C and could serve as the heat source for HP. Herten also seems to have sufficient agricultural land available for large-scale solar fields [39,49].

In addition, the city had already planned to use an existing waste incineration plant as a future heat supply for the southern part of the network because a large proportion of the available heat is currently not used.

3.4.2. Techno-economic data

3.4.2.1. Solar fields. CAPEX for solar thermal plants including storage are taken from solar DH guidelines [50]. The costs of land are derived from a Geographical Information System from the German state of North Rhine-Westphalia [49]. The lifetime was assumed to be 30 years for the solar plants including storages and the remaining technical characteristics are based on existing products [51]. Further results and modelled scenarios can be observed in

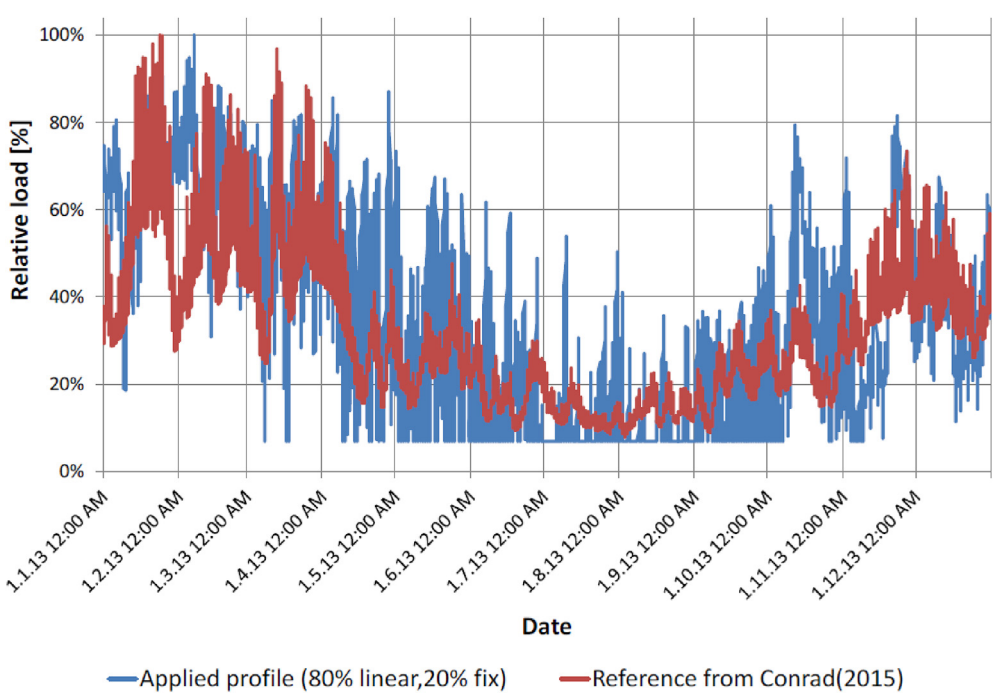

Fig. 5. Comparison of applied DH demand profile with Conrad (2015) [47].

Ref. [41].

3.4.2.2. Heat pumps. Two case studies were analysed for the heat pump model, one from Helsinki [52] and the other one from Bochum [53]. The Helsinki study features 5 HP with sewage as the heat source in the winter and seawater as the heat source in the summer. In total, the five HP have a maximum heat output of 83.9 MW in the winter and 90.6 MW in the summer. This provides reliable indications of the achievable COPs for large-scale HP depending on the heat source temperature. The Bochum study is of a demonstration project in nearby Herten, where pit water is evaluated as a heat source for ground source HP. This study provides measurement values for the temperature of the pit water in Herten. Table 3 presents the techno-economic data for the analysed HP model.

3.4.2.3. DH expansion cost. To calculate the CAPEX for expanding the DH network, a formula based on Persson et al. [55] is applied, which combines both heat and building density. The independent variables in this formula are population density, specific building space, specific heat demand and the effective width of the pipes. The dependent variable is the CAPEX per unit of energy additionally connected to the DH network (i.e. EUR/GJ annual heat demand). Persson et al. use empirical data from 83 cities in four European countries. The formula is used to analyse the potential CAPEX costs for expanding the DH network in areas within a city with different heat building densities (plot ratios) and under varying market shares for DH. Applying this formula to Herten yielded an average expansion cost for the DH network of about 7.3 EUR/MWh of additionally connected annual heat demand.

3.4.3. System design

The system design for the new RES heat generation capacities defines the size of the solar thermal collector field including storage volume and then the thermal capacity of the heat pump. A simplified piping scheme of the system design is presented in Fig. 6. Two criteria are applied: the LCOH and the heat delivered to the DH. The heat delivered to the DH by the solar field and the heat pump is compared to the overall demand and called the heat fraction. A stepwise approach is taken as described below.

→ First, the solar field and storage are defined so that the LCOH of the solar thermal collector field including storage is minimal ([34,41]).
→ Second, the thermal capacity of the heat pump is defined. Initially, this is done so that the current heat fraction is maximized for the combined system as much as possible. However, in the sensitivity analysis for the heat pump, the capacity is varied as well.

The energyPRO software [56] was used to model the DH supply mix. EnergyPRO is a modelling software package used for the combined techno-economic design, analysis and optimisation of a variety of heat, CHP, process and cooling energy projects. The software can conduct system optimisation of supply dispatch based on different technical properties of units, CAPEX, fuel costs, taxes and levies, fuel prices, weather conditions, etc. Fig. 7 illustrates a selected DH section modelled in energyPRO. The top graph shows a time series of the outside temperature. The middle graph shows the time series of the supply DH temperature, and the bottom graph illustrates the supply mix divided into solar thermal, HP and coal-fired CHP (obtained from the DH network in north Herten). As stated in chapter 3.3 a mean bias error of 14% is observed between the hourly data generated in energyPRO and the one of the aggregated data in Ref. [47]. This deviation might lead to some curtailment of the heat generated from the solar thermal system. Further calibration of the model was not considered due to the lack of measured hourly data for the specific DH network.

3.5. Scenario definition

The scenarios are distinguished in terms of alternative DH supply, DH expansion, thermal renovation, and decentralised supply. The techno-economic data defined above are the same across all scenarios. Please note that in the scenarios the potential new RES for the DH are added stepwise to show the effect of the thermal renovation, extended DH network, HP and the solar fields separated as well. Table 4 shows an overview of the considered scenarios:

- **Current situation (2014)**: Heat demand and supply shares of technologies are fixed at the 2014 level. At their end of life, old technologies are replaced by similar new ones. Energy prices develop as in the other scenarios.
- **1. RES for decentralised heat supply/no thermal renovation**: Replacement of individual heat generation units mostly by HP, biomass boilers, solar thermal and natural gas boilers and projections are made without any additional thermal building renovation. Thus, this scenario only shows the effect of replacing decentralised heat generation units. The DH network is still supplied by the existing coal-fired CHP units and is not extended.
- **2. Thermal renovation scenario**: Continuation of the conditions described in Chapter 3.2 that will lead to decreased demand due to building renovation and the replacement of old heat generation units. The DH network remains the same supplied by the existing coal-fired CHP units.
- **3. Renovation + Solar thermal in DH**: The same policies and measures as in the second scenario with the addition of 32 000 m^2 of solar fields and 6000 m^3 of thermal storages integrated into different parts of the DH distribution network.
- **4. Renovation + Heat pumps in DH**: The same policies and measures as in the second scenario. Three ground source heat pumps with a total installed thermal capacity of around 29 MW_{th} are integrated into different parts of the DH distribution network.

Table 3
Techno-economic data for the analysed large-scale HP model.

Economic data		Technical data	
CAPEX	1500 EUR/kWth	Supply from HP	80 °C
Economic lifetime	20 years	Return to HP	45–60 °C
Interest rate	7%	Heat source from	20 °C
Variable O&M	3 EUR/MWh	Heat source to	8 °C
Fixed O&M	1% of invest. annually	System efficiency	52%
Electricity price[a]	149 EUR/MWh	Average annual COP	3.02

[a] average price level excl. VAT for customers with annual consumption of 24 GWh [54].

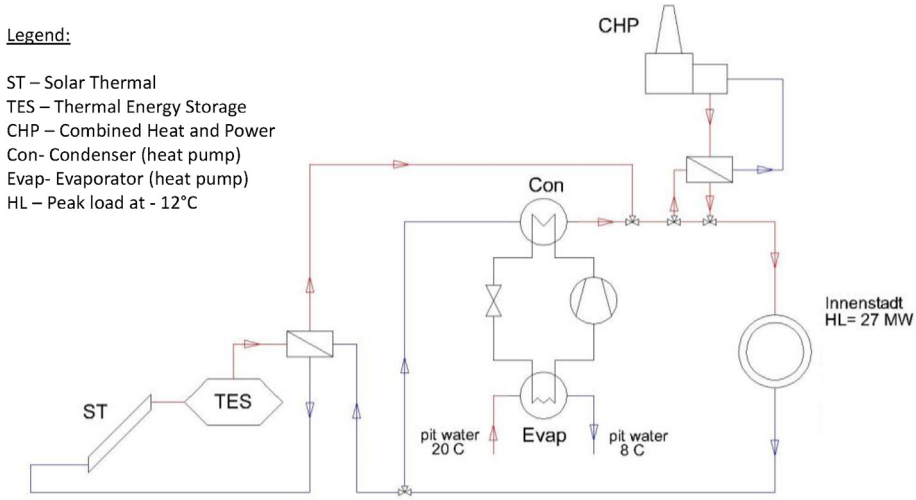

Fig. 6. Simplified piping scheme of the new system design for the Innenstadt district.

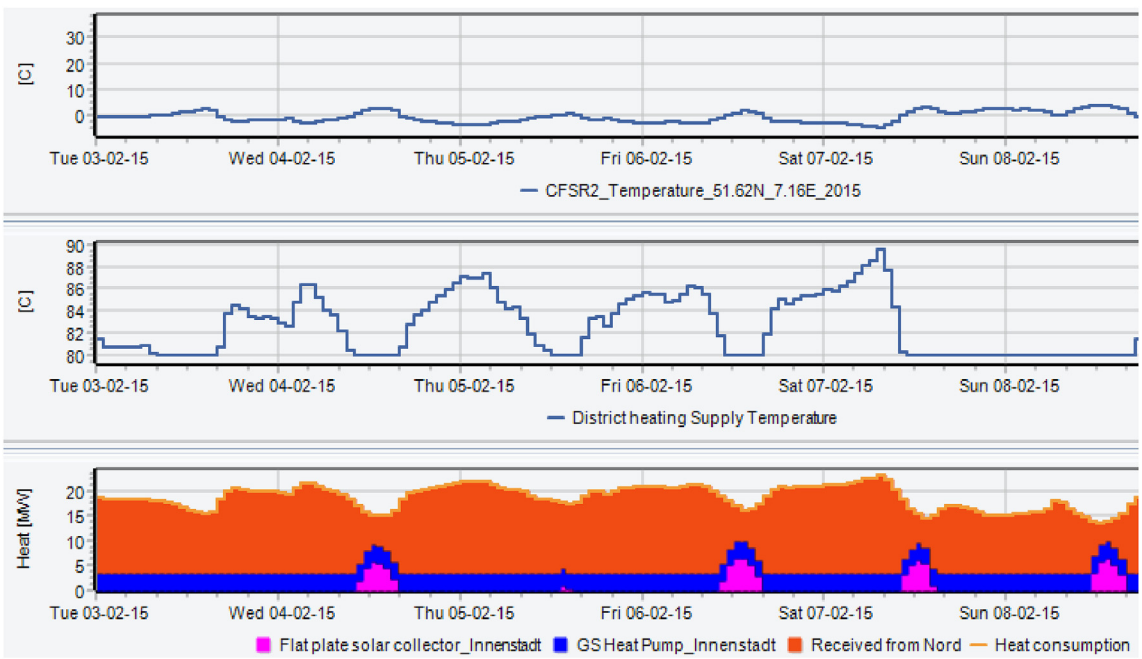

Fig. 7. Hourly representation of the outside temperature (top), DH supply temperature (middle), and supply mix (bottom) modelled with energyPRO for a selected sub-network in Herten.

Table 4
Overview of modelled scenarios.

Scenario	Decentralised supply	Thermal renovation	DH expansion	DH supply
1. RES for decentralised supply/no renovation	Continuous transition to RES supply and efficient fossil fuel boilers	No renovation (same demand as in 2014)	No expansion (same size as in 2014)	No replacement (2014 supply with coal CHP)
2. Thermal renovation		With renovation (52% demand reduction until 2050 compared to 2014)		
3. Ren. + Solar thermal in DH				With replacement (ST)
4. Ren. + Heat pumps in DH				With replacement (HP)
5. Ren. + RES DH expansion			With expansion	With replacement (ST + HP)
6. Ren. + Waste incin. in DH			No expansion (2014 size)	With replacement (more waste incineration heat)
7. Ren. + Roadmap			With expansion	With replacement (ST + HP + waste incineration heat)

- **5. Renovation + RES DH expansion**: The same policies and measures as in the second scenario. Expansion of the DH network with the goal of having a similar thermal demand in 2050 as in the year 2014. Solar thermal and HP are integrated into the network with the same installed capacity as in the scenarios 3 and 4, respectively.
- **6. Renovation + Waste incineration in DH**: The same policies and measures as in the second scenario. The southern part of the network is connected to the waste incineration plant. The rest of the DH network is still supplied by the existing coal-fired CHP units.
- **7. Renovation + Roadmap Scenario**: The same policies and measures as in the second scenario. In addition, the Roadmap Scenario combines decarbonisation elements from all the other scenarios and represents an integrated scenario with the goal of achieving Herten's emission reduction targets at lower costs. DH network expansion with the same goal as in scenario 5 and partial integration of RES into the DH network but using smaller HP and larger solar fields instead. This means for the period between **2030 to 2050**:
  - o Heat pumps with a total capacity of 1.85 MW_{th} (2030) and 18.5 MWth (2050)
  - o Solar thermal same as scenario 3 in 2030 and then double by 2050 (64 000 m^2 collector area and 12 000 m^3 storage)
  - o Southern part connected to the waste incineration plant (as scenario 6)
  - o Remaining demand covered by existing system in 2030 and existing system + biomass boilers in 2050

4. Results of modelled scenarios

In this chapter, all the results are based on private economic calculations, which include all the taxes and 7% interest rate. The results are presented for the period 2014-2030-2050 and are assessed in terms of CO_2 emissions reduction, energy supply mix and costs of heat supply. CO_2 emissions are accounted for according to a use balance sheet, which allocates emissions from electricity generation to the electricity consumer.

Fig. 8 shows the results of the different scenarios on the FED for SH and DHW in the residential sector. It can be observed that, due to building renovation, the FED decreases from around 470 GWh in 2014 to 220 GWh in 2050, which represents a very ambitious renovation pathway as well as demographic changes in the city. The CO2 emission reduction refers to the emissions in 1990. The Roadmap Scenario achieves a CO_2 reduction of 82% compared to 1990. Much of the remaining emissions are from individual gas boilers and DH energy supply from waste incineration. Even higher emission reductions would require addressing both these sources.

Note that the scenario without renovation but with ambitious introduction of RES in decentralised heating applications (scenario 1) already shows a substantial reduction of CO_2 emissions by about 43% compared to 1990 (of which 11% were achieved in 2014). HP and biomass boilers play a very important role in this scenario, while natural gas boilers are still the main source of decentralised heat. Individual coal and oil boilers are nearly phased out, contributing to the achieved CO_2 reduction.

Adding ambitious building renovations can increase CO_2 reduction to about 74% (scenario 2). The level of building renovation goes substantially beyond current practices and requires ambitious support policies targeting higher renovation rates. The emission reduction targets are achieved only in the scenarios with high shares of RES in the DH network (scenarios 4, 5 and 7).

Fig. 9 shows the shares of DH for the different scenarios and the share of the supply technologies used in it. The highest DH share, with around 62% of the total FED for SH and DHW, is for the scenarios featuring DH expansion (scenarios 5 and 7). The share of the different technologies supplying the DH network can be observed as well. Even though the size of the solar fields in scenario 3 and 5 is the same, the solar fraction in scenario 3 has increased due to the decreasing demand.

The share of DH in heat supply increases to about 62% in scenarios 5 and 7. This implies the connection of most MFH and other large buildings, whereas SFH are not connected in this scenario. Scenario 5 shows an extension of the DH network in combination with a comprehensive integration of RES into the network. Simply extending the network without including substantially more RES supply would have increased CO_2 emissions considerably, because coal-fired CHP generation would have replaced decentralised natural gas boilers and decentralised RES.

Fig. 10 presents the LCOH and total costs of heat supply for 2050. It can be observed that the scenarios with large shares of HP in the DH supply mix (scenarios 4 and 5) have the highest LCOH based on the forecasted electricity and fuel prices. The total costs of heat supply exclude renovation costs. Even though scenario 1 has the largest total costs of heat supply due to the highest demand, it has the lowest LCOH. By comparing scenario 4 and 5 it can be observed that if a higher share of HP is to be integrated in the network, a DH expansion is necessary in order to reduce the costs and keep the network cost-competitive. By adding additional RES technologies to the DH supply mix the price of heat can be furthermore reduced. For these reasons, the next section discusses the competitiveness of HP in detail and constructs a possible scenario where the costs of the HP are reduced to a similar level of the existing coal-fired CHP plants.

5. Heat pump cost-competitiveness and sensitivity analyses.

In order to shed more light on the cost-competitiveness of HP, we conducted a sensitivity analysis from a private-economic perspective by varying the most influential factors. These include the CAPEX, interest rate, size and CF, heat supply and heat source temperatures, electricity price, and COP. In the following, we first explore some of these factors individually, before constructing a combined simulation that takes multiple factors into account with the objective of making HP cost-competitive with the coal-fired CHP.

Fig. 11 shows **sensitivity** calculations for a heat pump with different **capacity factor (CF)** of CF = 0.86 (left) and CF = 0.46 (right). The capacity factor (CF) is defined as the actual annual working hours divided by 8760 h. We consider relative changes to the input parameters in the range of −50% and +50%. We can see that relative changes in electricity price and COP have the strongest impact on the LCOH for the heat pump with high CF. The CAPEX has increased influence on the heat pump with a lower CF. If the CF decreases even more (below 0.3), the results would look different and the CAPEX would become more important.

High installed capacities result in lower CF due to the unequally distributed heat demand over the year. It can be concluded that low CF increase the LCOH dramatically, due to the relatively high CAPEX for HP. The CF should be at least 0.45, implying that the HP should be operated for around 4000 working hours.

The **COP** of the heat pump depends strongly on the temperature difference and, thus, the heat **supply temperature in the DH network**. Fig. 12 shows the heat pump COP for different supply and heat source temperatures. It is apparent that the influence of the higher heat source temperature is much more pronounced for low supply temperatures of around 50 °C than for supply temperatures of 80 °C. This stresses the need for a transition to low-temperature DH networks, which will improve the efficiency and cost-effectiveness of the HP. For example, decreasing the supply

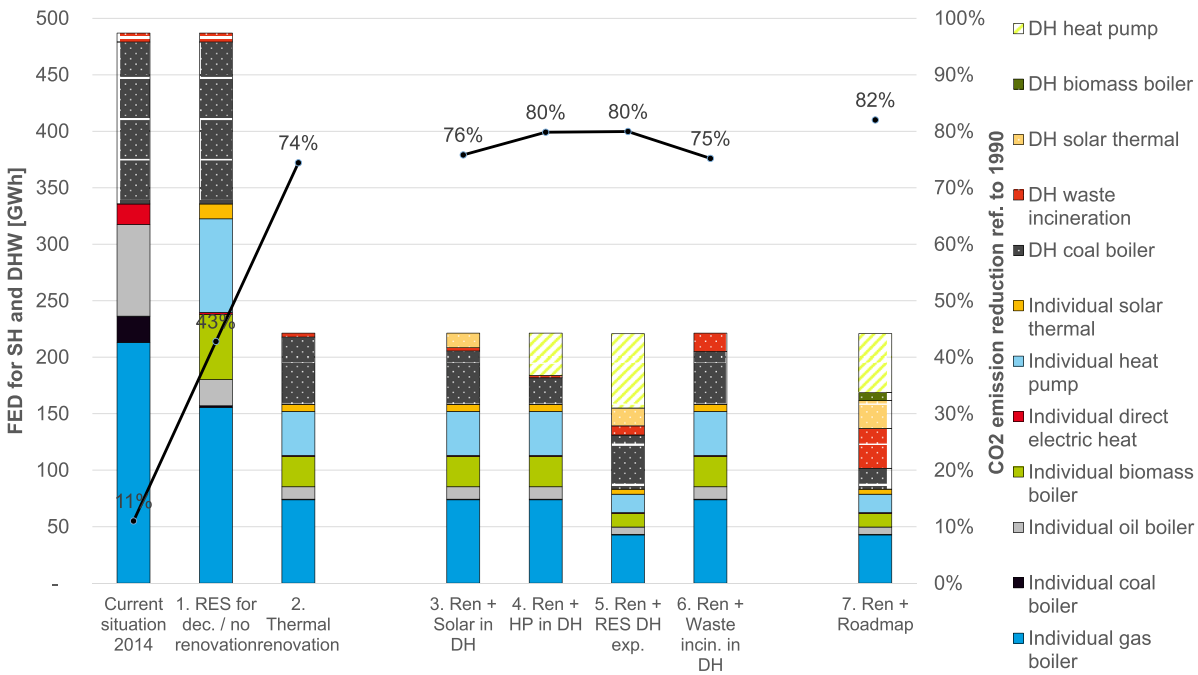

Fig. 8. Technology mix (left axis) and CO_2 emission reductions (right axis) in 2050.

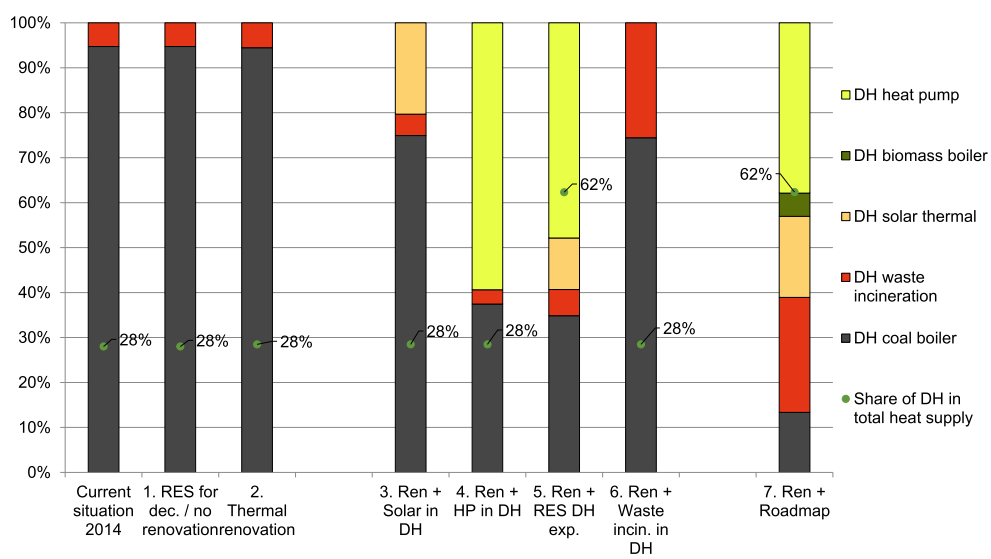

Fig. 9. DH share and supply mix in 2050.

temperature from 80 °C to 60 °C for a heat pump with a 20 °C heat source (as is the case in Herten) increases the COP from 3.0 to 4.5, resulting in around 33% lower electricity consumption for the same heat output.

Electricity prices for consumers are relatively high in Germany if there are no tax discounts involved. Fig. 13 shows the current prices typically paid by utilities for electricity consumed from the grid. While many industrial companies receive high discounts, utilities often do not. This challenges the economic feasibility of HP in DH networks. The resulting price spread is huge, ranging from 50 EUR/MWh to 148 EUR/MWh. Making HP eligible for lower taxes and fees can be an effective way to improve their cost competitiveness. For the simulations, we assume a price reduction of 40%, which equals the discounts available to industrial companies under the German Renewable Energy Sources Act (EEG).

Finally, based on the above assessment, we construct two cases that make HP cost-competitive with the coal-fired CHP unit by incrementally changing the input parameters. Fig. 14 illustrates the incremental influence of different measures on the LCOH. First, we reduced the installed capacity to obtain a higher CF. This reduces the LCOH by about 36% for CF = 0.45 and by 46% for CF = 0.75. Reducing the CAPEX can lower the LCOH even more. In the long term, technical learning might contribute to this, while CAPEX grants are an option in the short term. We assume a grant that covers 30% of the total CAPEX. However, the resulting LCOH of the heat pump is still substantially above that of the coal-fired CHP.

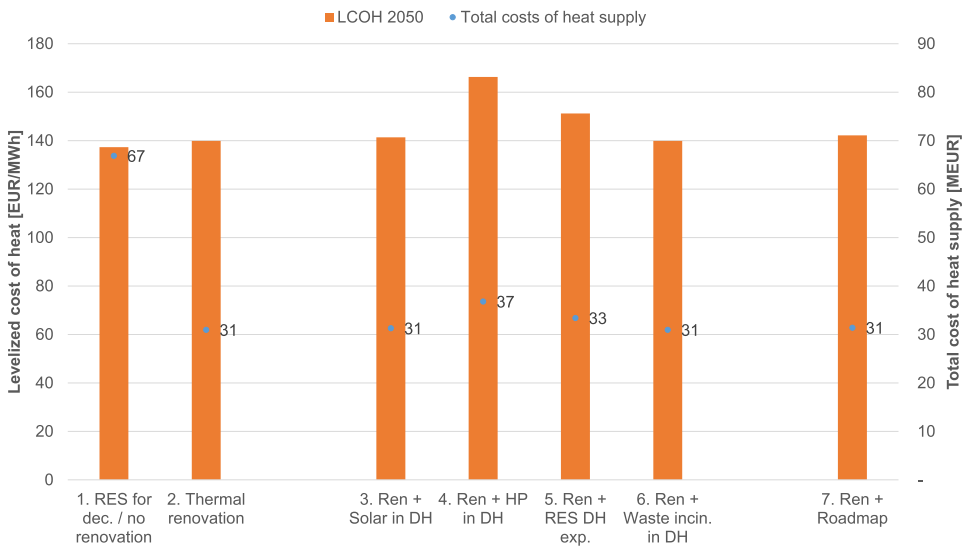

Fig. 10. LCOH (left axis) and total costs of heat supply per year (right axis) in 2050.

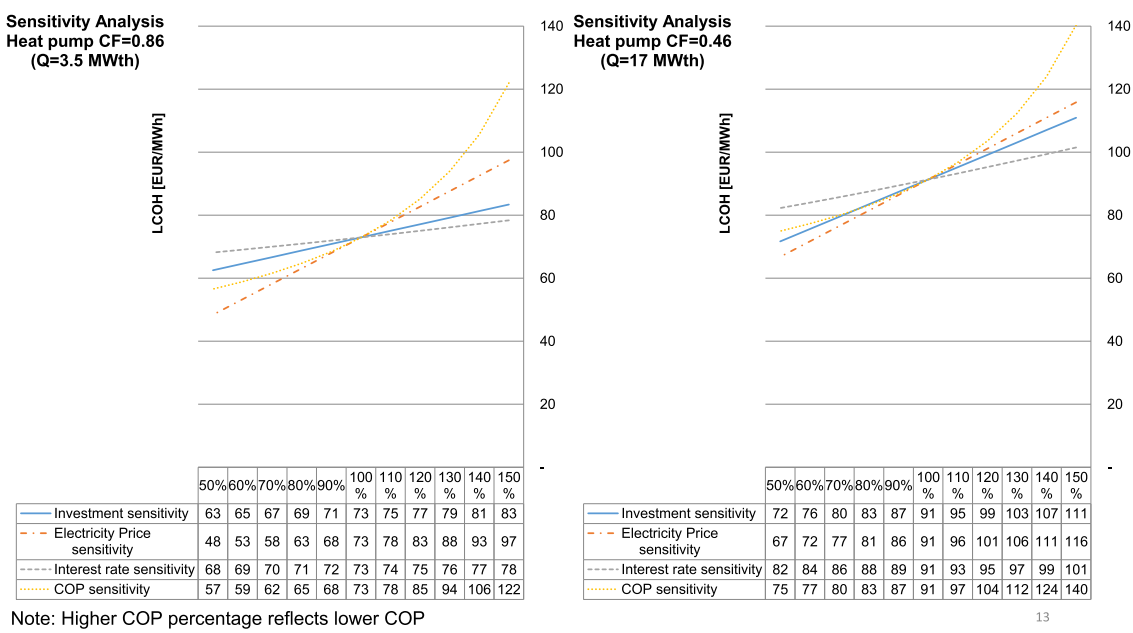

Fig. 11. Sensitivity analyses for heat pump with CF = 0.86 (left) and CF = 0.46 (right).

In the first case (Fig. 14 top) we first assume lower DH supply temperatures followed by reduced electricity prices due to different taxation. Reducing the DH supply temperature from 80 °C to 60 °C increases the COP and leads to an additional 12% reduction in the LCOH (Fig. 14 top). The remaining price gap can be bridged by either introducing a CO_2 tax or applying different electricity price taxation and purchasing systems. As an example, the LCOH can be brought down to a level comparable with the coal-fired CHP if the utility pays a variable electricity price based on the EPEX day-ahead prices instead of a fixed price from the supplier (41.9 EUR/MWh), or if it receives the same discount as industrial companies for the EEG surcharge.

In the second case (Fig. 14 bottom), we assume a reversed course of events by first applying the reduced electricity prices and then assume lower DH supply temperatures. Including EPEX day-ahead spot electricity prices results in an average electricity price of around 134 EUR/MWh instead of 148 EUR/MWh because the price on the spot market was below 40 EUR/MWh in more than 6650 h in 2015 [56]. By applying the same EEG surcharge reductions available for the industry additionally decreases the electricity price to 50.6 EUR/MWh and makes the heat pump competitive even at a higher supply temperature. In both cases the HP is used mainly for the base load. With a CF of 0.75, 65% of the total heat demand is supplied by the HP.

6. Discussion

Herten's climate protection targets require a comprehensive

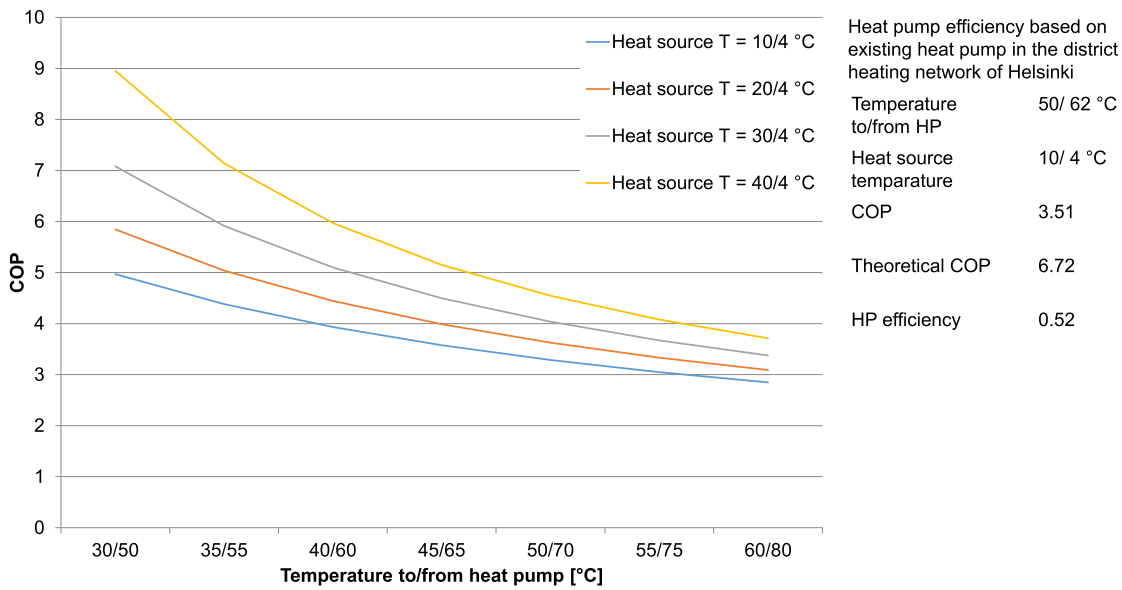

Fig. 12. Heat pump COP for different source and supply temperatures.

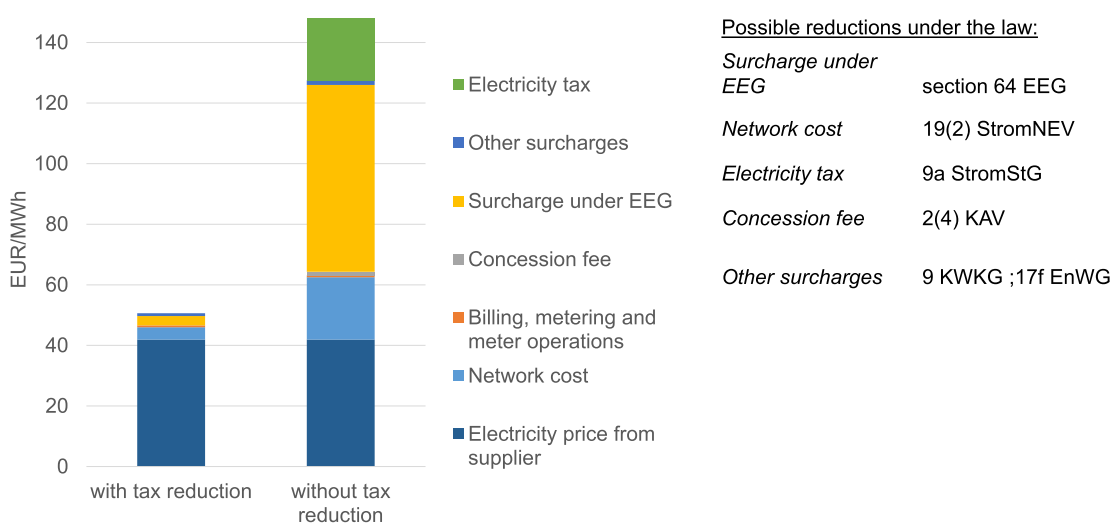

Fig. 13. Electricity price components for industrial/non-household consumers with and without possible tax reductions in 2015.

solution. Fig. 8 (scenario 2) shows that even reducing demand by 53% and replacing all the old inefficient fossil units achieves a CO2 reduction of 74% compared to 1990. The city of Herten needs the transition to a low-carbon DH supply to achieve its targets.

Even though the climate targets can be reached "only" by supplying 60% of the DH demand using HP (scenario 4 in Fig. 7) and without any expansion, this is the most expensive solution (Fig. 9) based on the forecasted prices and policy conditions. In order to make DH supply cost competitive in the long term, the network needs to be expanded to counteract the effect of improved building efficiency. More precisely, between 2020 and 2050, the DH network should expand with the goal to keep the demand constant like the one in 2014, which represents about 62% of the future demand in 2050. Such an expansion requires the connection of MFH and other large buildings. The share of SFH supplied by the DH network is the same as at present. This expansion will improve the cost-effectiveness of the future integration of RES in the DH network. It is important to note that simply expanding the DH network by connecting new customers does not result in CO_2 reduction. In contrast, replacing decentralised natural gas or RES technologies with DH supplied from the coal-fired CHP unit will increase emissions.

Some decarbonisation studies expect around 88% of the total DH demand to be supplied by RES until 2050, and 18% of this by large-scale HP [21]. Integrating such large shares of HP into DH networks based on current prices and policy conditions will certainly increase the price of the networks because heat supplied from HP is currently more expensive than that supplied from coal-fired CHP plants. The sensitivity analyses show that the OPEX costs are more influential than the CAPEX for the current electricity prices. Considering the fact that more than 50% of the electricity price consists of taxes [54,57], certain tax exemptions could improve the cost-competitiveness of large-scale HP. As an example, reducing the EEG surcharge or other bonus schemes that apply to electric heating customers could increase the numbers of customers switching to electric heating (4.2% in 2016 [54]). These EEG

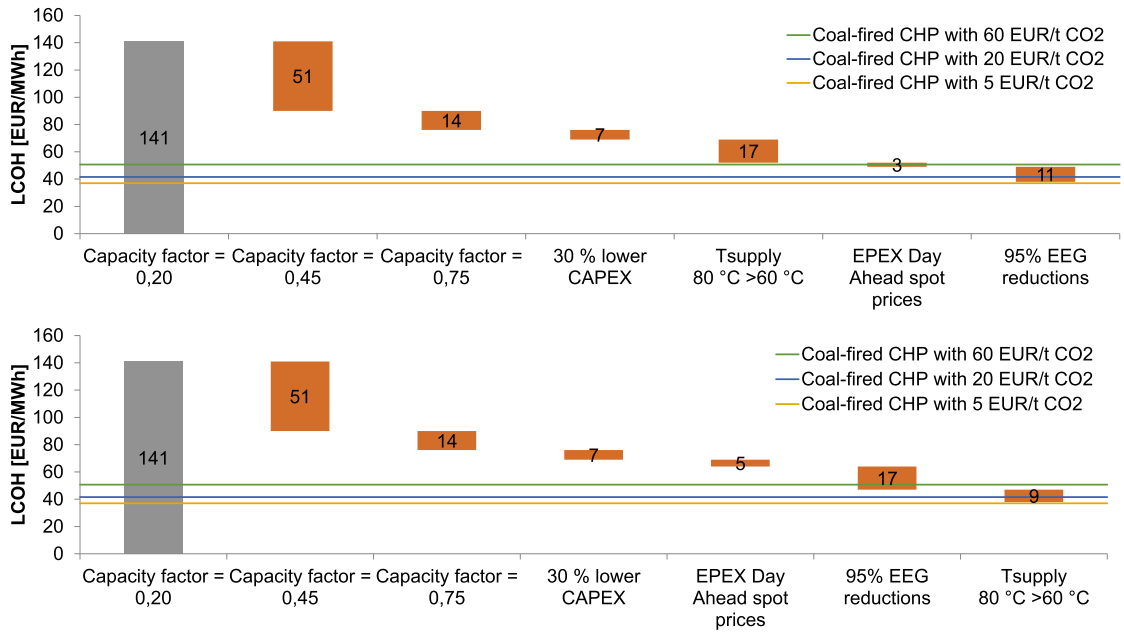

Fig. 14. Cumulative influence of different measures on the LCOH Note: The individual influence of certain measures may differ (e.g. the influence of 30% lower CAPEX is much higher for lower CF).

surcharge reductions already exist for some industrial consumers and utilities with CHP units under specific conditions[‡]. In order to reach the full technical potential of PtH solutions and accelerate their market diffusion, it seems essential to redesign the system of energy taxes and levies either by reducing the price of electricity for desired uses like HP, or by increasing the price of coal for the same competing market segments. Similar conclusions are drawn by other studies related to HP in DH supply [58] as well as individual HP [59] in Germany.

As the current state-of-the-art HP can provide temperatures of around 80 °C, their application is restricted to networks with lower forwarding temperatures or as suppliers for only a fraction of the heat needed. This fact highlights the need for transition to 4GDH that should accompany building thermal renovations. In the case of Herten, the supply temperatures in the existing DH networks exceed 100 °C in winter, limiting heat pump use to the remaining periods of the year. To overcome this obstacle, HP can be integrated into the distribution (subnetworks) of the DH system [60]. By zoning certain DH subnetworks in neighbourhoods where buildings have already undergone thermal renovation and have improved thermal properties, the DH supply temperatures can be decreased, which will lead to improved HP efficiency and cost-effectiveness. The current supply temperature could also be decreased by the following: better supply temperature management, hydraulic balancing, use of variable-speed pumps, ensuring internal system components (e.g. thermostatic valves) are working properly, longer thermal lengths in substation heat exchangers, etc. [61].

Additionally, HP should not be used to cover the peak demand of the DH network, as this would lead to small CF, which have a negative influence on the LCOH. Biomass boilers or direct electric heaters are the preferred option to cover peak demand. This is in line with the observation that a supply mix of several RES technologies (16% SDH share and 10% biomass) can decrease the overall DH supply costs in comparison to a solution supplied only by HP.

7. Summary and conclusions

We analysed the cost-effectiveness of decarbonising the DH supply in a German city by using HP. The analysed DH grid is currently supplied by coal-fired CHP, which is typical for many German cities. The low price of coal-based DH supply is a major challenge for alternative supply options. In our analysis, we first forecasted the future heat demand and DH extension potentials by simulating the evolution and energy use of the city's building stock. Having obtained the future DH demand, in a next step, we used a supply dispatch model with hourly resolution to calculate alternative scenarios and sensitivities for the supply mix with a focus on HP. We identified the impact of individual parameters on the cost of heat supply.

Our results show that the DH network plays a central role in the decarbonisation of the city's energy supply and that the city's long-term decarbonisation targets cannot be reached without changing the DH supply. The building stock analysis shows that expanding the DH grid by connecting additional MFH is possible and keeps the DH demand relatively constant until 2050. However, expanding the existing DH system only increases the share of coal in the city's energy supply, which is why it is indispensable to change the DH supply source.

Simulating the DH supply based on HP provides a detailed picture of its cost-effectiveness and the main influencing factors. We showed that large-scale HP are not competitive with fossil-fired CHP plants in our case study based on current and forecasted prices and policy conditions.

By adjusting the influencing parameters, however, we designed and simulated a heat pump-based DH supply system that has the same heat supply costs as the current coal-fired DH system. Five major levers were identified: First increasing the CF from 0.2 to 0.75 (equivalent to increasing the annual running hours from 1950 to

[‡] Federal Ministry for Economic Affairs and Energy (06.09.2018). *Modern Power Plant Technologies.* Retrieved from: https://www.bmwi.de/Redaktion/EN/Artikel/Energy/modern-power-plant-technologies.

6550) greatly decreases the heat supply costs. Second, reducing the average supply temperature from 80 to 60 °C also substantially reduces the heat supply costs. However, this would involve retrofitting of the DH system and probably incurs additional costs. Third, lowering the electricity price by removing levies related to the renewable feed-in tariff also significantly decreases heat costs. Fourth and fifth, further (but less pronounced) reduction of heat supply cost was achieved by reducing the heat pump CAPEX (either by grants or technical learning) and by operating the HP based on hourly spot market electricity prices and thereby providing flexibility to the electricity grid.

Even if all these options were implemented, a CO_2 price for the coal-fired heat supply of at least 20 EUR/t CO_2 is still needed to reach cost parity. A higher price of 40–60 EUR/t would allow more freedom of scope for the above-mentioned measures.

Thus, in order to make HP a cost-competitive DH supply option, they need to be operated for a maximum of hours per year and the DH supply temperature should be lower. In addition, the current system of levies and taxes on the electricity price needs to be revised in order to decrease the cost gap to coal-based CHP supply. A new regulatory framework is required that will make PtH solutions more cost-effective and the balancing power market more attractive. This could be achieved by either introducing much higher CO_2 prices of at least 60 EUR/t CO_2 that substantially increase the price of fossil fuels, or by providing electricity tax reductions for heat pump applications like the tax exemptions currently in place for large electricity-intensive industrial companies.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2019.05.122.

Annex

Energy prices and specific CO_2 emissions.

Table 5 shows the current and forecasted energy prices for an average consumer in the residential sector. Fossil fuel prices are assumed to increase, while the price of electricity should start to decrease after 2030. Table 6 presents the specific CO_2 emission factors.

Table 5
Households average energy prices for 2015, 2030 and 2050 [EUR/MWh]

Energy carrier	Price for 2015	Price for 2030	Price for 2050
Electricity	297	335	300
Natural gas	68	83	89
Heating oil	77	142	165
Hard coal	26	43	50
Biomass solid	47	61	66

Table 6
Specific CO2 emissions [CO2_kg/MWh] per energy carrier. Current state of DH

Energy carrier	2015	2030	2050
Electricity [48]	510	393	95
Natural gas [62]	202	202	202
Heating oil [62]	266	266	266
Waste incineration [62]	166	166	166
Hard coal [62]	338	338	338
Existing DH (coal-fired CHP) [37]	228	228	228
Biomass [62]	0	0	0

The reference price for purchasing heat from the larger utilities paid by the DH operator is 37.17 EUR/MWh with an additional 25 EUR/MWh for O&M costs [37]. Referring to the grid diagram in Fig. 2, the northern and southern parts of the DH network (pink and lilac shaded areas) make up more than 90% of the overall DH capacity. Table 7 lists the FED for the supplying units for these areas and additionally the supply from the waste incineration plant (RZR). The city already has plans in place to use the waste incineration plant (RZR) to provide the heat for the southern network. Thus, the case study focuses on the northern part of the DH network, which accounts for nearly 70% of the heating capacity listed in Fig. 2.

Table 7
DH supply structure, heat losses and FED in 2011 [36].

Plant	Supply [GWh]	Heat losses [GWh]	FED [GWh]
CHP Scholven	138	26	112
CHP Herne	39	7	31
Waste inc. CHP RZR	9	1	8
Total	**186**	**35**	**151**

Future scenarios with and without DH expansion.

Table 8
Resulting FED per year for DH in GWh

Building type	2014	2030	2050
Scenario 1 (without DH expansion)	129	79	61
Scenario 2 (with DH expansion)	129	124	135

Table 9
Resulting relative number of buildings supplied with DH in scenario 2 (with DH expansion)

Building type	2014	2030	2050
Detached house	14%	14%	14%
Terraced house	25%	25%	91%
Apartment building	40%	59%	100%
Large apartment building	55%	100%	100%

Table 10
Resulting additional number of buildings connected to DH in scenario 2 (with DH expansion)

Building type	2014	2030	2050
Detached house	0	0	0
Terraced house	0	0	1021
Apartment building	0	1380	2688
Large apartment building	0	20	20

Modelled individual heating systems.

Table 11
Individual units' costs in 2030 [63,64].

Natural gas boiler	EFH	RH	MMH	GMH
Thermal Capacity [kW]	13.5	11.5	49.5	88.5
Investment [EUR/kW]	522	522	334	334
Interest Rate [%]	7%	7%	7%	7%
Economic Life [years]	25	25	25	25
Fixed O&M [% of inv.]	2%	2%	2%	2%
Efficiency [%]	100%	100%	100%	100%
Fuel Costs [EUR/kWh]	0.098	0.098	0.098	0.098
LCOH [EUR/kWh]	0.145	0.142	0.129	0.122
Heating oil boiler	**EFH**	**RH**	**MMH**	**GMH**
Thermal Capacity [kW]	13.5	11.5	49.5	88.5
Investment [EUR/kW]	616	616	399	399
Interest Rate [%]	7%	7%	7%	7%
Economic Life [years]	20	20	20	20
Fixed O&M [% of inv.]	4%	4%	4%	4%
Efficiency [%]	85%	85%	85%	85%
Fuel Costs [EUR/kWh]	0.169	0.169	0.169	0.169
LCOH [EUR/kWh]	0.269	0.265	0.246	0.235
Hard coal boiler	**EFH**	**RH**	**MMH**	**GMH**
Thermal Capacity [kW]	13.5	11.5	49.5	88.5
Investment [EUR/kW]	283	283	196	196
Interest Rate [%]	7%	7%	7%	7%
Economic Life [years]	20	20	20	20
Fixed O&M [% of inv.]	2%	2%	3%	3%
Efficiency [%]	75%	75%	75%	75%
Fuel Costs [EUR/kWh]	0.051	0.051	0.051	0.051
LCOH [EUR/kWh]	0.095	0.093	0.089	0.084
Electricity boiler	**EFH**	**RH**	**MMH**	**GMH**
Thermal Capacity [kW]	13.5	11.5	49.5	88.5
Investment [EUR/kW]	647	647	638	638
Interest Rate [%]	7%	7%	7%	7%
Economic Life [years]	30	30	30	30
Fixed O&M [% of inv.]	0.1%	0.1%	0.1%	0.1%
Efficiency [%]	100%	100%	100%	100%
Fuel Costs [EUR/kWh]	0.399	0.399	0.399	0.399
LCOH [EUR/kWh]	0.443	0.440	0.444	0.433
Biomass boiler	**EFH**	**RH**	**MMH**	**GMH**
Thermal Capacity [kW]	13.5	11.5	49.5	88.5
Investment [EUR/kW]	974	974	974	800
Interest Rate [%]	7%	7%	7%	7%
Economic Life [years]	25	25	25	25
Fixed O&M [% of inv.]	2%	2%	2%	2%
Efficiency [%]	90%	90%	90%	90%
Fuel Costs [EUR/kWh]	0.072	0.072	0.072	0.072
LCOH [EUR/kWh]	0.167	0.162	0.171	0.137
AS Heat pump	**EFH**	**RH**	**MMH**	**GMH**
Thermal Capacity [kW]	13.5	11.5	49.5	88.5
Investment [EUR/kW]	1130	1130	1130	750
Interest Rate [%]	7%	7%	7%	7%
Economic Life [years]	20	20	20	20
Fixed O&M [EUR/unit]	150	150	150	450
Efficiency [%]	260%	260%	260%	260%
Fuel Costs [EUR/kWh]	0.399	0.399	0.399	0.399
LCOH [EUR/kWh]	0.252	0.248	0.249	0.204
GS Heat pump	**EFH**	**RH**	**MMH**	**GMH**
Thermal Capacity [kW]	13.5	11.5	49.5	88.5
Investment [EUR/kW]	1675	1675	1675	1675
Interest Rate [%]	7%	7%	7%	7%
Economic Life [years]	20	20	20	20
Fixed O&M [EUR/unit]	200	200	200	600
Efficiency [%]	315%	315%	315%	315%
Fuel Costs [EUR/kWh]	0.399	0.399	0.399	0.399
LCOH [EUR/kWh]	0.245	0.239	0.242	0.210
Solar thermal	**EFH**	**RH**	**MMH**	**GMH**
Area [m2]	17	15	63	113
Thermal Capacity [kW]	12	11	44	79
Investment [EUR/kW]	800	800	800	500
Interest Rate [%]	7%	7%	7%	7%
Economic Life [years]	30	30	30	30
Fixed O&M [EUR/year]	40	40	40	100
Variable O&M [EUR/year]	22	22	22	500
Annual Solar Irradiation [kWh/m2]	900	900	900	900
LCOH [EUR/kWh]	0.164	0.166	0.155	0.113

Table 12
Individual units' costs in 2050 [63,64].

Natural gas boiler	EFH	RH	MMH	GMH
Thermal Capacity [kW]	8.5	7.5	30	70
Investment [EUR/kW]	522	522	334	334
Interest Rate [%]	7%	7%	7%	7%
Economic Life [years]	25	25	25	25
Fixed O&M [% of inv.]	2%	2%	2%	2%
Efficiency [%]	100%	100%	100%	100%
Fuel Costs [EUR/kWh]	0.106	0.106	0.106	0.106
LCOH [EUR/kWh]	0.143	0.140	0.130	0.128
Heating oil boiler	**EFH**	**RH**	**MMH**	**GMH**
Thermal Capacity [kW]	8.5	7.5	30	70
Investment [EUR/kW]	616	616	399	399
Interest Rate [%]	7%	7%	7%	7%
Economic Life [years]	20	20	20	20
Fixed O&M [% of inv.]	4%	4%	4%	4%
Efficiency [%]	85%	85%	85%	85%
Fuel Costs [EUR/kWh]	0.196	0.196	0.196	0.196
LCOH [EUR/kWh]	0.286	0.281	0.266	0.264
Hard coal boiler	**EFH**	**RH**	**MMH**	**GMH**
Thermal Capacity [kW]	8.5	7.5	30	70
Investment [EUR/kW]	283	283	196	196
Interest Rate [%]	7%	7%	7%	7%
Economic Life [years]	20	20	20	20
Fixed O&M [% of inv.]	2%	2%	2%	3%
Efficiency [%]	75%	75%	75%	75%
Fuel Costs [EUR/kWh]	0.060	0.060	0.060	0.060
LCOH [EUR/kWh]	0.101	0.100	0.096	0.095
Electricity boiler	**EFH**	**RH**	**MMH**	**GMH**
Thermal Capacity [kW]	8.5	7.5	30	70
Investment [EUR/kW]	647	647	638	638
Interest Rate [%]	7%	7%	7%	7%
Economic Life [years]	30	30	30	30
Fixed O&M [% of inv.]	0.1%	0.1%	0.1%	0.1%
Efficiency [%]	100%	100%	100%	100%
Fuel Costs [EUR/kWh]	0.357	0.357	0.357	0.357
LCOH [EUR/kWh]	0.392	0.389	0.391	0.389
Biomass boiler	**EFH**	**RH**	**MMH**	**GMH**
Thermal Capacity [kW]	8.5	7.5	30	70
Investment [EUR/kW]	974	974	974	800
Interest Rate [%]	7%	7%	7%	7%
Economic Life [years]	25	25	25	25
Fixed O&M [% of inv.]	2%	2%	2%	2%
Efficiency [%]	90%	90%	90%	90%
Fuel Costs [EUR/kWh]	0.078	0.078	0.078	0.078
LCOH [EUR/kWh]	0.156	0.150	0.155	0.140
AS Heat pump	**EFH**	**RH**	**MMH**	**GMH**
Thermal Capacity [kW]	8.5	7.5	30	70
Investment [EUR/kW]	1130	1130	1130	750
Interest Rate [%]	7%	7%	7%	7%
Economic Life [years]	20	20	20	20
Fixed O&M [EUR/unit]	150	150	150	450
Efficiency [%]	260%	260%	260%	260%
Fuel Costs [EUR/kWh]	0.357	0.357	0.357	0.357
LCOH [EUR/kWh]	0.220	0.215	0.211	0.185
GS Heat pump	**EFH**	**RH**	**MMH**	**GMH**
Thermal Capacity [kW]	8.5	7.5	30	70
Investment [EUR/kW]	1675	1675	1675	1675
Interest Rate [%]	7%	7%	7%	7%
Economic Life [years]	20	20	20	20
Fixed O&M [EUR/unit]	200	200	200	600
Efficiency [%]	315%	315%	315%	315%
Fuel Costs [EUR/kWh]	0.357	0.357	0.357	0.357
LCOH [EUR/kWh]	0.211	0.203	0.198	0.193
Solar thermal	**EFH**	**RH**	**MMH**	**GMH**
Area [m2]	11	10	38	89
Thermal Capacity [kW]	8	7	27	62
Investment [EUR/kW]	600	600	600	400
Interest Rate [%]	7%	7%	7%	7%
Economic Life [years]	30	30	30	30
Fixed O&M [EUR/year]	40	40	40	100
Variable O&M [EUR/year]	22	22	22	500
Annual Solar Irradiation [kWh/m2]	900	900	900	900
LCOH [EUR/kWh]	0.133	0.135	0.119	0.099

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