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REUSEHEAT

Scenarios for urban excess heat exploitation

Modelling of future energy systems in four European cities

WP 1
Task 1.4
Deliverable 1.6

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Summary

This report is the Deliverable 1.6 in the ReUseHeat project and is the result of the work carried out in Task 1.4 as part of Work Package 1. The aim of Task 1.4 is to assess urban excess heat (EH) possibilities from a district heating (DH) system perspective. This includes to assess conditions and potential for cost-efficient utilization of available urban EH in DH systems of four demo cities of the ReUseHeat project, Berlin (Germany), Brunswick (Germany), Madrid (Spain) and Nice (France), and to assess energy systems impacts of utilizing urban EH sources in DH.

The assessment is carried out at a city energy system level while taking impacts on the surrounding energy system, such as the electricity and building sectors, local and international fuel markets and climate policies, into account. Utilization of urban EH sources from four different sources are analysed: data centres, waste water treatment, metro ventilation and cooling of service sector buildings. These heat sources are low-temperature sources for use in DH systems, meaning that a heat pump (HP) is needed to increase the temperature to the temperature level of the DH system.

The study applies a case study approach using dynamic energy system modelling for scenario analysis in which different policy and technology assumptions are contrasted. The TIMES model generator is used to develop a model application in which the heating sector of the four cities are represented. The model results portray how the system should evolve over time to minimize system cost while meeting heat demands and emission constraints.

The results show that large compressor HPs based on low-temperature EH are often a cost-efficient option for DH production. EH upgraded with HPs for DH supply is in many of the analysed cases included in the cost-optimized result. This means that introduction of balanced levels of large HPs based on low-temperature heat sources can lower the system cost for meeting heat demands at the city level. Large HPs based on low-temperature heat sources can also contribute to an increased competitiveness of DH compared to individual heating solutions such as fuel boilers and ambient temperature HPs. The model results suggest that the technology solution could be an important driver for DH development in cities that currently has low DH coverage.

The performance of large HPs based on low-temperature EH are dependent on the character of the system in terms of current production capacities and availability of other energy options. Generally, replacing heat-only production (in the DH system and/or as individual heating in houses) is more advantageous than replacing CHP production. Furthermore, in cases where large potentials of other advantageous heating options are available, e.g. high-temperature EH sources not requiring upgrading, the cost-efficient use of low-temperature EH sources is limited. Competition from other heating options, as well as a seasonal distribution discrepancy between the supply of urban EH and the heating demand, also results in that the cost-efficient use of urban EH is considerably lower than the available EH potential.

Use of EH can contribute to reducing CO_2 emissions as well as lower primary energy use. However, due to the electricity use of compressor HPs, CO_2 emissions and primary energy use is dependent on the emission and resource characteristics of the electricity generation. The results of the analysis point to that the use of low-temperature EH sources can make important contributions in a development in which both the heating sector and the electricity sector evolve in a sustainable direction.

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List of abbreviations

CHP	Combined heat and power
COP	Coefficient of performance
CO_2	Carbon dioxide
DH	District heating
EH	Excess heat
EU	European Union
HP	Heat pump
HPL	Heat plant (heat only)
MSW	Municipal solid waste
O&M	Operation and maintenance

1. Introduction

This report is the Deliverable 1.6 in the ReUseHeat project and is the result of the work carried out in Task 1.4 as part of Work Package 1. The work covers future scenarios for urban waste heat exploitation at urban level, and links to the EH potential assessments of Task 1.2 and national energy system assessments of Task 1.3 of the ReUseHeat project (Deliverables 1.4 and 1.5).

1.1. Background

In the European Union (EU), the building sector accounts for 40% of the total energy use and 36% of the carbon dioxide (CO_2) emissions [1]. The EU has set a long-term goal of reducing greenhouse gas emissions by 80-95% by 2050 compared to 1990 levels (in the context of necessary reductions being made by developed countries as a group) [2]. With district heating (DH), the EU goal can be achieved at a lower cost, with heating and cooling costs reduced by approximately 15% [3]. Utilization of waste/excess heat streams, e.g. excess heat (EH) from power plants, industry and waste incineration could potentially be an important contributor to such a development.

Various non-fossil heat sources, e.g. biomass, EH from waste incineration and thermal power plants and industrial processes as well as solar and geothermal heat, have been utilized for heat production in countries with large shares of DH. In addition to these common non-fossil heat sources, an international review of DH and cooling systems from 2017, identified EH from urban sources as an alternative that could replace current fossil-based plants to reduce CO_2 emissions in the heating sector [4].

Studies within the Heat Roadmap Europe project [5] estimated an increase of the DH share to 50% of the entire heat demand by 2050 in Europe. Of this, 25-30% was supplied using large-scale heat pumps (HPs) [5]. Results also showed that there are essentially seven types of heat sources are currently being used in large-scale HPs [5]. In order of installation share, these are: 1) sewage water (10-20 °C), 2) ambient water (i.e. sea, lake and river; 2-15 °C), 3) industrial waste heat (12-46 °C), 4) geothermal water (9-55 °C), 5) flue gas (34-60 °C), 6) district cooling (0-9 °C) and 7) solar heat storage (10-35 °C). Heat sources with temperatures above 55-60°C could be used directly in low-temperature DH systems (i.e. lower supply and return temperatures in DH distribution networks) [5]. Lund and Persson [6] investigated low-temperature EH from industrial processes, supermarkets, waste water, drinking and usage water, ground water, rivers, lakes and sea water as the possible heat sources for HPs in Denmark. They concluded that ground water both had the highest geographical availability and potential heat volume. Supermarkets, with a relatively high geographical availability but a low potential heat volume, as well as rivers, with a relatively low geographical availability but a high potential heat volume, were important potential sources for HPs.

Recently, recovery and reuse of waste heat from unconventional urban sources for use in DH has attracted attention. Davies et al. [7] investigated technical, environmental and economic advantages of EH recovery from cooling London's underground train tunnels and its reuse as a heat source for space heating and domestic hot water in nearby social housing. Preliminary results showed large savings in costs and avoided carbon emissions, compared to current natural gas heating system. Wahlroos et al. [8] assessed potential heat recovery from data centres for use in DH systems in Nordic countries. The study concluded that although plenty of potential for reuse of waste heat generated in data centres exist, there are still a lot of barriers slowing down the utilization of waste heat. The barriers were mainly not technical problems, but rather lack of information on how to make a profit on the heat for the data centre operators. Davies et al. [9] identified that there is significant opportunity for use of recovered heat from data centres in London. The potential reduction of energy use and carbon emissions from interaction of data centres with DH systems was studied. The results showed that heat recovery from a 3.5 MW data centre at 70 °C to DH could lead to savings of over 4000 tonnes of CO_{2e} and nearly £1 million per year.

Europe is becoming more urban. In 1950, 51.7% of the population of Europe were living in urban areas while in 2018 the corresponding number was 74.5% [10]. This trend of urbanization is expected to continue [10], implying that EH availability from urban sources in DH systems will continue to grow. Although environmental and economic impacts of industrial EH use in DH systems have been assessed in several studies, e.g. [11, 12], EH from urban sources; data centres, metro stations, sewage systems and service sector buildings, is to a large extent unexploited. Investment cost of DH infrastructure constitutes a large share of DH cost, thus low-cost heat sources combined with their vicinity to heat sinks may improve the competitiveness of DH systems compared to individual heat devices (e.g. boilers and HPs) in buildings. Some costs are associated with EH extraction for use in DH: investment and operation and maintenance cost of a heat exchanger and a HP. The HP is needed when the EH has a lower temperature than the corresponding DH supply temperature. Compared to EH from industrial processes, waste incineration and thermal power plants, urban EH sources are available at lower temperatures (below 50ºC), meaning that investment in a HP is required to utilize these sources. However, unlike industrial EH, urban EH sources are closer to heat sinks (they are located within cities where heat demands exist) which could result in lower DH infrastructure costs.

Under the condition that the EH is available regardless whether it is used or not, there are not any additional CO_2 emissions linked to EH use and its utilization could contribute to climate change mitigation if it replaces fossil fuel use. To fully assess the climate impacts of EH use, a broad system perspective is required since DH systems interact with other parts of the energy system. The DH interaction with the electricity system through CHP plants, large HPs and electric boilers may lead to indirect impacts on the electricity system if urban heat sources replace fuel use in the DH system. Changes in electricity generation and use in the local heating sector can affect production and investment decisions in the electricity system and, consequently, related carbon emissions.

Decisions on heat sources for the heating sector are of strategic importance for countries' ability to cost-efficiently mitigate greenhouse gases as well as to cope with local air pollution. Such decisions also have long-term impacts due to long infrastructural lifetimes. Thus, due to the importance of the investment decision, comprehensive knowledge is essential and, due to the dynamics of the systems and fuel costs, a long-term system approach taking into account the dynamics and the interactions between the heat, electricity and buildings energy systems is needed to acquire the necessary knowledge.

1.2. Aim and scope

In this study, the possibilities for utilization of different urban EH sources will be investigated from a wide system perspective and with a long-term perspective up to year 2050. The aim of the study is to assess urban waste heat possibilities from an urban DH system perspective. This includes an assessment of conditions and potentials for cost-efficient utilization of available urban EH sources in DH systems and energy systems impacts of utilizing urban EH sources in the DH systems. The following questions are addressed:

- To what extent and under what climate ambitions is DH production based on urban EH a cost-efficient option for heat supply from a wide system perspective?
- How does the introduction of urban EH use affect the cost-efficient technology mix of the urban heating supply, primary energy use and system costs?

The assessment is made at a city/urban level and takes interactions between DH, electricity systems and individual heating of buildings into account. It includes urban EH from data centres, metro stations, sewage systems and service sector buildings for use in DH systems in four case cities: Berlin and Brunswick in Germany, Nice in France and Madrid in Spain.

2. Method and data

The study applies a case study approach, using dynamic and quantitative energy system modelling for scenario analyses in which different policy and technology assumptions are contrasted. The developed model includes descriptions of the heating system of the four case study cities and assumptions for the heating sector interaction with electricity and fuel supply systems. The data used in the study regarding urban EH are based on four different types of urban EH sources. The urban EH sources as well as the case study cities correspond to the demonstrator projects of the ReUseHeat project. In this section, the model, important data assumptions and scenarios used in the modelling are presented.

Result parameters that will be analysed include cost-optimal fuel and technology mixes, cost-efficient levels of urban EH in heating, system cost reductions and primary energy use reductions of introduction of cost-efficient levels urban EH. For specific system cost reductions and specific primary energy use reductions, descriptions of the calculation procedures can be found in Appendix A: Result calculations.

2.1. Model

In the study, the well-established TIMES (The Integrated MARKAL-EFOM System) energy system model is used for the analysis [13] [14].

A TIMES model can be used to optimize energy systems over a mid- to long-term horizon. The model is driven by exogenously given demands for energy services and based on a perfect-foresight, linear programming bottom-up approach, where the objective function is minimization of the total system cost. The studied energy system is represented by different processes that are connected by flows of commodities. Each process (such as an energy conversion technology) is described, e.g., by its input and output commodities, efficiency, availability, lifetime and costs, whereas each commodity (such as a fuel) is described, e.g., by its availability, extraction or import cost and environmental impacts.

For this study, a TIMES model application representing the local energy systems of the studied cities is developed, here referred to as the TIMES_CityHeat model. The TIMES_CityHeat model represents the heating sector in cities, including both DH production and individual heat production in buildings. The electricity system as well as international markets for fuels are treated exogenously.

The objective function of the TIMES_CityHeat model minimize the cost of meeting the heat demand (residential and service sectors) of cities, both based on individual heating and DH, under consideration of any constraints put on the system, such as emission constraints and limited energy resources. The system cost, which is minimized, is the net cost of supplying heat in the sense that it includes revenues for electricity sale (at exogenously assumed prices) from electricity production in CHP plants. The shares of centralized DH and individual heating in houses are endogenously decided in the model optimization.

The TIMES_CityHeat model covers the time period between 2015 and 2052. The modelled time period is divided into 9 model years (the model years represent between 1-5 years each). Each model year is divided into eight time slices, representing day and night in four different seasons. The seasons are: winter, spring, summer and fall. For each model scenario (set of model input assumptions), the model generates an "optimal" future energy system development and calculates the associated system costs. A discount rate of 5% is used in the model.

In its current version, the model includes four regions, each region representing one of the four case cities: Berlin, Brunswick, Madrid and Nice. The heating sector of each city is represented in detail, including existing individual heat boilers/devices in buildings, existing DH system and DH distribution network. Heat demand in the case cities are defined for each time slice. Energy efficiency measures in buildings are handled exogenously and projections for future heat demands (including implementation of efficiency measures) are provided as input to the model.

The base year (2015) model representation of individual heat boilers/devices and DH systems in the case cities is based on the current fuel mix in the heating sector and existing production units in the respective DH systems. Under the modelled period, current production capacity will gradually be phased out and replaced by new technologies as a result of the model optimization. Technologies are described by parameters such as fuel input, capacities, efficiencies, lifetimes, availabilities, heat to electricity ratios (only for CHP plants) and operation and maintenance (O&M) costs. A selection of technology data used in the model is presented in Appendix B: Energy technology data.

2.2. Case study cities

In the following sections, a brief description of the current heat supply system of the studied cities are given as well as projections of future heat demand developments.

2.2.1. Berlin

In Berlin (Germany), the existing DH system is mainly supplied by ten large-scale fossil fuel CHP plants. In total, the DH system has thermal capacity of about 4125 MW and electric capacity of about 2310 MW. Hard coal, natural gas and a small share of biomass constitute the fuel use in the system which covers about 43% of total heat demand in the city of Berlin (about 36 PJ DH of 84 PJ total heat demand) [15, 16].

The heat demand not covered by DH is supplied by installed heat devices (boilers and HPs) in each building. At the national level in Germany, the fuel mix in individual heating are as follows: natural gas 47%, coal 9%, oil 22%, LPG 3%, thermal solar 1%, electricity 9% and biomass 9% [17]. In the current study, the base year (2015) fuel mix of individual heating in Berlin is assumed to be like the mix on the national level.

According to scenarios of the Heat Road Map project, the heat demand in Germany is expected to decrease significantly by 2050 due to implementation of energy efficiency measures in existing buildings and construction of new low-energy buildings [18]. In the current study, it is assumed that in Berlin the heat demand reduction is slightly lower compared to the country as a whole due to larger percentage population growth [10]. Total heat demand is reduced by 23-29% by 2050 compared to the current amount (depending on scenario).

2.2.2. Brunswick

In Brunswick (Germany) a DH system was initiated in 1924 and has been expanded continuously. Today, the DH system has a market share of approximately 34% of the city's total heat demand (about 2.9 PJ DH of 8.6 PJ total heat demand) [16]. Fossil fuels and a minor share of biofuels are used in CHP plants to supply DH.

The fuel use that supply the rest of the city's heat demand, i.e. individual heating, is assumed to be similar to corresponding national fuel mix (see Section 2.2.1) for the base year of the study (2015).

In the current study, it is assumed that in Brunswick the heat demand reduction is slightly lower compared to the country as a whole due to larger percentage population growth (population growth for Brunswick is assumed to be similar as for Hannover, the capital of Lower Saxony in which Brunswick is located) [10]. Total heat demand is reduced by 23-29% by 2050 compared to the current amount (depending on scenario).

2.2.3. Madrid

Today, Madrid has a DH and cooling system with capacity of 282MW. Out of these, 214 MW are DH and 68 MW are district cooling. The current DH system has the market share of 1.5% of total heat demand (about 0.8 PJ DH of 55 PJ total heat demand) [16]. DH is produced in natural gas CHP, a large-scale HP and natural gas and biomass boilers.

Fuel use to supply the individual heating in Spain, on average, constitutes of natural gas 32%, oil 13%, LPG 12%, thermal solar 3%, electricity 11% and biomass 30% [19].

In Spain, the heat demand is, according to Heat Road Map Europe scenarios, expected to remain almost at the same level of today's demand by 2050 [20]. Due to urbanisation and population growth [10] the heat demand in the city of Madrid may increase by 13-23% compared to the current demand by 2050.

2.2.4. Nice

In Nice (France), the production of the current DH system is based on a waste incineration CHP plant with electricity generation capacity of 14 MW. In 2016, the DH system had a market share of approximately 2.5% of the city's total heat demand (about 0.4 PJ DH of 17 PJ total heat demand) [16].

The fuel use that supply the rest of the city's heat demand, i.e. individual heating, is assumed to be similar to corresponding national fuel mix: natural gas 43%, coal 7%, oil 16%, LPG 3%, electricity 18% and biomass 12% [21].

In France the heat demand is, according to Heat Road Map Europe scenarios, projected to decrease by 25-34% by 2050 as a result of implementation of energy efficiency measures [22]. Urbanisation and population growth may slightly slow down the heat demand reduction in cities [10]. In Nice, the total heat demand is assumed to decrease by 20-30% by 2050 compared to current demand.

2.3. Excess heat

2.3.1. Urban heat recovery concepts

In this study, the cost-effectiveness of heat recovery from low-temperature urban EH heat sources for use in DH systems is assessed. A common property of low-temperature heat sources is that a HP is required to upgrade the heat before it can be utilized in DH systems. As previously mentioned, heat recovery from four different types of urban heat sources is in focus: metro stations, data centres, sewage systems and service sector buildings.

The concept of heat recovery from metro stations is inspired by an earlier planned case in Bucharest (Romania). This case was initially one of the demonstrators of the ReUseHeat project but was during the project duration switched to a similar demonstrator case in Berlin. The basic idea of the concept is that heat can be recovered from a metro station's ventilation system. The heat is generated by the stations' electrical equipment, the braking of the trains in the station and passengers. In Bucharest, a water-to-water HP with a capacity of 250-300 kW and COP of 3.5-4 was planned to recover 4.0 TJ_{heat} annually. The expected investment cost of this earlier planned installation was 324,200 EUR [23].

The concept of heat recovery from data centres is inspired by the ReUseHeat demonstrator case in Brunswick, Germany, in which heat recovery from a new data centre for use in a new low-temperature DH (70°C) is being installed. A heat exchanger and a water-to-water HP with a COP of 3.6 and a capacity of 300 kW_{heat}, producing 6.3 TJ_{heat}/year, is installed to extract EH from the data centre. The recovered heat supplies the base heat load of 400 houses built as low energy buildings with annual heat demand of 7.6 TJ. The investment cost of heat recovery from the data centre is 360,000 € [23].

The concept of heat recovery from sewage systems is inspired by the ReUseHeat demonstrator case in Nice, France. A central heat exchanger is planned to be installed to extract sewage system EH. The recovered heat is distributed through DH network at low-temperature levels. At each building substation, in addition to a heat exchanger, there is a reversible water-to-water HP with the COP of 4. By 2022, 61 TJ heat and 79 TJ cooling are estimated to be recovered and used per year. The investment cost of the sewage system DH extraction is 24 M€ [23].

The concept of heat recovery from service sector buildings is inspired by the ReUseHeat demonstrator case in Madrid, Spain. Here, heat recovery from a hospital's cooling system is planned. EH from the chillers' cooling circuit water at 29°C is upgraded by a water-to-water HP with the COP of 3 to be delivered to an existing DH system. In total, 7.6 TJ_{heat}/year is estimated to be recovered. The investment cost is estimated to be 325,000€ [23].

2.3.2. Excess heat potentials

The EH sources in the model include low-temperature EH from the four urban sources but also high-temperature (conventional) EH, primarily from industrial processes. Further, ambient source temperature (sea, ambient air, etc.) is also included as potential low-temperature heat source in the model.

The model assumptions for efficiencies and costs of large-scale HP technologies for upgrading of low-temperature heat sources are presented in Table 1. The values for the HP coefficient of performance (COP), i.e. the ratio of useful heat output to required electricity, is based on Deliverable 1.5 of the ReUseHeat project [24]. The increase in COP from 2015 to 2050 is due to both assumed cycle efficiency improvements of the HP technology and to reduced DH supply temperatures [24]. HP cost data are based on [25].

Available EH potentials from the different sources and cities are presented in Table 2. Base year (2015) potentials are based on Deliverable 1.4 of the ReUseHeat project [26] and PETA 4.3 [16]. For data centres, it is assumed that available EH will triple by 2050 compared to current levels in all studied cities in line with assumptions made in Deliverable 1.5 of the ReUseHeat project [24]. Similarly, for EH from the service sector buildings, it is assumed that the potential will increase during the studied period in line with assumptions made in Deliverable 1.5 [24] (increases correspond to the increases in cooling of the sector in scenarios from the Heat Road Map Europe project [18]). For the other heat sources (metro stations, sewage systems and conventional sources), it is assumed EH potentials remain unchanged by 2050.

Table 1. Techno-economic data used for large compressor HPs in DH based on different heat sources (based on [24], [25]). The span for COP values within the same year is due to seasonal variations.

Low-temperature heat source	COP Seasonal average (yearly average)		Specific investment cost	Fixed (O&M) cost	Variable (O&M) cost	Life-time
	2015	2050	k€/MW$_{heat}$ 2015/ 2050	k€/MW	k€/TJ 2015/ 2050	year
Service sector buildings	3.5-4.7 (4.1)	5.0-7.9 (6.4)	700/ 533	2	0.6/ 0.4	25
Metro stations	3.6-5.8 (4.6)	4.7-8.9 (6.6)	700/ 533	2	0.6/ 0.4	25
Data centres	3.7-4.0 (3.8)	5.3-6.0 (5.7)	700/ 533	2	0.6/ 0.4	25
Sewage systems	3.5-3.9 (3.7)	4.6-5.2 (4.9)	700/ 533	2	0.6/ 0.4	25
Ambient temperature	2.9-4.1 (3.5)	3.9-5.4 (4.8)	700/ 533	2	0.9/ 1.1	25

Table 2. Available urban and conventional EH (PJ/year) in the four demo-cities. Primarily based on [26]. See text for additional assumptions.

City	Service sector buildings	Metro stations	Data centres	Sewage systems	Conventional sources
	2015/2050	2015/2050	2015/2050	2015/2050	2015/2050
Berlin	1.9 / 6.1	2.2 / 2.2	3.8 / 11.3	8.5 / 8.5	1.4 / 1.4
Brunswick	0.1 / 0.4	0 / 0	0.005/ 0.014	1.2 / 1.2	6.3 / 6.3
Nice	1.0 / 3.2	0 / 0	1.7 / 5.2	1.9 / 1.9	0.5 / 0.5
Madrid	21.4 / 45.4	4 / 4	6.1 / 18.4	7.6 / 7.6	1.4 / 1.4

The temporal distribution of urban EH over the year is presented in Figure 1, which is based on Deliverable 1.5 of the ReUseHeat project [24]. It can be noted that for heat recovery from cooling of service sector buildings and for heat recovery from metro station ventilation about half of the potential is during the summer season. EH from data centres and from sewage systems show smaller variations over the year.

Figure 2 presents available urban EH in the four cities relative to total heat demand, for the model base year 2015 (a) and for 2050 (b). Due to increasing EH availability (from data centres and service sector buildings) and lower heat demand (due to increased energy efficiency in the building stock) the shares are higher in 2050 than in 2015.

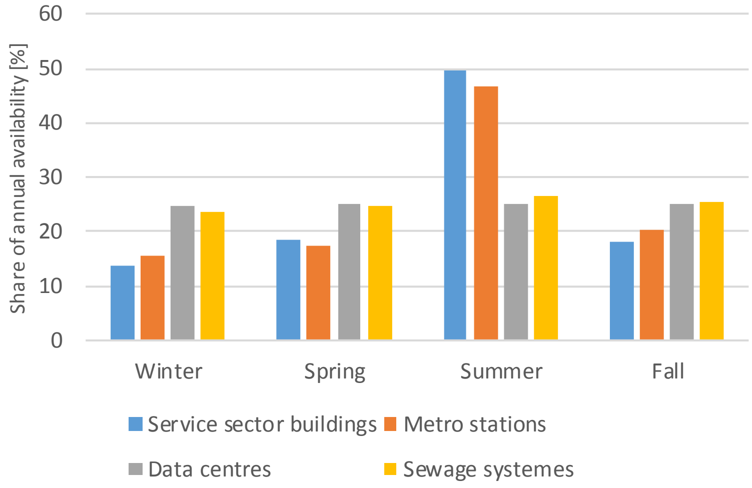
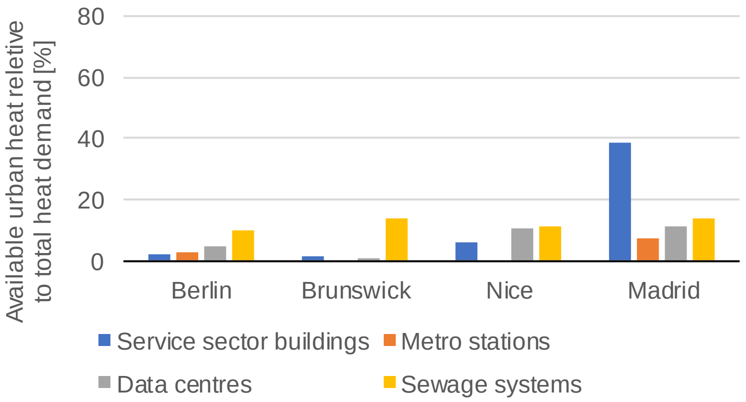
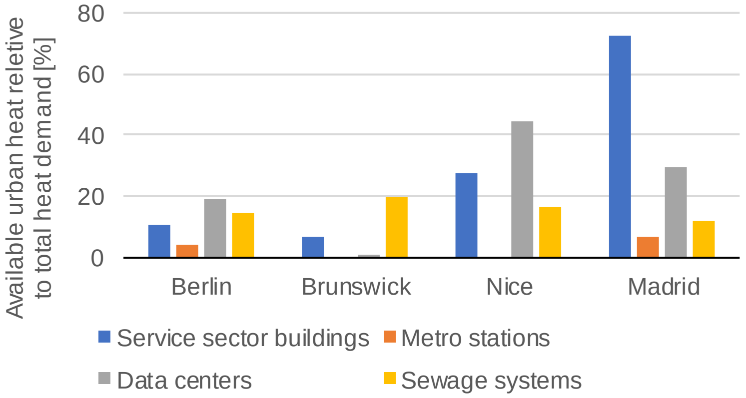


Figure 1. Seasonal distribution of available heat from the different urban EH sources



(a) 2015



(b) 2050

Figure 2. Available urban heat sources in the four case cities relative to total heat demand in 2015 (a) and 2050 (b).

2.4. DH infrastructure

Heat demand vary in different parts of the studied cities and this has implications for the potential development of DH infrastructure. Since investment cost of DH infrastructure (including DH transmission and distribution network) depends on heat demand density (i.e., greater heat demand densities give lower DH network investment costs), in the model, each city has been divided into five zones. The division of heat density zones as well as the estimation of corresponding investment cost of DH network expansion is for each city based on PETA 4.3 [16].

The model zones and the corresponding heat demands for the model base year (2015) are presented in Table 3. Figure 3 presents the shares of heat demand for different heat density levels.

Table 3. Heat demand in the five city zones for model base year (2015), based on [16].

Model zone	Heat demand density	Berlin	Brunswick	Madrid	Nice
	[TJ/km²]	[TJ/year]	[TJ/year]	[TJ/year]	[TJ/year]
A	>300	44 464	4 576	30 056	3 407
B	120-300	27 190	2 242	18 572	4 643
C	50-120	10 432	1 456	3 682	5 269
D	20-50	1 568	272	2 224	2 563
E	<20	570	77	612	782

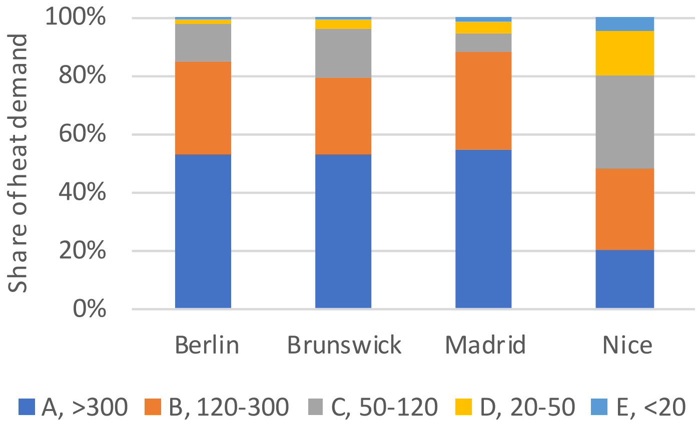


Figure 3. Share of heat demand for different heat density levels (TJ/km²) and corresponding model zones (A-E)), based on [16].

Figure 4 presents the DH network investment costs used in the model. Since the heat demand densities in the model zones D and E are very low, a DH network expansion in these zones is assumed not to be feasible and no costs are given. The cost increases stepwise with increasing build-up of DH. For each zone three cost levels are given. The heat demands in each zone (Table 3) is divided in three parts which each is linked to one of the three DH infrastructure cost levels (Figure 4).

Costs in PETA 4.3 [16] include distribution pipes for DH. Costs for service pipes to buildings or costs for substations are not included. Building-related DH costs, such as DH heat exchangers, are represented in other parts of the model (see also Appendix B: Energy technology data). However, due to cost uncertainties of large build-up of DH in cities which currently only have small DH shares, a sensitivity analysis linked to DH infrastructure cost is also carried out (see Section 2.5.4).

In PETA 4.3, DH distribution cost data are provided based on annualised investment cost (calculated by assuming 3% interest rate and a 30-year investment lifetime) per unit of heat. Here, these numbers have been recalculated to total upfront investment costs (through equations (1,2) below) before included in the model.

Investment cost = annuity present value factor * annualized investment cost [EUR/(GJ/year)] (1)

Annuity present value factor $= \frac{1-(1+r)^{-n}}{r}$ (2)

Where: r rate per period (3%), n number of periods (30 years)

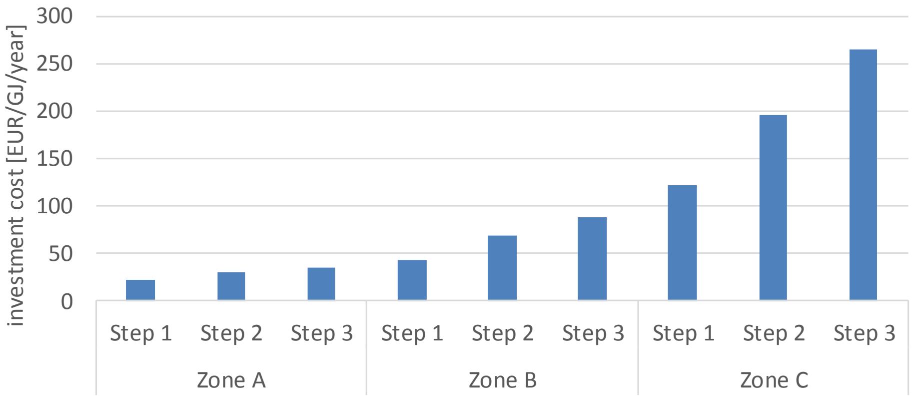


Figure 4. DH network investment cost in different city zones. Each heat density zone has three cost levels (steps) which is linked to specific potentials.

2.5. Scenarios

In the analysis, four main scenarios are used to assess a span of outcomes with regards to parameter values for which future levels are uncertain and of particular relevance for the present study. The four scenarios are composed of two climate policy scenarios and two heat supply scenarios. In addition to these scenarios, a sensitivity analysis is carried out in which selected parameters are varied to test the robustness of the results.

The two climate policy scenarios, “Climate High” and “Climate Low”, are designed to reflect two diverging ambition levels for climate change mitigation, both on the city scale and in the world at large. The Climate High scenario represents a development with ambitious climate change mitigation strategies and the Climate Low scenario represents a development with less ambitious climate change mitigation strategies. In the model, the different climate policies scenario influences three main types of model inputs: (1) the applied CO_2 reduction constraint for the cities, (2) fuel and electricity prices (as well primary energy factors for electricity), and (3) the level of energy efficiency of the building stock and, thus, the end-use demand for heating.

The two heat supply scenarios, "with large HPs" and "without large HPs", are designed to assess the impact of urban EH utilization on the energy system. Large HPs in DH systems are needed to boost the urban and other low-temperature (e.g. ambient) heat sources to temperature levels of corresponding DH system. Since electricity is used in compressor HPs, investments in and utilization of HPs have effects both on local energy system of the studied cities and on the electricity system. In the heat supply scenarios, investments in large HPs are allowed in the "with large HPs" scenario, while not allowed in the "without large HPs" scenario.

Table 4 presents an overview of the four main scenarios. In the following sections, related assumptions are presented in more detail.

Table 4. Composition of four main scenarios.

Scenario	Large HPs available in DH	CO_2 reduction	Fossil fuel prices (excl. CO_2 cost)	Electricity prices (incl. CO_2 cost)	End-use heat demand
Climate High – with large HPs	Yes	High (-95%)	Low	High	Low
Climate High – without large HPs	No	High (-95%)	Low	High	Low
Climate Low – with large HPs	Yes	Low (-40%)	High	Low	Baseline
Climate Low – without large HPs	No	Low (-40%)	High	Low	Baseline

2.5.1. Fuel and electricity prices

The climate policy scenarios "Climate High" and "Climate Low" are designed in line with Sustainable Development Scenario and New Policies Scenario of the International Energy Agency (IEA)'s World Energy Outlook 2017 (WEO) report [27], respectively.

The Sustainable Development scenario of the WEO report is an ambitious climate policy scenario which starts with a certain vision of where the energy sector needs to reach and then works back to the present. This vision of the future incorporates three major elements. First, it describes a pathway to the achievement of universal access to modern energy services by 2030. Second, it describes a development to 2040 that is consistent with the direction needed to achieve the objectives of the Paris Agreement, including a peak in emissions being reached as soon as possible, followed by a substantial decline. Third, it posits a large reduction in other energy-related pollutants.

The New Policies Scenario of the WEO report is a less ambitious climate policy scenario which incorporates not just the policies and measures that governments around the world have already put in place, but also the likely effects of announced policies, including the

Nationally Determined Contributions made for the Paris Agreement. In contrast, the New Policies Scenario aims to provide a sense of where today's policy ambitions seem likely to take the energy sector.

Fuel and electricity prices and costs assumed in the study are presented in Table 5. Fossil fuel prices are based on the Sustainable Development Scenario and New Policies Scenario of the International Energy Agency (IEA)'s World Energy Outlook 2017 (WEO) report [27, 28]. Biomass price assumptions are based on Danish Energy Agency's report for energy prices for industrial and central power plants [28] consistent with the WEO scenarios.

Electricity prices are calculated based on the assumption that the variable cost of the marginal technology (i.e., the sum of fuel cost, CO_2 charge and variable operation and maintenance cost) determines the electricity price. Since the price setting technology depends on the climate ambition, these are scenario dependent. The calculations are based on a selection of various coal and natural gas thermal power plant technologies. The variable cost of the marginal technology is assumed to set the electricity price for each time period and time slice.

Table 5. Summary of input data for the Climate High and Climate Low scenarios (EUR/GJ).

	Climate High	**Climate Low**
	2020/2030/2040	**2020/2030/2040**
Energy prices - International markets		
Natural gas	5.6/7/7.3	4.8/6.5/7.8
Fuel oil- light	11.8/14/12.2	12/14.5/16.8
Fuel oil- heavy	7/9.5/7.5	7.3/9.9/12.1
Coal	2.4/2.4/2.3	2.7/2.8/2.9
Bio pellets	10.2/14/17.7	9/9.4/9.6
Electricity (a) - Spring/fall	22.9/23.8/28.5	16.6/16.1/19.3
Electricity (a) – Summer	16.5/23.8/28.5	13/16.1/19.3
Electricity (a) – Winter	24.3/37.1/43.3	17.6/18.8/23
Energy costs - Local markets (limited potential)		
Wood chips	6.8	6.8
Straw	5.8	5.8
Municipal solid waste (b)	-4	-4
Excess heat (c)	0	0

(a) CO_2 charges used for calculating electricity prices are based on World Energy Outlook 2017 [21]. Electricity prices in table is for DH sector. Electricity prices for households are assumed to be 30-50% (depending on the climate scenario and season) higher than the electricity prices [30].
(b) For municipal solid waste, revenues from the gate fee (i.e., the fee charged for treating the waste) is included, based on [29].
(c) Excluding the technical costs of bringing the heat to the DH system.

Markets for wood chips, straw, municipal solid waste (MSW) and EH are assumed to be primarily local, and potentials for these fuels are constrained in the model based on local availability for each respective city, based on PETA 4.3 [16]. For locally constrained biomass, a cost of extraction is assumed (rather than a market price) which is constant throughout the studied time period. For MSW, revenues from the gate fee (i.e., the fee charged for treating the waste) is included, based on [29].

Possible future competition for constrained resources (e.g., biomass) from other sectors than the heating sector (e.g., for production of biofuels for transport), and indirect effects on prices and/or emissions linked to this, is not captured by the model.

2.5.2. CO_2 emissions and primary energy

2.5.2.1. Emission factors

The model calculates CO_2 emissions and primary energy use associated with heating of buildings. Table 6 presents CO_2 emission factors and primary energy factors used for fuels and electricity.

Table 6. CO_2 emission and primary energy factors. Based on [32] and authors assumptions.

Fuel/ Electricity	Primary energy factor	CO_2 emission factor [kt/PJ]
Coal	1.15	96
Heavy and light oil	1.11	82
LPG	1.11	60
Natural gas	1.09	60
Wood pellet	1.11	0 (a)
Wood chip	1.06	0 (a)
Straw	1.05	0 (a)
Municipal waste	0.05	35 / 17.5 (b)
Solar	0.22(c)	0
Excess heat	0	0
Electricity - Climate High (d)	2.9/ 2.7/ 1.5/ 1.0/ 0.4	224/ 196/ 78/ 50/ 30
Electricity - Climate Low (d)	2.9/ 2.7/ 1.8/ 1.4/ 1.3	224/ 196/ 99/ 76/ 71

(a) Biomass is here assumed to be carbon neutral. The assumption is discussed in Section 4.
(b) Values refer to model years: 2015/2050. Reduction based on assumption on lowered fossil content in the waste.
(c) From production and distribution of the equipment.
(d) Values refer to model years: 2015/2020/2030/2040/2050. Values in table are annual averages, while in the model seasonal differences can exist.

The heating sector interacts with the electricity sector through HPs, electric boilers and CHP plants. Consequently, the choice of heat production technology influences emissions from electricity production and, in the long term, investment decisions in the electricity system. Net use of electricity for heating is here assumed to, in the short run, impact emissions and primary energy use associated with the marginal production technology in the current electricity system (operating margin) and, in the long run, also affect investment decisions and the emissions and primary energy use associated with newly constructed electricity production capacity (build margin) [31].

The influenced marginal electricity is assumed to be a based on a mix of coal, natural gas and renewables: coal-based production is assumed to dominate in the short term, gas-based electricity in the medium term, and renewables in the long term. As is reflected in the development of the primary energy and CO_2 emission factors given in Table 6, the extent and rate at which renewables are introduced differ between Climate High and Climate Low scenarios with a faster and larger influence in the former case.

2.5.2.2. CO_2 emission constraints

The cities are forced to reduce their CO_2 emissions in the modelled scenarios. In Climate High, CO_2 emissions are constrained so that an emission reduction level of 95% is met by 2050 compared to the emission level of 2015. In Climate Low, a corresponding constraint reducing emissions by 40% to 2050 is applied. The emission constraints are applied so that the allowed amount of emissions each year linearly decreases between 2016 and 2050 (for each city individually), see Figure 5.

In the scenarios, two categories of CO_2 emissions are constrained at the same time. On the one hand, the direct CO_2 emissions from combustion of fossil fuels within the modelled systems, i.e. the heating sector of each city (both DH and individual heating), are constrained. On the other hand, system-wide CO_2 emissions including both direct CO_2 emissions and indirect emissions in the surrounding system due to electricity use and production within the modelled system are also constrained. Use of electricity will increase emissions outside the model system while production of electricity (in CHP plants) will reduce emissions outside the modelled system.

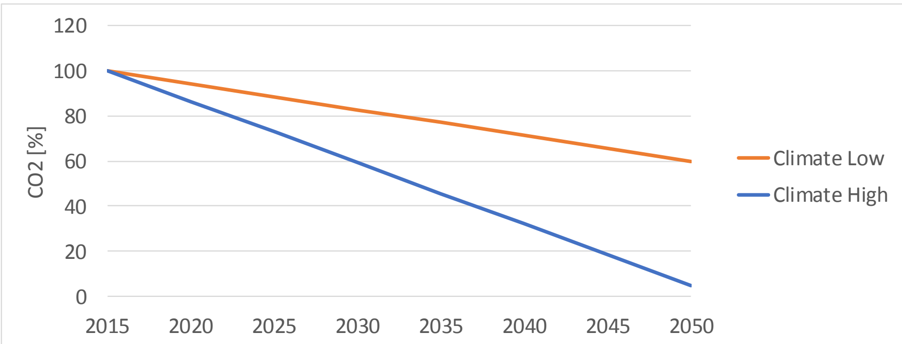


Figure 5. Upper bounds for CO_2 emissions in the model scenarios. Constraints apply both to fossil fuel CO_2 emissions within the heating sector of the cities and to system-wide CO_2 emissions when effects on electricity production outside the modelled system are taken into account.

The applied CO_2 constraints imply that each city at the same time needs to consider both their direct use of (fossil) fuels and their net use of electricity. For low/medium reduction levels, the two categories of CO_2 emission constraints will have different importance and impacts in the different cities. For high reduction levels (approaching zero emissions), differences between cities will to a higher degree even out. The reason is the different characteristics of the heating sector of the different cities at the model base year (2015) (see Section 2.2), and thus different starting points regarding levels of "fossil CO_2" (within the heating sector of the city) and "total CO_2" (with system-wide effects), see Figure 6.

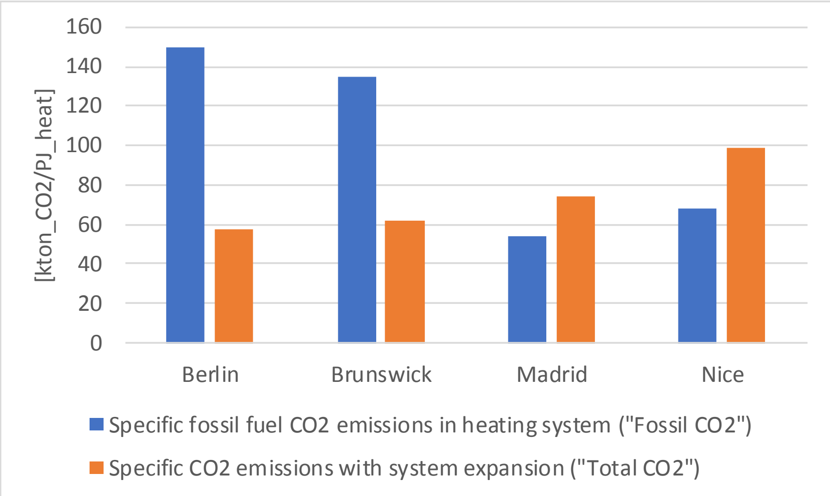


Figure 6. Specific CO_2 emissions, i.e. CO_2 emissions per unit of heat demand for the model base year (2015) in each city.

2.5.3. Heat demand

Total heat demand including both individual and DH is an exogenous input to the model (the share between individual heating and DH is endogenously decided in the model). Residential and service sector heat demand is covered.

The total heat demand level for 2015 and for 2050 for each city is presented in Figure 7. Total demand levels for 2015 are based on PETA 4.3 [16] and the future levels are based on national projections from the Heat Road Map Europe project ([18], [22], [20]), with adjustments made for projected urban population developments compared to national population developments [10]. For the Climate High scenario, the "HRE 2050" scenario of the Heat Road Map Europe project is used, while for the Climate Low scenario the baseline scenario ("BL 2050") is used.

The seasonal distribution of the heat demand over the year is presented in Figure 8. The distributions are based on data from the national EnergyPlan models utilized for the analysis presented in Deliverable 1.5 of the ReUseHeat project [24].

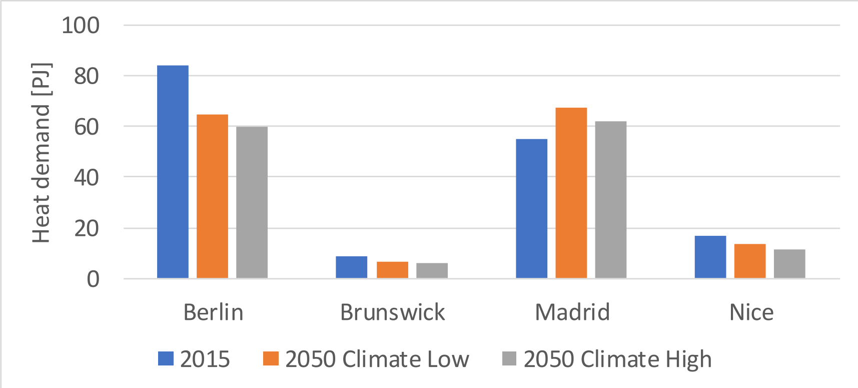


Figure 7. Total demand in model base year (2015) and in 2050 for the two climate policy scenarios

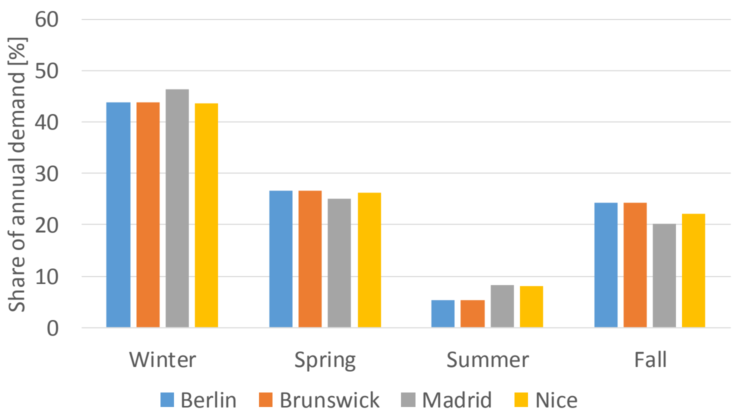


Figure 8. Seasonal distribution of heat demand for the studied cities

2.5.4. Sensitivity cases

In addition to the four main scenarios, supplementary model runs (about 40 per city) are carried out to test the sensitivity to variation of selected model input parameters. Specifically, the influence on the share of EH from low-temperature sources of the following changes to the base assumptions of the main scenarios are studied:

- Level of allowed CO_2 emissions are varied between 0% reduction and 100% reduction (all cities).
  - The climate policy scenarios Climate High and Climate Low apply different CO_2 reduction levels (-95% and -40% by 2050, respectively) as well as differences regarding, e.g., energy prices and end-use demand levels. To specifically test the influence of the CO_2 reduction level, additional model runs in which the level is varied are carried out.
- No geothermal energy in the DH supply in Berlin.
  - According to PETA 4.3 [16], there are geothermal energy potentials in the Berlin area. The total potential in terms of use in future DH is however hard to quantify. In the HRE scenario of the Heat Road Map Europe project, the potential for geothermal energy in DH at national level in Germany is estimated to 8% of the DH supply [18]. Given that the share should be

higher in local areas with nearby geothermal heat sources, in this study, an upper bound corresponding to about 15% of the current DH supply is assumed for Berlin. To test the sensitivity to this assumption, alternative model runs not including geothermal energy as an option is carried out.

- No availability of high-temperature industrial EH in Brunswick.
  - In the base assumptions, Brunswick has a high availability of industrial EH (see Table 2). This potential is the result of one nearby industry (metal and steel industry) [16], and the prospects of using this source can be linked to barriers and uncertainty in the long term. Alternative model runs are carried out to test impact of less access to industrial EH in Brunswick.
- Higher cost of DH infrastructure development in Nice and Madrid.
  - Nice and Madrid currently have a low share of DH in their heat supply. The cost of a significant build up DH in cities might involve barriers and costs not fully captured by the model. To test the sensitivity to this, the DH infrastructure costs (as presented in Section 2.4) are in these alternative model runs increased by 50% compared to the base assumptions.

Except for these parameters, the sensitivity cases apply the same conditions as in the Climate High and Climate Low scenarios.

3. Model results

In this chapter, the results of the modelling are presented. The first sections present, for each city, the energy system development in terms of fuel and technology use in the heating sector, with focus on impacts of use of urban EH sources, as well as effects on energy system costs (Sections 3.1, 3.2, 3.3, 3.4). Thereafter, the cost-efficient urban EH use in relation to availability is compared for the four case cities (Section 3.5). Lastly, results of the sensitivity analysis are presented (Section 3.6).

3.1. Berlin

3.1.1. Heating in buildings

In Berlin, the share of DH heating of total heating in buildings is already at the start of the modelled time period (2015) relatively high (about 40%). In all scenarios, the use of DH furthermore increases, both in absolute terms and as market shares, see Figure 9. In Climate High scenarios, the DH use (in absolute terms) decreases somewhat towards the end of the modelled period due to competition from individual heating based on HP as well as due to energy efficiency improvements reducing total demand for heating. At the end of the studied period (2050), DH receives a market share of 69-74% in Climate High scenarios and 79-83% in Climate Low scenarios.

Utilization of large HPs in both climate policy scenarios increases competitiveness of DH compared to other energy sources for building's heating. In both Climate High and Climate Low scenarios, a higher use of DH can be noted in cases allowing HPs in DH based on urban low-temperature EH sources (in the results graphs, large HPs are included in the DH category).

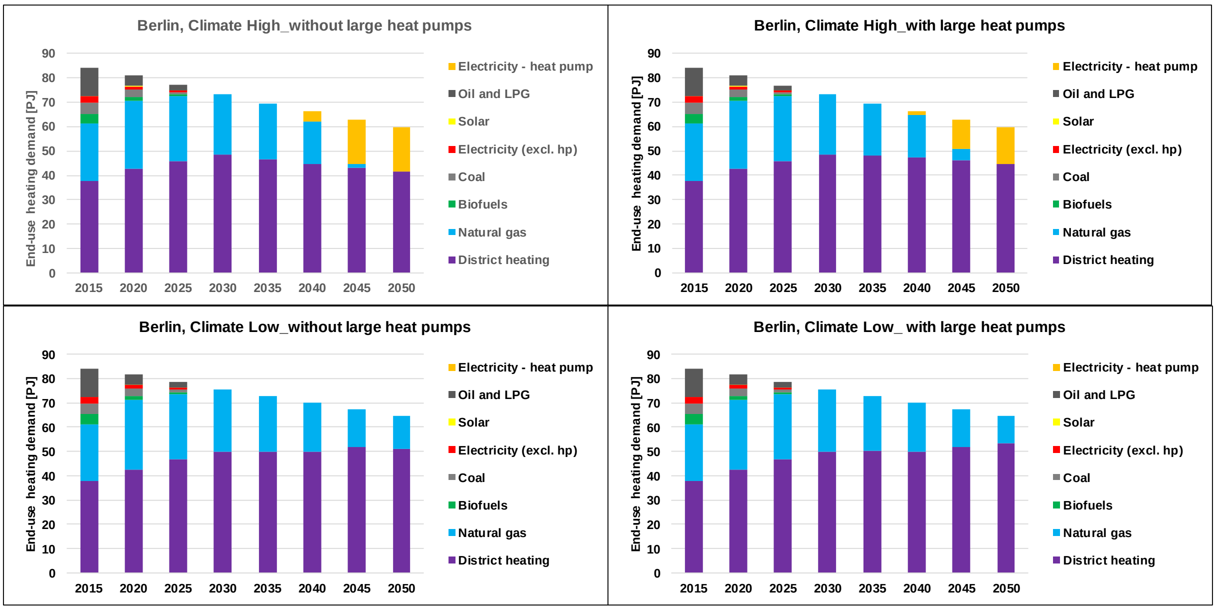


Figure 9. End-use demand for heating in buildings in Berlin (residential and service) divided by energy source.

3.1.2. District heat production

Fuels and technologies used for DH production are scenario dependent and varies over time. Figure 10 presents the cost-efficient development of DH production in Berlin for the different scenarios.

In Climate High, the current fossil fuel-based technologies are gradually replaced by bio fuels CHPs and industrial EH in the first model periods continued by geothermal heat and solar towards the end of model periods if investments in large HPs do not occur. Possibility for investment in HPs based on low-temperature sources changes the development from 2040 onwards. In the latter case, HP based on urban EH accounts for 26% of the DH production in 2050.

In Climate Low, the current fossil fuel-based technologies for DH production are also gradually replaced by renewables but at a slower rate compared to Climate High. In Berlin, the modest requirements for CO_2 reduction (in Climate Low) allow a high share of fossil fuel-based production also at the end of the studied period. A contributing factor to this is that a large part of the CO_2 reduction is taken care of by the foreseen reduction of heat demand due to energy efficiency measures. Natural gas CHP dominates the DH supply, and less room is left for urban EH than in Climate High scenario. When HPs are allowed in DH, HPs based on urban EH receive a 14% share of the DH production in 2050.

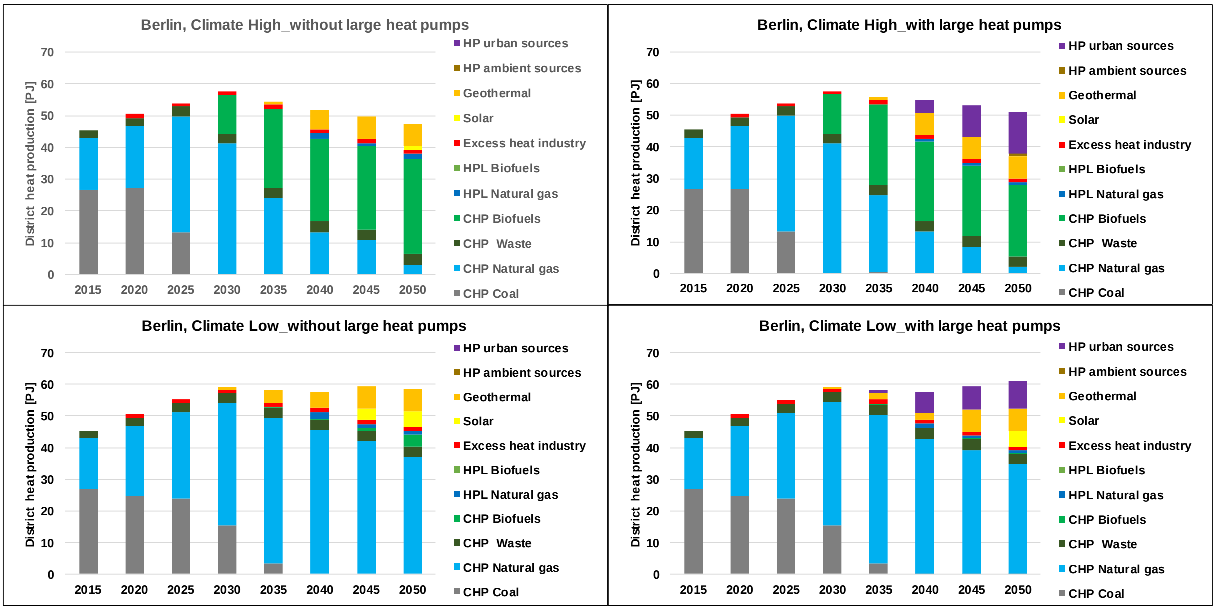


Figure 10. DH production in Berlin, Climate High with and without large heat pumps (top) and Climate Low with and without large heat pumps (bottom).

3.1.3. Primary energy use

Utilization of urban EH sources reduces the primary energy use of the heating sector of Berlin. On a system level, Climate High_with large HPs show a 14 PJ lower primary energy use than Climate High_without large HPs in 2050. Corresponding value for Climate Low is 7 PJ. Effects in the electricity system are accounted for both regarding changes in electricity use and electricity production (based on primary energy factors presented in Section 2.5.2.1).

Figure 11 presents the primary energy reduction (when "without large HPs"-cases are compared with "with large HPs" cases) as specific primary energy reduction per unit of heat demand. Variation of specific primary energy reduction due to changes in fuel and electricity use and electricity production (orange, grey and blue bars, respectively) and the net effect of these (yellow line) are shown. The specific primary energy use is reduced by 0.24 PJ/PJ_{heat} and 0.10 PJ/PJ_{heat} for Climate High and Climate Low, respectively. The reduction is primarily due to lower fuel use.

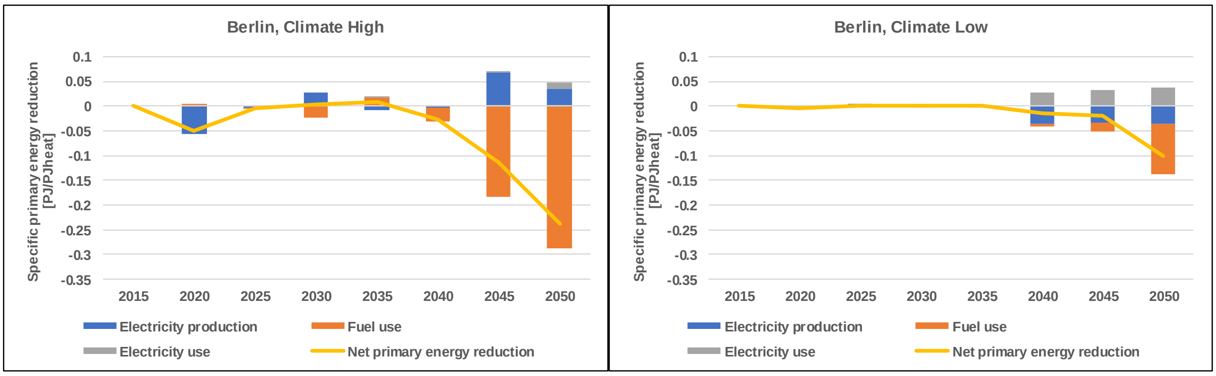


Figure 11. Specific primary energy reduction in Berlin, Climate High (left) and Climate Low (right).

3.1.4. System cost

Between 2020 and 2050, the introduction of cost-efficient levels of low-temperature EH reduces system costs by an average of 6.3 MEUR/year for Climate High and 2.4 MEUR/year for Climate Low. This corresponds to 1.7% and 0.9% of the total annual system cost for Climate High and Climate Low, respectively.

Figure 12 presents the system cost reduction expressed as the specific reduction per unit of heat demand. The cost reduction of Climate High is due to lower capital and fixed operation and maintenance costs with large HPs compared to the case without large HPs. In Climate High, urban EH mainly replaces biofuel CHP, which has comparably high investment and fixed operation and maintenance costs. In Climate Low, reduction is primarily linked to lower capital costs, mostly due to less CHP investments.

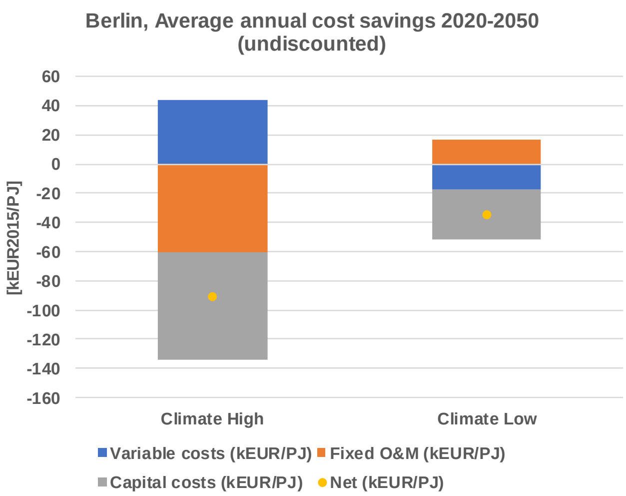


Figure 12. Average annual cost savings in Berlin (2020-2050) expressed per unit of total heat demand.

3.2. Brunswick

3.2.1. Heating in buildings

Similar to Berlin, Brunswick has from the start of the modelled time period (2015) a well-established DH system accounting for a large part of the city's heating. In the model result, the use of DH increases in future years, both in absolute terms and as market shares in all scenarios, see Figure 13. Independent on the scenario, DH use increases between 2015 and 2035 while it remains almost at 2035 levels by 2050.

In Climate High, DH constitutes 82% of the total heat demand in 2050. Individual heating based on natural gas which compete with DH in the first model years are replaced by individual HPs by the end of the model time period.

In Climate Low, individual heating based on natural gas gradually become the only competitor to DH for building's heating. In 2050, DH accounts for 84% of the heating market share.

In Brunswick, no effect from utilization of urban EH is noted on the share of DH for the main scenarios.

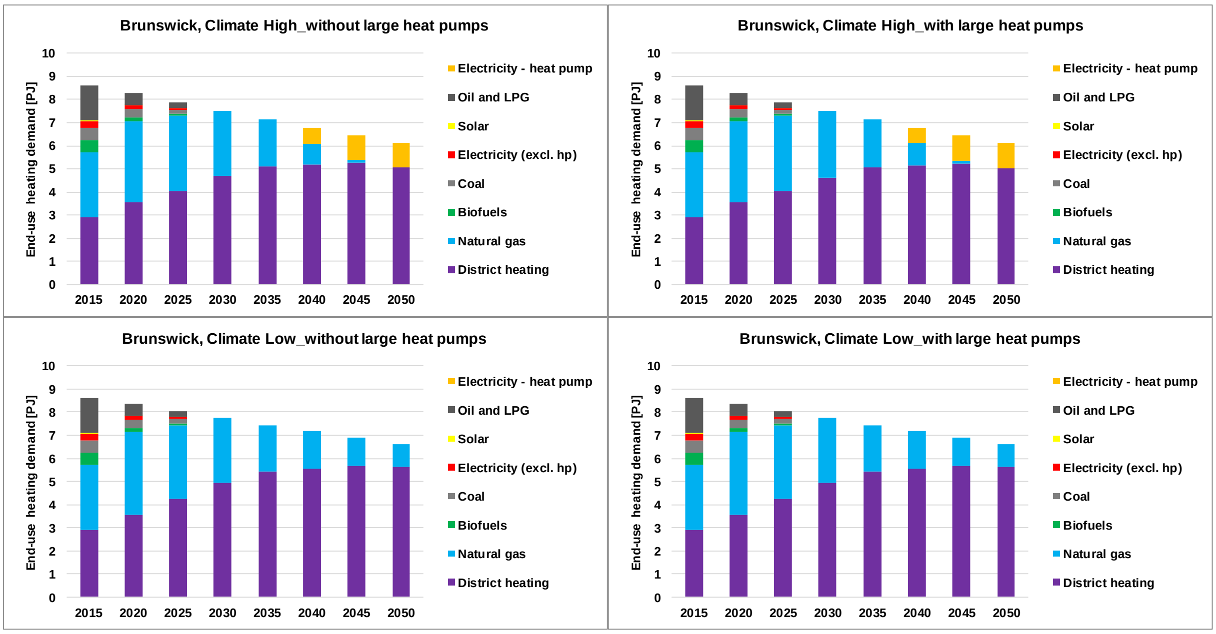


Figure 13. End-use demand for heating in buildings in Brunswick (residential and service) divided by energy source.

3.2.2. District heat production

Fuels and technologies used for DH supply to buildings in Brunswick are scenario dependent and vary over time. Figure 13 presents the cost-efficient development of DH production in Brunswick for the different scenarios.

In Climate High, industrial EH is the dominant source for the city's DH from 2020 (averagely 66% of the total DH supply). The rest of the heat is supplied mainly by natural gas CHPs and a small share of MSW CHP by 2030. From 2035 natural gas CHPs are gradually substituted by biofuel CHPs and, if investment in DH HPs are allowed in the model, small share of large HPs utilizing urban EH sources. HPs based on urban EH reaches a 7% share of the total DH supply in 2050.

In Climate Low, use of industrial EH is lower than in Climate High but still covers more than one-third of DH supply from 2020. The rest of heat is supplied by MSW CHPs, natural gas CHPs, coal CHPs and a small share of biofuel boilers. No contribution from urban EH in the city's DH is present in this scenario (i.e., there is no difference between the "without large HPs" and the "with large HPs" cases).

The high use of industrial EH significantly limits the use of low-temperature EH sources in the model results for Brunswick. In the sensitivity analysis (Section 3.6), the impact of alternative assumptions regarding industrial EH availability in Brunswick are tested.

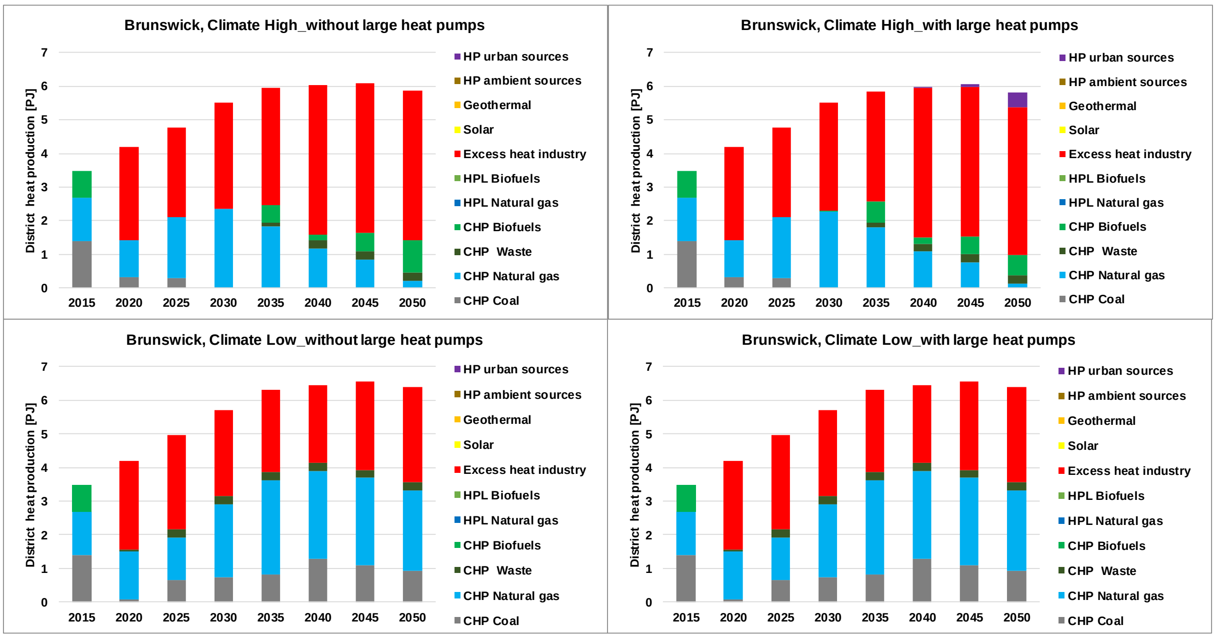


Figure 14. DH production in Brunswick, Climate High with and without large heat pumps (top) and Climate Low with and without large heat pumps (bottom).

3.2.3. Primary energy use

In the Climate High scenario, utilization of urban EH sources reduces the primary energy use of the heating sector of Brunswick. On a system level, the Climate High_with large HPs scenario shows a 0.7 PJ lower primary energy use than Climate High_without large HPs in 2050.

Figure 15 presents the reduction in primary energy use (when "without large HPs"-cases are compared with "with large HPs" cases) as specific primary energy reduction per unit of heat demand. In 2050, the specific primary energy use is reduced by 0.11 PJ/PJ_{heat} due to lowered fuel use. As mentioned, there is no difference for the Climate Low scenario for allowing the large HP option in the model.

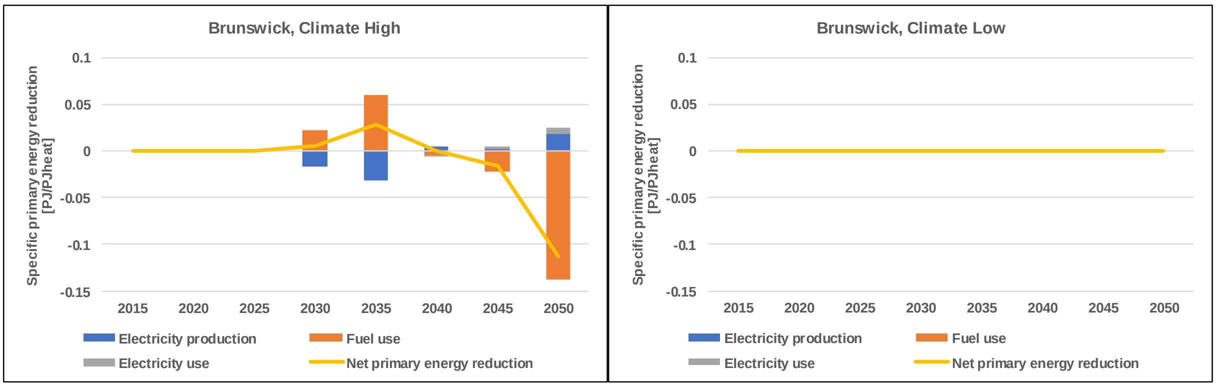


Figure 15. Specific primary energy reduction in Brunswick, Climate High (left) and Climate Low (right).

3.2.4. System cost

Since urban EH is only utilized in a very limited extent in Brunswick, the cost savings are minimal. Between 2020 and 2050, the introduction of cost-efficient levels of low-temperature EH reduces system costs by an average of 3 kEUR/year for Climate High (no change in for Climate Low). This corresponds to 0.02% of the total annual system cost.

Figure 16 presents the system cost reduction expressed as the specific reduction per unit of heat demand. In Climate High, reduced capital cost is almost completely outweighed by increased variable costs and fixed operation and maintenance costs.

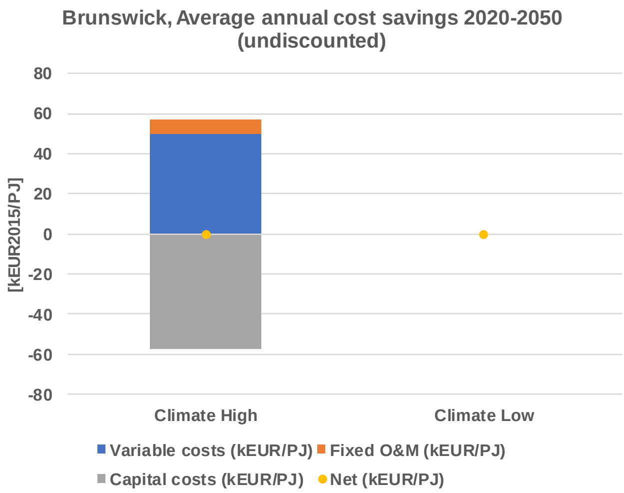


Figure 16. Average annual cost savings in Brunswick (2020-2050) expressed per unit of total heat demand.

3.3. Madrid

3.3.1. Heating in buildings

As Figure 17 shows, the heating sector in Madrid significantly changes over time compared to the current situation in all scenarios. Today DH contributes to only a very minor share of the heating supply in Madrid. However, in the modelled scenarios, the use of DH increases substantially, and DH reaches 51-68% of total buildings' heating demand in 2050 in Climate High, and 30-58% in Climate Low.

In Climate High, individual heating based on natural gas and individual electric HPs are the main competitors to DH. Like the Climate High scenario, in Climate Low without large HPs scenario, natural gas and HPs are the main competitors to DH; however, the contribution of natural gas is much larger. In the Climate Low and with large HPs scenario, only natural gas-based heating competes with DH.

Utilization of large HPs in both climate policy scenarios increases competitiveness of DH compared to other energy sources for building's heating. In both Climate High and Climate Low scenarios, use of DH is significantly higher in cases allowing HPs based on urban low-temperature heat sources in DH.

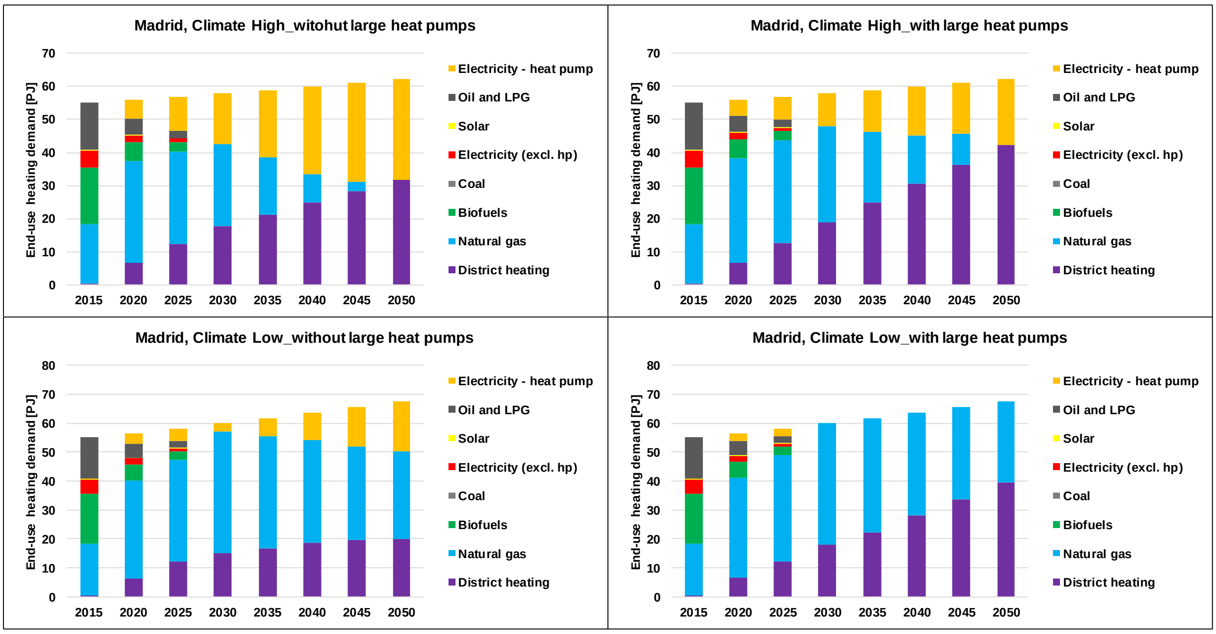


Figure 17. End-use heat demand in Climate High with and without large heat pumps (top) and in Climate Low with and without large heat pumps (bottom) in Madrid.

3.3.2. District heat production

In Madrid, a considerable build-up of DH capacity from 2015 to 2050 is noticeable in all the studied scenarios (Figure 18). In Climate High without large HPs, MSW CHP, biofuel CHP, natural gas CHP, solar and small share of industrial EH supply the city's DH. Given possibility of investments in large HPs, utilization of urban EH significantly increases DH production while urban EH partially replaces biofuels and natural gas CHPs. In this case, HP based on urban EH accounts for 23% of the DH production in 2050.

In Climate Low without large HPs, MSW CHP, biofuel CHP, natural gas boilers, solar and small share of industrial EH produce the city's DH. Possibility of investment in large HPs opens opportunities for larger share of DH of the total heat demand. Urban EH also replaces biofuel CHP production. HPs based on urban EH receive a 50% share of the DH production in 2050.

In contrast to, e.g., Berlin, the heat demand of Madrid increases during the studied period, and no CO_2 reduction is therefore received without effort in the model. Also, a comparably low fossil fuel use (per heat demand) in 2015 does not allow the city to choose fossil fuel-based CHP to any larger extent (as is done in Berlin and Brunswick) for its future heat supply while meeting CO_2 emission reduction constraints. However, the modest CO_2 reduction required in Climate Low allows the model to avoid the biofuel CHP option (which is costly but advantageous in regard to CO_2), and instead choose a higher share of urban EH HP than in Climate High scenario.

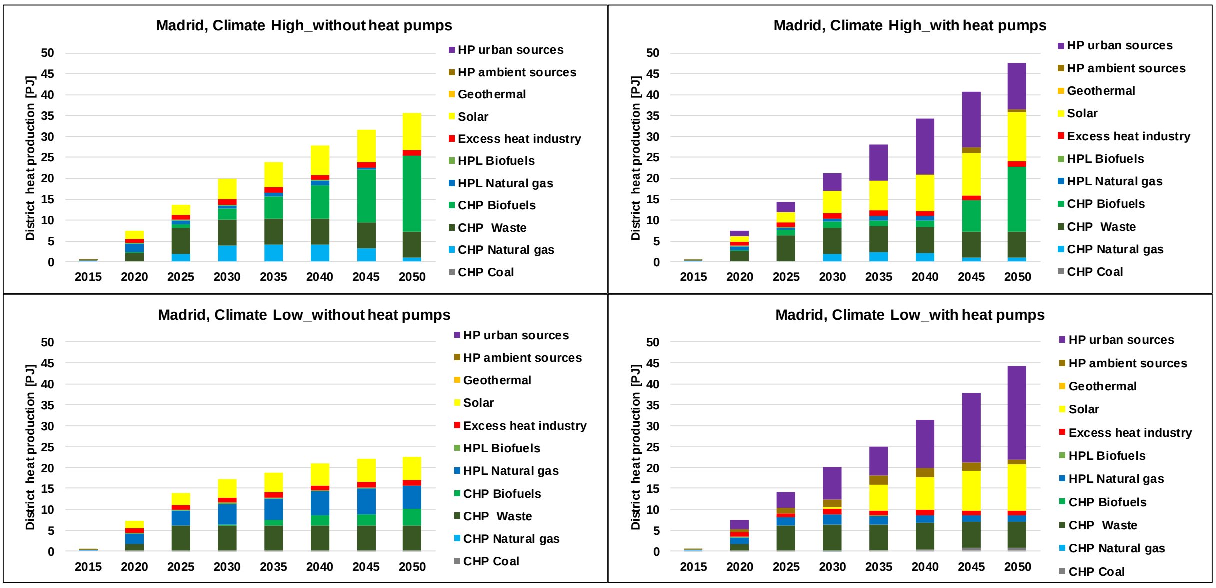


Figure 18. DH production in Madrid, Climate High with and without large heat pumps (top) and Climate Low with and without large heat pumps (bottom).

3.3.3. Primary energy use

Introducing urban EH in DH reduces the primary energy use of the heating sector of Madrid. On a system level, the Climate High_with large HPs scenario shows a 5 PJ lower primary energy use than Climate High_without large HPs in 2050. Corresponding value for Climate Low is 7 PJ.

Figure 19 presents the primary energy reduction (when "without large HPs"-cases are compared with "with large HPs"-cases) as specific primary energy reduction per unit of heat demand. Variation of specific primary energy reduction due to changes in fuel and electricity use and electricity production (orange, grey and blue bars, respectively) and the net of these (yellow line) are shown in the figure.

The specific primary energy use is reduced by 0.07 PJ/PJ_{heat} and 0.11 PJ/PJ_{heat} for Climate High and Climate Low respectively. The reduction is to large extent due to lower fuel use; however, in particular in the middle of the studied period for Climate High, the net reduction is somewhat lowered by the decrease in electricity production following the HP introduction (due to less CHP).

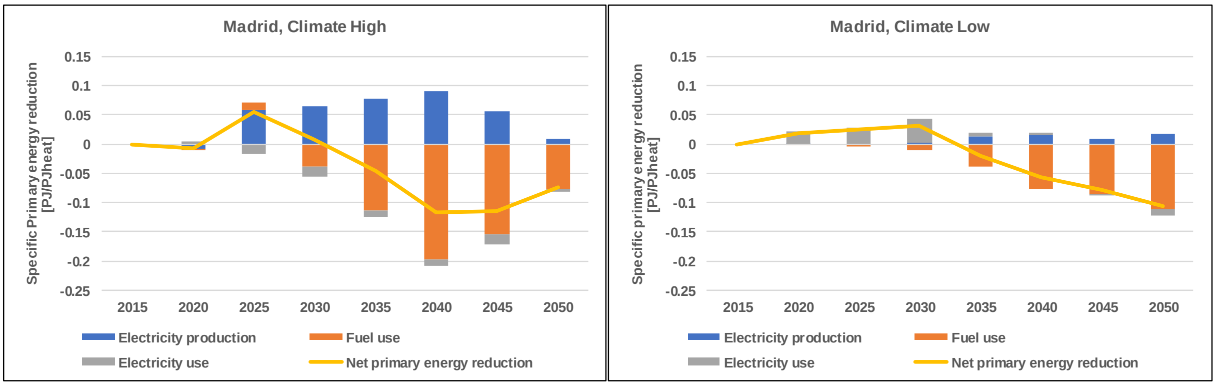


Figure 19. Specific primary energy reduction in Madrid, Climate High (left) and Climate Low (right).

3.3.4. System cost

Between 2020 and 2050, the introduction of cost-efficient levels of low-temperature EH reduces system costs by an average of 41 MEUR/year for Climate High and 33 MEUR/year for Climate Low. This corresponds to 5.7% and 6.0% of the total annual system cost for Climate High and Climate Low, respectively.

Figure 20 presents the system cost reduction expressed as the specific reduction per unit of heat demand. Variable costs decrease the most followed by fixed cost. Urban EH increases competitiveness of DH investments and DH production compared to investment in and operation of individual natural gas devices and individual HPs. In DH production, urban EH primarily replaces biofuel CHP. This imply less fuel use for heating purposes and therefore lower variable cost. Capital costs increase, a contributing factor to this is the investment costs associated with a larger DH infrastructure development.

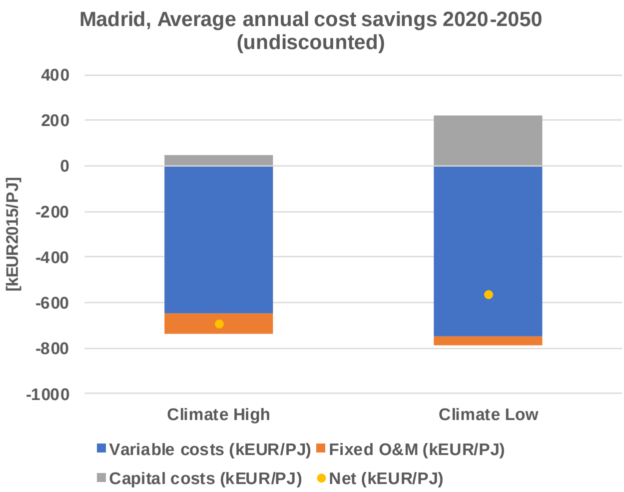


Figure 20. Average annual cost savings in Madrid (2020-2050) expressed per unit of total heat demand.

3.4. Nice

3.4.1. Heating in buildings

In Nice, like in Madrid, the heating sector goes through large changes over time compared to its current situation in all scenarios, see Figure 21. A market shift from individual heating to DH is seen in all scenarios to a varying degree. From the very low levels of DH in the start of the modelled period (2015) the DH market share reaches 44-59% in 2050 in Climate High. In Climate Low, market shares of 34-41 % are reached in 2050.

Composition of the individual heating market is scenario dependent. In Climate high, while individual gas boilers in buildings in the first model years play a dominant role, individual HPs in buildings play a more vital role towards the end of modelled time horizon. In Climate Low, individual heating based on natural gas is the main competitor to DH.

Use of large HPs in the both climate policy scenarios increase competitiveness of DH compared to other energy sources for building's heating. In both Climate High and Climate Low scenarios, use of DH is higher in cases allowing HPs based on urban low-temperature heat sources in DH.

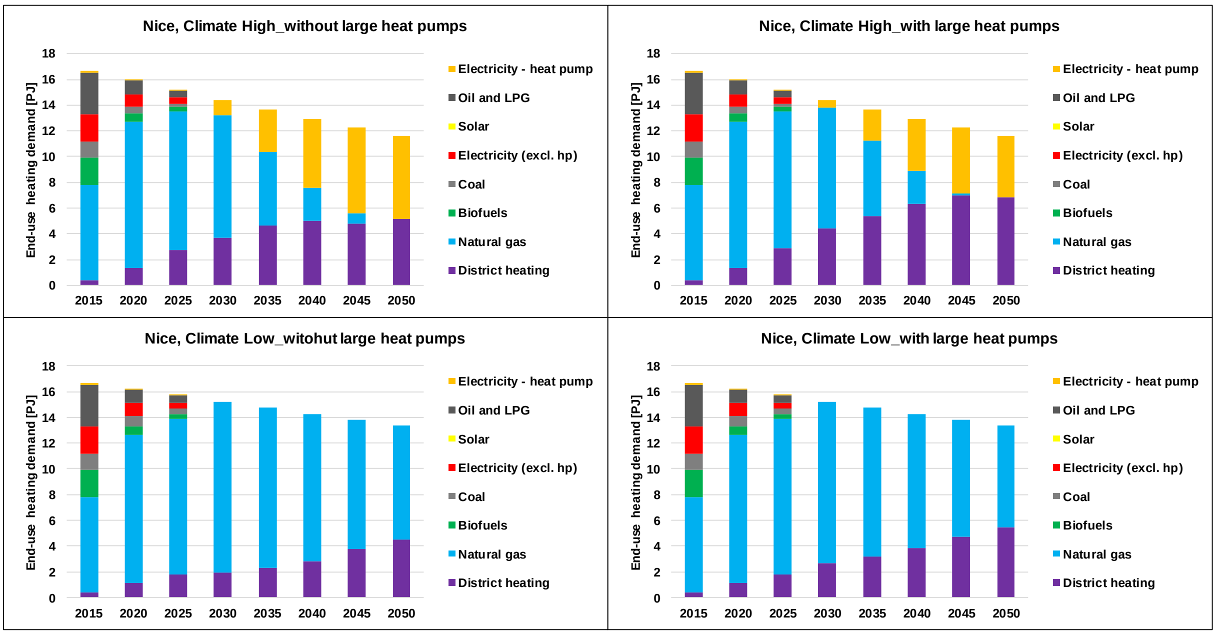


Figure 21. End-use heat demand in Climate High with and without large heat pumps (top) and in Climate Low with and without large heat pumps (bottom) in Nice.

3.4.2. District heat production

In Nice, current DH production is based on MSW incineration. As the DH production increases over time, depending on the scenario, different fuels and technologies contribute to DH production, see Figure 22.

In Climate High, in addition to the waste incineration plant, from 2020 natural gas CHP and industrial EH and, from 2025, biofuel CHP and solar collectors also contribute to DH production. Given that investment in large HPs is an available option (Climate High-with large HPs), from 2030 urban EH is also used, contributing to 30% of DH production in

2050. In turn, this results in larger share of DH of the total heat demand, primarily replacing HPs in individual heating.

In the Climate Low_without large HPs scenario, the fuel and technology mix is similar to the respective Climate High scenario except for that coal CHP and natural gas boiler is used which give lower shares to biofuels and natural gas CHPs. In Climate Low, when HPs are allowed, from 2030 large share of urban EH and from 2040 small share of ambient temperature heat sources are utilized for HP production. HPs based on urban EH receive a 58% share of the DH production in 2050. The use of HPs results in that no biofuel CHPs, natural gas heat-only boilers or solar collectors are used. Urban EH utilization also increases the share of DH in building's heating demand, replacing natural gas in individual heating.

In a similar manner as Madrid, Nice shows a higher use of urban EH in Climate Low compared to Climate High. The reasons are similar; with modest CO_2 restrictions as in Climate Low, HPs are a more cost-efficient alternative than options such as biofuel CHP and natural gas heat-only boilers. At the same time, Nice (as well as Madrid) cannot rely and large shares of fossil fuel CHPs since that would raise the CO_2 emissions within the city and not comply with the CO_2 constraint (this is to a higher degree possible in Berlin and Brunswick due to the higher share of such technologies in the base year 2015, see also Section 2.5.2.2).

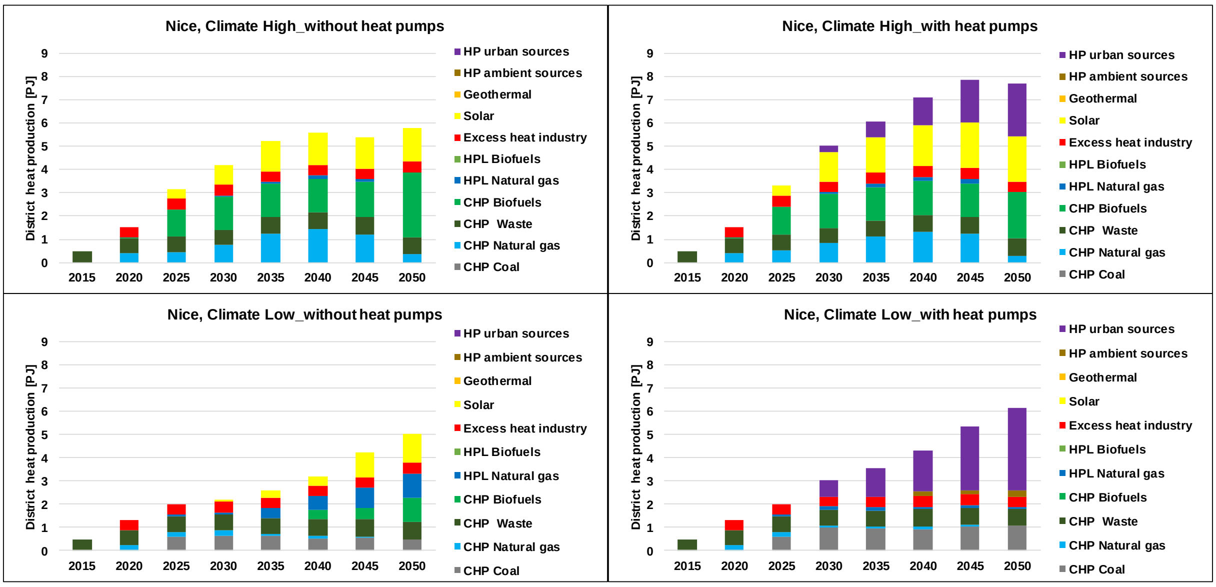


Figure 22. DH production in Nice, Climate High with and without large heat pumps (top) and Climate Low with and without large heat pumps (bottom).

3.4.3. Primary energy use

Urban EH in DH reduces the primary energy use of the heating sector of Nice. On a system level, the Climate High_with large HPs scenario shows a 1.3 PJ lower primary energy use than Climate High_without large HPs in 2050. Corresponding value for Climate Low is 1.4 PJ.

Figure 23 presents the primary energy reduction (when "without large HPs"-cases are compared with "with large HPs" cases) as specific primary energy reduction per unit of heat demand. Variation of specific primary energy reduction due to changes in fuel and electricity use and electricity production (orange, grey and blue bars, respectively) and the net of these (yellow line) are given in the figure. The specific primary energy use is reduced by 0.11 PJ/PJ_{heat} and 0.10 PJ/PJ_{heat} for Climate High and Climate Low respectively. The reduction is to large extent due to lower fuel use; however, for Climate Low, the net reduction is somewhat lowered by the increase of electricity use following the HP introduction.

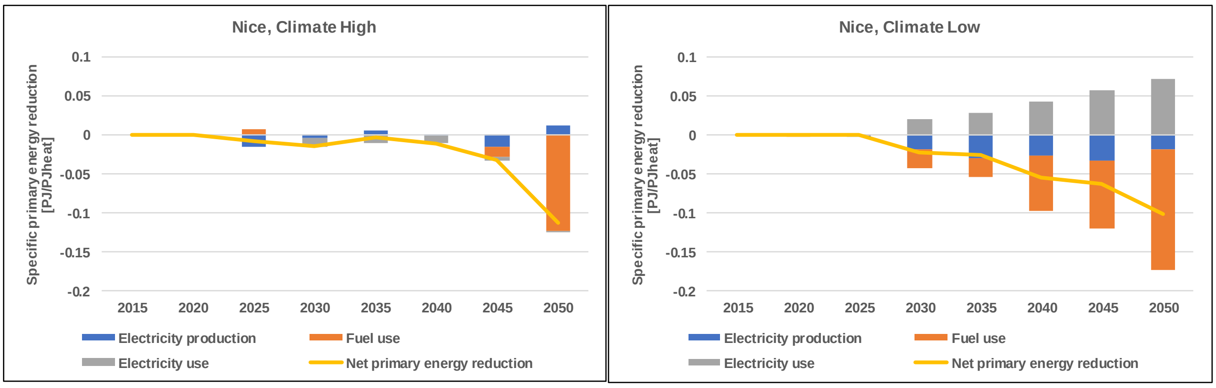


Figure 23. Specific primary energy reduction in Nice, Climate High (left) and Climate Low (right).

3.4.4. System cost

Between 2020 and 2050, the introduction of cost-efficient levels of low-temperature EH reduces system costs by an average of 3.8 MEUR/year for Climate High and 1.5 MEUR per year for Climate Low. This corresponds to 2.8% and 1.4% of the total annual system cost for Climate High and Climate Low, respectively. In both climate scenarios, variable cost decreases due to less fuel use for heating purposes because of replacement of, e.g., biofuels and natural gas. Capital costs increase, a contributing factor to this is the investment costs associated with a larger DH infrastructure development.

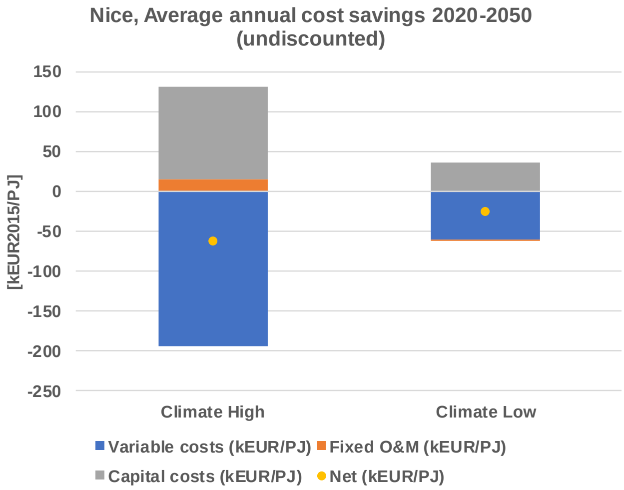


Figure 24. Average annual cost savings in Nice (2020-2050) expressed per unit of total heat demand.

3.5. Urban EH use in relation to availability

The results indicate that use of low-temperature EH for DH can be feasible and cost-efficient regardless of climate policy scenario; however, the available potential of urban EH is larger than what is cost-efficient to use, see Figure 25.

For Climate High, 12-37 % of the estimated potential of urban EH were used at the end of the modelled time horizon (2050), while for Climate Low, 0-28% is used (Table 7). The cost-efficient utilization levels are limited by the fact that the seasonal availability of urban EH vary significantly with a high availability in summer and a low in winter, i.e. the opposite to the seasonal heat demand distribution. Competition from CHP options, industrial EH and/or renewables (under stringent CO_2 constraints), further limits the cost-efficient level of utilization.

In the model results, all types of urban EH sources are included for DH production (except for EH from metro stations since this source does not exist in Brunswick and Nice). No clear conclusions about whether one option is preferable over the other can be drawn based on the modelling. In general terms, high availability and high COP in seasons with high heat demand (i.e. winter) is, of course, desirable.

As previously shown, which of the future climate policy scenarios could better motivate urban EH use in DH systems differ between the cities due to the different characteristics of the heating sectors (e.g. in regard to share of DH versus individual heating, share of CHP versus heat-only boilers, and level of foreseen energy efficiency improvements). Under the condition that fossil fuel use within the cities should not increase during the studied period, regardless of starting point, the modest CO_2 reduction requirements of Climate Low impact the cities differently: Berlin and Brunswick can continue to allow a comparably high share of fossil-based CHP production (and a lower use of EH) while Madrid and Nice to a higher degree turn to EH. With an almost complete decarbonization as in Climate High, results are more similar between cities.

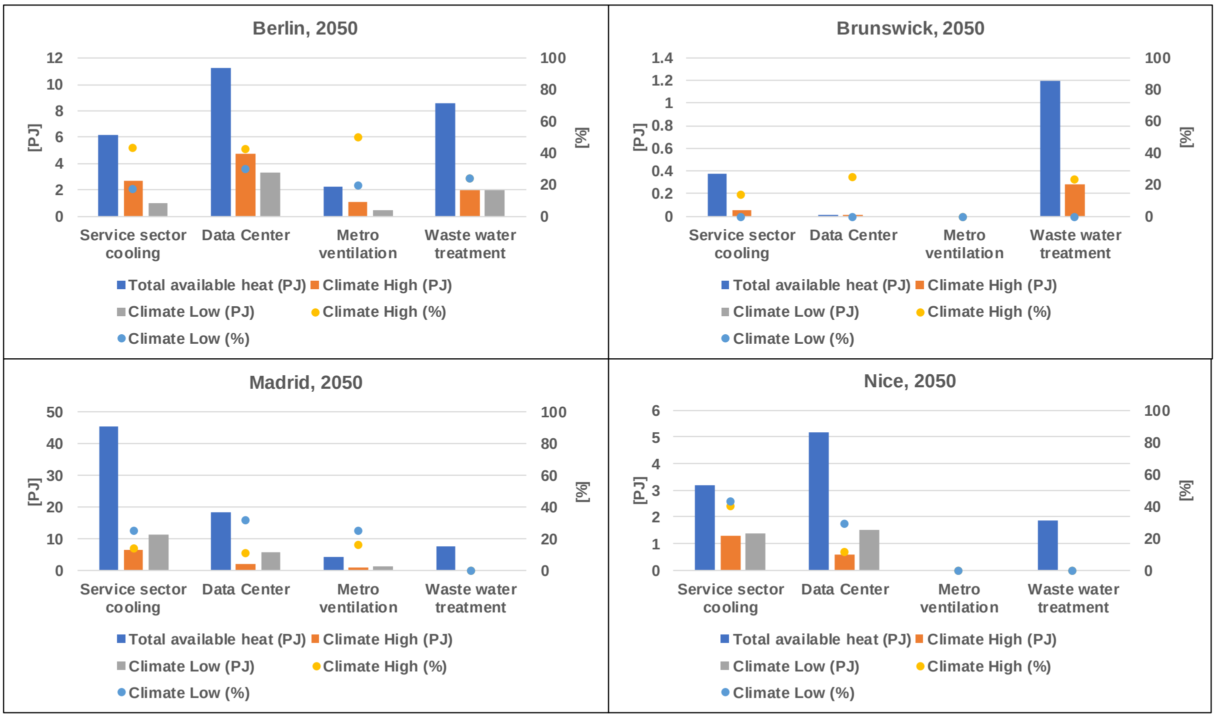


Figure 25. Cost-efficient urban EH utilization for different heat sources in 2050 (in absolute energy terms (bars) and as share of available potential (dots)).

Table 7. Cost-efficient use of urban EH in 2050 as share of available potential.

	Berlin	Brunswick	Madrid	Nice
Climate High	37%	21%	12%	18%
Climate Low	24%	0	24%	28%

3.6. Sensitivity cases

Impact of alternative assumptions on the use of low-temperature EH in the model results are tested in a sensitivity analysis. As previously described (Section 2.5.4), alternative assumptions for the following parameters have been investigated:

- Level of allowed CO_2 emissions (all cities)
- Geothermal energy use in the DH supply in Berlin
- Availability of high-temperature industrial EH in Brunswick
- Cost of DH infrastructure development in Nice and Madrid

Figures below present the outcome of the alternative model runs (Figure 26, Figure 27, Figure 28 and Figure 29). The figures visualize the level of HP production based on low-temperature heat sources in DH as share of total heat demand (both individual and DH) and as a function of the CO_2 reduction level for the model 2050. In the same way as in the main scenarios, the CO_2 reduction refers to both CO_2 emissions within the heating sector from fossil fuel combustion and CO_2 emissions with a wider system perspective taking also effects on the electricity system into account (see also Section 2.5.2.2). Figures show both results from: (1) CO_2 emission reduction variations in which all other assumptions are kept equal (solid lines) and (2) CO_2 emission reduction variations with the alternative assumptions on the site-specific parameters mentioned above (dotted/broken lines).

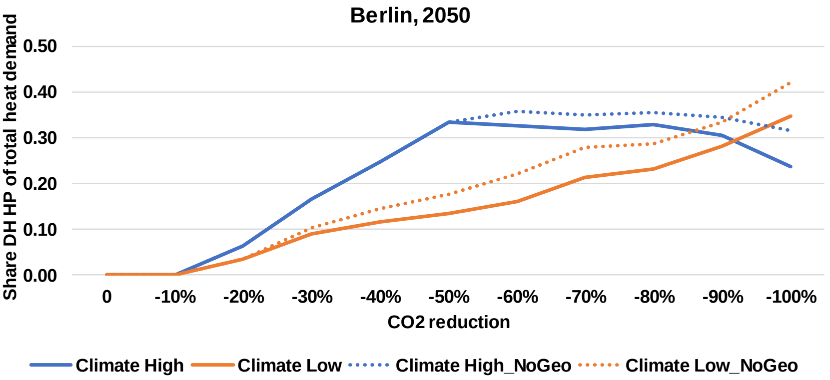


Figure 26. Share of low-temperature EH (upgraded by HP in DH systems) of total heat used in Berlin in 2050 as a function of CO_2 reduction level. Dotted lines represent alternative assumptions with no use of geothermal heating.

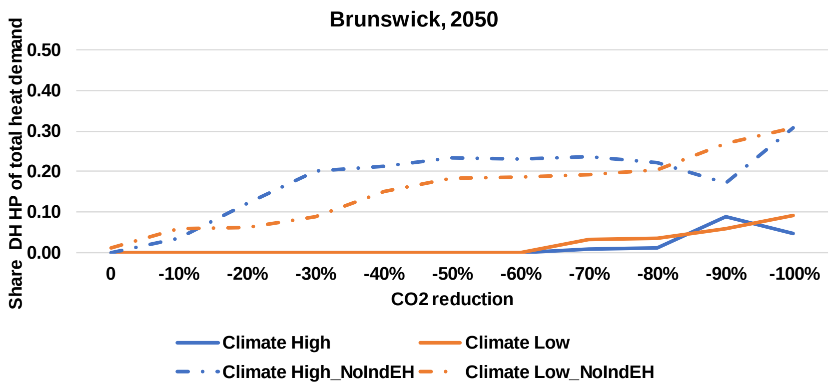


Figure 27. Share of low-temperature EH (upgraded by HP in DH systems) of total heat used in Berlin in 2050 as a function of CO_2 reduction level. Dotted lines represent alternative assumptions with no use of industrial EH.

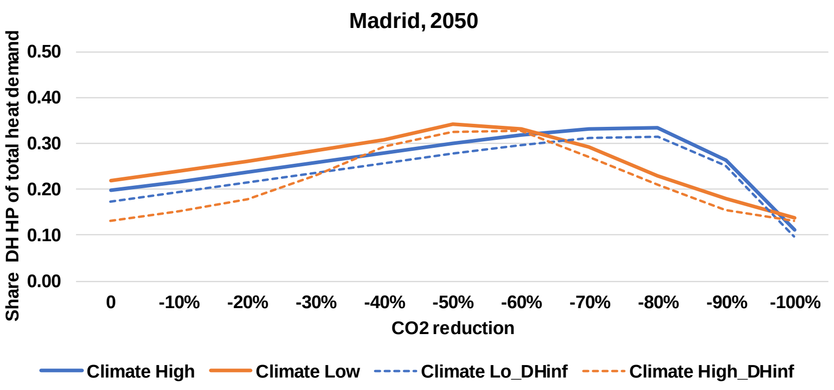


Figure 28. Share of low-temperature EH (upgraded by HP in DH systems) of total heat used in Berlin in 2050 as a function of CO_2 reduction level. Dotted lines represent alternative assumptions with 50% higher DH infrastructure costs.

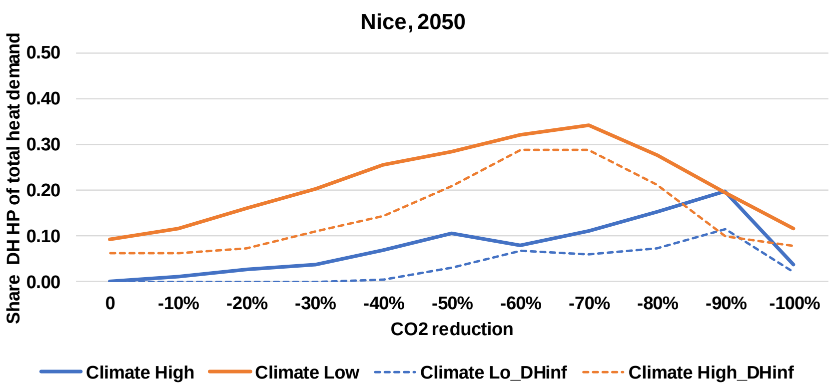


Figure 29. Share of low-temperature EH (upgraded by HP in DH systems) of total heat used in Berlin in 2050 as a function of CO_2 reduction level. Dotted lines represent alternative assumptions with 50% higher DH infrastructure costs.

3.6.1. Influence of CO_2 reduction levels

Results show that the level of CO_2 reduction has an important impact on the cost-efficient utilization levels of HPs in DH. To large extent, the share of DH increases with increasing CO_2 emission reduction levels. However, at very high reduction levels, the trend is in many cases the opposite. The reason is the increasing competition from renewables such as biofuel CHP and solar, combined with the fact that the electricity use of the HPs are linked to CO_2 emissions in the electricity sector. If lower CO_2 emission factors had been assumed for electricity (see Section 2.5.2.1), this could improve the performance of HPs at very high CO_2 reduction levels.

As seen in the results, an urban heating system can use compressor HPs and still have net-zero CO_2 emissions even if the electricity sector is not decarbonized; however, this requires electricity production from CHP plants which can off-set the electricity used by HPs.

3.6.2. No geothermal heat in Berlin's DH

If geothermal heat turns out not to be a feasible option for Berlin, the HPs based on low-temperature sources get larger shares in the model results (Figure 26). The results show that in the Climate High scenario, the share for large-scale HPs utilizing low-temperature EH sources slightly increases for CO_2 emission reduction levels above 50% compared to the base case assumptions. In Climate Low, the share for large-scale HPs utilizing urban EH sources compared to the base case assumptions slightly increases but from CO_2 emissions reduction levels of 20%.

If geothermal heat has larger potential than what here has been assumed, the opposite effect on EH use in the model results can be expected.

3.6.3. No industrial EH in Brunswick

If a large use of industrial EH is not possible in Brunswick, the prospects for use low-temperature EH changes considerable (Figure 27). In both climate scenarios, a large impact from the alternative assumption is seen for all CO_2 emission reduction levels. A much higher share of large-scale HPs utilizing urban EH sources are noted compared to the base assumptions. Shares for HPs based on low-temperature EH reach about 20-30% of total heat demand for Brunswick under stringent CO_2 constraints.

3.6.4. High DH infrastructure cost in Madrid and Nice

The results for 50% higher costs of DH infrastructure in Madrid and Nice compared to base assumptions (Figure 28 and Figure 29) show that for all CO_2 emissions reduction levels share of large-scale HPs utilizing urban EH decreases in the both climate policy scenarios. However, the reduction in share of large-scale HPs differs between the two cities. In Madrid, the reduction is generally small, except for at low CO_2 reduction levels for Climate Low. In Nice, the impact is higher and is noted in both climate policy scenarios.

The impact on low-temperature EH use is to a high degree linked to the impact on the share of DH in the total heat supply. In Madrid, the effect on DH use from the higher infrastructure cost is generally small. In Nice, the effect is larger. The reason for the difference between the cities is the difference in heat density and related costs for DH distribution. Madrid has a much higher heat density than Nice (see Table 3 and Figure 3) and is therefore less sensitive to an increase in DH distribution costs.

4. Discussion

In this study, possibilities for utilization of urban EH sources have been investigated from a wide system perspective and with a long-term perspective. Conditions and potentials for cost-efficient utilization of urban EH sources have been assessed, and energy system impacts investigated.

The quantitative dynamic optimization modelling approach applied in the study is a powerful method for framing and addressing complex and data-intensive energy system investigations. The performed modelling has given insights both to the mid-term and the long-term system impacts of utilization of urban EH sources in the heating systems of the case cities. This represents an advantage of the applied approach since energy systems are dynamic and the response to any intervention in the systems can differ over time.

As earlier pointed out, the results represent the least-cost development of the energy system to meet energy service demands under the conditions and constraints put on the system, e.g., regarding CO_2 emissions. As such, the development is not a prediction of the future development, but rather an explorative assessment to study the specific questions of the study.

It is not within the scope of the work to assess the probability of certain developments or policies to occur, none of the scenarios and pathways presented is thus considered more likely than the other. They are instead constructed to present a span of relevant and plausible results in terms of urban EH use and system effects. Nevertheless, given the reality of climate change as well as EU polices and targets, scenarios with stringent CO_2 reductions represent the desirable pathways from a normative perspective.

Since the model base its decisions on direct energy technology-related costs, indirect costs or other barriers hindering a certain development might not be reflected in the results. For instance, the significant build-up of DH capacity seen in some scenarios for cities currently only have very small DH capacity (Madrid and Nice) will certainly be linked to challenges. However, this does not change the results which do suggest that such development is advantageous from the perspective of the techno-economic aspects taken into account.

Biofuel CHP receive an important role in the DH production in the model results. Linked to this, some of the assumptions made on biomass use can be highlighted. In the CO_2 emissions calculations, biomass is considered to be carbon neutral. Biomass is a renewable source of energy, but it is also a limited resource. Under climate stringent policies, when all sectors of energy systems need to reduce their CO_2 emissions, use of biomass for heating purposes could potentially limit the use in the transport and electricity sectors. This in turn, with a wide system perspective, could indirectly affect net global CO_2 emissions. Such potential consequences are not accounted for in the present study. Further, in this study, a local market for unrefined biomass is assumed, resulting in just cost of biomass extraction (while refined bio pellets are assumed to be traded on international markets). However, in the future and under climate stringent policies, competition between different sectors for biomass use could also lead to an international market for unrefined biomass. This could in turn improve competitiveness of urban EH sources compared with biomass in DH systems.

For EH, all EH (urban and industrial) sources are assumed to be carbon neutral in the calculations, since there are no direct emissions associated with their utilization. This might to some degree misrepresent CO_2 emissions reduction possibilities because it does not account for any increase in emissions from the industrial process and urban sources that might occur if the price of the EH is sufficiently high to make less energy-efficiency measures profitable.

Since urban EH sources are not continuously available for DH during an entire year and the availability mismatches with buildings' heating demand (i.e. EH from metro stations and service sector cooling are more available during summer when DH demand is limited), thermal heat storages could improve the competitiveness of urban EH sources compared to other heat sources by making them equally available over the year. However, there are also additional investment costs associated with such storage. The costs and benefits of storage solutions has not been in depth analysed by the present analysis.

The presented assessment is based on specified local conditions (of the four case cities) and on the use of specific urban EH resources. The same method can be applied to other cities and EH resources, but the outcomes of the study are to a certain degree case dependent as is shown in the results for the four different case cities. Due to diversity of heating sectors and DH systems in terms of use of fuel and locally available resources, the replaced technologies and cost-efficient potentials for urban EH vary between systems.

5. Conclusions

The analysis has provided several results that identify circumstances for and impacts of utilization of the four EH sources in the urban energy systems analysed in the study. Several of the findings confirm the findings from modelling carried out at the national scale in Task 1.3 of the ReUseHeat project (Deliverable 1.5 [24]). Below results are summarized and conclusions of the work are drawn.

- Large HPs based on low-temperature heat sources are often a cost-efficient option for DH production

Urban EH upgraded with HPs for DH supply is in many of the analysed cases included in the cost-optimized result. In a scenario with ambitious climate targets (Climate High), the share of heat from urban EH sources in the total heat demand (DH and individual heating) corresponds to 19%, 6%, 16% and 18% in Berlin, Brunswick, Madrid and Nice, respectively, at the end of the modelled time horizon (2050). The share of urban EH sources in the DH production corresponds to 26%, 7%, 23% and 30% in Berlin, Brunswick, Madrid and Nice, respectively. In a scenario with less ambitious climate targets (Climate Low), the corresponding shares are 12%, 0%, 30% and 24% in Berlin, Brunswick, Madrid and Nice, respectively, for total heat demand and 14%, 0%, 51% and 58% for DH production.

- Balanced shares of large HPs based on low-temperature EH sources can lower system cost

In many cases, integrating large HPs in DH systems lower the techno-economic system cost of heat supply in the studied cities. In a scenario with ambitious climate targets (Climate High), the introduction of cost-efficient levels of low-temperature EH reduces the annual system costs between 2020 and 2050 by an average 1.7%, 0.02%, 5.7%, 2.8% for Berlin, Brunswick, Madrid and Nice, respectively. In a scenario with less ambitious climate targets (Climate Low), the corresponding system cost reductions are 0.9%, 0%, 6.0%, 1.4% for Berlin, Brunswick, Madrid and Nice, respectively.

- When large potentials of high-temperature EH sources are available, the cost-efficient use of low-temperature EH sources is limited

In cases where large amounts of high-temperature EH (not requiring upgrading by HP) from, e.g., industry, is available, there will be a limited use of HPs based on low-temperature EH since this generally is a less cost-efficient option. In the model cases, large potentials for industrial EH were included in the city of Brunswick due to nearby steel and metal industries, which resulted in low use of large HPs in DH. However, the possibility to utilize industrial EH can be linked to barriers and the long-term availability is uncertain. In sensitivity analysis, not including the option of industrial EH utilization, shares for HPs based on low-temperature EH reach about 20-30% of total heat demand for Brunswick under stringent CO_2 constraints.

- Large HPs based on low-temperature heat sources could be an important driver for DH development in cities which currently has a low DH coverage

Large HPs based on low-temperature heat sources increase competitiveness of DH compared to individual heating solutions such as fuel boilers or ambient temperature HPs. In the model results, there is a considerable difference in DH deployment in cities which currently has very little DH coverage (Madrid and Nice) in cases in which large HPs are available compared to cases in which large HPs are not available.

- Using low-temperature EH for replacing heat-only production is more advantageous than replacing CHP production

In the model results, cities with heat production capacity that is currently primarily based on heat-only production in individual heating in houses (Madrid and Nice) show an earlier introduction of large HPs in DH compared to cities with a high share of CHP (Berlin). Under the condition that local CO_2 emissions should be reduced, the possibilities of introducing fossil CHP in the former mentioned type of cities is not a feasible alternative (CHP has a comparably high fuel use per heat output).

- The availability of urban EH is larger than what is cost-efficient to use

The share of available urban EH compared to the total heat demand is high; In 2050, the share corresponds to 47%, 26%, 121% and 88% for Berlin, Brunswick, Madrid and Nice, respectively for the included urban EH sources. However, the seasonal availability of urban EH vary significantly with a high availability in summer and a low in winter, i.e. the opposite to the seasonal heat demand distribution (see also ReUseHeat deliverable 1.5 [24]). This limits the potential use of urban EH. Competition from CHP, industrial EH and/or renewables (under stringent CO_2 constraints) further limits the cost-efficient level of utilization. In a scenario with ambitious climate targets (Climate High), the utilized share of urban EH compared to the total available potential correspond to 37%, 21%, 12%, 18% for Berlin, Brunswick, Madrid and Nice, respectively, at the end of the modelled time horizon (2050). In a scenario with less ambitious climate targets (Climate Low), the corresponding share is 24%, 0%, 24% and 28% in Berlin, Brunswick, Madrid and Nice, respectively.

- Cost-efficient levels of large HPs based on low-temperature urban EH sources lower system primary energy use

Use of large HPs in DH generally lowers the primary energy use of the heating supply in cities. While there can be a negative effect on the cities' electricity balance due to higher electricity use (from urban EH HPs) and, potentially, lower electricity production (from CHP), the total effect on primary energy use is generally dominated by a reduction of direct fuel use for heat supply within the cities. In a scenario with ambitious climate targets (Climate High), the reduction in primary energy use per unit of heat demand (both DH and individual heating) as an effect of introduction of cost-efficient levels of urban EH is 0.24 PJ/PJ_{heat}, 0.11 PJ/PJ_{heat}, 0.07 PJ/PJ_{heat} and 0.11 PJ/PJ_{heat} for Berlin, Brunswick, Madrid and Nice, respectively, in 2050. In a scenario with less ambitious climate targets (Climate Low), corresponding values are 0.10 PJ/PJ_{heat}, 0 PJ/PJ_{heat}, 0.11 PJ/PJ_{heat} and 0.10 PJ/PJ_{heat} for Berlin, Brunswick, Madrid and Nice, respectively.

- The role of large HPs in DH in a future with a completely decarbonized heating sector is dependent on the ability of the electricity sector to decarbonize

Due to the electricity use of HPs, the system-wide CO_2 emissions linked to HP use is dependent on the fossil fuel content of the electricity generation. With CO_2 reduction constraints in heating sector approaching zero emissions, the relative competitiveness of renewables such as solar and biofuels increases compared to HPs. Nevertheless, the sensitivity analysis shows that an urban heating system can utilize HPs and still have net-zero CO_2 emissions even if the electricity sector is not decarbonized; however, this requires electricity production from CHP plants which can off-set the electricity used by HPs.

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Appendix A: Result calculations

System costs calculations

The model calculates total system cost discounted to 2015 as well as undiscounted variable costs (including energy flow cost, activity cost and taxes and subsidies), fixed operation and maintenance and capital costs for each demo-city and each model year. From the model results, average annual system cost savings for each demo-city is calculated based on equations (3) and (4):

$$\text{Average annual cost (j) saving (year 2020 to 2050)} = \big(\text{Average cost (j)}\,(\text{year 2020 to 2050, Climate policy (i, with large heat pumps)}) - \text{Average cost (j)}\,(\text{year 2020 to 2050, Climate policy (i, without large heat pumps)})\big) / \text{Average total heat supply } [\text{kEUR}_{2015}/\text{PJ}_{\text{heat}}] \quad (3)$$

$$\text{Average annual system costs savings (year 2020 to 2050)} = \sum_j \text{Average annual cost (j) saving (year 2020 to 2050)}\ [\text{kEUR}_{2015}/\text{PJ}_{\text{heat}}] \quad (4)$$

Where:

"i" is either Climate High or Climate Low

"j": variable cost, fixed operation and maintenance cost or capital costs

Specific primary energy reduction calculations

From the model results specific primary energy reduction for each demo-city is calculated based on equation (5),

Specific primary energy reduction= [Primary energy use $_{\text{(Climate policy (i, With large heat pumps))}}$- Primary energy use $_{\text{(Climate policy (i, without large heat pumps))}}$]/ total heat supply [PJ/PJ heat] (5)

where "i" is either Climate High or Climate Low.

Appendix B: Energy technology data

From 2020 various investment options for DH supply technologies, and different individual heat production technologies in the cities are included in the model. In Table A1 and Table A2, examples of included technologies and a selection of the technology data are presented. For data for large HPs in DH, see Table 1.

Table A1. Investment options for DH supply based on Danish Technology Data for Energy Plants [25]

Technology		Electricity Efficiency (Total)	Specific investment cost	Fixed O&M cost	Variable O&M cost	Lifetime
		2016 / 2050	**2016 / 2050**	**2016 / 2050**	**2016 / 2050**	
Combined heat and power plants			**k€/MWel.**	**k€/MW**	**k€/TJ**	**years**
Coal Power Plant		0.46 / 0.54 (1.07 / 1.06)	1930 / 1780	31 / 29	0.82 / 0.76	25
Gas Turbine Single Cycle		0.41 / 0.45 (0.84 / 0.90)	600 / 520	20 / 18	1.3 / 1.1	25
Gas Turbine Combined Cycle		0.58 / 0.63 (0.92 /0.92)	900 / 800	30 / 26	1.3 / 1.1	25
Gas engines		0.46 / 0.50 (0.97 / 0.98)	1000 / 850	10 / 8.5	1.5 / 1.4	25
Waste-to-energy		0.22 / 0.24 (0.96 / 0.97)	8000 / 6500	54 / 37	1.6 / 1.6	25
Biomass Steam Turbine	Wood chips	0.28 / 0.28 (1.05-1.06)	3500 /3000	100 / 86	1.1 / 1.1	25
	Straw	0.29 / 0.29 (0.94-0.93)	3500 / 3000	129 / 105	0.53 / 0.53	25
	Bio pellets	0.31 / 0.31 (0.91-0.92)	2400 / 2000	66 / 56	0.44 / 0.44	25
Heat-only boilers		**Heat efficiency**	**k€/MWheat**	**k€/MW**	**k€/TJ**	**years**
Electric boiler		0.98 / 0.99	70 / 60	1.1 / 0.92	0.22 / 0.28	20
Biomass boiler	Straw	1.0 / 1.0	910 / 760	53 / 43	0.17 / 0.17	25
	Wood chips	1.1 / 1.1	700 / 590	33 / 29	0.28 / 0.28	25
	Bio pellets	1.0 / 1.0	740 / 670	34 / 29	0.14 / 0.14	25
Geothermal heat (high temperature) [(a)]		0.93 / 0.94	1400 / 1200	28-20	0 / 0	25-30

Solar heating with diurnal storage (c)	-	367 / 283	0.07-0.06	0.05-0.1	30
Waste-to-energy	1.05-1.06	1800-1550	85-69	2.1-2.4	25
Industrial excess heat	0.9	200 (d)	0	0	20

(a) Potential for high temperature geothermal heat only exists in Berlin [16] and is assumed to be 7 PJ, i.e. 15% of current DH production in the city.
(b) Investment capacity in solar DH is constrained in the model. Heat supply from solar DH is limited to not more than 25% of total DH production in each DH system [25].
(c) The availability factor for solar heating varies between seasons and between cities and is based on Energyplan models used in [24]: Berlin: 0.05-0.27; Brunswick: 0.05-0.27; Madrid: 0.10-0.30; Nice: 0.07-0.27.
(d) Investment cost represents cost of constructing a DH transmission pipeline between industry and DH system assuming an average distance of 10 km from source to DH network, based on [33].

Table A2. Investment options for individual heat devices in buildings based on Danish Technology Data for Heating Plants [25].

Technology		**Efficiency**	**Specific investment cost**	**Variable O&M cost**	**Life-time**
		2016 / 2050	**2016 / 2050**	**2016 / 2050**	
			k€/MW$_{heat}$	**k€/TJ**	**years**
Natural gas boiler		0.98 / 0.99	113 / 94	0 / 0	25
Oil boiler		0.85 / 0.91	123 / 103	4.9 / 4.1	20
Biomass boiler (Bio pellets)		0.82 / 0.92	236 / 198	5.4 / 4.5	20
Electric boiler		0.97 / 0.97	101 / 85	0 / 0	30
Heat pump	Air-to-water	2.7-4.2 / 3.0-4.7 (a)	375 / 285	0.14 / 0.11	20
	Brine-to-water	2.9-4.1 / 3.2-4.5 (a)	662 / 505	0 / 0	20
Heat pump- gas absorption	Air-to-water	0.94-1.5 / 1.2-1.8 (a)	409 / 175	0 / 0	20
	Brine-to-water	1.0-1.4 / 1.3-1.7 (a)	750 / 314	0 / 0	20
Solar collector (b)		-	614 / 479	52 / 65	20
DH heat exchanger		0.97 / 0.97	62 / 52	0 / 0	25

(a) Coefficient of performance (COP) for heat pumps with seasonal variation.
(b) The availability factor for solar heating varies between seasons and between cities and is based on Energyplan models used in [24]: Berlin: 0.05-0.27; Brunswick: 0.05-0.27; Madrid: 0.10-0.30; Nice: 0.07-0.27.

ReUseHeat