100% renewable heat supply in Berlin by 2045 – a model-based approach

Themenbereich 2 – Energieerzeugung/-infrastruktur und Netze

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1 Abstract

Motivation and central research question

The current energy crisis poses major challenges, especially for the heating sector. The European gas price increased from 16€/MWh in March 2021 to 227€/MWh in March 2022 [1], which has led to a rethinking about the future of heat supply. Nevertheless, the complexity, uncertainty, and often ignorance in the heating sector makes many actors reluctant to make the necessary investments to reduce dependence on natural gas. An independence from natural gas and other fossil energy imports by 2045 would be possible with a switch to a 100% renewable heat supply for Berlin. The present paper investigates the feasibility of a 100% renewable heating sector in Berlin.

Methodology

The heating sector lacks good quality data. In Germany, cities are obliged to prepare plans for the heating system in the coming years, which should represent heat demand and renewable heat potentials [2], however, the data is not yet fully available. We therefore conduct scenario analyses for relevant input parameters to map possible developments in heat supply. The input parameters include renovation rates, renewable heat potentials, and the availability of hydrogen imports. The scenario analysis accounts for uncertainties on the input side and reflects this in different decarbonization pathways.

For the analysis, we use the open-source, cost-optimizing, techno-economic energy system model GENeSYS-MOD which covers the electricity, building, industry, and transport sectors. This enables the assessment of sector coupling in energy systems and its impact on electricity, hydrogen and other energy carriers.

We apply GENeSYS-MOD to the area of Berlin. Hence, we adapt the existing data set and connect it to scenarios for Europe from the H2020 research project openENTRANCE [3]. Relevant data points are extracted from the scenarios (e.g. demand forecasts, transmission capacities) and implemented in the disaggregated model. The paper focuses on the challenges of the heat transition in the building sector and the associated phase-out of coal and fossil gas. For this purpose, the modeling of district heating in GENeSYS-MOD is refined and additional technologies, especially different types of large-scale heat pumps, are added.

Results and Conclusions

The goal of the scenario analysis is to develop robust decarbonization pathways for Berlin´s heating sector that are both technically and economically feasible and meet the climate targets for Berlin. From the results, "no-regret solutions" can be identified which are necessary steps for the decarbonization

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and should be implemented despite any current uncertainty regarding e.g. renovation rates and hydrogen availability. The results will provide an investment strategy that allows the identification of bottlenecks, e.g. in terms of workers needed for building refurbishments and heating retro-fitting. The consideration of a sector-coupled energy system also allows an estimation of how the heating market will change with respect to the availability of hydrogen. Through the involvement at the European and German level, Berlin's current plans to replace fossil gas with hydrogen can be evaluated in a larger context.

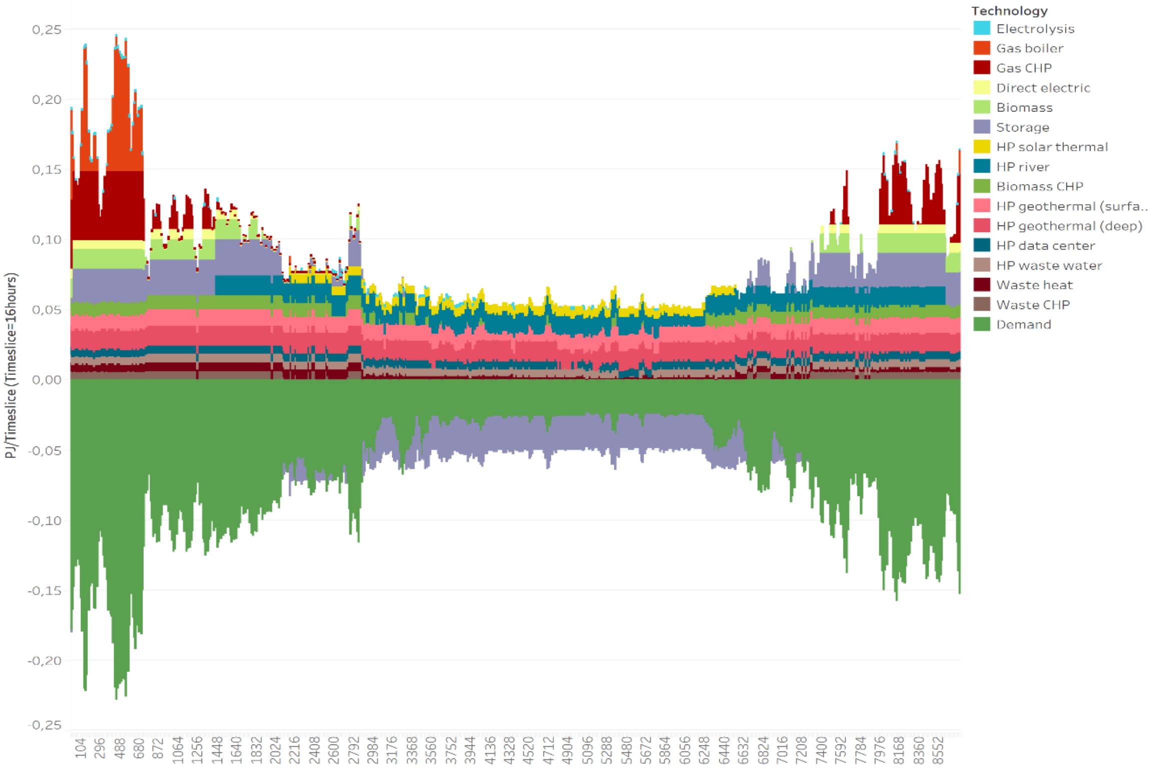

Figure 1: Preliminary results of early model runs for district heat supply in 2045 for Berlin

Preliminary results show that CHPs will play a minor role in district heating because CHP power generation has limited compatibility with a power system based on solar and wind. Instead, heat will be replaced predominantly by large-scale heat pumps and heat generation by boilers with hydrogen/synthetic gases to provide peak heat (see Figure 1).

For decentralized heat generation, the importance of gas-fired heating is declining significantly. Nevertheless, depending on the availability of hydrogen, bivalent heat systems consisting of heat pumps and boilers might contribute to heat supply.

Literature

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2 State of research on the transition of the heating sector

So far, the energy transition has placed a strong focus on the electricity sector. Though the heating sector is responsible for 50% of the energy demand in Germany, it has received little attention in the context of energy transition so far (BMWi 2019a, 17). However, all sectors must be involved to achieve an energy system based on renewables and in compliance with climate targets. Three key approaches combined enable to achieve a heat transition, namely, (1) the overall energy demand has decrease via efficiency measures, (2) district heating has to be decarbonized, and (3) heat generation needs to be electrified through heat pumps, ultimately allowing heat to be generated from renewable energy sources (Fraunhofer IWES/IBP 2017).

Increasing efficiency in the heating sector will need to emphasize reducing heat demand for buildings. However, increasing energy efficiency in the housing sector has been slow. This is partly due to a shortage of craftsmen and hesitant building owners. Refurbishment rates range at 0.8%, missing the target rate of 2.1% by a large margin. Especially, owners that do not live in the building themselves are hesitant to invest since they do not profit from the energy savings. This dilemma has to be addressed in the future because a heat and energy transition cannot be realized without reducing the final energy demand in the building sector (Pritzl 2019).

On the supply side, decarbonization can be achieved through sector coupling. Sector coupling interlinks the energy sectors of transport, heat, and power generation. Through better connections between the sectors, energy sources can be exchanged with each other. For example, electric cars can be used as battery storage to relieve the electricity grid when a high level of renewable energies feeds in more electricity than is demanded. With increased sector coupling, the heating sector will be taking over system services based on renewable power generation (Maurer et al. 2020). With increased flexibility in heat demand, more surplus electricity from renewables can be used for heat generation, as studies by Bleoß et al. (2018), Rinaldi et al. (2021), or David et al. (2017) suggest.

Other approaches to sector coupling, such as power-to-gas, though promising, pose their challenges. Converting excess electricity into e. g. hydrogen suffers from low efficiency due to high losses during conversion and will likely play a minor role in the heating system (Gerhardt et al. 2020). The available quantities of hydrogen, natural and from renewables-based production, will mostly be used in sectors that are hard to decarbonize. These include aviation and shipping, as well as certain industrial processes (e.g., steel production). Currently, there is still much uncertainty regarding the availability of hydrogen. Estimates for the hydrogen demand range from 250TWh to 500TWh in 2050 for Germany (Matthes et al. 2021).

2.1 The state of (urban) heat transition modeling

2.1.1 Modeling the heat transition in Europe and Germany

On a European level, modeling can develop insights about the general market penetration of technologies. Studies by Lund et al. (2016; 2014) or Connolly et al. (2014) focus on the role of district heating and the need for district heating networks to lower the temperature and integrate renewable energy sources to decarbonize the heating sector. Lund (2018) further highlights the importance of cross-sectoral usage of gas, electricity, and heating grids to save investment costs for a 100% renewable-based energy system, whereas Möller et al. (2019) suggest decarbonizing the European heat sector by including excess heat into the district heating networks. David et al. (2017) collect data on existing large-scale heat pumps to highlight that the necessary technology to decarbonize the heating sector already exists and can be deployed on a large scale.
In addition to deploying renewable technologies, reducing the heating demand will be crucial for achieving a 100% renewable-based energy system. Hence, Hansen et al. (2016) examine the cost-efficient amount of efficiency measures in the heating system. They conclude that reducing the heating demand to 30-50% and suppling the remaining demand with renewable heat will be the cost-efficient solution for a 100% renewable energy system. Similarly, Thellufsen and Lund (2016) examine efficiency measures not only in the building sector but the electricity sector as well. They emphasize the importance of considering both sectors when implementing efficiency measures to determine the optimal amount of efficiency measures.

Like the studies on a European level, country-level studies have proven the feasibility of a renewable-based energy supply for Germany. Existing studies identify market penetration of heat pumps, the reduction of heat demand through efficiency measures, and the decarbonization of district heating as the main success factors (Kobiela et al. 2020; Hansen, Mathiesen, and Skov 2019; Fraunhofer

IWES/IBP 2017). In the past, European energy system models have been used to feed-in results to more granular models that examine heating systems on a national level, e.g. Zwickl-Bernhard et al. (2022) for the Austrian case study.

2.1.2 City-level heat transition

Analyzing decarbonization pathways requires analyses that factor in regional and sub-regional differences. Zwickl-Bernhard et al. (2022) develop decarbonization pathways for district in Vienna, Austria, and their results emphasize the possibility of an urban heat transition independent of gas distribution grids. Instead the heating system can rely on district heating and electrification. Bloeß (2020) examines the decarbonization of district heating at the Berlin level. He places a particular focus on the role of heat pumps in combination with renewable electricity. Further, a feasibility study for a climate-neutral Berlin highlights different decarbonization options for the sectors trade, households, buildings, and energy (Reusswig et al. 2014). This feasibility study was updated by Hirschl et al. (2021) and expanded by Dunkelberg et al. (2021) to include the decarbonizing of the heat supply in Berlin. In the study, the authors show a path for a climate-neutral heat supply in 2050. Here, it is important to mention the studies by Hirschl et al. (2021) and Dunkelberg et al. (2021) do not conduct cost-optimal modeling. Instead, the authors follow a restriction-based approach that focuses on the feasibility of specific measures and thus draws a viable path until 2050.

Another approach to decarbonizing district heating, shown in the example of Berlin, is the exploitation of heat potentials of wastewater (Dunkelberg, Deisböck, Hirschl, et al. 2020). Besides, the study underlines the importance of neighborhood planning as an essential instrument for a coordinated heat transition (Dunkelberg, Deisböck, Hirschl, et al. 2020). Further, Dunkelberg, Deisböck, Herrmann et al. (2020), and Ritzau et al. (2019) conducted studies examining the replacement of coal in two different subgrids of Berlin's district heating network. Whereas Dunkelberg, Deisböck, Herrmann et al. (2020) identify decarbonization options that use local heat potentials to replace the coal capacities in the examined subnetwork, Ritzau et al. (2019) propose the replacement of coal mainly with gas CHPs. Preliminary results by Egelkamp et al. (2021) present a potential pathway for Berlin that fully exploits the available renewable heat potentials to ensure an entirely renewable-based heat supply by 2035. However, a large part of the potentials must be verified in a subsequent study to determine their actual feasibility.

2.2 Challenges for the heat transition in Berlin

The success of the heat transition depends on the timely expansion of heat pumps and their market penetration, an increase in efficiency measures (especially the energy-efficient refurbishment of existing buildings), and the decarbonization of district heating networks (Prognos, Öko-Institut, and Wuppertal-Institut 2021; Albert et al. 2019; Fraunhofer IWES/IBP 2017). For a metropolitan area like Berlin, however, there are obstacles to the deployment of heat pumps and efficiency measures, which are discussed below.

2.2.1 Decentral heat pumps in urban areas

In the future, air- and ground-source heat pumps will be increasingly applied in decentral heat supply. Ground-source heat pumps are preferred due to efficiency advantages in winter when ambient heat in the ground is higher than in the air. However, the use of ground-source heat pumps is limited in urban areas due to minimum distances between systems. Therefore, their application will most likely concentrate on peripheral areas with one- and two-family housings (Dunkelberg et al. 2021, 110). Furthermore, the general use of ground-source heat pumps is limited by groundwater protection regulations. Air-source heat pumps can provide a suitable alternative for these cases. In inner-city areas, respective systems will be installed, yet performance limits might be reached in unrenovated buildings.

Further obstacles to the deployment of heat pumps are noise pollution and space problems. Therefore, regulations must be established to allow for heat pumps outside buildings with sound insulation if necessary. In cases where air-source heat pumps cannot be installed or their heat production is insufficient, synthetic gases can be used. However, the primary goal is to connect these buildings to a district heating network.

2.2.2 Building refurbishment

Due to the high energy demand of the residential heating sector, the most vital prerequisite for the heat transition is the refurbishment of buildings. The energetic refurbishment potentially enables air-source heat pumps by reducing the required temperature for the heating circuit. However, the measures must be extensive, and in many cases, the buildings' facades, windows, and heating systems require modernization. For example, with underfloor heating, flow temperatures of the heating circuit can be below 60°C. Therefore, in comparison to widely used radiators, significantly less energy is consumed for heating. However, modernization is not feasible in every building and is associated with high costs.

Currently, building refurbishment efforts are insufficient. The Berlin Energy and Climate Program 2030 (BEK 2030) stipulates renovation rates around 1.3 % in 2020, whereas in reality, they only equal 0.8%. According to the BEK 2030, the rates need to increase to 2.6 % in 2030 and then decend to 2% until 2030 (Senatsverwaltung für Umwelt, Verkehr und Klimaschutz 2018). The depth of renovation, i.e., buildings with a high level of refurbishment (renovated facade, new windows, modern heating), should be 15% in 2020, 50% in 2030, and 98% in 2050 (Senatsverwaltung für Umwelt, Verkehr und Klimaschutz 2018) (see Figure 1).

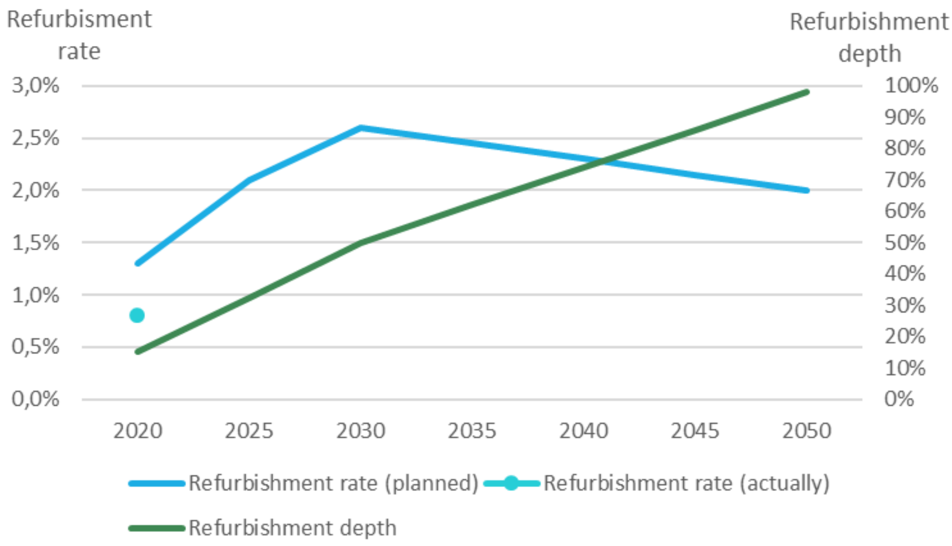

Figure 1: Refurbishment rate and depth for Berlin according to BEK 2030.

Source: Own illustration.

2.2.3 Prevent lock-ins and dependencies

Berlin plans to phase out coal by 2030 and replace it primarily with gas-fired CHP plants (Ritzau, Langrock, and Michels 2019). Both gas and CHP plants are only suitable for energy transition and climate protection to a limited extent. When considering the entire value chain, fossil gas causes equally high emissions as coal due to methane leakage during extraction and transport (Howarth 2014). It thus does not provide any relief for the climate. Moreover, the replacement of coal-fired power plants with gas-fired CHPs may lead to new lock-ins that were initially intended to be solved by a coal phase-out.

Due to the increasing feed-in of renewable energies, the CHP plants are less utilized and no longer run at the optimum operating point, significantly reducing their efficiency (Bloess 2020). Instead, it would be more effective to use heating-only plants to cover the heat demand. Given that renewable energies are to supply the electricity in the future, CHP as technology is hardly suitable for the energy transition as they block renewable energies from being fed in. From a regulatory perspective, it is essential to introduce measures that allow renewable energy to be fed into district heating networks and minimize the risk of gas lock-in. Nevertheless, gas-fired CHP plants with a total thermal capacity of more than 1 GW and an electrical capacity of 730 MW have been built in Berlin over the past five years, and additional power plants are planned (Ritzau, Langrock, and Michels 2019, 10 f.).

According to Vattenfall's plans, new gas CHP plants will replace the coal-fired power plants. The fossil gas used in these plants is supposed to be replaced by hydrogen and synthetic gases step-by-step to decarbonize Berlin's energy sector (Ritzau, Langrock, and Michels 2019, 98). However, replacing fossil gas with hydrogen or synthetic gases is only adequate from a climate perspective if surplus renewable energy is used for generation. It will be some time before hydrogen is available in sufficient quantities. Therefore, basing the heat supply on hydrogen is subject to considerable uncertainties. In addition, in a decarbonized energy system, hydrogen will be more urgently needed elsewhere, as specific processes such as steel production, aviation, and shipping are nearly impossible to decarbonize without hydrogen (Bundesregierung 2020, 11). Estimates for the hydrogen demand range from 250 TWh to 500 TWh in

2050, whereas the domestic production ranges only between 30 and 250 TWh (Matthes et al. 2021, 24, 69). From a regulatory point of view, it is therefore important to take measures that allow renewable energy to be fed into district heating networks and minimize the risk of gas lock-in.

2.3 Contribution of the paper to the urban heat transition research

This paper will model the feasibility of a 100% renewable energy supply for Berlin. To the author's knowledge, this study is the first cost-optimal investigation of the decarbonization of the heating market considering the tightened CO_2 reduction targets from 2021, and taking restrictions such as expansion rates and uncertainties regarding renewable potential into account. In addition, the study examines a decarbonized heat supply (decentral and central) for Berlin as a whole and not just a sub-grid. Regarding the heat transition, the study investigates what a renewable-based heat supply for the city of Berlin could look like. Based on a moderate building heat demand, two scenarios are modeled that consider different availabilities of renewable heat sources. The scenarios show how a gas lock-in can be mitigated, and Berlin's energy system can be based on 100% renewable energy.
Due to the public availability of the model and the data (open source), high transparency and traceability of the calculations are given. This enables an open discourse about a viable path in the decarbonization of the heat transition in Berlin.

A brief description of the applied model GENeSYS-MOD follows, containing the central extensions of the model compared to the model version GENeSYS-MOD v3.0 (cf. chapter 3). In chapter 4, a brief overview of the heating market in Berlin is given. Chapter 5 gives a short description of the scenarios. A more detailed version of the scenario assumptions can be found in the Appendix. This includes a description of the regulatory framework, the available renewable energy potentials, and the availability of key energy sources such as renewable electricity and hydrogen. In chapter 6 the results of the modeling are presented and evaluated. Chapter 7 then concludes.

3 Methodology – energy system modeling with GENeSYS-MOD

3.1 GENeSYS-MOD

GENeSYS-MOD is a linear techno-economic model suitable for representing a high level of detail of technical aspects of an energy system. The structure of GENeSYS-MOD allows modeling the development of technologies and their deployment. Linear models can calculate the cost-optimal solution to meet the energy demand and allow the consideration of different sectors such as electricity, heat, transport, and industry as well as their interactions. Thus, statements can be made about the long-term development and decarbonization of the energy system. GENeSYS-MOD has already been used to perform several case studies with corresponding data sets e.g., China, Europe, Germany, and globally (Bartholdsen et al. 2019; Burandt et al. 2019; Löffler et al. 2019; 2017).

GENeSYS-MOD is a multi-node flow-based model. Technologies and regions are nodes connected by energy flows or goods and services (e.g., passenger transport). The temporal resolution of the model reaches up to hourly steps.

The results of (linear) models are driven in particular by assumptions about economy and costs, as well as human behavior in energy consumption and political decisions. The assumptions partially reflect the modelers' frame of reference and beliefs, which must be considered and communicated when building the models and interpreting the results. Detailed documentation on the GENeSYS-MOD model, including underlying assumptions, can be found online as an open-source version of the recent model version on GitLab[3] as well as in Burandt et al. (2018). This paper includes a description of assumptions and data for the application of GENeSYS-MOD to heat supply in Berlin.

3.2 Adjustments of GENeSYS-MOD for the modeling of an urban heat transition

GENeSYS-MOD has been applied to examine large-scale energy systems before, yet case studies at the federal state or city level have not been conducted so far. In addition, GENeSYS-MOD does not primarily focus on the heat sector. Therefore, GENeSYS-MOD is adapted to model an urban heat transition, which will be explained in the following. Hereafter, the extension of GENeSYS-MOD v3.0 made in this paper will be referred to as GENeSYS-MOD URBAN HEAT.

[3] https://git.tu-berlin.de/genesysmod/genesys-mod-public/-/releases/genesysmod3.0

3.2.1 Implementation of district heating – adding new fuels

For GENeSYS-MOD URBAN HEAT, district heating was implemented, as it is of central importance in urban areas. The model considers the generation and demand of district heat to meet the demand for heat in the building sector and low process heat in the industry. Hence, new fuels are considered. Low heat is split between central and decentral heat generation, as depicted in Figure 2. The differentiation of technologies and fuels prevents decentral demand from being met by central generation (i.e. district heating). This differentiation reflects the reality since consumers are usually either connected to district heating or a decentral heat generator. Besides low heat (HLI), the model considers medium (HMI) and high process heat (HHI) in the industrial sector.

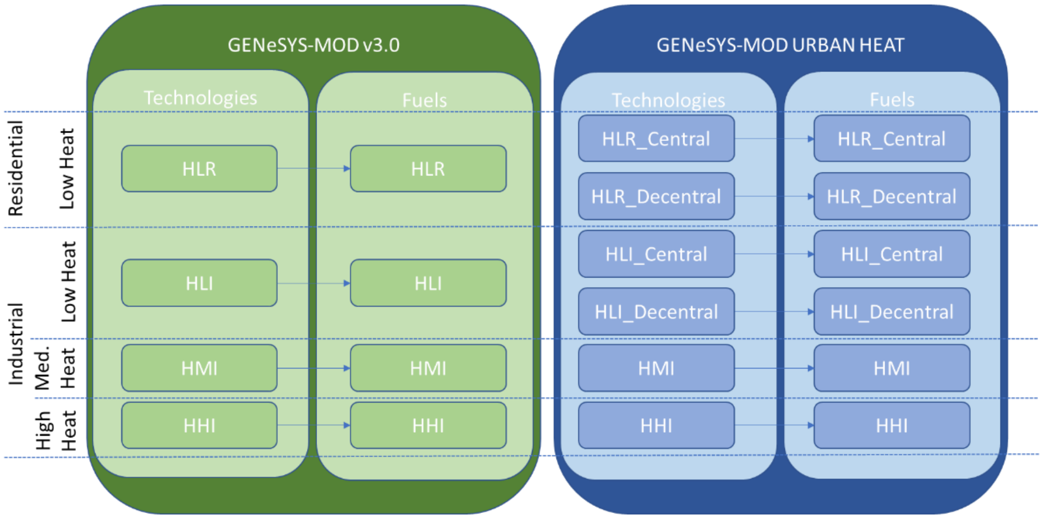

Figure 2: Fuels and technologies in GENeSYS-MOD heating extension.

Source: Own illustration.

3.2.2 Adjusting the data for a higher spatial resolution – availability of crucial data for modeling an urban heat transition

The focus on Berlins heat supply requires a revision of the existing input data of GENeSYS-MOD v3.0. The Berlin-specific data included in GENeSYS-MOD v3.0 is part of an Europe-wide data set with a low depth of detail. Hence, the input data is of limited use for a detailed analysis of Berlin's heat supply. Among others, the following crucial values for heat supply are adjusted:

- Heat demand and profiles for the different heating fuels (cf.
- Figure 2). In particular, the demand for building heat accounts for the largest share. Regarding the building heat demand, there are assumptions on the renovation rate and renovation depth of the buildings as well as their future development, as these rates significantly influence the demand for building heat.
- Age and type of existing capacities for (district) heat generation
- Parameters for district heat generation technologies
- Potentials for (renewable) heat sources in Berlin.

3.2.3 Reducing the complexity of the model for a higher temporal resolution of the energy system – adjusting the trades between the regions

For large model sizes with high complexity, the intra-year resolution needs to be reduced to a fraction of the 8760 hours to yield results. However, an higher temporal resolution may lead to different outcomes as demand spikes can be modeled in more detail, leading to a different deployment of technologies. Trade-offs in the complexity of the model accompany an increased temporal resolution due to the limitations imposed by computing capacity.

In this case study, complexity is reduced by limiting the modeling to the Berlin region. Generally, GENeSYS-MOD calculates several regions as individual nodes, each with energy balances and fuel trade (e.g. electricity, fossil fuels) with other regions. Previous results of model runs for Germany are parameterized for the Berlin study to represent the exchange of fuels. The fuel import to Berlin is realized by import technologies (e.g. *Z_Import_H2, Z_Import_Power*) that consider the exchange's physical limits.

3.2.4 Considering local potentials – adding new technologies

In order to realize a heat supply based on renewable energies, existing local potentials must be exhausted. In some cases, heat pumps are required to increase the temperature of a heat source before it can be fed into the district heating network. Therefore, the necessary technologies are implemented in GENeSYS-MOD URBAN HEAT. The technologies added for the Berlin case study are as follows:

- Heatpumps connected to various heat sources such as:
  - Waste heat from data centers
  - Geothermal (deep)
  - Geothermal (surface)
  - River
  - Solar thermal
  - Wastewater
- Waste heat from industry (in the model directly used as HLI_Central)
- Waste CHP (for the thermal utilization of Berlin's waste)
- Electrolysis produces waste heat as a byproduct, which can be used in district heating.

3.2.5 Revising crucial technologies – adding new parameters

Since heat pumps will play a significant role in (de-)centralized heat supply in the future, their modeling is revised for GENeSYS-MOD URBAN HEAT. Heat pumps use ambient heat and raise it to a higher temperature level, usually with electricity. By utilizing ambient heat, heat pumps can achieve higher efficiencies than Power-to-Heat (PtH/P2H) systems that only convert electricity into heat directly. The efficiency of heat pumps depends on the temperature level of the respective ambient temperature and the required temperature at the heat pump outlet (i.e., the temperature of the supply of the heating circuit in the house or the district heating network).

Since, in most cases, source temperature levels vary throughout the year, the efficiency needs to be adjustable within a year. However, in GENeSYS-MOD, the efficiency is only variable with respect to the modeling year but is invariant throughout the year and constant at each modeled hour.

So far, the time dependency of heat pumps is determined like for fluctuating renewables such as wind and photovoltaics (PV). In the case of wind and solar, the hour-dependent *Capacity Factor* is used to adjust the available capacity of the technologies. For PV, the capacity factor at night is zero, i.e., when the sun is not shining, 0% of the installed capacity of PV is available for energy production.

There is a more suitable way for heat pumps to implement variability than adjusting the capacity factor. In contrast to PV and wind, the heat pump has two input variables: the used ambient heat and electricity. If the input temperature decreases, the power supply needs to increase to provide the same heat output. The fluctuation of the ambient heat source can be compensated in the heat pump by increased electricity consumption. This substitution allows the available capacity to remain the same, and only the ratio of electricity to heat input changes. This is enabled by the introduction of a time-dependent efficiency parameter. If the capacity factor remains unchanged, the model will not build additional capacity, as could be the case if the adjustment is made using the capacity factor.

The calculation of the time-varying efficiency parameter is derived from the efficiency equation of heat pumps. For heat pumps, the efficiency is often referred to as the coefficient of performance (COP).

The heat pump coefficient of performance is determined by $COP = \frac{Q_c}{W}$, with Q_c being the heat output and W the electricity input.

The COP depends on the level of the input temperature T_{cold} and output temperature T_{warm}. T_{warm} corresponds to the temperature of the heating circuit in buildings or district heating networks, and T_{cold} to the temperature of the ambient heat source. Both temperatures vary throughout the year depending on the respective heat source (e.g. geothermal or solar thermal).

The maximum COP is described as:

$$COP_{max} = \frac{1}{\eta_C} = \frac{T_{warm}}{T_{warm} - T_{cold}}$$

The quality grade η_{HP} of a heat pump is expressed by the following statement:

$$\eta_{HP} = \frac{COP}{COP_{max}} = \frac{Q_C}{W * COP_{max}}$$

After reformulations, using the equation for COP_{max} and η_{HP}, the heat output Q_C can be stated as:

$$Q_C = \eta_{HP} * COP_{max} * W = \eta_{HP} * \frac{T_{warm}}{T_{warm} - T_{cold}} * W$$

or rearranged as the expression for the electricity input W:

$$W = \frac{1}{\eta_{HP} * \frac{T_{warm}}{T_{warm} - T_{cold}}} * Q_C$$

The time dependency of the efficiency is implemented in the model via using a new parameter called *TimeDepEfficiency.* Its value is specific to the region (r), technology (t), hour (l), and year (y).

The parameter is added to the equation *Eba4_RateOfFuelUse1* in GENeSYS-MOD v3.0:

$$RateOfActivity(y,l,t,m,r) * InputActivityRatio(r,t,f,m,y) * TimeDepEfficiency(r,t,l,y) = RateOfUseByTechnologyByMode(y,l,t,m,f,r)$$ [4]

The $RateOfActivity(y,l,t,m,r)$ corresponds to Q_C and $RateOfUseByTechnologyByMode(y,l,t,m,f,r)$ to W. Hence, the reciprocal quality grade of heat pumps η_{HP} is implemented as the $InputActivityRatio(r,t,f,m,y)$. The $TimeDepEfficiency(r,t,l,y)$ for heat pumps is the reciprocal of the quotient $\frac{T_{warm}}{T_{warm}-T_{cold}}$. For all other technologies, the $TimeDepEfficiency(r,t,l,y)$ equals 1.

As a further new parameter in GENeSYS-MOD, the loss factor *LF* for district heating networks is implemented. The factor ensures that heat transfer losses are considered in the model. The factor is constant within a year and can vary from year to year and region to region. The factor is added in the equation *Eba11_ EnergyBalanceEachTS5:*

$$Production(y,l,f,r) = LF(y,f,r) * Demand(y,l,f,r) + Use(y,l,f,r) + NetTrade(y,l,f,r) + Curtailment(y,l,f,r)$$

4 Heating sector in Berlin

4.1 Heating demand in Berlin

In 2020, Berlins heating demand equaled 37 TWh (Dunkelberg et al. 2021, 52). Heat is demanded at different temperature levels. Usually, a distinction between residential heat (i.e. buildings) (consisting of space heating and hot water supply) and process heat is made (see Figure 3). Based on the application balances of AG Energiebilanzen, the energy sources are divided into different forms of heat.

[4] $y = year, l = timeslice\ or\ hour, t = technology, m = mode\ of\ operation, r = region.$

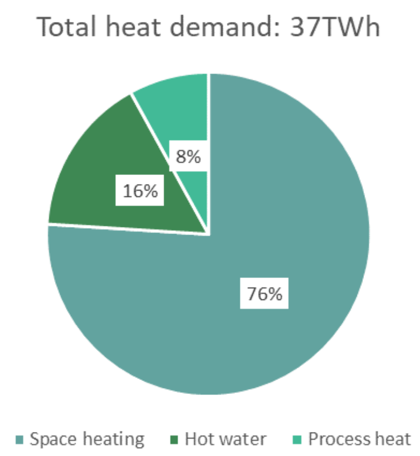

Figure 3: Heating demand in Berlin in 2020.

Source: Own illustration based on Dunkelberg et al. (2021, 52).

In Berlin, heat demand for space heating dominates with a 76% share (ca. 28TWh), followed by hot water with 16% (ca. 6TWh). Process heat only plays a minor role since Berlin's industrial sector is limited.

4.2 Heating supply in Berlin

Heat supply is realized through decentral and central generation. In 2020, district heating accounted for approximately 32% (12 TWh) of total energy consumption for residential and process heat (see Table 1 and Figure 4). Nevertheless, the respective share of energy consumption through fossil gas usage in decentral heat supply dominates with over 43%. Since fossil gas is also used in district heating generation, overall fossil gas consumption for heat generation is even higher (see chapter 4.3 for district heating in Berlin). In third place, oil continues to be an essential energy source for Berlin's heat generation. The share of renewable energies (e.g. solar thermal, biomass, ambient heat) was hardly significant in 2020.

Table 1: Final energy consumption of Berlin heat supply in 2020 (in GWh).

2020	Residential heat	Process heat	Total	Share of total
District heating	11,016	848	11,864	32.3%
Oil	5,944	128	6,072	16.5%
Fossil gas	14,759	1,257	16,016	43.6%
Solar thermal	28	0	28	0.1%
Biomass	235	7	242	0.7%
Power	1,646	590	2,236	6.1%
Coal	59	23	82	0.2%
Ambient heat	162	1	163	0.4%
Total	33,849	2,854	36,703	100%

Source: Dunkelberg et al. (2021, 104f.).

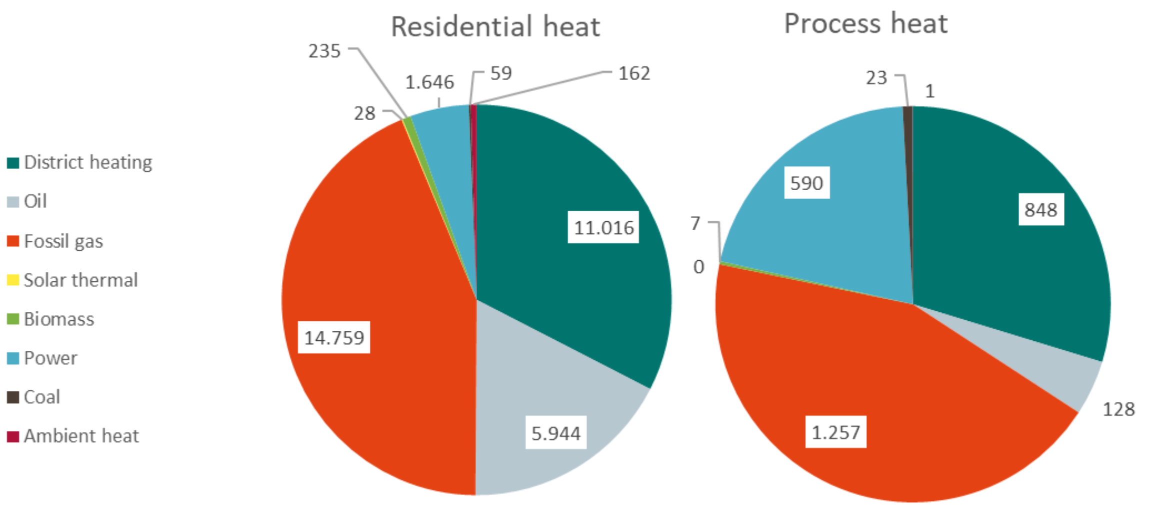

Figure 4: Final energy consumption for residential and process heat in 2020 (in GWh).

Source: Own illustration.

By 2020, about 275,000 gas boilers and 56,000 oil boilers were providing residential heating (see Table 2). While new gas boilers are still being installed, the implementation of oil boilers will be prohibited from 2025, according to Building Energy Act (GEG 2020, §72). Additionally, the GEG stipulates that radiators must be replaced after 30 years at the latest, which will require the replacement of 30,000 oil boilers and nearly 150,000 gas boilers until 2030 (Dunkelberg et al. 2021, 103). Beginning in 2025, new heating installations must have a renewable share of at least 65%. This will result in mainly bivalent heating systems consisting of gas heater combined with a heat pump. To ease the reporting process and accounting for the actual share of renewable feed-ins, the government proposed, that heat pumps must at least contribute 30% of the capacity to the overall capacity of the hybrid heating system, in order to comply with the 65% renewables share regulation.

Table 2: Installed heating technology in the residential sector.

Technology (pcs.)	2020
Gas boiler	275,060
Oil boiler	55,870
Heat pump	7,000
Biomass	1,070

Source: Based on Dunkelberg et al. (2021, 103).

4.3 District heating in Berlin

Following decentral fossil gas, district heating is the second most crucial energy supply in Berlin's heating market, with 11.8 TWh in 2020 (see Table 1). Covering a total length of over 2200 km, the district heating network in Berlin is the largest in Europe after Moscow and Warsaw (BTB 2022; FHW 2022; Bloeß 2020, 153; Ritzau, Langrock, and Michels 2019). Every year, it is extended by more than 20 km and connected to about 400 new buildings (Ritzau, Langrock, and Michels 2019, 6).[5] Berlin's district heating is not a single network but consists of 70 sub-networks. As the leading provider, Vattenfall supplies 90% of Berlin's district heating demand (Ritzau, Langrock, and Michels 2019, 5). The second-largest network is operated by the Neukölln district heating plant with a supply share of 2.3%, partly obtaining heat from Vattenfall's grid. The last operator highlighted is BTB, with several smaller networks producing a total of 600 GWh (5.1%) (BTB 2022).

With a share of 55%, fossil gas also dominates centralized district heating generation (see Figure 5). It is burned in Combined Heat and Power (CHP) plants and gas boilers to cover peak loads. Coal-fired

[5] This corresponds to 25,000 new flat unit equivalents of 4,5kW each.

CHP plants generate 16% of district heating in Berlin and will operate until 2030. Renewable energy and other energy sources each account for 14%. These primarily include waste incineration and biomass.

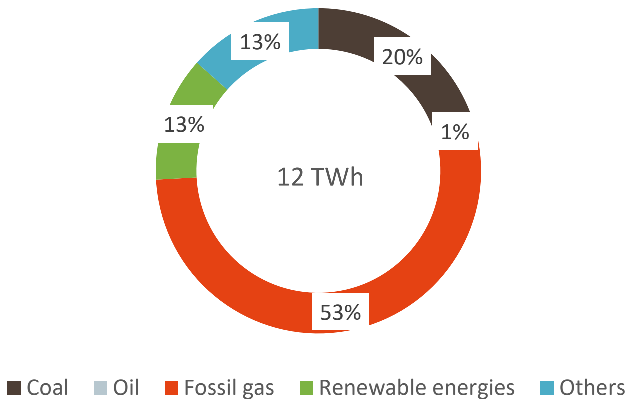

Figure 5: Fuel demand for district heating.

Source: Own illustration based on Amt für Statistik Berlin-Brandenburg (2021).

4.4 Emissions

In 2018, emissions from primary energy consumption amounted to 18.5 Mt CO_2, while final energy consumption led to emissions of 15.5 Mt CO_2. The development of emissions in Berlin since 1990 is depicted in Figure 6. CO_2 emissions have fallen by around 10 Mt (30%) in the last 30 years. The reduction is mainly caused by the replacement of outdated power plants and decentral heating technology.

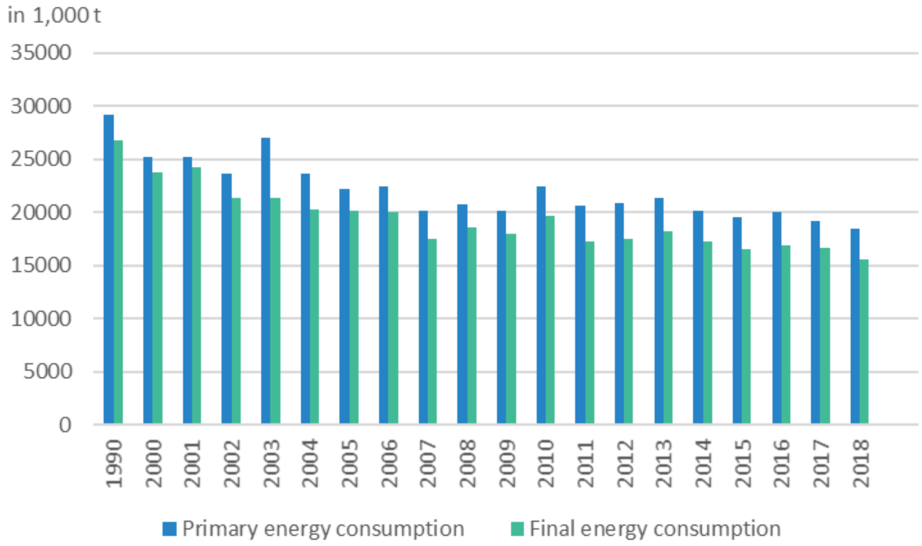

Figure 6: CO_2 emissions by primary and final energy consumption.

Source: Own illustration based on Amt für Statistik Berlin und Brandenburg (2021).

In 2018, the energy and transport sector each accounted for one-third of CO_2 emissions in Berlin (see Table 3). Around 4 Mt CO_2 were attributable to the decentral heating of buildings and the commercial, trade, and service sector.

Table 3: CO_2 emission for energy, industry, transportation, households, and services.

	Total	Energy sector	Industry	Transportation	Households and commercial sector
1990	26,780	14,065	1,545	4,269	6,902
2018	15,527	5,914	271	5,194	4,148

Source: Amt für Statistik Berlin und Brandenburg (2021).

5 Scenarios for the development of the heating system in Berlin

The development of Berlin's heating system is largely determined by the regulatory framework for deployment targets or prohibitions on technologies and energy carriers, as well as the availability of renewable energy sources. To deal with the uncertainty regarding the availability of renewable energy sources we examine two scenarios. Both scenarios share the same development in the final energy demand and climate goals but differ in the deployment of renewable energies in the heating sector. For Berlin, a study exists showing that renewable heat supply is possible by 2035. However, the potentials assumed in the study are still subject to uncertainties as a feasibility study for these potentials is still pending. Therefore, the present study examines two scenarios, one scenario with medium renewable heat potential ("MedRes") and one scenario with low potential ("LowRes"). The choice of these two scenarios enables the modeling of decarbonization paths that consider the uncertainties regarding the realizable renewable energy potentials. This increases the robustness of the results and allows better conclusions on an economically efficient decarbonization. A detailed description of the assumption can be found in the appendix.

6 Results

6.1 LowRes scenario – Low exploitation of theoretic renewable heat potential

6.1.1 Heating

6.1.1.1 Decentral residential heating

CAPACITY

In the LowRes scenario, the capacity in decentral building heat generation more than halves from 11.4 GW in 2020 to 4.4 GW in 2050 (cf. Table 4). The reduction relates to the renovations and the increasing district heating connections.

Of the 7.4 GW of decentral gas boilers installed in 2020, 1.4 GW will remain in 2050. Beginning in 2025, only hybrid new installation of gas heating systems can be realized. Then, at least 65% of the heating needs to be renewalbe. The government proposed that this is achieved when e.g. a heat pump contributes 30% of the overall capacity of the installed hybrid heating system. This leads to approx. additional 1.3 GW of gas capacity that will benewly installed by 2035. However, as Figure 8 highlights, gas only contributes marginally to decentral heating in 2050 since the capacities will only be used for peak loads. Further, no new oil heating systems will be installed, even before the ban on oil heating comes into force in 2025. The installed capacity of oil heating systems will continuously decrease from 3 GW in 2020 to 0 GW in 2050. The oil boilers will be replaced mainly by heat pumps (cf. Figure 7). The installed capacity of heat pumps (bivalent and monovalent) increases from about 70 MW in 2020 to 2.2 GW in 2050, with air source heat pumps dominating with 1.8 GW. The low installation of ground source heat pumps (380 MW) results from the cautiously chosen upper limits for their deployment in urban areas. In 2050, the model will add high capacities for air source heat pumps with 1.7 GW. This is partly because the heat pumps built around the year 2025 reach the end of their assumed lifetime and need replacement (about 0.7 GW). Additionally, the capacity increases due to the zero emissions mandated in the model for 2050. Heat pumps are the most efficient technology for decarbonization and are implemented before direct electric heating systems and synthetic gases. Biomass does not supply decentral heat starting in 2035. No new biomass heating systems are installed in the model, and thus the capacity drops from 120 MW in 2020 to 0 MW in 2035.

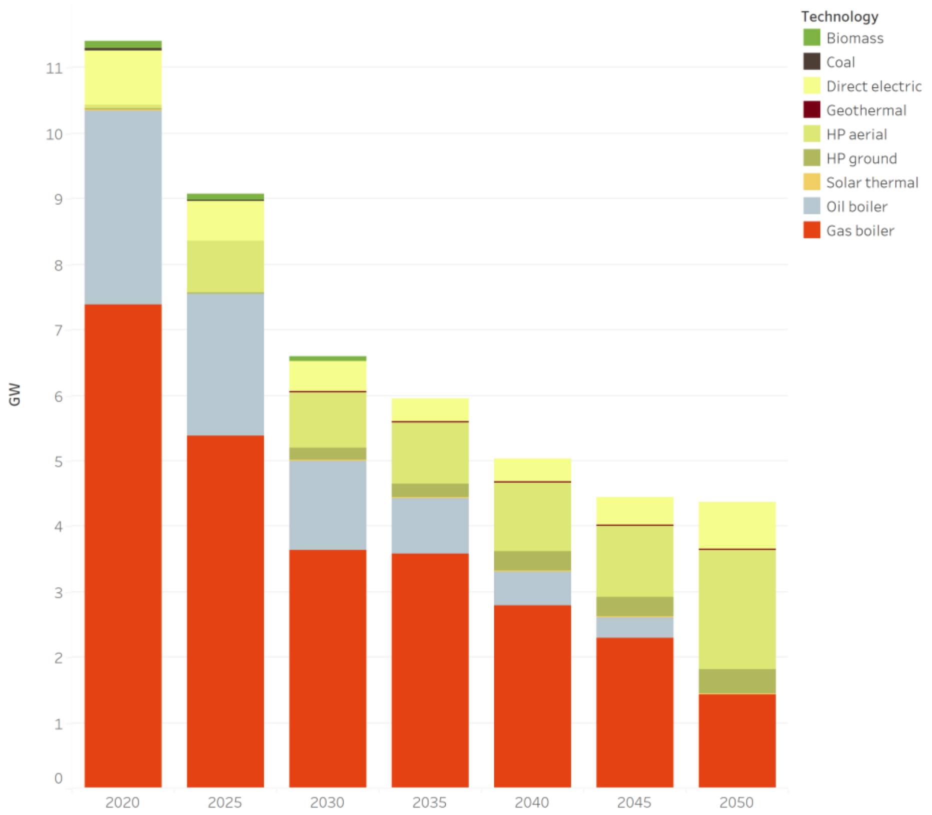

Figure 7: Decentral residential heat capacity in the LowRes scenario (2020-2050).

Source: Own illustration.

Table 4: Decentral residential heat capacity in the LowRes scenario in GW (2020-2050).

Technology	2020	2025	2030	2035	2040	2045	2050
Biomass	0.12	0.09	0.07				
Coal	0.03	0.02					
Direct electric	0.82	0.62	0.46	0.35	0.36	0.43	0.72
Geothermal			0.01	0.01	0.01	0.01	0.01
HP aerial	0.07	0.78	0.87	0.95	1.06	1.08	1.82
HP ground	0.01	0.01	0.19	0.21	0.28	0.30	0.38
Solar thermal	0.01	0.01	0.01	0.01	0.00	0.00	0.00
Oil boiler	2.97	2.17	1.37	0.86	0.54	0.34	
Gas boiler	7.38	5.39	3.64	3.58	2.79	2.29	1.44
Total	**11.41**	**9.08**	**6.60**	**5.96**	**5.04**	**4.45**	**4.37**

Source: Own calculations.

PRODUCTION

Gas plays the most crucial role in decentral heat supply in 2020 with 46 PJ (cf. Table 5 and Figure 8). This halves to about 21PJ by 2035, amounts to only 6.2 PJ in 2045, and in 2050 decentral heat production will be supplied with only a fraction of gas (0.2PJ). Three-quarters of the gas used in 2050 is synthetic gas. Before 2050, synthetic gas does not contribute to decentral heat production as a substitute for fossil natural gas. Similar to gas, oil decreases from 20 PJ in 2020 to 0.3PJ in 2035 and is no longer present after that. Heat generation from direct electricity increases slightly to 5.6 PJ until 2050. In 2020, heat production by direct electricity equaled 5.2 PJ.

Since district heating supplies an increasing amount of buildings each year, in 2050, decentral and central heat will contribute equally to the residential heat supply. However, the additional heat demand caused by new buildings connected to district heating will be compensated by refurbishment measures, allowing the central heat supply to remain constant. A detailed analysis of district heating generation follows in section 6.1.1.2.

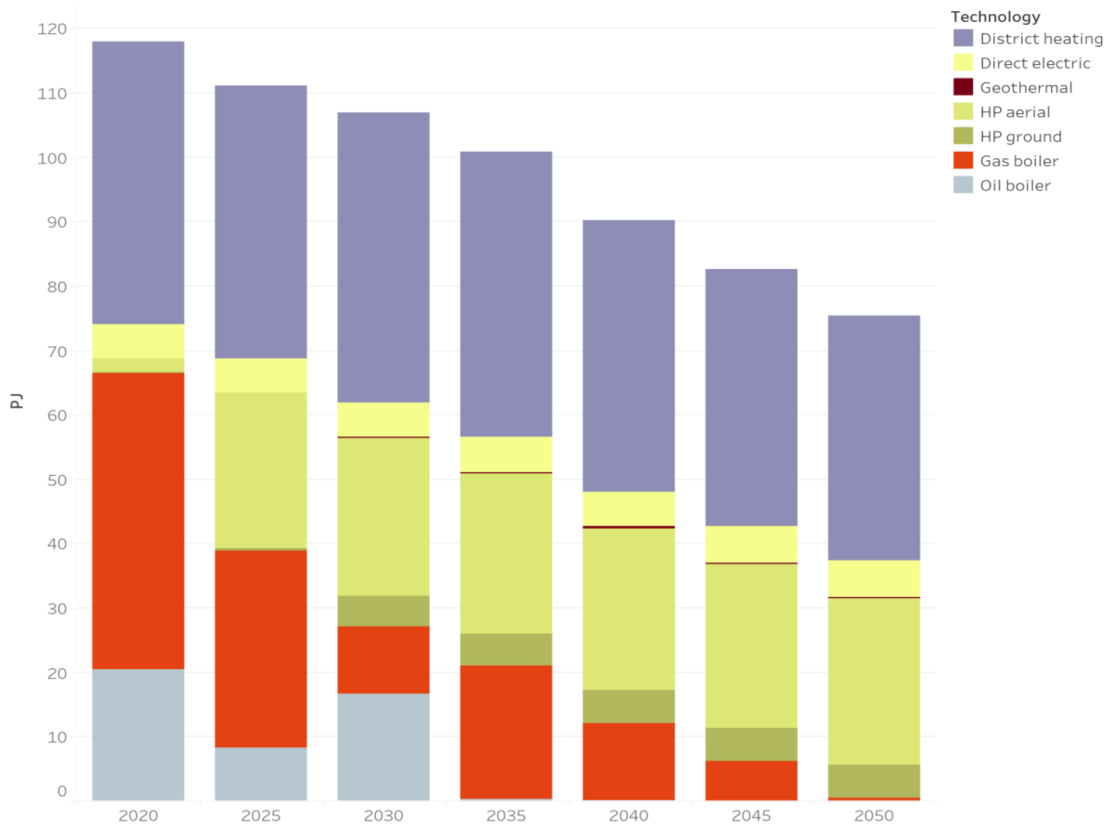

Figure 8: (Decentral) residential heat supply in PJ in LowRes scenario (2020-2050).

Source: Own illustration.

Table 5: (Decentral) residential heat supply in PJ in LowRes scenario (2020-2050).

Technology	2020	2025	2030	2035	2040	2045	2050
District heating	43.97	42.26	44.91	44.28	42.06	39.94	37.98
Direct electric	5.19	5.26	5.33	5.4	5.47	5.54	5.61
Gas boiler	46.02	30.68	10.38	20.75	12.01	6.15	0.5
Geothermal			0.14	0.3	0.3	0.31	0.31
HP aerial	2.07	24.21	24.52	24.84	25.17	25.49	25.82
HP ground	0.29	0.3	4.9	4.96	5.03	5.09	5.16
Oil boiler	20.45	8.36	16.71	0.33	0.17	0.09	
Total	**117.99**	**111.07**	**106.89**	**100.86**	**90.21**	**82.61**	**75.38**

Source: Own calculations.

Figure 9 shows the decentral heat generation for 2045. In 2045, emissions will decrease by at least 95% compared to 1990. Accordingly, heat pumps and direct electric heating lead to increased electrification of the heating sector. Heat pumps provide space heating and hot water throughout the year. In the winter months, when the efficiency of air-source heat pumps drops significantly and heat demand increases, gas boilers and direct electricity heating will cover peak loads. This means that monovalent (heat pump + direct electric heating) or bivalent heating systems (heat pump + gas boiler) will achieve a cost-efficient heat supply. By supporting heat pumps with other generators, the heat pumps can be aligned with the year-round consumption and thus be smaller and more efficiently sized. Decentral heat storage systems, which store excess heat generated at times of excess supply of renewable electricity, are not used in the model but would make sense in reality. However, the model does not prioritize these storage facilities because the electricity supply is not volatile enough. Since the modeled electricity imports do not fluctuate, limited deviations between electricity supply and demand occur. Without these deviations, the need for storage decreases.

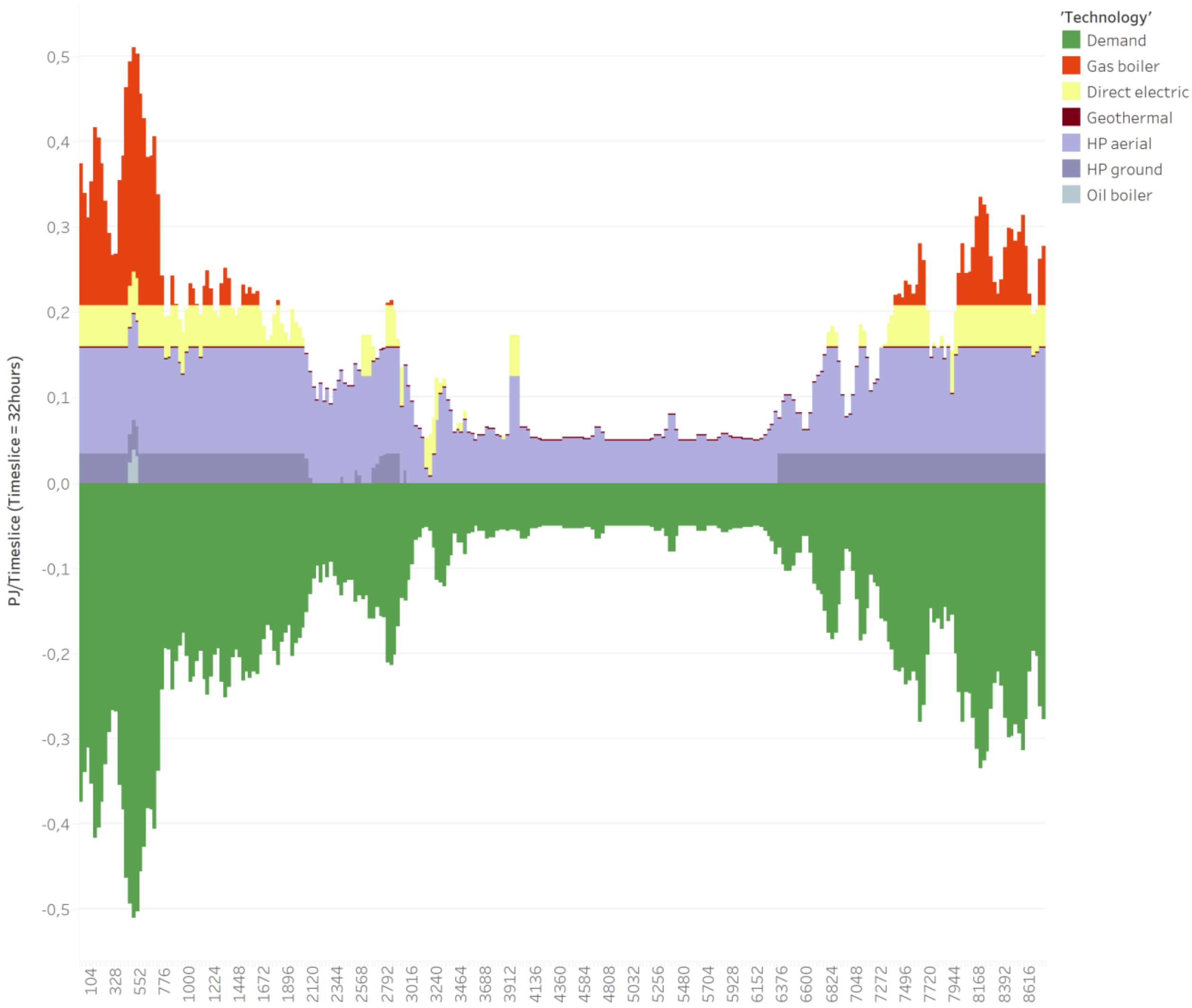

Figure 9: Decentral heat supply in 2045.

Source: Own illustration.

6.1.1.2 District heating

District Heat Capacity

District heating capacity added up to about 5.6 GW in 2020. Gas boilers and CHPs account for the majority, with over 4 GW. By 2030, despite the phase-out of coal and oil-fired power plants in Berlin, installed capacity will increase slightly to 5.9 GW due to the increasing central heat demand. By 2050, generation capacity will decrease to about 5.4 GW. In addition to the generation capacity in 2050, 440 MW of seasonal thermal storage are installed (cf. Table 6).

The shutdown of over 1 GW of coal and oil CHPs by 2030 is compensated on the heating side by gas boilers (0.8 GW), heat pumps, and industrial waste heat (cf. Figure 10). The installed capacity of gas boilers increases from 2.1 GW in 2020 to 2.9 GW in 2030. By 2050, the capacity will decrease to 2 GW. In contrast to gas boilers, no more gas CHPs will be built and will shut down after reaching their maximum lifetime. This development highlights that fossil CHPs are not suitable for a renewable energy-based energy system, as the coupled heat and power production displaces the renewable power production in case of heat demand. The preferred option are heating-only plants.

Besides gas boilers, heat pumps utilizing different heat sources (wastewater heat, geothermal (deep and surface), river water, solar thermal) replace coal and oil CHPs with a total of 390 MW in 2030. By 2040, heat pumps will fully exploit the potential for renewable heat sources.

After 2040, the emission targets, mainly the target of zero emissions in 2050, lead to the deployment of direct electric heating since the heat pump potentials are exhausted. In 2050, almost 1 GW of P2H (direct electric) capacity will be installed. Biomass plants equal only 310 MW (CHP & boiler together) since the biomass potential available for Berlin limits further deployment.

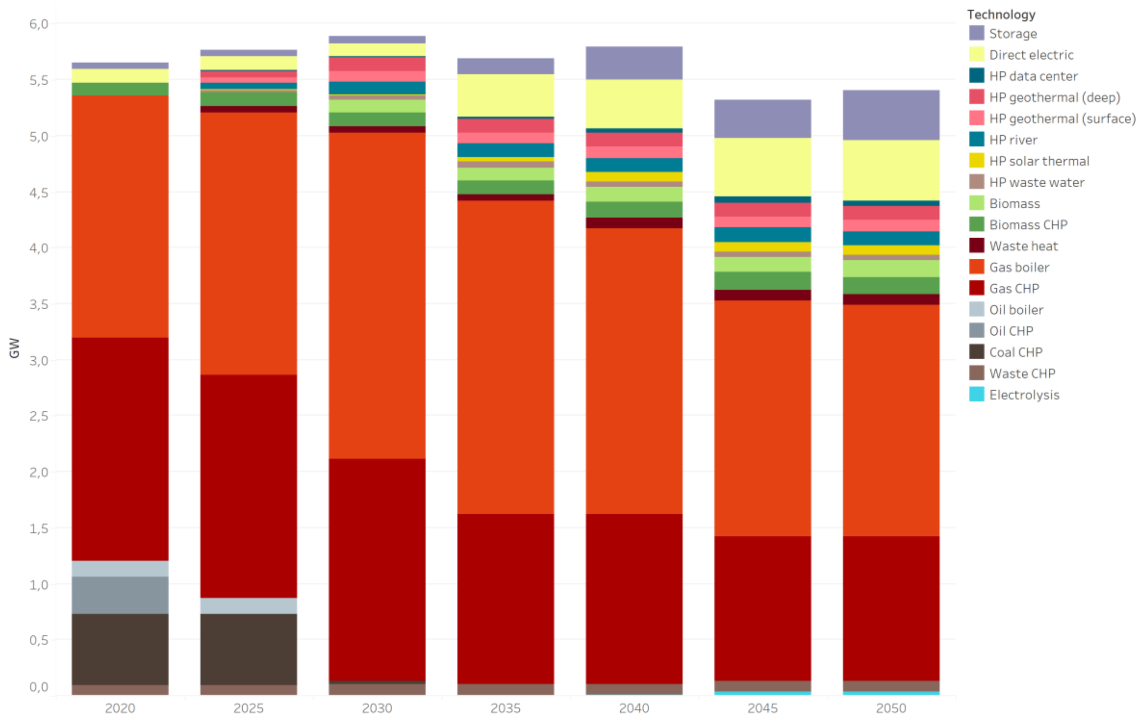

Figure 10: District heating capacity in LowRes scenario (2020-2050).

Source: Own illustration.

Table 6: District heating capacity in LowRes scenario (2020-2050).

Technology	2020	2025	2030	2035	2040	2045	2050
Storage	0.062	0.062	0.062	0.139	0.292	0.335	0.44
Direct electric	0.12	0.12	0.12	0.383	0.43	0.529	0.54
HP data center		0.005	0.01	0.02	0.045	0.05	0.05
HP geothermal (deep)		0.063	0.119	0.12	0.124	0.125	0.125
HP geothermal (surf.)		0.046	0.095	0.096	0.098	0.1	0.1
HP river		0.063	0.116	0.118	0.125	0.125	0.125
HP solar thermal		0.002	0.004	0.046	0.085	0.086	0.088
HP wastewater		0.025	0.046	0.049	0.05	0.05	0.05
Biomass			0.109	0.117	0.13	0.137	0.145
Biomass CHP	0.12	0.121	0.123	0.125	0.142	0.153	0.154
Waste heat		0.06	0.06	0.06	0.1	0.1	0.1
Gas boiler	2.163	2.342	2.907	2.796	2.545	2.108	2.066
Gas CHP	1.986	1.986	1.986	1.519	1.519	1.285	1.285
Oil boiler	0.143	0.143					
Oil CHP	0.33						
Coal CHP	0.635	0.635	0.032				
Waste CHP	0.099	0.099	0.099	0.099	0.099	0.099	0.099
Electrolysis		0	0.002	0.002	0.008	0.036	0.036
Total	**5.658**	**5.772**	**5.89**	**5.689**	**5.792**	**5.318**	**5.403**

Source: Own calculations.

Heat Production

As we saw earlier, the heat supplied by district heating remains constant in contrast to the decentral heat supply between 2020 and 2050.

Biomass boilers (3.4 PJ) and heat pumps (11.3 PJ) will compensate for the coal and oil phase-out. Except for heat pumps combined with solar thermal heat, renewable heat sources are entirely exhausted from 2030. At the same time, heat supplied by fossil gas continuously decreases from 32 PJ in 2020 to

26 PJ in 2030 and 8.5 PJ in 2045. Synthetic gases do not contribute to the central heat supply until 2040. The amount of synthetic gas then increases from 1.4 PJ in 2040 to almost 9 PJ in 2050. In 2050, synthetic gases will replace fossil gas. Thus, heat supplied with synthetic gas equals 6.3PJ in 2050. This corresponds to about 16% of district heat generation. Biomass also has a share of about 16%. The local biomass potentials are already exhausted from 2030. The slight increase in biomass in district heating is only made possible by decreased use in the industrial sector.

The increase of direct electric heating is remarkable in the LowRes scenario. Since the renewable heat sources are fully exploited by heat pumps and the biomass potential limit is reached, further decarbonization of the heat supply can only be achieved by direct electric heating.

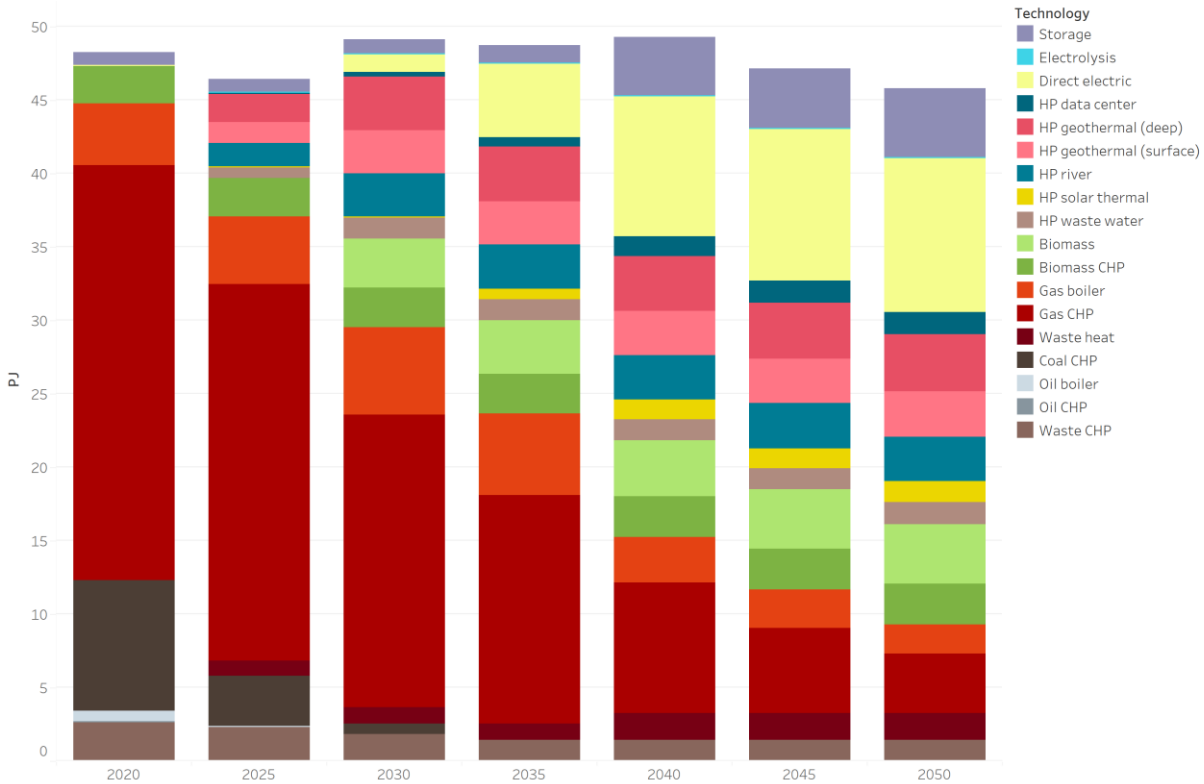

Figure 11: District heating supply in LowRes scenario (2020-2050).

Source: Own illustration.

Table 7: District heating supply in LowRes scenario (2020-2050).

Technology	2020	2025	2030	2035	2040	2045	2050
Storage	0.87	0.88	0.89	1.22	4	4.06	4.73
Electrolysis		0	0.01	0.01	0.01	0.01	0.01
Direct electric	0.02	0.04	1.27	5.07	9.54	10.39	10.53
HP data center		0.15	0.31	0.62	1.35	1.48	1.5
HP geothermal (deep)		1.93	3.67	3.72	3.76	3.81	3.86
HP geothermal (surface)		1.43	2.93	2.97	3.01	3.05	3.09
HP river		1.58	2.93	2.97	3.01	3.04	3.08
HP solar thermal		0.03	0.07	0.72	1.34	1.35	1.37
HP wastewater		0.77	1.43	1.45	1.47	1.49	1.51
Biomass			3.38	3.62	3.81	4.01	4.06
Biomass CHP	2.59	2.63	2.66	2.7	2.73	2.77	2.8
Gas boiler	4.22	4.56	5.95	5.58	3.14	2.62	1.96
Gas CHP	28.25	25.61	19.96	15.58	8.87	5.83	4.09
Waste heat		1.08	1.08	1.08	1.8	1.8	1.78
Coal CHP	8.91	3.43	0.69				
Oil boiler	0.72	0.08					
Oil CHP	0						
Waste CHP	2.69	2.28	1.86	1.45	1.45	1.45	1.45
Total	**48.27**	**46.48**	**49.09**	**48.76**	**49.29**	**47.16**	**45.82**

Source: Own illustration.

In Figure 12, we recognize the prioritization of technologies due to their efficiency and CO_2 emissions. The figure displays the heat supply in the year 2045. Industrial waste heat, waste CHP and renewable heat pumps will cover the baseload. The heat pumps connected to geothermal sources and data center supply space heating and hot water all year round and hence can be operated at maximum efficiency. In contrast, river and solar thermal heat pumps only operate seasonal. Therefore, the solar thermal heat is fed into seasonal storage. River pumps feed into seasonal storage as well but supply heat at the end and the beginning of the heating period. Since the heat pump potential is limited in the LowRes scenario, the less efficient direct electric heaters supply significant shares of space heating in winter and autumn. The installed gas capacities supply the peak load in winter.

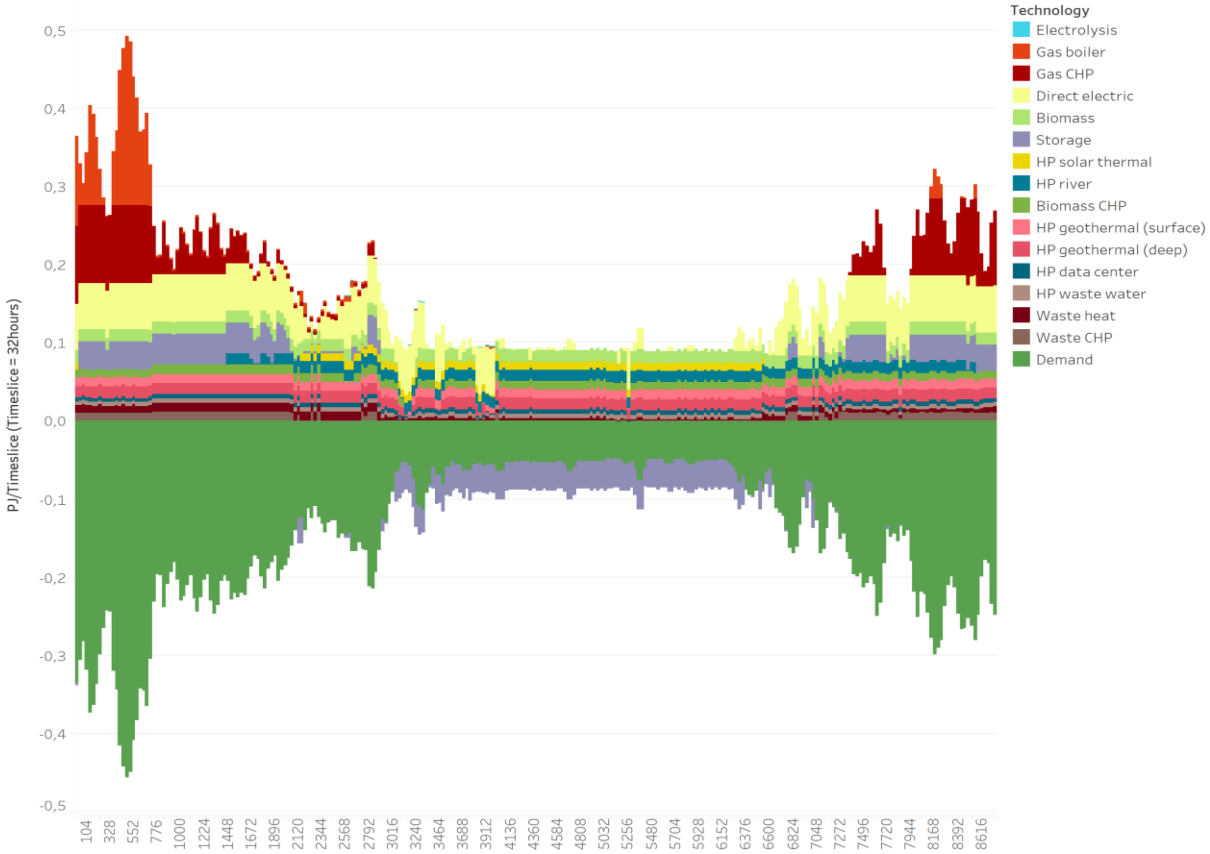

Figure 12: District heating supply in the LowRes scenario in 2045.

Source: Own illustration.

6.1.1.3 Process heat

In 2020, process heat will also be dominated by fossil fuels, above all fossil gas. A mix of biomass and electricity-based heating will gradually replace fossil gas (cf. Figure 13). From 2040 on, parts of the fossil gas will be replaced by synthetic gases. In 2040, the share of synthetic ranges about 20%, increases to 25% in 2045, and in 2050 100% of the gas will be synthetic.

By 2035, increasing amounts of hydrogen contribute to the process heat generation, until in 2050, 4.1 PJ are provided by hydrogen. Electricity contributes 3.3 PJ and biomass 1.6 PJ (cf. Table 8).

The modeling underlies the conservative assumption that heat pumps will not be able to provide process heat efficiently. However, this might change due to further technical development, which leads to reduced electricity demand for process heating.

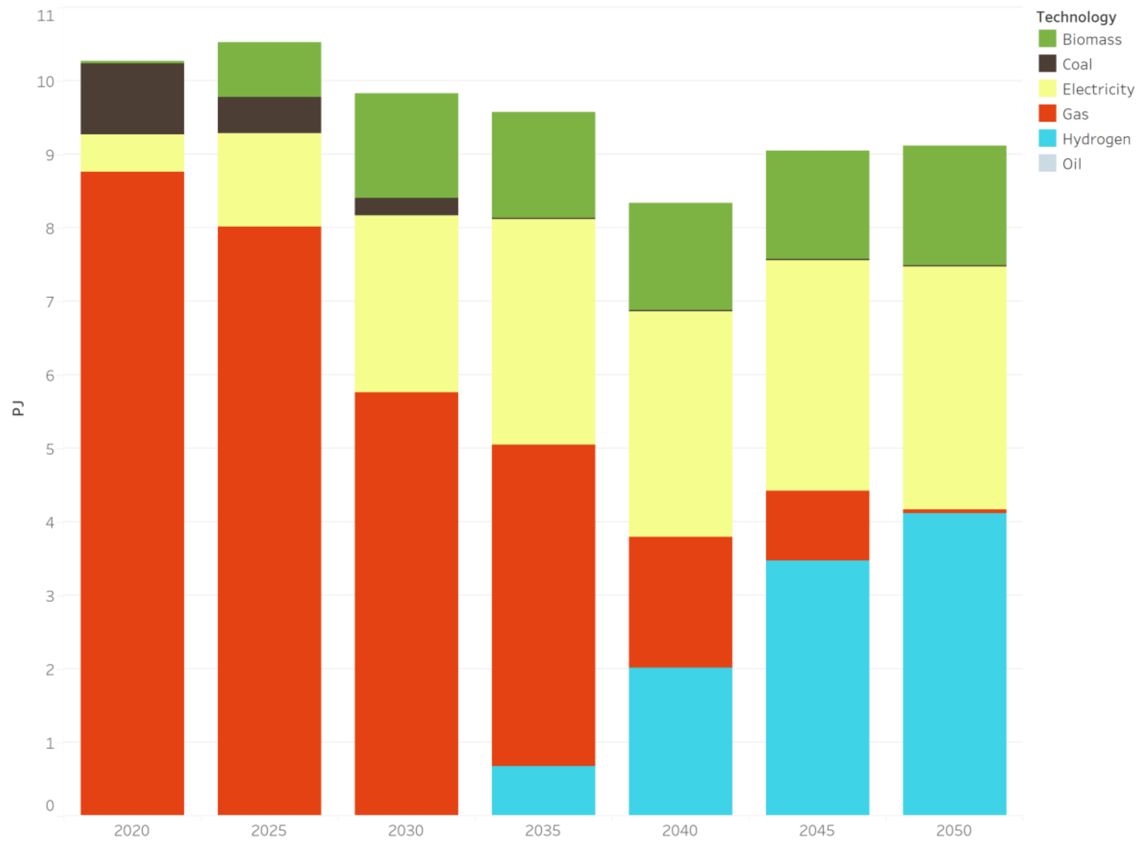

Figure 13: Process heat supply in LowRes scenario by fuel (2020-2050).

Source: Own illustration.

Table 8: Process heat supply in LowRes scenario by fuel in PJ (2020-2050).

Technology	2020	2025	2030	2035	2040	2045	2050
Biomass	0.0	0.7	1.4	1.4	1.5	1.5	1.6
Coal	1.0	0.5	0.3	0.0	0.0	0.0	0.0
Electricity	0.5	1.3	2.4	3.1	3.1	3.2	3.3
Gas	8.8	8.0	5.8	4.4	1.8	0.9	0.1
Hydrogen				0.7	2.0	3.5	4.1
Oil	0.0	0.0	0.0	0.0	0.0	0.0	
Total	**10.3**	**10.5**	**9.8**	**9.6**	**8.3**	**9.1**	**9.1**

Source: Own illustration.

6.1.2 Electricity

In addition to heat pumps, direct heat generation by electricity in district heating increases significantly and causes the demand to increase from about 53 PJ in 2020 to over 81 PJ in 2050 (cf. Table 9). The other main driver for an elevated demand is the electrification of transportation (cf. Figure 14).

Berlin has only limited potential for renewable electricity generation due to its dense built-up area. As an electricity sink, Berlin depends on the surrounding regions (i.e., Brandenburg and coastal regions) with high renewable feed-in. Therefore, the increasing electricity demand will be met by higher electricity imports. In addition, the decline in fossil fuel power generation in Berlin is compensated by a substantial expansion of PV systems on building roofs. The expansion limits for PV for Berlin are fully utilized.

In 2050, based on earlier modeling by GENeSYS-MOD, which serves as input for GENeSYS-MOD URBAN HEAT, electricity imports will decrease slightly. Fuel cells will close the resulting supply gap with 11 PJ.

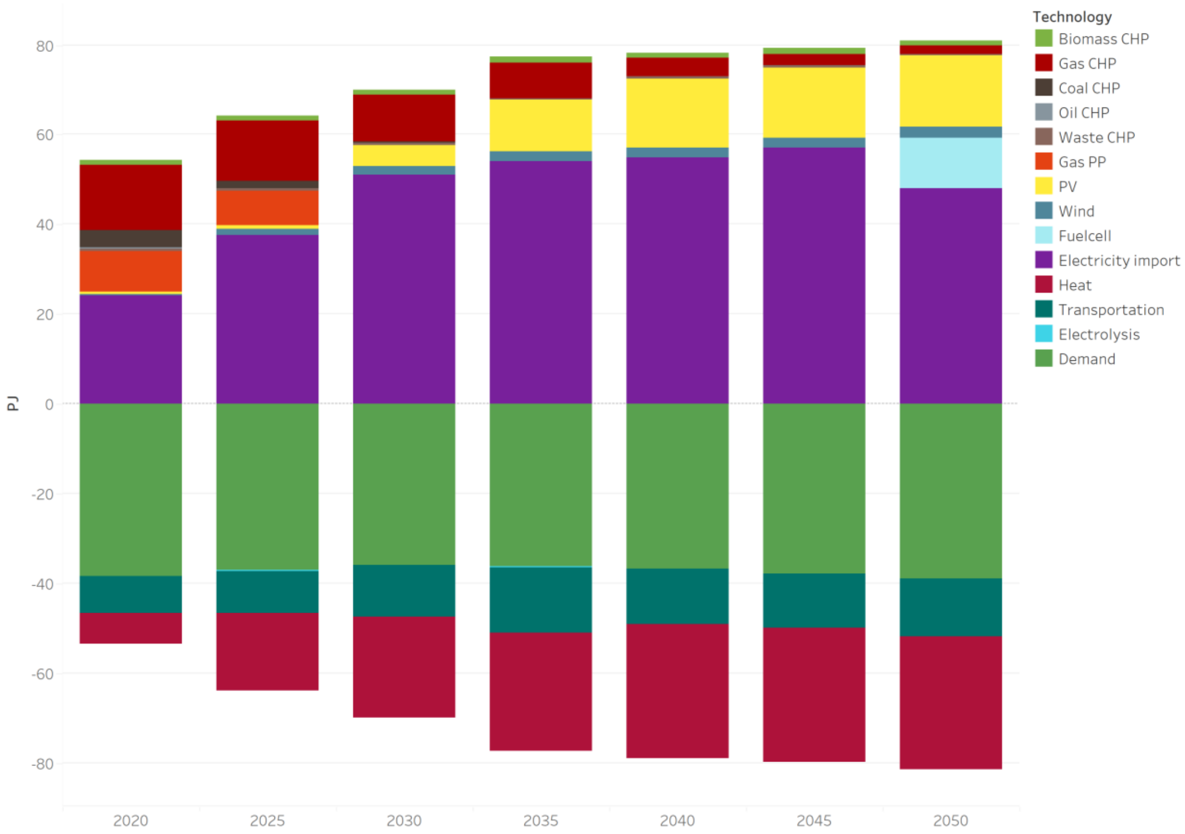

Figure 14: Electricity supply and demand in the LowRes scenario in PJ (2020-2050).

Source: Own calculations.

Table 9: Electricity supply and demand in the LowRes scenario in PJ (2020-2050).

in PJ	2020	2025	2030	2035	2040	2045	2050
				Generation			
Biomass CHP	1.15	1.16	1.18	1.19	1.21	1.23	1.24
Gas CHP	14.4	13.32	10.32	8	4.04	2.65	1.82
Coal CHP	3.95	1.52	0.3				
Oil CHP	0						
Waste CHP	0.83	0.71	0.58	0.45	0.45	0.45	0.45
Gas PP	8.96	7.58					
PV	0.59	1.01	4.49	11.55	15.37	15.7	15.91
Wind	0.08	1.2	2.13	2.15	2.18	2.21	2.24
Electricity (Import)	24.38	37.69	51	54	55	57	48
Fuelcell							11.42
Total	**54.34**	**64.19**	**70.00**	**77.34**	**78.25**	**79.24**	**81.08**
				Demand			
Heat	-6.85	-17.29	-22.48	-26.2	-29.76	-30.02	-29.58
Electrolysis		-0.01	-0.06	-0.06	-0.06	-0.06	-0.06
Transportation	-8.3	-9.37	-11.36	-14.68	-12.38	-11.98	-12.95
Demand	-38.25	-37.08	-35.91	-36.24	-36.57	-37.72	-38.88
Total	**-53.40**	**-63.75**	**-69.81**	**-77.18**	**-78.77**	**-79.78**	**-81.47**

Source: Own calculations.

6.1.3 Emissions

The emissions decrease from 16 Mt CO_2 in 2020 to 0 Mt CO_2 in 2050. This results in total emissions of approximately 196 Mt CO_2 between 2020 and 2050. The CO_2 budget calculated by Hirschl et al (2021, 21) for Berlin to be consistent with the 1.5°C target equals 185 Mt CO_2 (at 50% likelihood). Hence, the scenario LowRes is close to a 1.5°C compatible decarbonization path. However, the emissions considered by the model do not include the emissions connected to imported electricity. If they were to be included, it becomes apparent that the emission targets set by the Berlin Senate do not comply with a 1.5°C compatible scenario. The CO_2 targets are more in line with the 1.75°C budget, which is about 290 Mt CO_2 for a 67% probability of occurrence.

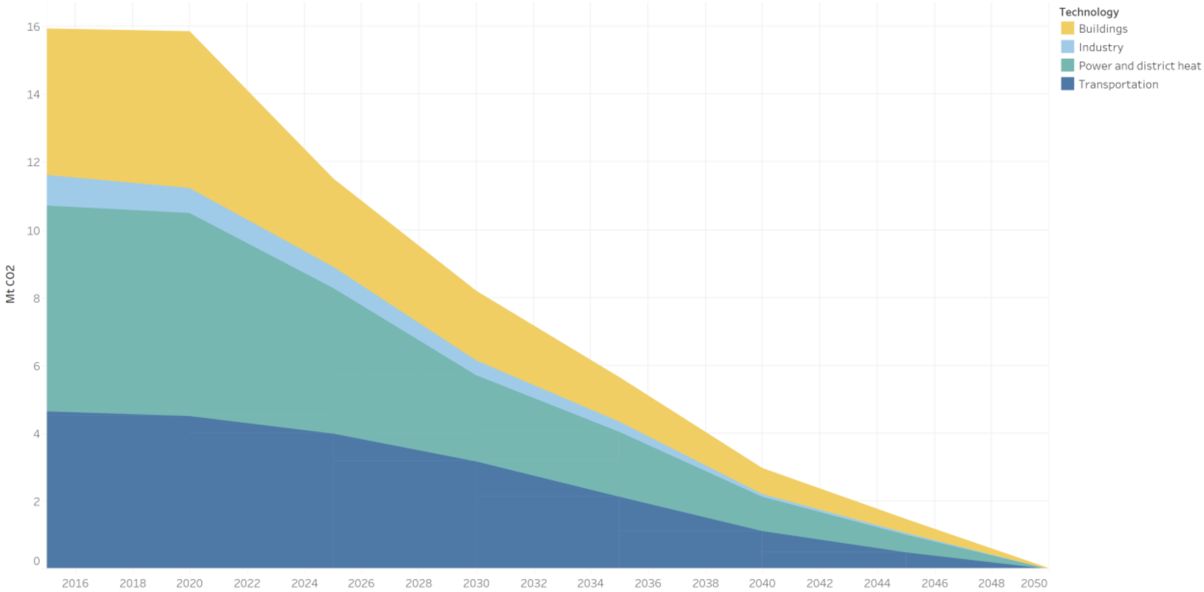

Figure 15: CO_2 emissions in the LowRes scenario (2020-2050).

Source: Own illustration.

Table 10: CO_2 emissions in the LowRes scenario in Mt (2020-2050).

Technology	2015	2020	2025	2030	2035	2040	2045	2050
Buildings	4.3	4.6	2.6	2.0	1.3	0.7	0.4	0.0
Industry	0.9	0.7	0.6	0.4	0.3	0.1	0.0	0.0
Power and district heat	6.1	6.0	4.3	2.5	1.9	1.0	0.5	0.0
Transportation	4.6	4.5	4.0	3.2	2.1	1.1	0.5	0.0
Total	**15.9**	**15.8**	**11.5**	**8.2**	**5.6**	**3.0**	**1.4**	**0.0**

Source: Own calculations.

6.2 MedRes scenario – medium exploitation of theoretic renewable heat potential

6.2.1 Heat

6.2.1.1 Decentral residential heating

CAPACITY

The assumptions for decentralized building heat hardly differ between the LowRes and MedRes scenarios. Only the assumed CO2 prices between 2025 and 2040 are higher in the MedRes scenario (cf. Table 21). However, this does not influence the decentral residential heat capacity leading to almost identical results (cf. Table 4 and Table 11). For a description of the results, please refer to chapter 6.1.1.1.

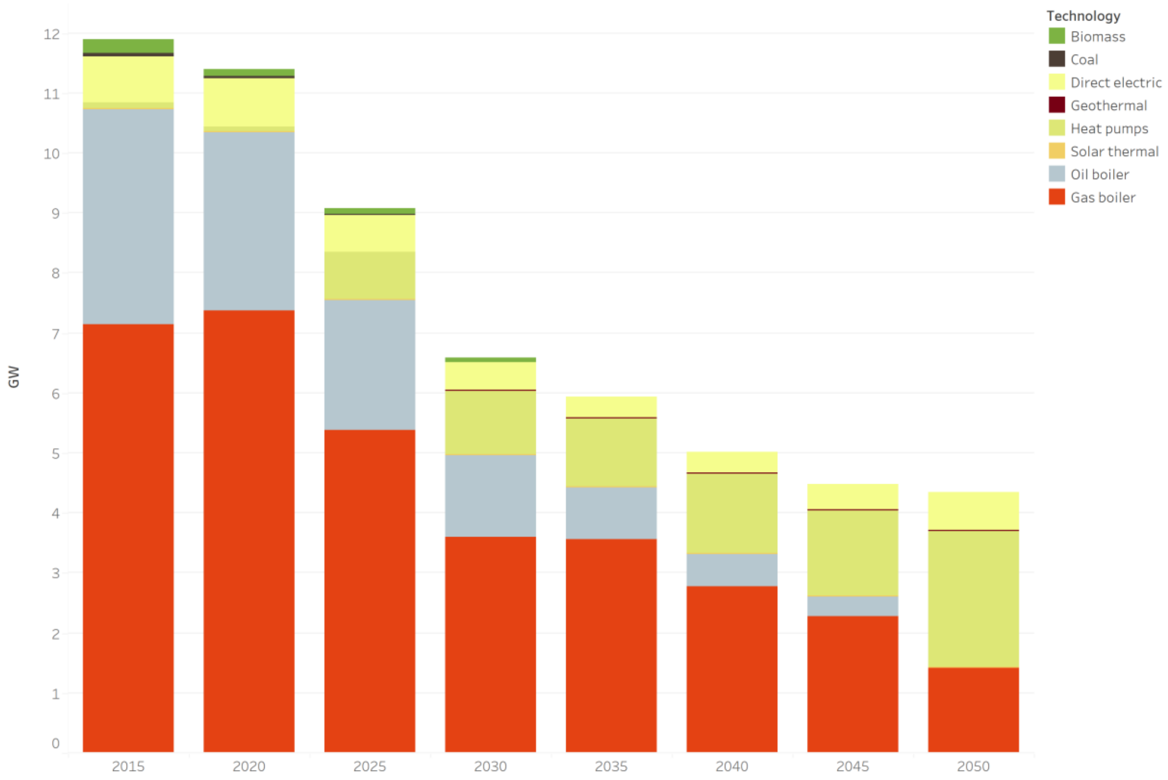

Figure 16: Decentral residential heat capacity in the MedRes scenario (2020-2050).

Source: Own illustration.

Table 11: Decentral residential heat capacity in the MedRes scenario in GW (2020-2050).

Technology	2020	2025	2030	2035	2040	2045	2050
Biomass	0.12	0.09	0.07				
Coal	0.03	0.02					
Direct electric	0.82	0.62	0.46	0.35	0.35	0.41	0.63
Geothermal			0.01	0.01	0.01	0.01	0.01
Heat pumps	0.08	0.8	1.09	1.17	1.36	1.45	2.29
Solar thermal	0.01	0.01	0.01	0.01	0.00	0.00	0.00
Oil boiler	2.97	2.17	1.37	0.86	0.54	0.34	
Gas boiler	7.38	5.39	3.60	3.57	2.78	2.28	1.43
Total	**11.41**	**9.09**	**6.60**	**5.96**	**5.04**	**4.50**	**4.37**

Source: Own calculations.

PRODUCTION

While the installed capacity in the MedRes and LowRes scenarios is almost identical, the effect of the higher CO_2 prices is evident in heat generation in 2025 and 2030. These lead to a quasi-phase-out of oil heating, as it is no longer competitive with gas heating due to the higher specific emissions. Although, the higher CO_2 prices only result in a switch from oil to gas. The increase is insufficient to cause a fuel switch towards more renewable heat (compared to LowRes).

However, the shift from oil to gas is critical from a model perspective since real constraints are not represented at this point. It should not be possible for gas heaters to produce heat instead of oil heaters. Since buildings are usually connected to only one form of heating, switching the fuel without installing new heating systems cannot be realized. Therefore, in the future, additional constraints should be considered to prevent a fuel switch without new construction first.

Besides the shift from oil to gas, the MedRes scenario is identical to the LowRes scenario.

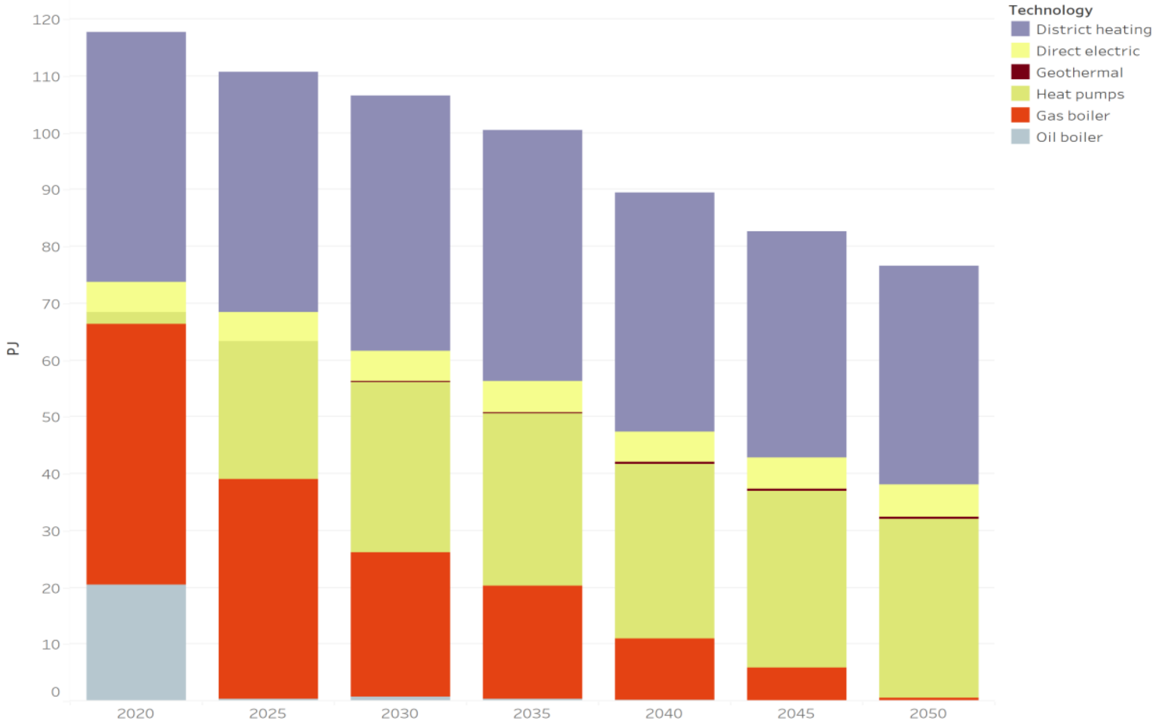

Figure 17: (Decentral) residential heat supply in PJ in MedRes scenario (2020-2050).

Source: Own illustration.

Table 12: (Decentral) residential heat supply in PJ in MedRes scenario (2020-2050).

Technology	2020	2025	2030	2035	2040	2045	2050
District heating	44.03	42.26	44.91	44.28	42.06	39.94	38.53
Direct electric	5.19	5.26	5.33	5.4	5.47	5.54	5.61
Geothermal			0.15	0.16	0.3	0.31	0.31
Heat pumps	2.07	24.21	29.99	30.38	30.77	31.18	31.58
Gas boiler	46.02	38.65	25.44	19.94	10.75	5.75	0.55
Oil boiler	20.45	0.38	0.77	0.4	0.21	0.07	
Total	**117.76**	**110.76**	**106.59**	**100.56**	**89.56**	**82.79**	**76.58**

Source: Own calculations.

6.2.1.2 District heating

DISTRICT HEAT CAPACITY

As in the LowRes scenario, the renewable heat potential is exhausted in the MedRes scenario by 2030 except for solar thermal systems in combination with heat pumps. Additionally, the majority of the storage capacity will be built by 2030. The phase-out of coal can therefore be achieved through the rapid expansion of renewable heat potential. Renewables are supported by additional gas boilers, which show a net addition of about 400MW until 2035 compared to 2020 (cf. Table 13). Therefore, the addition of gas boilers can be reduced significantly in the MedRes Scenario compared to the LowRes Scenario where 800 MW gas boilers are installed. Similar to the LowRes scenario, no new construction of gas CHPs occurs, and hence, the installed capacity of gas CHPs gradually decreases as the plants reach the end of their lifetime. In 2045 and 2050, a total of 3GW of gas capacity remains (1.3 GW of which is CHPs). Solar thermal systems are not deployed until 2040. From 2040, biomass boiler capacity triples to about 300MW by 2050, so by 2050, a total of about 600MW of biomass capacity (boilers & CHPs) is then installed. In 2050, the capacity of direct electric plants (P2H) will increase slightly to 170 MW. Compared to the LowRes scenario, which relies on 540 MW P2H, the new capacity of P2H will be only marginal. The preferred technology will be heat pumps with various renewable heat sources.

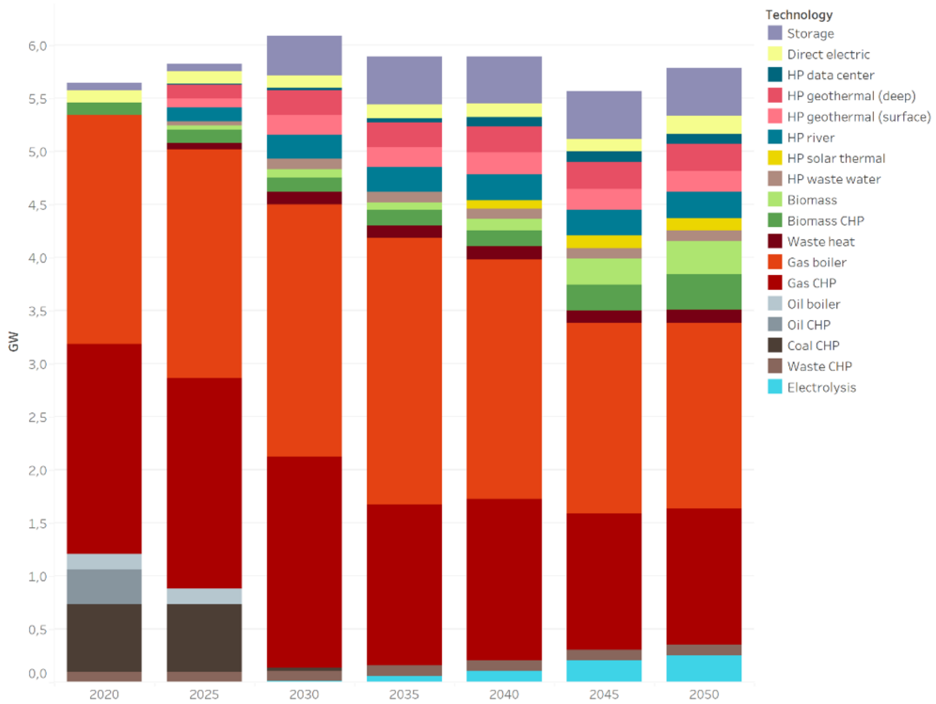

Figure 18: Installed capacities in Berlin´s district heating network in the MedRes scenario (2020-2050).

Source: Own illustration.

Table 13: Installed capacities in Berlin´s district heating network in GW in MedRes scenario (2020-2050).

Technology	2020	2025	2030	2035	2040	2045	2050
Storage	0.06	0.06	0.37	0.45	0.45	0.45	0.45
Direct electric	0.12	0.12	0.12	0.12	0.12	0.12	0.17
HP data center		0.01	0.02	0.04	0.09	0.10	0.10
HP geo (deep)		0.13	0.24	0.24	0.25	0.25	0.25
HP geo (surface)		0.10	0.18	0.19	0.20	0.20	0.20
HP river		0.12	0.23	0.23	0.24	0.25	0.25
HP solar thermal					0.08	0.11	0.11
HP wastewater		0.05	0.10	0.10	0.10	0.10	0.10
Biomass		0.04	0.07	0.07	0.11	0.25	0.31
Biomass CHP	0.12	0.12	0.14	0.14	0.15	0.24	0.34
Waste heat		0.06	0.12	0.12	0.12	0.12	0.12
Gas boiler	2.15	2.16	2.37	2.51	2.26	1.79	1.75
Gas CHP	1.98	1.98	1.98	1.52	1.52	1.29	1.29
Oil boiler	0.14	0.14					
Oil CHP	0.33						
Coal CHP	0.64	0.64	0.03				
Waste CHP	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Electrolysis		0.00	0.01	0.06	0.11	0.20	0.25
Total	**5.65**	**5.82**	**6.09**	**5.89**	**5.90**	**5.57**	**5.79**

Source: Own illustration.

District Heat Production

The heat generation shown in Figure 19 illustrates the preferred use of heat pumps instead of P2H due to higher efficiency. Although direct electric P2H plants exist, they are not used until 2030. Instead, heat pumps contribute a quarter of the district heat (11 PJ), so in 2025, coal and gas use can already be reduced significantly. Compared to the LowRes scenario, the reduction of gas consumption in the district heating due to the higher renewable heat potential in the MedRes scenario is significant, with around 38% (cf. Table 15).

Table 14: Gas savings in district heating - MedRes scenario compared to LowRes scenario (2020-2050).

	2020	2025	2030	2035	2040	2045	2050
Gas savings in %	0%	23%	38%	28%	19%	32%	36%

Source: Own calculations.

A combination of biomass boilers, maximum utilization of heat pumps (except solar thermal), industrial waste heat, and P2H replace coal until 2030. At the same time, a decrease in gas use is observed. As most renewable heat sources are fully utilized from 2035, P2H plants and solar thermal, combined with heat pumps and storage, become the preferred decarbonization option. In 2050, synthetic gas replaces fossil gas resulting in complete decarbonization of the district heat supply.

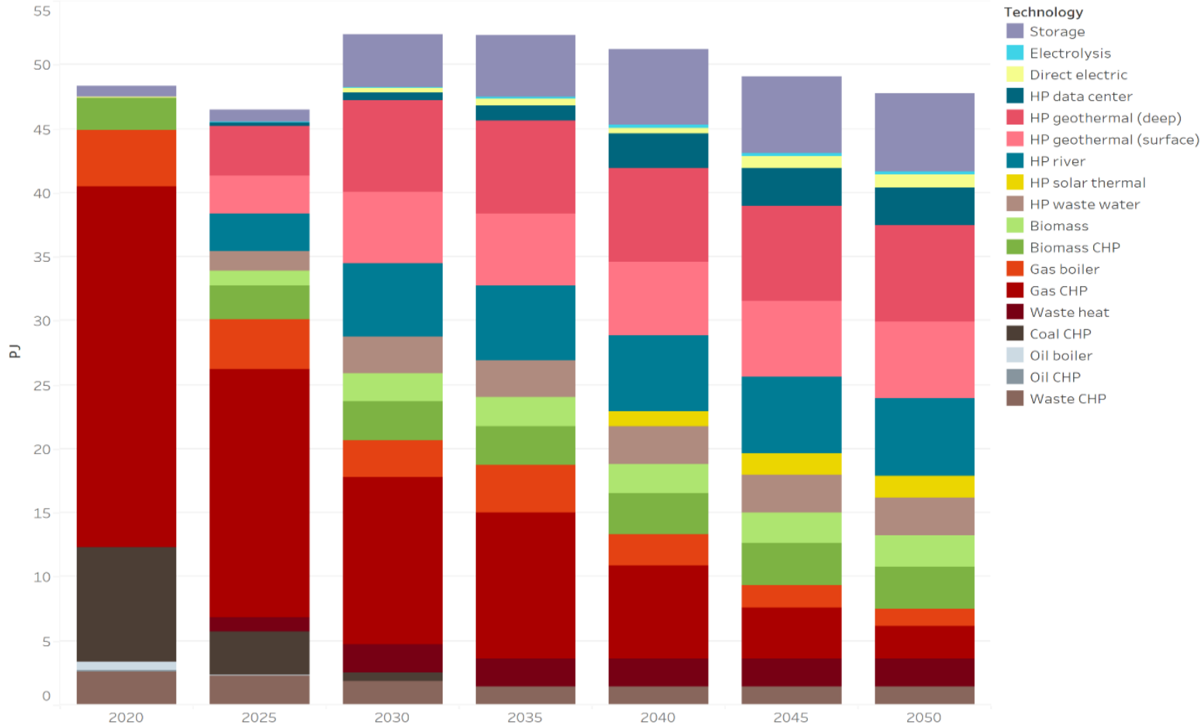

Figure 19: District heating production in Berlin in MedRes (2020-2050).

Source: Own illustration.

Table 15: District heating production in Berlin MedRes (2020-2050).

in PJ	2020	2025	2030	2035	2040	2045	2050
Storage	0.85	0.86	4.13	4.81	5.91	5.99	6.07
Electrolysis	0.00	0.02	0.02	0.23	0.24	0.24	0.24
Direct electric	0.01	0.04	0.42	0.43	0.43	0.96	0.97
HP data center	0.00	0.30	0.60	1.19	2.67	2.93	2.97
HP geothermal (deep)	0.00	3.86	7.16	7.26	7.35	7.45	7.54
HP geothermal (surface)	0.00	2.94	5.58	5.68	5.79	5.87	5.94
HP river	0.00	3.01	5.72	5.79	5.90	6.01	6.09
HP solar thermal	0.00	0.00	0.00	0.00	1.18	1.67	1.70
HP wastewater	0.00	1.49	2.81	2.86	2.90	2.93	2.97
Biomass	0.00	1.20	2.25	2.28	2.31	2.43	2.46
Biomass CHP	2.60	2.63	3.02	3.06	3.19	3.24	3.28
Gas boiler	4.41	3.82	2.88	3.73	2.49	1.76	1.38
Gas CHP	28.22	19.42	13.09	11.43	7.25	4.01	2.52
Waste heat	0.00	1.08	2.16	2.14	2.16	2.16	2.16
Waste CHP	2.69	2.28	1.86	1.45	1.45	1.45	1.45
Coal CHP	8.88	3.43	0.69	0.00	0.00	0.00	0.00
Oil boiler	0.71	0.07	0.00	0.00	0.00	0.00	0.00
Oil CHP	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	**48.37**	**46.45**	**52.39**	**52.34**	**51.23**	**49.09**	**47.74**

Source: Own calculations.

Figure 20 depicts the heat supply and demand for the year 2045. The baseload of heat will be provided by geothermal energy (deep and near-surface), wastewater heat, and waste heat from data centers combined with heat pumps. The continuous heat supply by industrial waste heat is also available for the baseload supply. In the heating months, the biomass boilers and CHPs also cover the baseload. Seasonal heat storage will support the heating generators with solar thermal and river heat accumulated in the summer months. The required storage capacity in the scenario is about 1500 GWh. The storage size results in a land consumption of 1.3 km^2, which corresponds to about one-third of the area of the former Tempelhof airport.

Peak load coverage is provided by gas and biomass boilers, gas CHPs, and direct electric heaters. Total heat generation from gas equals 5.7 PJ, resulting in full load hours (flh) of about 1100 flh (cf. Figure 27 and Table 32). The low full load hours highlight the minor role gas will play in the future heating system of Berlin. The gas used in 2045 is still exclusively fossil gas but will be replaced with synthetic gas by 2050.

Berlin will cover a small part of the demand for synthetic gas through local electrolysis capacities. The heat released during hydrogen production is used in district heating. However, the contribution is small with 0.3 PJ. Nevertheless, summer electrolysis enables some seasonal storage of excess electricity produced by PV in summer using P2Gas.

Waste generated in Berlin also serves as heat storage in the model. The model shifts waste incineration towards the heating season. Whether this is legally possible in the future must be examined. Although, the volume of waste decreases due to measures for a circular economy (see chapter 8.2.5), which should make storage easier.

The capacity required to provide the maximum heat load is approx. 4.3 GW.

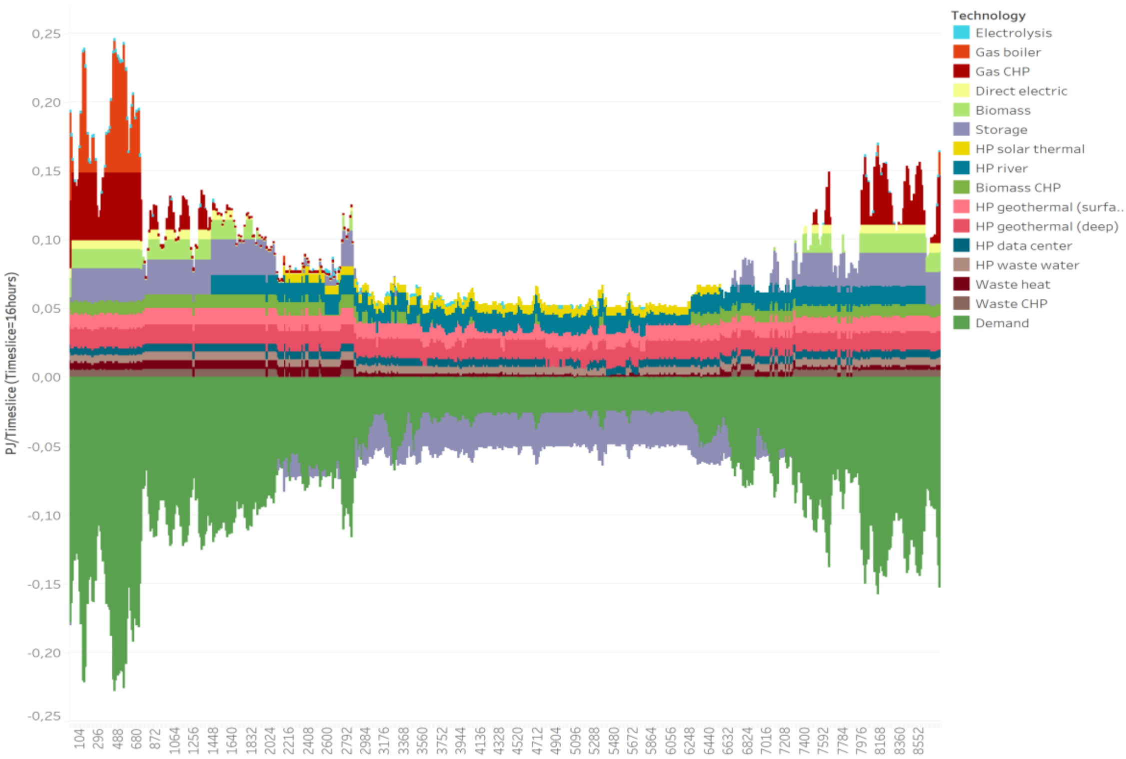

Figure 20: District heat generation and demand in 2045.

Source: Own illustration.

Table 16: Heat generation, installed capacities, and full load hours of district heating technologies in Berlin in 2045.

in 2045	PJ	GWh	GW	Full load hour
Electrolysis	0.3	84	0.204	412
Gas boiler	1.7	485	1.792	271
Gas CHP	4.0	1101	1.285	857
Direct electric	1.0	268	0.120	2230
Biomass	2.4	669	0.248	2701
Biomass CHP	3.2	899	0.243	3700
HP geothermal (surface)	5.9	1631	0.200	8155
HP geothermal (deep)	7.4	2066	0.250	8263
HP data center	2.9	815	0.100	8151
HP wastewater	2.9	815	0.100	8155
Waste heat	2.2	600	0.120	4997
Waste CHP	1.3	352	0.099	3554
HP river	6.0	1668	0.250	6672
HP solar thermal	1.7	467	0.112	4163
Total	**42.9**	**11,921**	**5.123**	**-**

Source: Own calculations.

6.2.1.3 Process heat

Fossil gas dominated the process heat generation in 2020. From 2040, hydrogen will replace fossil or synthetic gases in process heat. Biomass and electricity, which gain importance starting after 2020, will complement the energy mix. Further, savings via efficiency measures determine the development of process heat demand. However, these savings will be compensated by the assumed economic growth, so from 2040 onwards, the demand for heat will increase slightly to 9.1 PJ (cf. Table 17).

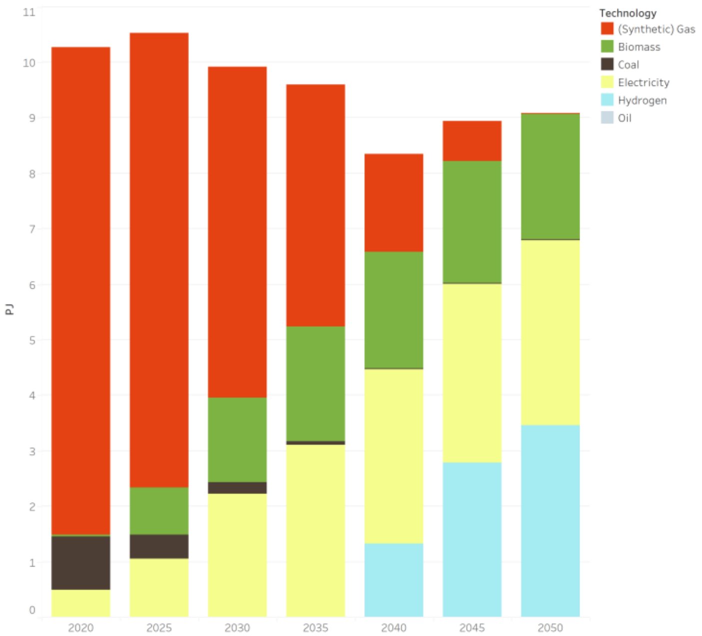

Figure 21: Process heat generation in Berlin by fuel in MedRes scenario (2020-2050).

Source: Own illustration.

Table 17: Process heat generation in Berlin by fuel in MedRes scenario (2020-2050).

in PJ	2020	2025	2030	2035	2040	2045	2050
Fossil/Synth. Gas	8.80	8.19	5.95	4.36	1.76	0.73	0.01
Biomass	0.03	0.85	1.52	2.08	2.10	2.19	2.26
Coal	0.96	0.44	0.21	0.06	0.00	0.00	0.00
Electricity	0.49	1.06	2.23	3.11	3.16	3.24	3.34
Oil	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydrogen	0.00	0.00	0.00	0.00	1.33	2.78	3.47
Total	**10.28**	**10.53**	**9.91**	**9.60**	**8.35**	**8.94**	**9.09**

Source: Own calculations.

6.2.2 Electricity

The decarbonization of the heat and transport sector through electrification leads to rising electricity demand. The demand increases by about 50% from 2020 to 2050. We can observe that the increase in electricity demand in the heating sector is around 17% lower in the MedRes scenario than in the LowRes scenario in 2050. This is due to the higher efficiency of heat pumps compared to P2H systems, which are deployed on a larger scale in the MedRes scenario.

The phase-out of fossil fuels in electricity and heat generation is achieved on the electricity side through imports and the expansion of renewable energy. Both PV and wind energy will be fully expanded. Regarding the operation of fuel cells in 2050, the same concerns as described in chapter 6.1.2 apply.

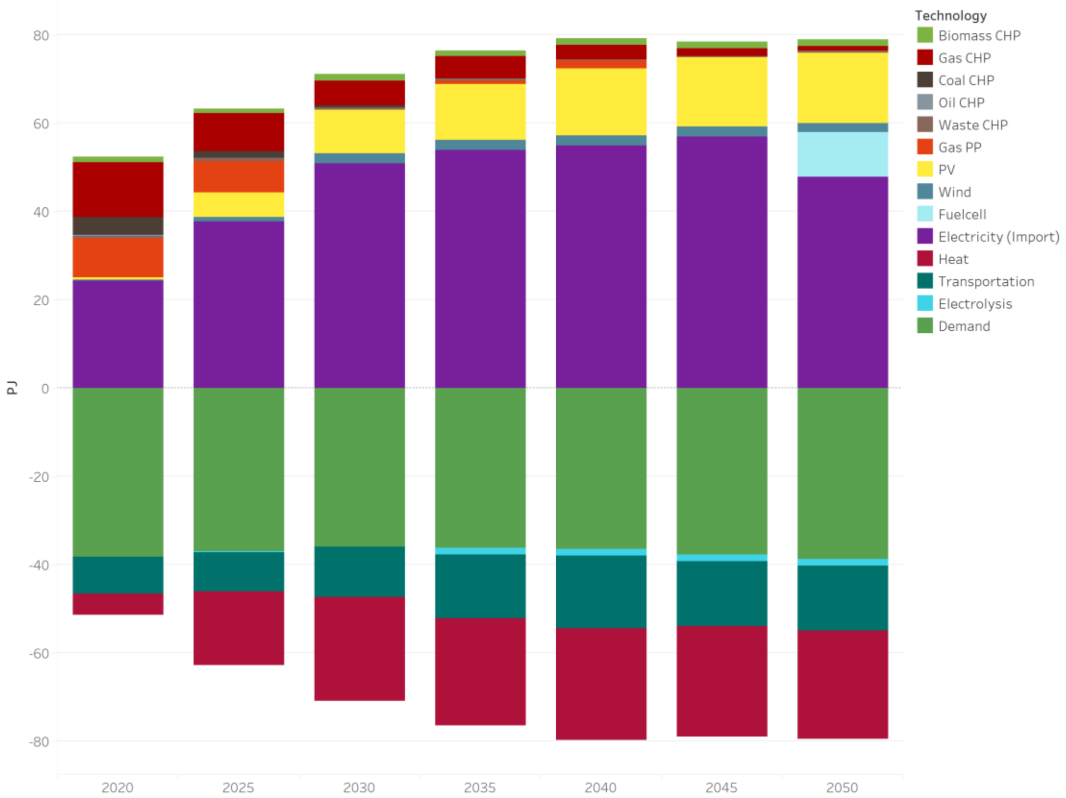

Figure 22: Electricity generation and demand in the MedRes scenario (2020-2050).

Source: Own illustration.

Table 18: Electricity generation and demand in MedRes scenario (2020-2050).

in PJ	2020	2025	2030	2035	2040	2045	2050
				Generation			
Biomass CHP	1.15	1.16	1.34	1.35	1.41	1.43	1.45
Gas CHP	12.50	8.60	5.79	5.06	3.21	1.77	1.11
Coal CHP	3.93	1.52	0.30	0.00	0.00	0.00	0.00
Oil CHP	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Waste CHP	0.83	0.71	0.58	0.45	0.45	0.45	0.45
Gas PP	8.96	6.95	0.00	0.96	1.63	0.00	0.00
PV	0.59	5.58	10.02	12.68	15.37	15.70	15.91
Wind	0.08	1.20	2.13	2.15	2.18	2.21	2.24
Electricity (Import)	24.38	37.69	51.00	54.00	55.00	57.00	48.00
Fuelcell	0.00	0.00	0.00	0.00	0.00	0.00	9.96
Total	**52.43**	**63.41**	**71.16**	**76.66**	**79.25**	**78.57**	**79.12**
				Demand			
Heat	-4.93	-16.89	-23.51	-24.18	-25.19	-25.14	-24.47
Electrolysis	0.00	-0.11	-0.16	-1.50	-1.51	-1.53	-1.55
Transportation	-8.30	-8.89	-11.38	-14.59	-16.50	-14.76	-14.65
Demand	-38.25	-37.08	-35.91	-36.24	-36.57	-37.73	-38.88
Total	**-51.48**	**-62.97**	**-70.95**	**-76.51**	**-79.77**	**-79.15**	**-79.55**

Source: Own calculations.

6.2.3 Emissions

The emissions decrease from 16 Mt CO_2 in 2020 to 0 Mt CO_2 in 2050 in the MedRes scenario, which results in total emissions of approximately 188 Mt CO_2 between 2020 and 2050. The CO_2 budget calculated by Hirschl et al. (2021, 21) for Berlin to be consistent with the 1.5°C target equals 185 Mt CO_2 (at 50% likelihood). Hence, the scenario MedRes is close to a 1.5°C compatible decarbonization path. However, the emissions considered by the model do not include the emissions connected to imported electricity. If they were to be included, it becomes apparent that the emission targets set by the Berlin Senat do not comply with a 1.5°C compatible scenario. The CO_2 targets are more in line with the 1.75°C budget, which is about 290 Mt CO_2 for a 67% probability of occurrence.

The emissions savings in the MedRes scenario compared to the LowRes scenario equal around 8 Mt CO_2, which corresponds to savings of 4%.

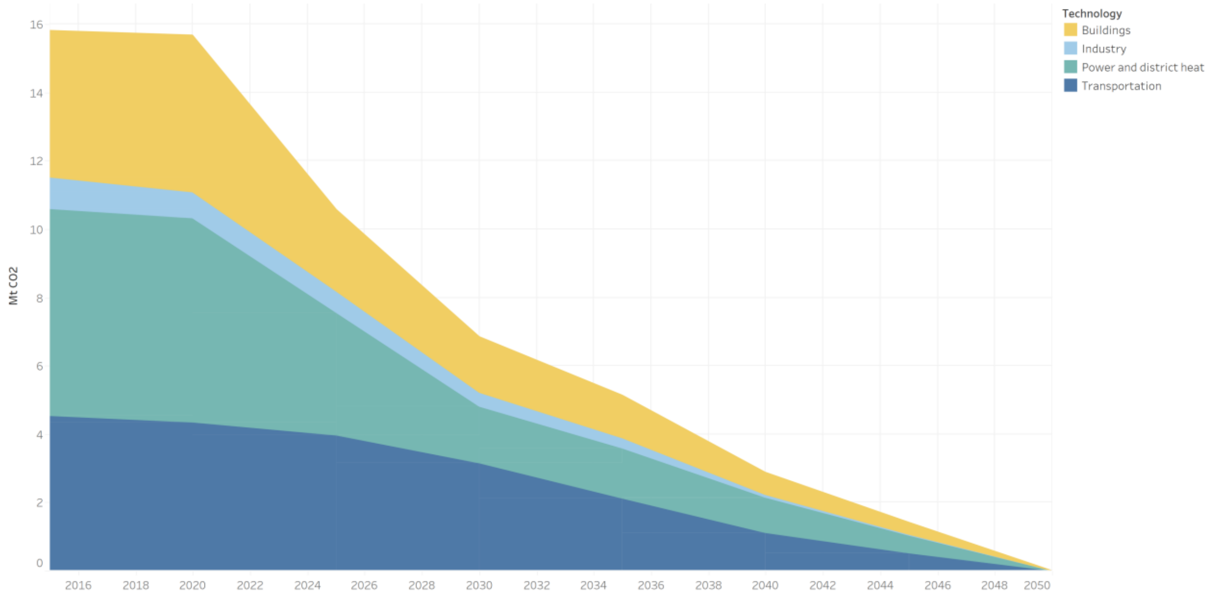

Figure 23: CO_2 emissions in the MedRes scenario by sector (2020-2050).

Source: Own illustration.

Table 19: CO_2 emissions in the MedRes scenario by sectors in Mt CO_2 (2020-2050).

Technology	2015	2020	2025	2030	2035	2040	2045	2050
Buildings	4.3	4.6	2.4	1.6	1.2	0.7	0.3	0.0
Industry	0.9	0.7	0.6	0.4	0.3	0.1	0.0	0.0
Power and district heat	6.1	6.0	3.6	1.6	1.5	1.0	0.5	0.0
Transportation	4.5	4.3	4.0	3.2	2.1	1.1	0.5	0.0
Total	**15.8**	**15.7**	**10.6**	**6.8**	**5.1**	**2.9**	**1.4**	**0.0**

Source: Own calculations.

6.3 Comparison with other studies

Comparing the modeling results with existing studies for the future development of district heating generation verifies the calculated values from the GENeSYS-MOD URBAN HEAT scenarios MedRes and LowRes.

Compared to the very ambitious study of Egelkamp et al. (2021), which achieves a 100% renewable heat supply by 2035 with maximum utilization of renewable heat potentials, we can observe that the current climate targets by the Berlin Senate (as considered by GENeSYS-MOD URBAN HEAT), still allow for high gas consumption in 2035 (cf. Table 20). Although, the low gas consumption in Egelkamp et al. (2021) is possible mainly due to the extremely high assumptions for industrial waste heat. However, this seems very unlikely given existing studies (cf. chapter 8.2.1). The heat generation by gas determined in the MedRes and LowRes scenario is somewhat comparable to the values of Dunkelberg et al. (2021). When comparing gas use with Dunkelberg et al. (2021), it is noticeable that the use of hydrogen and synthetic gases is already significantly higher in 2035. The same is true compared to Egelkamp et al. (2021). While both studies assume values between 880 and 1050 GWh for synthetic gases in 2035, no synthetic gases are used in the heat supply in the MedRes & LowRes scenarios. In 2050, Dunkelberg et al. (2021) assume synthetic gases amounting to 2700 GWh, whereas in the MedRes only 1080 GWh, and in the LowRes scenario 1680 GWh of synthetic gases are used. Instead, the GENeSYS-MOD URBAN HEAT scenarios rely on electricity-based heat generation. This appears to be a more sensible approach given the high-efficiency advantages of P2H over heat generation with P2G via multiple conversion steps.

Furthermore, it is noticeable that although the present study has set significantly lower expansion caps for heat pumps compared to Egelkamp et al. (2021), the heat generation of geothermal and wastewater heat pumps is not much lower, especially in the MedRes scenario. This is due to the much more constant utilization of the heat pumps in GENeSYS-MOD (GM) URBAN HEAT with full load hours of over 8000h (cf. Table 16). High utilization of the heat pumps is always to be aimed at for an efficient operation, which is why the present modeling results are considered reasonable.

Table 20: Comparison of the scenario results for district heating with existing other studies.

in GWh	2035				2050		
	Egelkamp et	Dunkelberg	GM URBAN HEAT		Dunkelberg et	GM URBAN HEAT	
Technology	**al. (2021)**	**et al. (2021)**	**MedRes**	**LowRes**	**al. (2021)**	**MedRes**	**LowRes**
Waste heat	3146	550	594	300	600	600	494
HP river	1712		1608	825		1692	856
HP solar thermal	2196	*800	0	200	*900	472	381
HP wastewater	925		794	403		825	419
HP geo (deep)	2387	400	2017	1033	600	2094	1072
HP geo (surface)	1704	0	1578	825	600	1650	858
Waste CHP	448	650	403	403	250	403	403
Direct electric	46	450	119	1408	1600	269	2925
H_2/synth. gas	884	1050	0	0	2700	1083	1681
Fossil gas	0	5800	4211	5878	0	0	0
Oil	0	0		0	0	0	0
Biomass	0	1300	1483	1756	1700	1594	1906
Electrolysis	0	100	64	3	0	67	3
Total	**13448**	**11100**	**12872**	**13033**	**8950**	**10750**	**10997**

*The presented value is aggregated for all types of heat pumps.
Note: Values for Dunkelberg et al. (2021) in 2035 are interpolated since only the years 2030 and 2040 were available; Egelkamp et al. (2021) only state values for 2035.

Source: Own calculations, Egelkamp et al. (2021), and Dunkelberg et al. (2021).

7 Conclusion and further research

The results suggest a rapid expansion of the renewable heat potential in Berlin and an increase in the use of biomass from the surrounding area of Berlin. Especially in the case of geothermal energy, the expansion should be started quickly since these projects are fraught with uncertainties to find suitable heat sources. These uncertainties have previously been inhibiting for geothermal projects. Therefore, suitable measures should be implemented to financially secure these projects against the risk of not finding a suitable heat source when drilling for a heat source.

Furthermore, it is evident that Berlin will not be self-sufficient even if all available renewable energy potentials are utilized but will be dependent on imports of renewable electricity and hydrogen or synthetic gases in the future. A large part of the synthetic gases will be required in the transport sector, and fuel cells which generate electricity in 2050. Both aspects will have to be investigated in more detail in consecutive studies. In this study, the transport sector was not considered in detail. It is, therefore, possible that a more detailed analysis will show an increasing focus on electromobility instead of hydrogen. An adjusted modeling setup should give clarity as far as the use of hydrogen in power generation in 2050 in Berlin is concerned. If Berlin is modeled as one node among many in Germany and the power exchange is thus endogenized, the use of fuel cells in Berlin's power supply will most likely no longer be needed. In addition, the volatility in the power exchange should be increased in further considerations to reflect the fluctuation of renewable electricity better. The implemented fluctuation thus allows investigating the role of electricity storage or short-term heat storage, which are not deployed in the existing model setup. However, modeling Berlin isolated in this study allowed for a high temporal resolution, which provided informative results for the operation of technologies within the years.

The results of both scenarios illustrate that Berlin can meet future electricity and heat demand without new gas CHPs. Investments in new gas CHPs are not compatible with a renewable-based energy system and should be omitted to prevent a gas lock-in. An adjustment of the CHP law supporting the construction of CHPs should therefore be considered to end the support for further development of CHPs by the state. Instead, geothermal projects and seasonal heat storage should be promoted to make the available renewable heat potentials usable in the fall and winter months. It is shown that new types of seasonal storage constructions can significantly reduce space consumption, which will be of high importance for a densely populated area like Berlin. This should be considered for future storage.

Further, the results highlights show how renewable heat sources can be fed-in despite high grid district heating temperatures. For example, in the model, renewable heat sources are almost exclusively fed into the grid using heat pumps, which means that the grid temperature only needs to be moderately lowered. This could prove problematic in a heating system as large and complex as the one in Berlin, as lowering the grid temperature is only feasible with extensive and coordinated measures on the consumer side. If the grid temperature can be lowered further than assumed, this would reduce the investment costs on the heat generator side, since fewer heat pumps are necessary, or at least reduce the electricity demand, since the heat pumps can be operated more efficiently.

In summary, a 100% renewable electricity and heat supply for Berlin is possible by 2050. By reducing the energy demand in the building sector and a determined expansion of the available renewable potentials, the use of gas in the heating sector can be reduced to such an extent that only small amounts of hydrogen will be necessary for the future to replace fossil gas. The amount of hydrogen required is in a range that makes an exclusive supply of domestic hydrogen feasible. The domestic and preferably local energy supply should be the goal of the Energiewende, as this is crucial to achieving independence from other countries regarding the energy supply. Without energy autarchy, the future of energy supply will always be fraught with uncertainty and price fluctuations. With a self-sufficient energy supply, Germany can become less dependent on geopolitical conflicts in energy matters, strengthening its negotiating position in future conflicts.

For future research, it will be highly beneficial for the improvement of GENeSYS-MOD to feed the regional results from studies like this back to the larger European or German model to enhance the modeling of the heating sector on the larger scale.

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8 Appendix

8.1 Regulatory framework of the heat transition

Various factors determine the development of Berlin's heating system. On the one hand, by the regulatory framework for expansion targets or bans on technologies and energy sources as well as by laws and regulations concerning climate and efficiency goals at European, German, and Berlin level. On the other hand, subsidy programs and measures determine the development of the heating market.

8.1.1 CO_2-Emissions – reduction targets and prices

The CO2-emissions targets were tightened with the Green Deal and the renewed European Climate Protection Act at the European level. The revised targets are reductions of 55% until 2030 (compared to 1990) and net neutrality until 2050 (EU 2021).

In Germany, a new Climate Protection Act was passed in 2021, after the Federal Constitutional Court declared the Climate Protection Act unconstitutional in parts, resulting in a reinforcement of reduction targets, i.e., 65% emissions reduction by 2030 compared to 1990 and emissions neutrality by 2045 (Bundesregierung 2021b). In particular, the energy sector is expected to decrease annual CO_2 emissions to 108 mill. t by 2030 (previously 175 mill. t in 2030).

At the Berlin level, the Berlin Energiewende Act was also amended to set the CO_2 reduction at 40% by 2020, 70% by 2030, 90% by 2040, and 95% by 2045 compared to 1990 levels (EWG Bln 2021).

CO_2 certificates trading is used to control emissions. However, this has not developed its steering effect due to the low prices in previous years. Following reforms, the price rose significantly in 2021 despite the Covid pandemic, but without a binding minimum price for CO_2, the development is fraught with uncertainty. CO_2 certificates for the heat and transport sectors have been required since 2021. In 2022, the price for 1 t CO_2 rose from around 50 € in 2021 to around 100 €/t CO_2 (Ariva 2022). However, the future development of the CO_2 certificate price is not predictable, as speculation is a driving factor (Hermann, Matthes, and Keimeyer 2021). The CO_2 certificate prices assumed in the model are conservative given the price peaks in 2021 and 2022 and increase only slowly over the modeling period to 120 € in 2050.

Table 21: Price development for CO_2 emission certificates.

in €/t CO_2	2015	2020	2025	2030	2035	2040	2045	2050
LowRes	15	50	55	60	75	90	105	120
MedRes	15	50	80	90	90	100	105	120

Source: Own assumptions.

8.1.2 Renewable targets

The EU's Renewable Energies Directive defines feed-in quotas for renewable energies in the heating sector to increase by 1.1 to 1.3% annually.

At the German level, according to the National Energy and Climate Plan, renewable energies are to account for 30% of gross final energy consumption by 2030 (BWMi 2020, 46).

For Berlin, the new Energy Transition Act stipulates at least 40% of district heating from renewable energy sources in 2030. In addition, producers of renewable heat will have the right to feed into the grids of all heating network operators (EWG Bln 2021). Additionally, by 2023, solar installations will be mandatory on new buildings and after roof renovations in Berlin (Solargesetz Berlin 2022, §3). Moreover, changes in regulations for the self-use of renewable electricity in the Renewable Energy Act (EEG 2021) reform serve as an incentive to install heat pumps for heat generation that use self-produced electricity from PV modules.

8.1.3 Efficiency goals

The targets by the European Union for the primary energy consumption stipulated in the Energy Efficiency Directive require a reduction of 20 % by 2020 and 32.5 % by 2030. The reductions result in at least 1.5 % annual savings by 2021 and 0.8 % by 2030 (EC 2018).

Germany sets out to save 30% of primary energy consumption compared to 2008, as declared in the Energy Efficiency Strategy 2050 (BMWi 2019b, 9). Further, the heating demand should decrease by 20 % until 2020 and the primary energy demand in the building sector by 80% until 2050 (Bundesregierung 2021a). These goals are likely to increase in the future since European and German climate protection targets tightened.

Berlin's targets for the building sector are defined in the BEK 2030. Refurbishment rates are to be increased by more than 2 % to achieve the necessary energy savings (compare chapter 2.2.2) (Senatsverwaltung für Umwelt, Verkehr und Klimaschutz 2018, 66).

8.1.4 Fuel restrictions

In Germany, the commercial use of nuclear energy will end after 2022 (Bundesgesetzblatt 2011), and by law, coal phases out until 2038 at the latest (BMWi 2020).

In Berlin, the Energy Transition Act stipulates the coal phase-out by 2030 (EWG Bln 2021). By 2026, installing oil and coal heating systems for decentralized heat supply will be banned, except for a few hardship cases, thus entailing their disposal by 2056 the latest due to the 30-year replacement obligation for heating systems (GEG 2020).

8.2 Potentials of renewable heat sources

The availability of renewable energies determines the decarbonization pathway of the energy sector. Although several renewable energies are provided in Berlin, they are insufficient to meet the projected energy demand. Berlin depends on importing renewable energy sources and electricity from surrounding areas. The following sections outline the potential for renewable energy in and around Berlin.

8.2.1 Industrial waste heat

Industrial processes both require and generate heat. The excess heat can cover the heat demand for other purposes. However, industrial waste heat is volatile, depending on the respective industrial processes. Feeding it into the district heating network or a storage facility may be beneficial to compensate for the fluctuations and increase usability.

Table 22: Estimations for the available industrial heat potential in and around Berlin.

		Capacity (in MW)	Heat output (GWh)	Full load hours
Egelkamp et al. (2021)	in Berlin (economic)	30	263	8,760
	around Berlin (economic)	120	1051	8,760
Ritzau et al. (2019)	theoretic	135	700	5,185
	economic	*58	300	*5,185
Dunkelberg et al. (2021)	economic	*120	600	*5,000

*estimated by the authors.

Source: Based on Egelkamp et al. (2021), Dunkelberg et al. (2021), and Ritzau et al. (2019).

A detailed survey on the potential of industrial waste heat is not available for Berlin, but estimates suggest a range between 30 MW and 135 MW (Egelkamp, Wett, and Kallert 2021, 21; Ritzau, Langrock, and Michels 2019, 73). Due to differing implicit full load hours for industrial waste heat, the heat output ranges between 260 and 700 GWh. Egelkamp et al. (2021) also consider the industrial waste heat potential outside of Berlin and identify two sites with potential waste heat on the outskirts of Berlin with a substantial capacity of 120 MW. The necessary costs for connecting those sites to the district heating network can be reduced as the sites are close to potential solar thermal sites.

In the present study, the considered waste heat potential equals 120 MW with the heat output totaling 600 GWh. The cost for heating pipes is 800 €/rm for GENeSYS-MOD URBAN HEAT, which is on the upper end of estimations for 2020 (European Commission. Joint Research Centre., ILF Consulting Engineers Austria GmbH., and AIT Austrian Institute of Technology GmbH. 2017, 158). The assumed length for the pipes needed to connect the waste heat sites is 10km. Besides the costs for connection to the grid, no further costs are considered for waste heat. This leads to an installation cost assumption of 66 €/kW_{th}.

8.2.2 Central heat pumps

Heat pumps are vital to include renewable potentials into the heating system. Large-scale heat pumps can use local heat potentials and feed them into the district heating grid. Heat pumps primarily run on electricity, and for them to generate renewable heat, the electricity must originate from surplus renewable energy. The ratio between the amount of electricity used and the amount of heat delivered is called the coefficient of performance (COP). The higher the temperature of the heat source and the lower the temperature of the heat sink (i.e., district heating network), the more efficient heat pumps operate.

The following sections describe the available heat sources used by heat pumps in Berlin. An overview of the investment costs and the potentials of each heat source for the heat pumps follows in chapter 8.2.2.6.

8.2.2.1 River water

In Berlin and the surrounding area, various standing and flowing water bodies can be considered as heat sources for heat pumps. Large river heat pumps extract part of the heat from the water, raise it to a higher temperature, and feed it into the district heating network. After the heat has been extracted from the river water, it flows at a lower temperature. Usually, heat pumps work with a temperature gradient of 5°C, i.e., the river water temperature is 5°C warmer before extraction than afterward (Dunkelberg, Deisböck, Hermann, et al. 2020, 44).

The availability of the river heat pump is determined by the temperature and flow velocity of the river water. The minimum temperature before extraction is about 5-8°C (Dunkelberg, Deisböck, Hermann, et al. 2020, 44; Egelkamp, Wett, and Kallert 2021, 13). The cooling of the entire river water must not exceed 1°C due to the extraction. The problem with river heat pumps is the partial inoperability of the systems in the winter when most of the heat is needed due to the low river water temperatures. Therefore, the plants are mainly used in the transition months or equipped with seasonal storage to provide the heat generated in summer during the winter months.

Egelkamp et al. (2021) estimated the potential for river water pumps at around 525 MW, with an annual heat yield of 1.7 TWh. However, a feasibility assessment for the potentials is still pending.

Dunkelberg et al. (2021, 44) and Ritzau et al. (2019, 77) conducted studies for different parts of Berlin (Neukölln and North-West Berlin, respectively) and estimated the potential for river heat to be significantly lower. The authors of both studies point out that the temperatures of Berlin’s water bodies in the winter months are too cold for river water extraction. In GENeSYS-MOD, river water abstraction in the winter months is also excluded. The assumed temperature curve for Berlin´s waters was estimated according to Dunkelberg et al. (2020, 44).

To deal with the uncertainties regarding the potential of river heat pumps, the scenario MedRes considers a medium potential of 250 MW and the scenario LowRes a lower potential of 125 MW. For modeling the cost development of river heat pumps in Berlin between 2015 and 2050, the same trend as for regular heat pumps is assumed. Cost development of heat pumps until 2050 was described by the European Commission et al. (2017, 59). According to this trend and Dunkelberg et al.´s (2020, 126) figures for river pumps from 2020, the investment costs for heat pumps were extrapolated (see Table 23).

8.2.2.2 Wastewater

The advantage of wastewater heat resides in its widespread availability. For efficient heat extraction, areas with sufficiently high flow density must be identified. The Berlin Water Operator (BWB) identified sites and prepared a potential analysis. However, a feasibility study is still pending (Dunkelberg et al. 2021, 138).

The maximum heat extraction is determined by the minimum temperature of wastewater reaching the treatment plant. At this point, the wastewater must be at least 8°C, otherwise, the digestion process is disturbed. The total extracted potential is estimated at 110 and 270 MW. Egelkamp et al. (2021) suggest a potential of 200 MW in combination with heat pumps, and Dunkelberg et al. (2021) assume an installed capacity of 90 MW. In the present model, heat output of 100MW is assumed for wastewater heat pumps in the MedRes scenario and 60 MW in the scenario LowRes. The wastewater temperatures used by the heat pumps vary between 13 and 20°C within the year.

The costs for wastewater heat pumps in 2020 are taken from Dunkelberg et al. (2020, 126), while the cost development until 2050 is based on the cost development for heat pumps described by the European Commission et al. (2017, 59) (see Table 23).

8.2.2.3 Solar thermal

So far, solar thermal energy has hardly been used in Berlin, as there is a conflict of use between decentralized rooftop collectors and PV systems. In addition, restrictions exist regarding the load-bearing capacity of the roofs, which often cannot support the weight of the fluid inside the collectors. Therefore, it is assumed that hardly any decentralized solar thermal energy is used in Berlin.

Berlin lacks the space to install larger collector areas for a centralized heat supply. Therefore, only areas outside the city can be considered. The largest solar collector areas have been built in Denmark, with outputs of up to 80GWh per year (SDH 2017). These solar farms are built in combination with underground storage pits (see chapter 4.2.6) and cover more than 100,000 m^2. For even larger projects, Egelkamp et al. (2021) identified areas in the vicinity of Berlin with a total area of 10km^2 (incl. earth reservoirs). This is approximately three times the area of the former airport Berlin Tempelhof. The authors assume a solar thermal potential, including heat pumps, of 350 MW.

Due to the extensive landuse by solar thermal collectors, it is subject to uncertainties if the capacity of this amount will be deployable. Thus, the present study assumes in the scenario MedRes a solar thermal potential (incl. heat pumps) of around 180 MW and in LowRes around 90 MW.

The considered expenses for solar thermal energy consist of the costs for the heat pumps and the collector areas (see Table 23).

8.2.2.4 Geothermal

Geothermal energy uses ground heat to generate electricity or heat. The availability depends on the geological conditions and therefore varies. Geothermal energy is usually divided into deep and near-surface geothermal energy with a threshold of about 400m (Acksel et al. 2021, 8). For Berlin, studies estimate the geothermal potential, however, the exact usable potential can only be determined by test drillings. Hence, the risk is to find geothermal energy for each site, which currently has an inhibiting effect on its use.

8.2.2.4.1 Surface Geothermal

The near-surface geothermal potential in Berlin that can be used sustainably is about 1TWh. It is obtainable by geothermal probes reaching up to 200m into the earth and extracting the heat at about 20°C. Furthermore, deeper water-bearing layers (aquifers) with a temperature of about 60°C exist and can be extracted efficiently (Blöcher et al. 2019, 7). Both forms of use are subject to groundwater protection restrictions.

The temperatures of the near-surface geothermal energy in Berlin are not sufficient to be fed directly into the district heating network. Therefore, heat pumps are used to raise the temperature. The potential assumed in the model in combination with heat pumps is 200 MW in the MedRes scenario and 100 MW in the LowRes scenario. These are conservative estimates compared to Egelkamp et al. (2021), who suggest 500 MW.

The near-surface geothermal energy can also function as seasonal heat storage. Surplus heat from the summers can be channeled into the ground and stored until the heating season.

8.2.2.4.2 Deep Geothermal

Especially for deep geothermal energy, there is great uncertainty about the potential. The theoretical potential ranges between 660 and 15,800GWh (SenUVK 2013, 33). This leads to high uncertainty for deep geothermal plants. The GFZ estimates up to 135°C at depths between 3000 and 4500 m for Berlin (Blöcher et al. 2019, 9). However, the actual temperature and potential can only be estimated after test drillings. Egelkamp et al. (2021, 19) assume that only heat sources with a lower temperature of 60°C can be used in Berlin and fed into the district heating network via heat pumps. The authors suggest a potential of 450 MW, including heat pumps. Dunkelberg et al. (2021) indicate the use of about 130 MW from deep geothermal energy in combination with heat pumps.

In this study, the conservative estimates of 60°C for the heat source are also assumed. Moreover, deep geothermal energy can only be utilized with heat pumps due to the low temperature. The proposed potential by Egelkamp et al. (2021) appears high considering that potential areas have to be identified first and there are restrictions due to groundwater protection. The upper limit for the use of deep geothermal energy in this study is set to 250 MW in the scenario MedRes and 125 MW in LowRes.

8.2.2.5 Data Center

In Berlin and its vicinity, numerous data centers already exist or are in planning that are potential sources of waste heat. The total installed capacity of data centers will sum up to around 200MW by 2024 (Rüdiger and Ostler 2021). Data centers require large amounts of cooling and electricity. The energy demand of data centers is estimated at 14 TWh in 2018, which corresponded to 2.5% of the electricity consumption of Germany in 2018 (Hintemann 2020, 1).

Data centers produce constant excess heat, which can be integrated into the district heating network. Egelkamp et al. (2021, 20) estimate a heat potential of 200 MW in combination with heat pumps. Even in winter, the temperature levels of the data centers lie at around 25-30°C.

The considered heat potentials by data centers in the present study range from 50 MW (LowRes) to 100 MW (MedRes). The assumed costs for the integration of the heat only include the cost for a regular heat pump (cf. Table 23).

8.2.2.6 Overview of costs and potentials of large-scale heat pumps

Table 23: Heat pump potential for different heat sources in the scenarios MedRes and LowRes.

Heat source	2015	2020	2025	2030	2035	2040	2045	2050
in MW				*Scenario MedRes*				
River	250	250	250	250	250	250	250	250
Geo (deep)	250	250	250	250	250	250	250	250
Geo (surface)	200	200	200	200	200	200	200	200
Solar	175	175	175	175	175	175	175	175
Wastewater	100	100	100	100	100	100	100	100
Data center	0	0	0	20	40	100	100	100
				Scenario LowRes				
River	125	125	125	125	125	125	125	125
Geo (deep)	125	125	125	125	125	125	125	125
Geo (surface)	100	100	100	100	100	100	100	100
Solar	88	88	88	88	88	88	88	88
Wastewater	50	50	50	50	50	50	50	50
Data center	0	0	0	10	20	50	50	50

Source: Own calculations based on Egelkamp et al. (2021), Ritzau et al. (2019), Dunkelberg et al. (2021,2020), Blöcher et al. (2019).

Table 24: Investment costs for large-scale heat pumps.

Heat source	2015	2020	2025	2030	2035	2040	2045	2050
				in M€/GW				
River	1077	987	942	898	868	838	823	808
Geo (deep)	2643	2613	2603	2593	2543	2493	2443	2393
Geo (surface)	2096	2066	2056	2046	1996	1946	1896	1846
Solar	3943	3943	3724	3509	3356	3205	3044	2954
Wastewater	1300	1200	1145	1091	1055	1018	1000	982
Data center	720	660	630	600	580	560	550	540

Source: Own calculations based on European Commission et al. (2017, 54) and Dunkelberg et al. (2020, 125 f.).

8.2.3 Decentral heat pumps

As described in chapter 2.2.1, there are restrictions for deploying decentralized heat pumps in dense urban areas such as Berlin with a high number of unrenovated multi-family houses.

Hirschl et al. (2011, 65) identify the usable potential for ground-source heat pumps after deductions for minimum distances between heat pumps and groundwater protection at 12.4 TWh_{th}. This amount is sufficient to cover the entire decentral heat demand by ground source heat pumps. Assuming 2000 full load hours, this corresponds to a capacity of about 6GW. Egelkamp et al. (2021) suggest a capacity of approximately 2.3 GW for ground-source heat pumps.

The ground-source heat pump potential in this study is estimated by assuming that most one- and two-family houses in Berlin can be equipped with a geothermal heat pump. According to the micro census, in 2019, the number of residential buildings was 329,000, of which 57% were one- and two-family houses. Deducting 20% of the buildings and assuming an average size for a ground source heat pump of 15 kW, results in a lower bound for ground-source heat pump potential of approximately 2.3 GW. This conservative estimate serves as the upper limit in the model.

There are limitations to the power supply for air-source heat pumps on very cold days with high heat demand. For old unrenovated buildings, installing air-source heat pumps is not efficient for such cases because the heat pump sizing is too large for year-round demand. In these cases, a bivalent heat pump with a gas boiler for peak load coverage or a monovalent system with supporting direct electric heating can be efficient.

8.2.4 Biomass

For reasons of sustainability, only the usage of regional biomass potential is considered.[6] The regional biomass potential depends on the chosen radius (cf. Figure 24). However, only about one-third can be used for energy, as there is a conflict of use for the existing biomass potential.

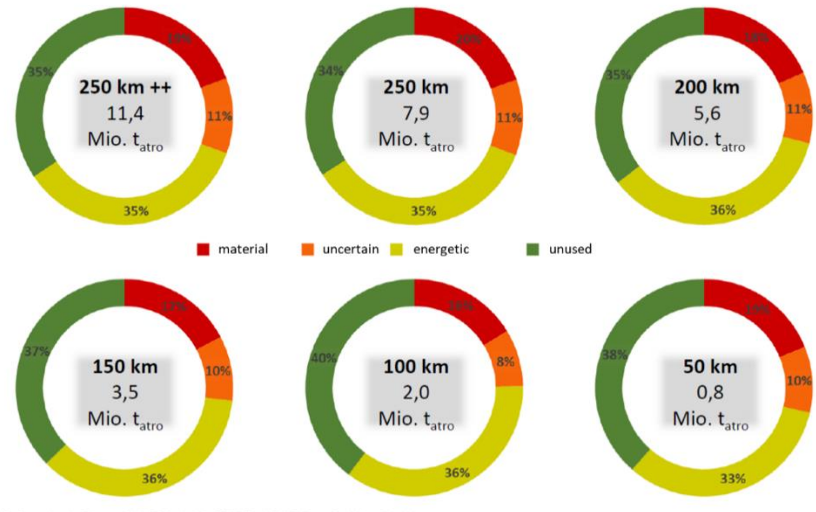

Figure 24: Biomass potential for Berlin.

Source: (Ritzau, Langrock, and Michels 2019, 71).

The values stated in Figure 24 refer to the absolute dry mass (atro). The assumed calorific value for the biomass equals 4 kWh/kg. In the study, a radius of 100 km is assumed, resulting in an energetically usable biomass potential of approximately 10 PJ. The assumption of biomass costs is about 5 mill. €/PJ.

8.2.5 Waste

The waste thermally utilized in the waste incineration plant in Ruhleben amounted to 581,000 t (Ritzau, Langrock, and Michels 2019, 94). In the future, the amount of waste will be reduced in the course of the Closed Substance Cycle Waste Management Act. Egelkamp et al. (2021) assume that the per capita waste volume will be reduced to 50 kg by 2030. At the same time, waste separation is to be improved, which leads to an increase in the calorific value of the waste. In addition to residual waste, Berlin has wood residues that are thermally recycled. Own calculations based on Ritzau et al. (2019, 94) and Egelkamp et al. (2021, 22) suggest that the energy supply by waste and wood residues will decrease from 3.5 PJ in 2020 to 1.8 PJ in 2035. The value is assumed to remain constant between 2035 and

[6] The biomass that accumulates as waste in Berlin is combusted in the waste incineration plant (see chapter **Error! Reference source not found.**)

2050. Total thermal potential for residual waste and waste wood of 100 MW is assumed for both scenarios. No costs and CO_2 emissions for waste incineration are accounted for in the model since the energy is regarded as a byproduct of waste treatment.

8.2.6 Storage

Storage is necessary to balance load and generation. In the heating sector, storage facilities are crucial because renewable heat potentials are predominantly available in the warm summer months, while most heat demand occurs in winter. Therefore, underground seasonal storage is needed to exploit the renewable potentials. Following Pavlov and Olesen (2011), four seasonal storage facilities are considered (see Figure 25).

- Aquifer Thermal Energy Storage (ATES) uses groundwater as heat storage. In Berlin, aquifers are found at depths between 200 and 600 m. The prerequisite for this is a low or no flow velocity of the groundwater.
- Borehole thermal energy storage (BTES): Heat is conducted directly into the earth via boreholes at a depth of approx. 30-200 m, where it is stored seasonally. A fluid serves as heat transfer.
- Water tank storage: reinforced concrete tank buried underground usually with thermal insulation
- Water gravel pit storage: buried storage with water-gravel mixture. The mixture has lower specific heat capacities, and therefore the pit storage is usually larger than water tank storage.

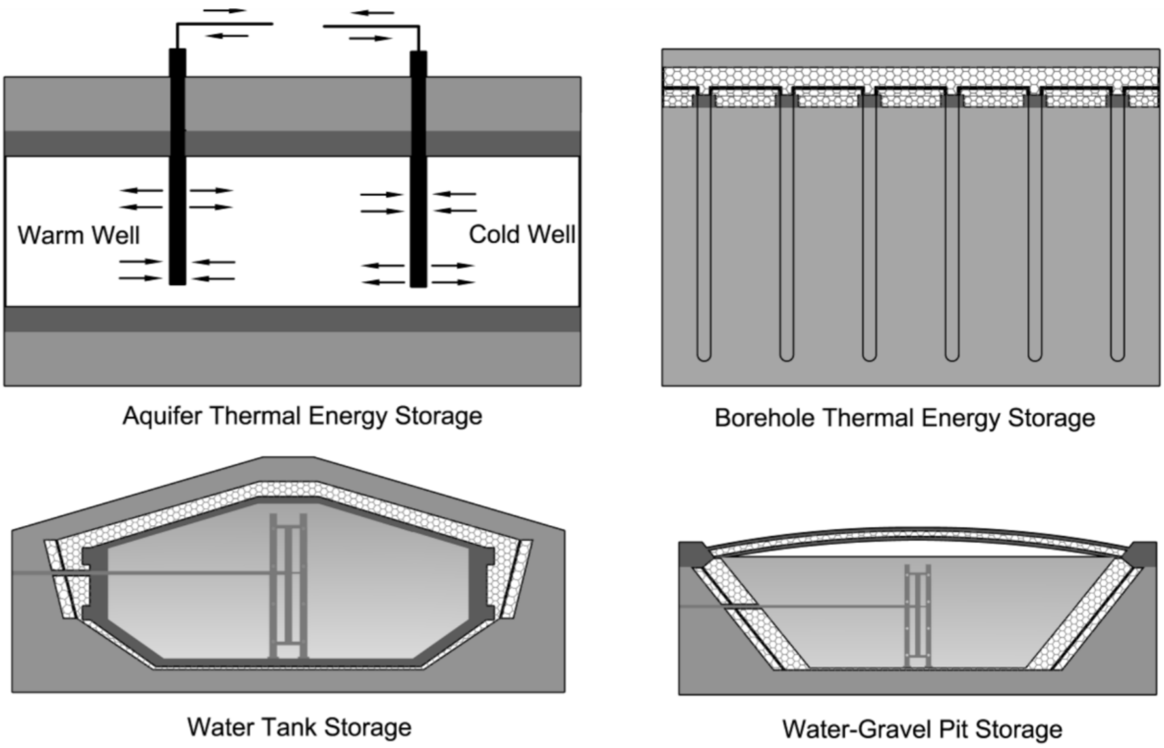

Figure 25: The four types of seasonal underground heat storages.

Source: Pavlov and Olesen (2011, 3).

In principle, all forms of storage can be considered for Berlin. For underground storage, water protection conditions must be met, which limits the potential. This concerns especially the drillings for ATES and BTES. The aquifers in Berlin are considered as heat sources for heat pumps rather than storages in various studies (Dunkelberg et al. 2021; Egelkamp, Wett, and Kallert 2021). Therefore, the heat potentials of aquifers are assigned to heat pumps in combination with geothermal energy in the present model (see chapter 8.2.2.4**Error! Reference source not found.**).

In the model, the pit storage serves as seasonal heat storage. These are inexpensive to produce compared to water tank storage and are suitable with solar thermal systems (Pavlov and Olesen 2011). Figure 26 shows the relationship between size and cost for different types of storage. It is advantageous from a cost and efficiency perspective to build larger heat storage. As the need for storage increases for a decarbonized heating system, the costs for underground storage tanks are therefore assumed to be in the low range.

The largest existing earth basin heat storage facilities have a storage volume of about 200,000 m^3 (Ramboll 2017). The necessary storage facilities for a district heating system the size of Berlin must be many times larger. However, the technology is scalable and therefore subject to relatively low uncertainties. It may be necessary to build the storage facilities significantly deeper to reduce land use in cities and near cities. The greater depth may require additional construction measures to ensure groundwater protection causing the costs to increase. The usual costs of approx. 30 €/ m^3 will then be hard to meet (van Helden et al. 2021, 6). The GigaTes research project investigated the feasibility of larger seasonal storage facilities in the vicinity of cities and identified costs of 60-80 €/m^3 for seasonal underground storage facilities of between 1 and 2 million m^3 (van Helden et al. 2021, 37).[7] The assumed storage capacity of the prototype is about 70 GWh for 1 mill. m^3, the efficiency of the storage is about 90% (see Table 25).

Table 25: Parameter assumptions for seasonal heat storages in 2020.

Storage	Size	Cost	Capacity	Cost/m^3	Cost/GWh	Efficiency
Hybrid Pit Storage	1 mill. m^3	80 mill. €	70GWh	80 €/m^3	1.14 mill €/GWh	90%

Source: Based on van Helden et al. (2021, 37 ff.)

Figure 26: Cost of seasonal storage for central solar heating plants with seasonal storage.

Source: Pavlov and Olesen (2011, 10).

8.3 Assumptions on the final energy demand and fuel availability

8.3.1 Assumptions on the final energy demand in Berlin

8.3.1.1 Residential heat

The demand for residential heat assumed in this study leans on the climate protection scenario for Berlin by Hirschl et al. (2021), which is an update of the feasibility study for climate neutrality that was prepared for Berlin originally in 2014. The study contains forecasts for the final energy demand in Berlin, which provided the basis of the GenesysMod URBAN HEAT study. Crucial for the development of residential

[7] Lower boundary is chosen because it is assumed that less dense populated locations in the vicinity of Berlin are also used. There, low costs of 30 €/m^3 can be achieved.

heat demand is population growth, the development of space demand per person, and the renovation rate and depth.

Hirschl et al. (2021, 110) assume an increase in population from 3.76 mill. inhabitants in 2020 to 3.92 mill. in 2030. The population is then expected to remain constant until 2050. The space demand per person increases slightly from 39.3m^2 in 2020 to 40m^2 in 2050 (Hirschl et al. 2021, 165). In addition to these estimations, the final energy demand for residential heat is influenced by assumptions about future renovation activities. Based on the climate protection scenario by Hirschl et al. (2021), Dunkelberg et al. (2021) project the heat demand in Berlin until 2050. Additionally to the climate protection scenario, Dunkelberg et al. (2021) describe a Business-as-usual (BAU) scenario with meager renovation rates of 0.86% (see Table 26).

While the renovation rates in the BAU scenario remain constant at the current low level, the rate in the climate protection scenario increases significantly to 2.6% in 2030 and 3.5% in 2035. From then on, the renovation rate remains constant until 2050. As a result, the building heat demand in the climate protection scenario can be more than halved by 2050 (see Table 27). This strong development of the renovation rate appears to be highly ambitious against the background of the difficulties encountered so far to increase it from 0.8% to 2.1% as required in the BEK 2030 (see 2.2.2). Even the 2.6% prescribed by the Berlin Senate in the BEK 2030 is difficult to achieve as things stand. However, due to the implementation pressure from rising energy prices and climate targets, the BEK 2030 targets appear to describe a more likely development than the BAU or climate protection scenario of Dunkelberg et al. (2021). Therefore, a medium heat demand scenario is used as the basis for further modeling, which is oriented to the renovation targets of the BEK 2030 and results in a moderate reduction of building heat demand. By 2050, demand can be reduced to 20 TWh (see Table 27). The demand forms the basis of the modeling for both the MedRes and LowRes scenario.

Table 26: Assumed renovation rates in different scenarios and BEK 2030.

Author	Scenario	2020	2025	2030	2035	2040	2045	2050
Berlin Senat	BEK 2030	*1.3%	2.1%	2.6%	2.5%	2.3%	2.2%	2.0%
Dunkelberg et al. (2021)	Climate Protection	0.8%	2%	2.60%	3.50%	3.50%	3.50%	3.50%
Dunkelberg et al. (2021)	BAU	0.8%	0.86%	0.86%	0.86%	0.86%	0.86%	0.86%

*Value as stipulated by the Berlin Energy and Climate Program 2030 (BEK 2030). The actual value equals 0.8%.

Source: Based on Dunkelberg et al. (2021) and BEK 2030 (Senatsverwaltung für Umwelt, Verkehr und Klimaschutz 2018).

Table 27: Finale energy demand for residential heat in GWh.

Study	in GWh	2020	2025	2030	2035	2040	2045	2050
Dunkelberg et al. (2021)	Climate Protection	33,862	31,353	28,843	24,890	20,937	18,626	16,315
Dunkelberg et al. (2021)	BAU	33,850	33,297	32,744	31,017	29,290	27,769	26,248
GENeSYS-MOD URBAN HEAT	MedRes & LowRes	33,850	31,353	30,000	27,000	24,000	22,000	20,000

Source: Based on Dunkelberg et al. (2021) and own estimations.

8.3.1.2 Process heat

For process heat, the development of economic growth is decisive. Dunkelberg et al. (2021) draw up a scenario of the process heat demand until 2050 based on the assumptions of Gerbert et al. (2018) on the future development of economic growth. The present paper adopts the process heat demand of the climate protection path of Dunkelberg et al. (2021). The distinction into low, medium, and high process heat is then carried out at the ratio described in chapter 4.1.

Table 28: Process heat demand for the different heat levels in TWh.

Process heat level	2015	2020	2025	2030	2035	2040	2045	2050
Low (Central)	0.85	0.85	0.84	0.84	0.83	0.82	0.81	0.81
Low (Decentral)	0.85	0.94	1.04	1.13	1.25	1.37	1.55	1.55
Medium	0.70	0.66	0.62	0.59	0.57	0.56	0.58	0.61
High	0.42	0.40	0.38	0.36	0.35	0.34	0.35	0.37
Total	2.83	2.85	2.88	2.91	3.00	3.09	3.30	3.33

Source: Own calculations based on Dunkelberg et al. (2021).

8.3.1.3 District heating

The current district heating network is about 2200 km long. It is assumed that 20 km are added annually, and around 400 new buildings are connected annually (Ritzau, Langrock, and Michels 2019, 6). Therefore, following the development of Dunkelberg et al. (2021), it is assumed that the district heating demand increases until 2030 to 43 PJ from 39 PJ in 2020 and then decreases to 38 PJ by 2050. However, the district heating demand's estimated decrease is lower than Dunkelberg et al. (2021) due to fewer renovation measures in the building sector.

Table 29: Development of Berlin´s district heating demand in MedRes and LowRes scenario (in PJ).

	2015	2020	2025	2030	2035	2040	2045	2050
District heating demand	38.1	38.7	41.5	43.8	43.6	41.5	39.9	38.4

Source: Own calculations.

The Berlin district heating network is currently operated with supply temperatures between 80° and 130°C. For new smaller grids and subgrids, a reduction down to 60°C can be realized. However, this has to be considered on a case-by-case basis. For the present model, a grid temperature of 90°C is assumed. This is in line with the conservative assumptions of the studies by Ritzau et al. (2019) and Egelkamp et al. (2021). The district heating network losses account for approx. 10% of the heat supply (Amt für Statistik Berlin-Brandenburg 2021). By lowering the network temperatures, the transmission losses also decrease. Therefore, it is assumed for the modeling that the losses will fall from 10% in 2020 to 7% in 2050.

Table 30: Development of flow temperatures and heat losses in Berlin´s district heating networks.

	2015	2020	2025	2030	2035	2040	2045	2050
Temperature				in °C				
Max	120	114	109	103	97	91	86	80
Min	80	79	77	76	74	73	71	70
Heat loss (%)	10	10	10	10	9	9	8	7

Source: Own calculations.

8.3.1.4 Electricity

The development of electricity demand for Berlin is based on the climate protection scenario from Hirschl et al. (2021). The electricity demand described there is divided between households, buildings, energy, businesses, and transportation. For the modeling of the present study, only the final energy demand for electricity for businesses and households was considered. The electricity demand of the other sectors is determined endogenously by the model.

Table 31: Electricity demand in the scenario MedRes and LowRes

in PJ	2015	2020	2025	2030	2035	2040	2045	2050
Electricity demand*	40.0	38.3	37.1	35.9	36.2	36.6	37.7	38.9

*The demand does not include electricity consumption of the transportation or energy supply sector as they are calculated by the model endogenously.

Source: Own calculations based on Hirschl et al. (2021).

8.3.2 Import of fuels

As Berlin is not energy self-sufficient, it depends on the import of fuels. As a result of this, the decarbonization pathway is largely determined by the availability of specific energy sources. The assumptions regarding their availability are presented below.

8.3.2.1 Electricity import

Decisive for the Berlin energy supply is the electricity import. The amount of electricity imports for the modeling period is taken from previous model runs of GENeSYS-Mod for the German and European energy system. This considers significant developments such as the German coal phase-out and the end of commercial use of nuclear power in Germany. The model runs consider a 100% renewable energy supply in 2050 and zero emissions in 2050.

The upper limits for electricity imports are displayed in Table 32.

Table 32: Upper limit for electricity imports in PJ.

in PJ	2015	2020	2025	2030	2035	2040	2045	2050
Electricity import	24	24	38	51	54	55	57	48

Source: Own calculations based on previous GENeSYS-MOD calculations.

8.3.2.2 Hydrogen import

Hydrogen only supports the energy transition if produced from surplus renewable electricity. If fossil electricity is used for production, hydrogen is not emission-free. Therefore, an energy transition that renounces fossil and nuclear energy sources should not rely on imported hydrogen produced with electricity from these sources. If these criteria are applied to the production of hydrogen, the availability of hydrogen decreases while the prices increase. The present study assumes that Germany is self-sufficient in hydrogen. This aligns with the BMWi’s (National Ministry for Economic and Energy) targets for Germany to aim for hydrogen self-supply (Bundesregierung 2020). Studies show that hydrogen production in Germany is not more expensive than imported hydrogen (Wietschel et al. 2021, 42). In the case study, assumed prices for hydrogen fall to around 15ct/kWh in 2050. This puts prices at the upper estimate of Merten et al. (2021, 34).