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D6.3 Heating and cooling strategies for pilot cities – Frankfurt

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Legal notice

The Hotmaps project

The EU-funded project Hotmaps aims at designing a toolbox to support public authorities, energy agencies and urban planners in strategic heating and cooling planning on local, regional and national levels, and in line with EU policies.

In addition to guidelines and handbooks on how to carry out strategic heating and cooling (H&C) planning, Hotmaps will provide the first H&C planning software that is

- **User-driven**: developed in close collaboration with 7 European pilot areas
- **Open source**: the developed tool and all related modules will run without requiring any other commercial tool or software. Use of and access to Source Code is subject to Open Source License.
- **EU-28 compatible**: the tool will be applicable for cities in all 28 EU Member States

The consortium behind

Scientific partners

Pilot areas for developing and testing the tool

Bistrita Municipality

Executive Summary

In the course of the Horizon 2020 project Hotmaps, a database and toolbox for strategic heating and cooling planning has been developed. Also, strategic heating (and cooling) planning in 7 pilot areas has been performed using the developed Hotmaps toolbox to demonstrate its usability in the strategic planning process.

This document presents a heating strategy for the city of Frankfurt developed within the Hotmaps project. This strategic planning document has been derived following a commonly defined strategy process and using the Hotmaps toolbox for quantitative scenario analysis. The strategy process hereby included the following steps: an analysis of barriers and drivers, a stakeholder analysis, the mapping of the existing heat demand and available resource potentials, the development of scenarios for heating demand and supply in the city in the year 2050, and the discussion of these steps and their results with relevant persons in the city. The outcome of this process is described in this document.

Frankfurt am Main is a city of around 750 thousand inhabitants located in the middle of Germany. Currently around 6,850 GWh/yr of heat is needed for space heating and hot water generation in the buildings of the city. At the moment this demand is supplied mainly with natural gas followed by district heating.

In the course of the analysis, various scenarios for future heat demand and supply of the city have been developed. Hereby, the costs and potentials for heat savings in buildings for both decentral heat and district heating supply have been investigated. The results of the analyses in these different parts of the heating system have been compiled to consistent scenarios for the entire city.

The quantitative scenario analysis shows that district heating should be considered the main future option for supplying the buildings' heat demand in the city (60-80%). District heating allows for the use of large potentials of heat sources in the city that would be difficult or impossible to be used without district heating. This applies especially to the industrial excess heat, excess heat in wastewater treatment plants, excess heat from data centres and from the river water. The calculations show remarkably higher costs for decentral supply compared to the costs of supply via district heating for all scenarios.

At the same time, buildings renovation is key to reach a fossil free heating system in the city due to restricted renewable and excess heat potentials. A large part of the building stock has to be renovated by 2050. Thus, also an ambitious and detailed renovation roadmap should be laid out. In parallel, a roadmap for district heating expansion should be developed in collaboration with the main district heating utility Mainova.

In the city of Frankfurt, significant amounts of energy are demanded for industrial production. In the future, the entire local biomass, as well as large parts of the municipal waste potentials, will be needed to supply that heat demand. For the supply of heat demand in buildings, only a small share of the municipal waste potential will be available. This will be needed to supply steam to the district heating steam network in the city centre. However, apart from the municipal waste, a broad variety of local energy sources are available to be used for providing space heating and hot water.

The amounts of identified heat sources to be used with heat pumps together with solar thermal energy will be able to supply large parts of the heat demand in the buildings in

Frankfurt in 2050. However, the calculations have shown that remarkable potentials are not available in times of high heat demand due to cold climatic conditions. Therefore, peak load capacities with very low full load hours will be required in the future heating system of Frankfurt.

Further steps on the way to a low carbon heating system for the city of Frankfurt are presented in the last chapter of the document.

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List of terms and abbreviations

ABG Holding	A local housing association
AGFW	German association of district heating companies, located in Frankfurt
ARCADIS	Global design, engineering and management consulting company
BAfA	Federal Office for Economic Affairs and Export Control
BMUB	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety
BMVBS	Federal Ministry of Transport, Building and Urban Affairs
CHP	Combined Heat and Power
CM	Calculation Module (in the Hotmaps toolbox)
COP	Coefficient of Performance
CO2	Carbon Dioxide
DH	District heating
EEG	Energy Economics Group, Institute of Energy Systems and Electrical Drives, TU Wien
Energiereferat	The local energy agency in Frankfurt
Enertile	Software for the computational analysis of the electricity sector and its linked energy services, developed by Fraunhofer ISI
EnEv	Energieeinsparverordnung, a regulation in Germany describing minimum requirements regarding energy use of new and renovated buildings
ESCO	Energy Service Company
EU	European Union
EUCO30	Model for an energy efficiency target of 30% developed by the EU Commission
Fraunhofer ISI	Fraunhofer Institute for Systems and Innovation Research
Fraunhofer IBP	Fraunhofer Institute for Building Physics
GFA	Gross Floor Area
GHG	Greenhouse Gas
GIS	Geographic Information System
GWh	Gigawatt hours
HDD	Heating Degree Day(s)

HMWT	Hessian Ministry of Economics, Energy, Transport and Housing
HMUKLV	Hessian Ministry for the Environment, Climate Protection, Agriculture and Consumer Protection
IBP	Fraunhofer Institute for Building Physics
IEA	International Energy Agency
Ifeu	Institute for Energy and Environmental Research
INEA	EU Innovation and Networks Executive Agency
Infas 360	Data Intelligence company based in Bonn
Invert/EE-Lab	Dynamic bottom-up techno-socio-economic simulation tool that evaluates the effects of different policy packages on the total energy demand, energy carrier mix, CO2 reductions and costs for space heating, cooling, hot water preparation and lighting in buildings. The tool is developed by the Energy Economics Group at TU Wien and e-think
KEG	A local housing association
kWel	Kilowatt electrical output power
KfW	A German state-owned development bank, based in Frankfurt, originally called Kreditanstalt für Wiederaufbau.
LCOH	Levelized costs of heat
Mainova	Largest District heating utility in Frankfurt
MFH	Multi-family houses
MW	Megawatt
MWel	Megawatt electrical output power
MWh	Megawatt hours
MWth	Megawatt heat output power
PH	Passive House
progRESsHEAT	A Horizon 2020 funded project supporting the progress of renewable energies for heating and cooling in the EU on a local level (2015 - 2017)
PRIMES	partial equilibrium modelling system that simulates an energy market equilibrium in the European Union and in each of its Member States, developed by National Technical University of Athens (NTUA)
SET-Nav	EU Horizon 2020 funded project “Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation” (duration from 2016 - 2019)
SNG	Synthetic Natural Gas
TU Wien	Technische Universität Wien

1 Introduction to Frankfurt

Location: Central Europe

Size: 248.31 km^2

Population: municipality (inhabitants): 750 Thousand approximately

Population: metropolitan area (inhabitants): 5,3 Million approximately

Figure 1: Heat demand density map of Frankfurt (Source: own calculations based on (TU Wien, e-think, 2015), (Frankfurt, 2018a), and (Frankfurt, 2018b)). See description in chapter 4.1.1)

Frankfurt am Main is among the most built-up cities in Germany; the population rose to around 750,000 in 2018 and continues growing by 2% every year. In 2017, approximately 23,400 Gigawatt hours (GWh) of final energy were consumed – just under 1% of Germany's final energy consumption. Heating for offices and households made up 31% of it, electricity 29%, transport 22% and the rest was for heat demand from the industrial sector.

Out of this energy, 95% was imported, i.e. generated outside of Frankfurt and, as a rule, outside of the region. As a result, only 5% of the total energy demand was covered by local renewable and excess heat sources.

Since the beginning of 2013, Frankfurt has developed the "Masterplan 100% Climate Protection" (City of Frankfurt and Fraunhofer IBP, 2015) – a vision of how the city can halve his final energy consumption by the year 2050 and meet the remaining demand entirely with renewable energy.

This energy consumption reduction is expected to go hand-in-hand with a 95% reduction of carbon emissions. The process is financially supported by the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB). The study, carried out by the Fraunhofer Institute for Building Physics (IBP)(City of Frankfurt and Fraunhofer IBP, 2015), shows measures and ways of achieving these objectives. It identifies means to reduce the energy consumption and the associated emissions through the development of predominantly local, renewable energy generation and through efficiency improvements.

In the implementation of the climate protection measures within the framework of the master plan, the energy supply, disjoint from future urban or neighbourhood development, often represents an obstacle. By integrating the energy supply in the urban development plans, current and future potentials can be identified and better taken into account when planning the energy supply. Consequently, efficiency measures and energy supply from renewable sources should be included as an integral part in the neighbourhood and urban planning. The Energiereferat is the agency responsible for implementing the climate protection goals of Frankfurt. Therefore, it should have a strategy for decarbonising the heating sector.

The following chart, Figure 2, shows the development of the heating sector for private households and office buildings in Frankfurt between 1990 and 2020. It can be observed that in this time span, both the heat demand in households and offices and the CO2 emissions dropped, by 14% and 22%, whereas the total number of inhabitants and the workforce increased, respectively by 18% and 15%. In Frankfurt, the employment-to-population ratio is 1,05, as there are approximately 715,000 workers vs. 750,000 inhabitants, where notably 400,000 commuters come to the city every day.

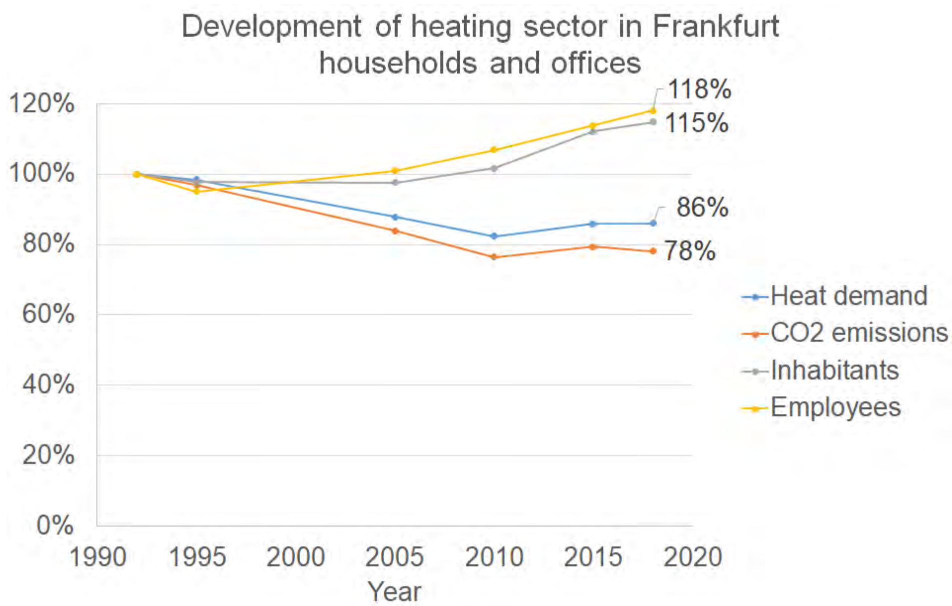


Figure 2: Development of the heating sector and related indicators in Frankfurt between 1990 and 2020 (Source: own calculations based on (ifeu and Energiereferat, 2018))

The chart also shows a decrease in energy demand and CO2 emissions until 2010, then reversed into a slight increase. The CO2 density of the heating sector also decreased in this period of time, mainly thanks to an increase of the share of district heating and a shift from heating oil to natural gas.

These results show somehow the success of the city energy strategy so far. Due to the action of the Energiereferat, nearly all newly developed areas have been connected to the district heating system. In addition, the energy agency managed to convince some investors to build more energy-efficient buildings. This combined with a subsidy programme for the passive house standard in social housing, and the obligation for investors to build at least 30% of social housing, led to an increase in the passive house floor area in Frankfurt.

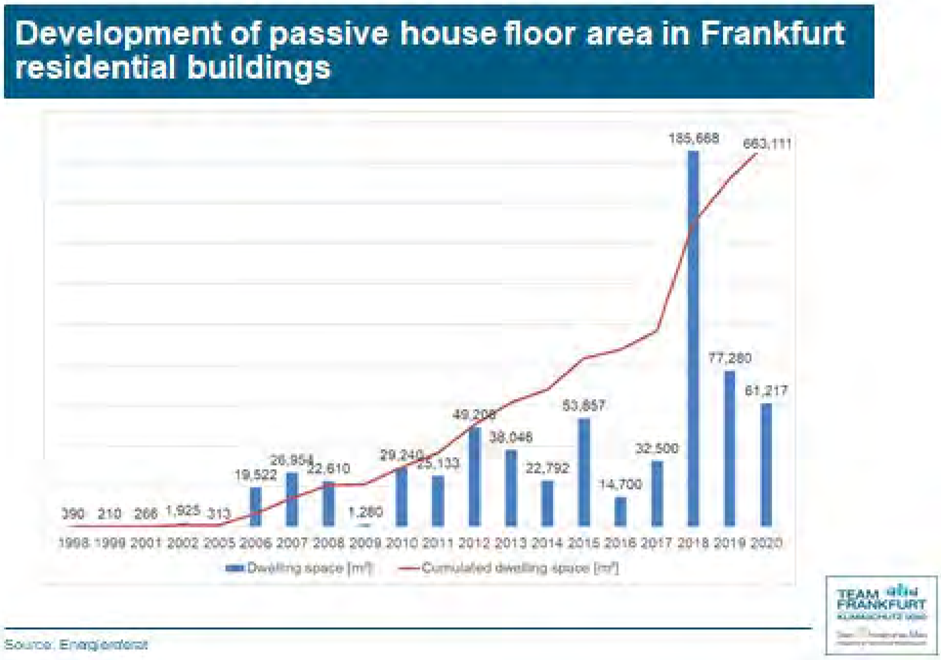


Figure 3: Development of passive house floor area in Frankfurt between 1998 and 2020 (Source: (Energiereferat, 2020a))

2 Objectives and approach

Based on pre-existing analyses carried out by the Energiereferat, namely the Masterplan100% Climate Protection (City of Frankfurt and Fraunhofer IBP, 2015), the following topics have been identified as the key fields to investigate in future strategy development work.

2.1 Themes to address in the strategy development process

- First, a better knowledge and understanding of the heat demand of the buildings in Frankfurt should be achieved. Therefore, the mapping of the buildings heat demand is the basis of the decarbonisation strategy of the heating sector, together with the projection of how it will develop in the future.

- Then, the excess heat potentials, previously investigated in a survey in 2018 (ECO.S and Fraunhofer ISE, 2018), should be associated with the suitable heat demand areas.
- Next, the renewable potentials, which have been calculated in the Masterplan, should be integrated and reviewed in the strategy process.
- After that, the climate strategy of the city of Frankfurt should be considered. In the urban planning of new districts, the city administration is already adopting a net-zero emissions energy strategy, having realized that climate neutrality can only be achieved with ambitious energy and emission standards, much lower than current legal requirements. Local renewable energy and excess heat (e.g. from the sewage system) together could potentially cover more than half of the energy demand. To exploit this potential, the city of Frankfurt, has set up a subsidy programme aimed at real estate investors, which makes investment in so-called "passive house buildings" more favourable. This subsidy programme is connected with the obligation of building 30% of the new buildings for social housing. The rest of the constructions should be built at an energy efficiency standard, 45% more stringent than the legal requirements (called KfW Efficiency House 55 standard). In addition to making efficient housing more attractive for real estate investors, the city aims at signing urban development contracts that specify the energy standard and the type of energy supply.
- As this planning process should be applied on existing areas of the city, the spatial planning department is carrying out so called "integrated urban development concepts" in three districts. The Hotmaps toolbox should also help set up energy concepts for these areas, by identifying the best solution to decarbonize these districts. This means concretely: highlighting what could be the best combination of measures e.g. buildings renovation with a reduction of the heat demand, exploiting the excess heat or renewable energy potential to meet the heating demand, etc. The solution most convenient for the national economy should be the benchmark.
- The scenario assessment is meant to identify the "best" solution to reach net zero carbon emissions by 2050. This implies determining how much the energy demand should be reduced to be able to meet the remaining demand with the limited renewable resources at the overall lowest cost. Solutions may vary for different areas, depending on the locally available excess heat or renewable energy sources, limiting long haul transmission and relative transportation costs.

2.2 Approach

2.2.1 Overall approach for the strategy development

In order to reach the political targets of greenhouse gas emission reduction and energy efficiency at local as well as national and EU level, heating and cooling systems in Frankfurt have to be changed. A strategic analysis is needed to find technically, economically and resource-efficient solutions fulfilling these targets. In the course of the Hotmaps project, a strategy development process for decarbonising the heating system in Frankfurt has been performed, according to the following steps:

1. Description of the city and stakeholder analysis:
    - Definition of local, regional and national targets for GHG emission reduction and energy (see chapter 3.1)

- Description of the existing heating and cooling system in the city (see chapter 4.2)
- Analysis of stakeholders relevant to address when seeking sustainable decisions in heating and cooling transition (see chapter 3.2)
- Analysis of barriers against and drivers towards a transition of the heating and cooling systems in the city (see chapter 5)

2. Mapping of demand, resource potentials and existing plants:
   - Mapping of the status quo of the heating and cooling system in the city including demand and supply points (see chapter 4.1)
   - Analysis and mapping of resource potentials of renewable and excess heat sources in the city potentially usable in the mid to long term (see chapter 4.1)

3. First stakeholder meeting
   - Held on 10th April 2019
   - 9 participants from Mainova, AGFW, HMWT, ebök, e-think and the City of Frankfurt
   - Topics discussed at the meeting: bottom-up vs. top-down heat demand calculation for the city, the Hotmaps database and toolbox and its data sources and available calculation modules, method for scenario calculation in the course of the strategy process, potential scenarios and sensitivities to be calculated

4. Setting up scenarios:
   - Compilation of economic input data for the economic assessment of future heating alternatives (see chapter 4.3)
   - Calculation of various potential alternatives for heating demand and supply from renewable and excess heat sources (see chapter 6.1)
   - Assessment of the calculated alternatives regarding costs and emissions (see chapter 6.1)

5. Second stakeholder meeting
   - Two online meetings have been organised on 31st March and on 18th May 2020
   - 3 persons from Mainova, the main district heating utility, and 5 persons from City of Frankfurt, e-think and TU Wien have participated in the meetings
   - Topics discussed at the meeting: the method, input data and results of the sensitivity analyses in the different parts of the heating demand and supply system in Frankfurt (heat savings, decentral supply, district heating network construction, heat supply to district heating), compilation of scenarios and resulting indicators (costs, emissions, energy) for the entire city of Frankfurt, preliminary conclusions out of the scenario assessment

6. Strategy formulation:
   - Prioritisation of alternatives and development of a roadmap for changes in the heating (and cooling) systems of the city in the next years (see chapter 6.2)

2.2.2 Technical approach to quantitative scenario assessment

To calculate scenarios of potential future heating demand and supply in the city and the relative costs and emissions, mainly modules developed in the Hotmaps project have been used. These calculation modules (CMs) were developed to analyse different parts of the heating and cooling system such as decentral heat supply, district heating distribution costs or district heating supply dispatch. Most CMs developed in the project have been integrated into the online version of the Hotmaps toolbox (Hotmaps, 2020). In the course of this analysis, stand-alone versions of all CMs have been used to allow more flexibility in the use of input parameters and automated calculation of a number of sensitivities. Furthermore, one calculation module has been used that is not part of the Hotmaps project development. This module is part of the **Invert/EE-Lab model** (TU Wien, e-think, 2015)and was used to derive cost curves of heat savings for the city. Also, the development of selected parts of the modelling environment used for the analysis has been performed in the course of two master theses at TU Wien. These were performed by Jeton Hasani and David Schmidinger. The corresponding parts of this document are based on (Hasani, 2020) and (Schmidinger, 2020).

Figure 4 shows the different CMs that were used in the analysis and the information that was created from or fed into the CMs.

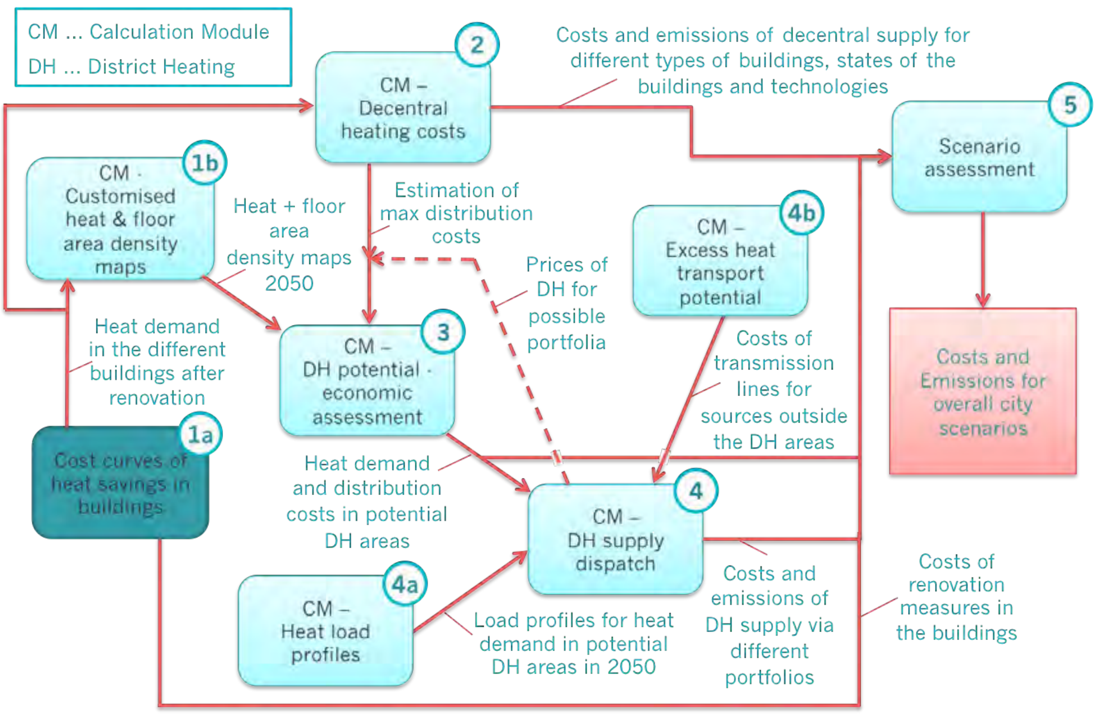


Figure 4: Method for calculating scenarios and sensitivities of heating demand and supply for this strategy process

The first step (1) in the analysis was to generate different scenarios of the state of renovation of the buildings in the city for the year 2050. This was started with setting up a database of the buildings in the city characterising their location, type, age, energy demand for space heating and hot water generation (see chapter 4.1.1 for further description). For all typical buildings in the city, various renovation packages, all reaching different relative savings of heat demand, have then been derived. Based on this data, the cheapest combination of building renovation packages, enabling to reach the 2050 predefined citywide saving targets, has been identified. For this reason, we used the renovation cost curve module of the **Invert/EE-Lab model** (TU Wien, e-think, 2015). Applying these results to the buildings' database of the city leads to different versions of the buildings' database reflecting different saving/renovation scenarios in 2050. A description of the data used for the renovation measures and the methodology applied is presented in chapter 4.3.4 The resulting databases were then fed into the **"CM - Customised heat and floor area density maps"** (Hotmaps Wiki, 2019a) (step 2) to generate heat demand and gross floor area density maps for different heat-saving levels in the city in the year 2050.

These heat demand and gross floor area density maps were further used to analyse the sensitivity of heat distribution costs in potential district heating (DH) networks (step 3). With the **"CM - District heating potential: economic assessment"** (Hotmaps Wiki, 2019b) the costs and location of potential DH networks were calculated for different saving levels, DH market shares, and thresholds for average heat distribution costs. The module hereby derives the size and location of a potential district heating system for a given threshold of average heat distribution costs in coherent areas of the system. The heat demand density map together with the market shares of DH in potential DH areas is the basis for estimating the heat potentially supplied by the DH system. The gross floor area density together with the heat potentially supplied is used to estimate the costs of the grid in the potential DH areas. A detailed description of the CM can be found in the Hotmaps wiki, a description of the data for the investment costs into the network infrastructure is presented in chapter 4.3.3.

With the **"CM - Decentral heating supply"** (Hotmaps Wiki, 2019c) the heat supply costs and related emissions from the application of decentral technologies were calculated for different types of buildings in Frankfurt, the different calculated states of renovation of the buildings and for various decentral technology options in each of these buildings (step 4). These costs have been used to calculate weighted average decentral heat supply costs for the different saving scenarios and a defined mix of decentral supply technologies. Chapter 4.3.1 shows the costs and efficiencies of the decentral technologies applied in the calculations. A description of the methodology for calculating the heat supply costs with the module is presented in the Hotmaps wiki.

The costs of supplying heat into the DH system were calculated with the **"CM - District heating supply dispatch"** (Hotmaps Dispatch Wiki, 2019) (step 5). This CM calculates the dispatch of different technologies installed in a potential DH system in order to reach minimum running costs while covering the heat demand in all hours of the year. For this strategy process, the dispatch and the resulting costs and emissions were calculated for various potential sizes of the DH network and related supply portfolios. A description of the technology data used in the analysis is presented in chapter 4.3.2 and of the modelled DH system sizes and related portfolios in chapter 6.1.2. A detailed description of the overall approach of the dispatch model can be found in the wiki of this model. The applied relation between the temperatures in the DH network, the heat sources and the Coefficient of Performance (COP) of different heat pumps are described in (Gumhalter, 2019).

An important input for the calculation of the DH dispatch is the load profile of the heat demand representing the heat demand of all consumers in the DH system for each hour of the year. These profiles are foreseen to change with decreasing heat demand for space heating due to renovation activities. Load profiles for future DH systems have been calculated with the **"CM - Heat load profiles"** (Hotmaps Wiki, 2018a) based on heat demand profiles of current DH systems according to the results of the different saving scenarios calculated in the first step of the analysis (also step 5).

In the last step (6) of the analysis, selected calculations of the different parts of the heating system in the city have been combined to consistent citywide scenarios of potential heating systems in the city of Frankfurt in the year 2050. For these scenarios, the following indicators have been calculated, split into different components such as technologies and system parts: the yearly costs of the heating system, the final energy demand, the CO2 emissions and the shares of DH and savings. For this step the (Hotmaps Wiki, 2020)has been used. The selection of the scenarios of the different parts of the heating system is presented together with the resulting indicators in chapter 6.1.2. A detailed description of this CM can be found in the Hotmaps wiki (Various Authors, 2018).

3 Target and policy instruments

3.1 Local, regional and national targets and policy instruments

Germany

As a member of the EU, Germany must incorporate EU requirements in the national legislation. However, Germany goes even further in many respects.

In its 2010 energy concept for an environmentally friendly, reliable and affordable energy supply(BMWi, 2010), the Federal Government sets the goal of an environmentally sound, reliable and affordable energy supply and adopts a long-term strategy.

With regard to greenhouse gas emissions, Germany decided to go beyond the EU target and aiming at a reduction of 55 % by 2030, compared to the emissions of the year 1990. Germany, like the European Union, aims to become greenhouse gas neutral by 2050.

In addition to that, Germany abides by the EU climate goals:

- Primary energy demand: minus 30% by 2030 (compared to 2008)
- Renewable energy: 30% of total energy demand by 2030

In order to increase the efficiency of heating systems in buildings and reduce energy consumption in the building sector, the existing instruments have been continuously further developed.

Hesse

In order to formulate short- and medium-term goals, the State of Hesse has adopted the Integrated Climate Protection Plan Hesse 2025 (HMUKLV, 2017). In this document, Hessen reaffirmed its commitment to meeting the European and German targets and even surpassed them in some respects. Unlike the European and national commitments, beyond the quantitative targets, Hessen set also qualitative targets, e.g. on climate adaptation.

The state actively supports various initiatives, such as the Alliance Hessen: the Climate Communities (formerly: 100 municipalities for climate protection), which supports municipalities in the implementation of climate projects and measures.

Concerning greenhouse gas emissions, Hessen has committed to a shorter time span, aiming at a 40% reduction by 2025, and a 90% reduction by 2050.

Frankfurt

The Frankfurt city council took up the issue of climate protection early on. The Frankfurt Building Construction Office opened his Energy Office already in 1983, to have a centralized approach to energy and water issues in urban buildings. This became the Energy Management Department for Urban Buildings in 1990. The same year, the Energiereferat was founded: a municipal energy and climate protection agency reporting directly to the Environmental Department.

The task of the Energiereferat is to design, implement and update the energy and climate protection concept of the City of Frankfurt am Main. In addition, the Energiereferat supports people and companies in Frankfurt in acting responsibly when it comes to climate protection, and it provides expert advice on climate protection projects.

The city of Frankfurt also participates in international climate protection activities, such as co-founding and joining in 1990 the Climate Alliance of European Cities with the Nations of the Amazon. The Alliance aims at establishing international networks to promote indigenous peoples and reduce greenhouse gas emissions in the municipal sector(“Climate Alliance - Municipal action,” n.d.).

This was followed in 2012 by the decision to participate in the federal programme "Master Plan 100 % Climate Protection" that set ambitious goals for the year 2050.

Thanks to constant efforts and further development in the field of climate protection, a 20% reduction in greenhouse gas emissions could already be achieved in Frankfurt between 1990 and 2017. In recent years, Frankfurt has received numerous awards for its climate action. In 2015 it was nominated the "most sustainable city" globally, ahead of London and Copenhagen, by ARCADIS, the leading global planning and consulting company for "natural and built assets" that compiles every year the Sustainable Cities Index to evaluate the sustainable actions of 50 cities in 31 countries worldwide.

As one of currently 41 "Masterplan municipalities" (as of March 2018), the City of Frankfurt a. M. has set the goal of halving its final energy consumption by 2050 compared to 2010, meeting the remaining energy demand with renewable energies, with a total reduction in greenhouse gas emissions of 95 %. The general concept "Master Plan 100 % Climate Protection" for the City of Frankfurt shows how these goals can be achieved (City of Frankfurt and Fraunhofer IBP, 2015). This is based on an increase in efficiency and a related energy saving of 50% by 2050 compared to 2010. The transition to 100% renewable energy should be completed by 2050, half from local and a half from regional sources.

In order to achieve the planned energy savings in the building sector, the City of Frankfurt is setting targets for the energy efficiency of new buildings. According to the municipal resolution "Building blocks for climate protection", these requirements apply to all new municipal buildings or buildings of other investors built on municipal land (“PARLIS - Beschlussausfertigung § 2443,” 2007).

The targeted energy standard is the Passive House (PH) of the Passive House Institute and thus a heating requirement of less than or equal to 15 kWh/m2 (net energy). For proven economic reasons, it is permissible to deviate from this, in which case the heating requirement of 30% less than the heating requirement of the respective EnEV reference building applies.

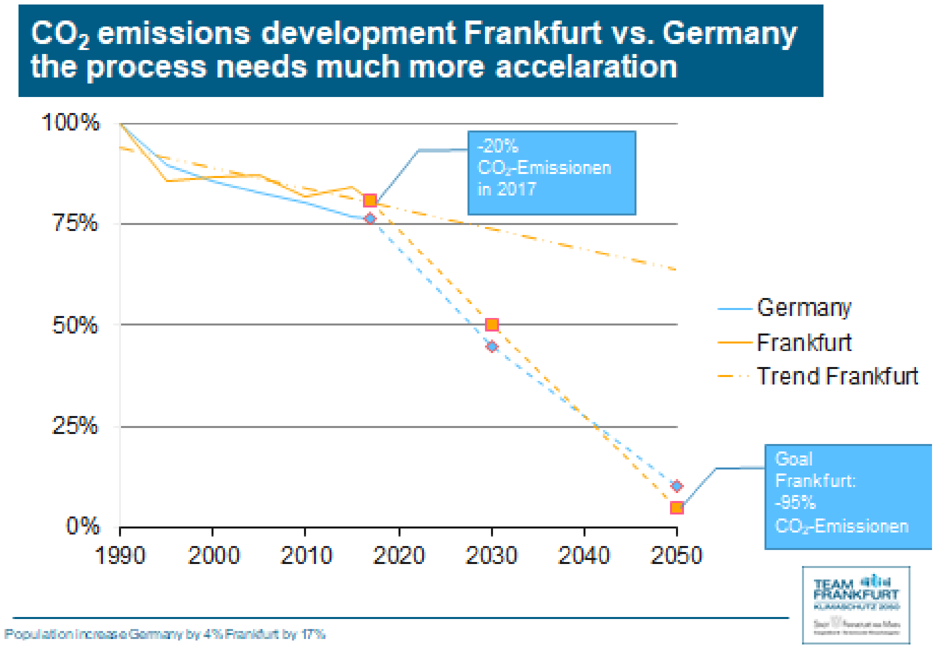


Figure 5: Development of the CO2 emissions in Frankfurt and in Germany (Source: (Energiereferat, 2020b))

But, looking at the actual development, the following graph shows that all efforts of reducing CO2 and increasing the share of renewable energy are much too slow in order to reach the ambitious goals. Thinking of the 1.5-degree goal of Paris - this goal already seems very difficult to reach.

3.2 Stakeholder Analysis

Local actors play a major role in the implementation of measures in an area. A participation concept for dealing with the most important actors in the individual areas should enable them to participate in the planning process. In particular, existing obstacles and implementation strategies are discussed.

In the first stage of the project, a lot of stakeholders have been identified. But the longer the work kept going, the more it became clear that the city-owned utility Mainova is the main stakeholder for the strategy development process. Without Mainova it will not be possible to implement the outcomes of the strategy. For further implementation, many other stakeholders should be involved, see Table 1 and Table 2 below.

Table 1: Stakeholders relevant to the development of the strategy (Source: own assumptions)

Who	Interest in process	Roles in strategy process	Influence on the strategy
Mainova - Largest District heating utility in Frankfurt (80% owned by the city of Frankfurt)	Profit, image, contribution to climate protection goals of the city	Main stakeholder, adopting the strategy	+++
AGFW - German association of district heating companies (located in Frankfurt)	Giving input according to their own strategy for DH in Germany	Thematic input, knowledge	+

Energy service companies	Profit, image	Thematic input, knowledge	0
Engineering companies	Getting exclusive information	Thematic input, knowledge	0
Hessian ministry for environment and Ministry for energy	Getting exclusive information, reducing of CO2, decarbonizing heating sector	Financing further scientific research	+
City Council	Reducing of CO2, decarbonizing energy sector vs. profitability of utility	Setting the political target of CO2 reduction and renewable energies (in advance),	+++
Energiereferat	Reducing CO2 and decarbonising heat sector	Thematic Input, knowledge, distribution of information,	+
e-think - carrying out the calculation and development of the strategy	Scientific interest, finding a way to reduce CO2 and increase the share of renewables in the heating sector	Conducting the work	++

Table 2: Stakeholders important for the implementation of the strategy (Source: own assumptions)

Who	**Interest/benefit in launch**	**Roles in launch process**	**Influence on process**
Mainova - utility (80% owned by the city of Frankfurt)	Profit, image, contribution to climate protection goals of the city	Main stakeholder, carrying out the launch	+++
Energy service companies	Profit, image	Carrying out the launch	++
Hessian ministry for environment and Ministry for energy	Reducing CO2 emissions	Financing the implementation (partly via subsidies)	+
City Council	Reducing of CO2, decarbonizing energy sector vs. profitability of utility	Possible recommendations to Mainova if the result of the strategy document convinces the politicians	+++
Spatial planning department	Getting clear guidance of how to deal with new construction areas, if the local politicians decide to follow the strategy document	Enforcement of the city's interests in negotiations with investors	+++
Energiereferat	Reducing CO2 and decarbonising heat sector	Making promotion for the decarbonising of the heating sector, initiating pilot projects, giving advice to investors, housing association, building owners	++
Investors, housing associations, building owners	Sustainable value retention of the property, better rentability	Contribute to the strategy, carrying out the outcome of the strategy process in terms of building renovation to low energy standard and connection to renewable DH-system or producing own renewable energy supply on site	+++

4 Description of energy demand and supply

4.1 Mapping of demand, resource potentials and existing plants

4.1.1 Energy demand in buildings

The basis for the bottom-up estimation of current heat demand and the development of a heat density map for the city of Frankfurt is a database of the buildings in the city. The database of the building stock is hosted by the City of Frankfurt, Stadtvermessungsamt (Amt 62) and was provided for the work within this project. For this work, the status of the database from March 2017 has been used. It exists in the form of a GIS shape file containing polygons of 280,155 buildings (and building parts) in the city. Various attributes of the buildings such as type of building, building footprint, number of floors or the address are linked to the building shapes. After sorting out polygons not relevant for heat demand due to their type (like garages or storage buildings) and also industrial buildings 125,744 buildings remain for further calculations.

Although the GIS database provides a majority of information to estimate the heat demand in the different buildings, the database was combined with further information in order to derive more valuable estimations. The following data sources have been integrated into the GIS database:

- The GIS database distinguishes 111 different building types. However, all residential buildings are categorised in one type. In the old version of the building database of Frankfurt, which was developed in the form of an Access Database and maintained until 2015, 4 different residential building types were distinguished. Therefore, the information on residential building types from the old Access database was integrated into the GIS database.
- The GIS database, as well as the Access database, does not contain information on the age of the buildings. This Information was integrated into the database from another database bought by the city from Infas 360. This database contains information on the construction periods of the different buildings for 97% of the buildings taken into account in the calculations.

Figure 6, shows the distribution of the gross floor area of buildings with relevant heat demand in the city. Multifamily houses (category 5) are the most important type of buildings in the city followed by private office buildings (category 9). It can be seen that remarkable shares of residential buildings have been constructed until the 1970s. Also, remarkable gross floor area has been constructed since 2011 in the field of office and residential buildings.

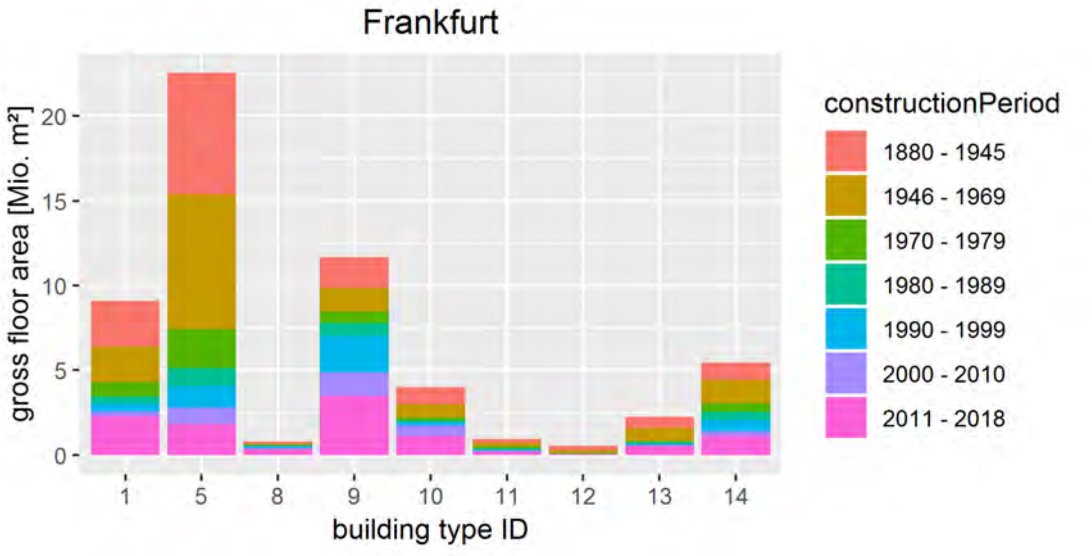


Figure 6: Gross floor area of buildings with relevant heat demand in the municipality of Frankfurt differentiated between building types and construction periods. Please see Table 3 for the reference of building type ID and type of building (Source: own calculations based on (TU Wien, e-think, 2015), (Frankfurt, 2018a), and (Frankfurt, 2018b)).

In a second step statistical energy demand values per gross floor area (GFA) for space heating and hot water generation have been joined with the resulting building dataset. These energy demand (per GFA) values were taken from the database of the Invert/EE-Lab model[1]. The values reflect the energy demand for space heating and hot water preparation of typical types of buildings from different construction periods in Germany and are calibrated for the national building stock and the national energy balance in 2015. Before joining with the dataset of buildings in Frankfurt the demand per GFA values were climate corrected from the average German climate to the climate in Frankfurt. For this the values of the heating degree days (HDD) from the Hotmaps database were used and an elasticity of 60% was assumed. According to this approach, the heat demand in buildings in Frankfurt is around 10% lower compared to the national average.

From the Invert/EE-Lab database we use the values of useful energy demand effective for the analyses. These values for space heating reflect the energy needed to keep the indoor temperature of the buildings at a certain set temperature and take into account various factors of user behaviour like higher indoor set temperatures for better insulated buildings or that parts of the buildings and flats are not heated such as pantries or staircases.

In the following Table 3 the results of the bottom-up calculation of heat demand for space heating and hot water generation are summarised. It shows the large share of residential and especially multi-family buildings on the gross floor area as well as the heat demand in the city: Multi-family buildings account for 32% and single-family buildings for 15% of total heat demand for space heating and hot water generation in the city. Offices are the most relevant

[1] The Invert/EE-Lab model is a bottom-up simulation model of the energy demand for heating and cooling (H/C) in buildings. It calculates the energy demand based on detailed data of the buildings like dimensions, u-values of the buildings' envelope, climatic conditions and user profiles. Future development of the building stock is derived by simulating investment decisions in H/C relevant equipment like insulation, windows or heating and heat distribution systems. The model has been developed and applied in national and international research and consulting projects in Europe for over a decade. More information can be found on https://www.invert.at/.

part of the service sector of the city both in terms of gross floor area and in terms of heat demand. The totals for the residential as well as non-residential sectors match reasonably well with estimations of useful energy demand in the city based on the consumption of gas, oil, district heating and electricity for heating and hot water generation (see chapter 4.2).

Table 3: Number of buildings, gross floor area and bottom-up estimation of the current useful energy demand for space heating and hot water generation in Frankfurt for different building types (Source: own calculations based on (TU Wien, e-think, 2015), (Frankfurt, 2018a), and (Frankfurt, 2018b))

		number of buildings [-]	gross floor area [m²]	useful energy demand [GWh/yr]	
				space heating	hot water
1	Single family houses	59,684	9,270,906	968	110
5	Multi family houses	71,977	22,707,880	1,840	270
8	Public Offices	786	814,865	107	1
9	Private Offices	13,970	13,025,762	1,601	23
10	Wholesale Retail	7,267	4,094,270	441	34
11	Hotels / Restaurants	1,818	1,062,874	117	6
12	Health	825	644,553	98	10
13	Education	4,129	2,569,775	357	5
14	Others	13,325	6,230,081	816	45
	Residential	134,919	32,765,232	2,808	381
	Non-residential	42,120	28,442,181	3,536	125
	Total	177,039	61,207,413	6,344	506

The resulting heat density map of the city is shown in Figure 1 in chapter 1.

4.1.2 Power and CHP plants

District heating (DH) and power production have a long tradition in Frankfurt. Not only for industry-which has always operated their own DH-network but also for the city. The Stadtwerke back in 1894 started the production of heat and electricity. The first customer was a hospital in Sachsenhausen.

Now **Mainova** is operating a district heating system with approx. 294 km of pipelines and a production capacity of 430 MWel and 1055 MWth. The total amount of DH delivered is approx. 2,250 GWh/yr.

Infraserv is producing steam and electricity for the industrial area in the western part of Frankfurt called Industriepark Höchst. The total production capacity is approx. 270 MWel and 1,400 MWth(Wilhelm, 2014). The electrical capacity shall be increased to 478 MW in 2022. Then the company will shut down energy production from coal and replace the plant with a gas-turbine. The amount of steam delivered on three different stages was around 3,750 GWh (Infraserv, 2017).

Besides large-scale CHP-units for district heating more than 500 small engines are operating in the city. Supplying heat for single buildings or smaller areas. The total installed capacity is 45 MWel, the average size of a plant is 88 kWel. The range goes from 1 kWel to 4,800 kWel:

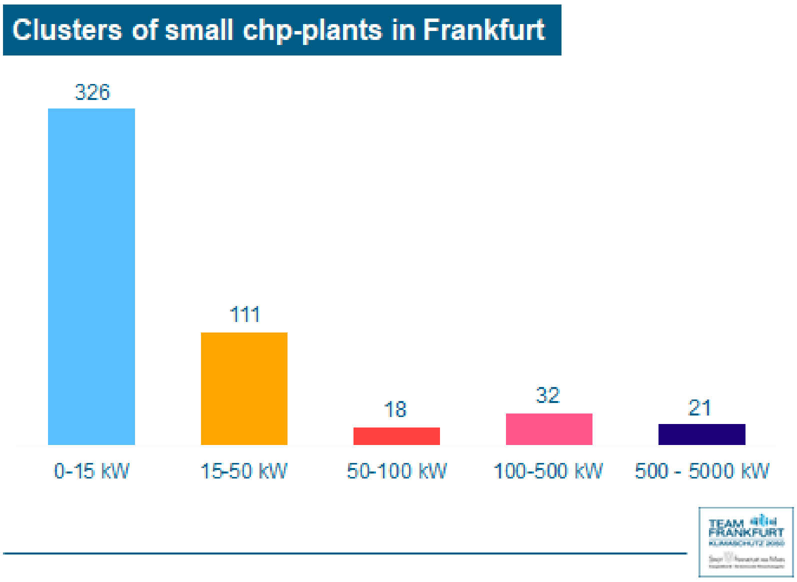


Figure 7: Number of installed Combined Heat and Power (CHP) plants in Frankfurt in 2017 according to the electric power of the plant (Source: (ifeu and Energiereferat, 2018))

Most of these Engines are operated with natural gas, but a number of 16 plants with together 9.5 MWel is running with biogas or biomethane.

An interactive map of climate protection projects in Frankfurt shows where these plants are located. Every location of a CHP-plant can be selected and an individual datasheet with detailed information can be displayed.

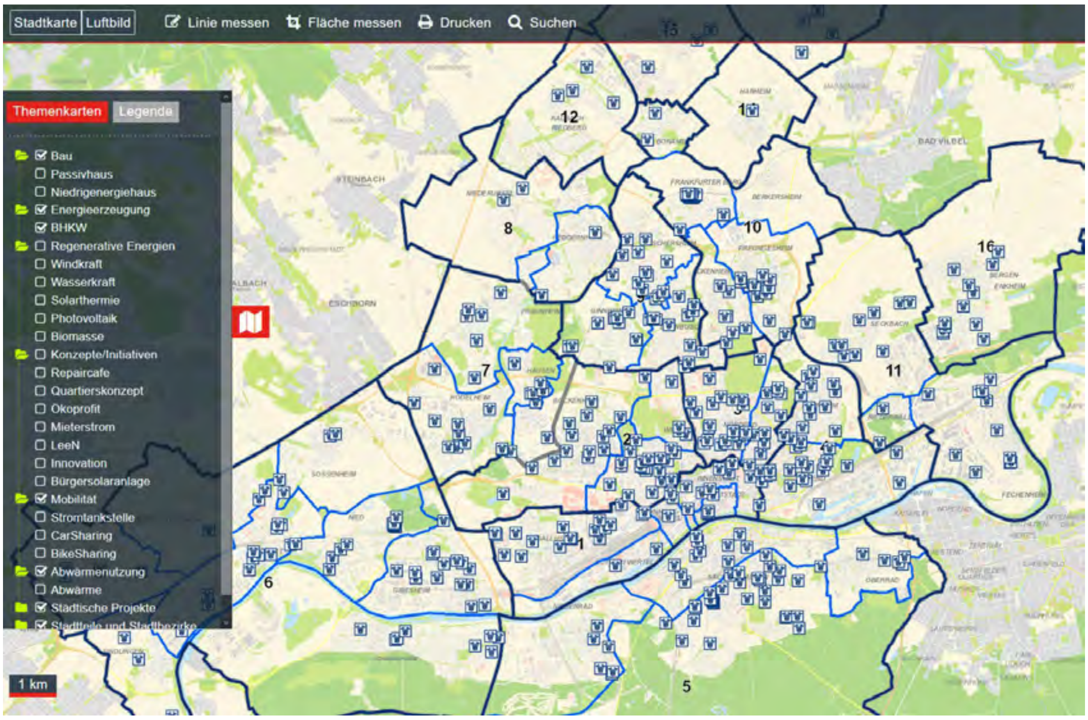


Figure 8: Map of small CHP units (< 5 MWel) in the city of Frankfurt (Source: Klimaschutzstadtplan Frankfurt (Energiereferat, 2020c))

4.1.3 Existing network infrastructure

The local utility Mainova AG is partly owned (>80%) by the city of Frankfurt. Mainova is operating DHin three main areas, which can be seen in the map below. In red the centre of the city is marked. This area is supplied by steam. The other colours show other areas with hot water supply (partly separated from each other):

- District heating grid: 294 km
- Total capacity of power plants: 1,055 MWth /426 MWel
- Customers: 21,000
- Heat supply: 2,250 GWh
- Cold supply: 130 GWh (airport)

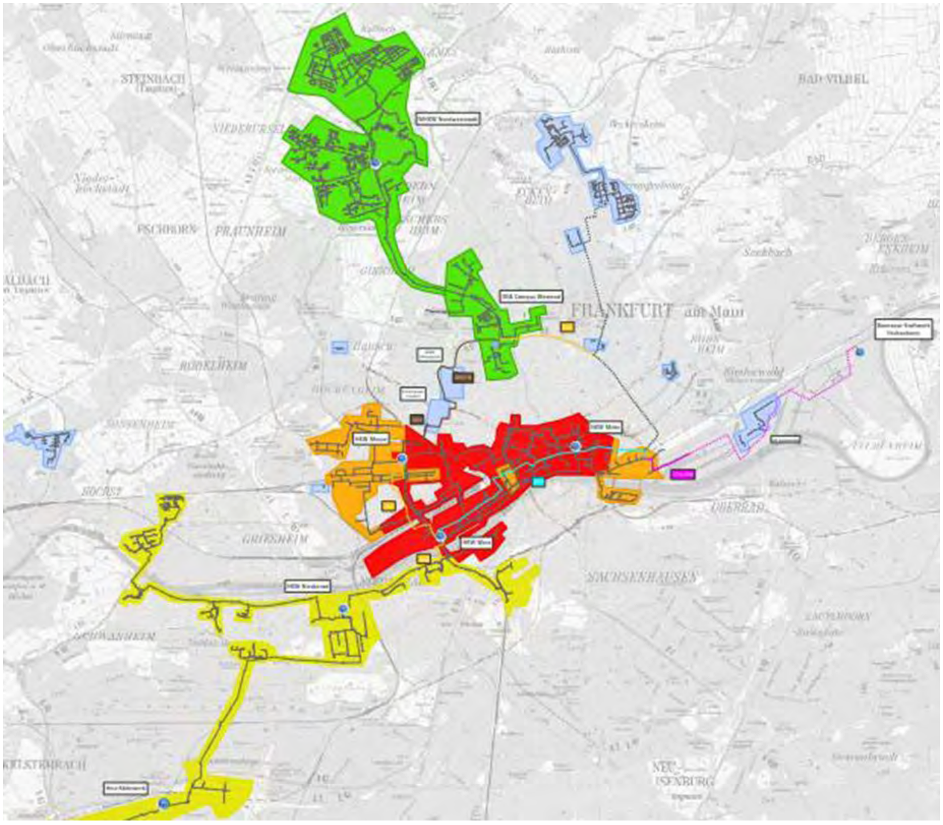


Figure 9: Existing district heating areas in the city of Frankfurt in the year 2017 (Source: (Mainova AG, 2020))

4.1.4 Local renewable energy resources

A low-carbon heating and cooling system is based on the use of renewable resources, excess heat sources as well as the incineration of municipal waste. For this analysis existing studies on the available potentials of these resources for the city and region of Frankfurt have been reviewed. They form the basis for the definition of the technology combinations for decentral and district heating supply in the calculated scenarios. In the following, these resource potentials and their sources are described.

An important literature source regarding available resource potentials in Frankfurt and surroundings is the analyses in the course of the Masterplan 100 (City of Frankfurt and Fraunhofer IBP, 2015). Within this strategy, the potentials of municipal waste, solid and gaseous biomass, solar thermal energy, photovoltaic, hydropower, wind and near-surface geothermal energy have been analysed for the city as well as for the region and the entire federal state of Hesse. These potentials have been used in the analyses of the Masterplan 100 to calculate scenarios for the entire energy demand and supply of the city of Frankfurt. This included the heat, the electricity and the mobility demand and supply. In contrast, this strategy focuses on the heat demand and supply of the buildings in the city of Frankfurt. Therefore, only a part of the identified potentials within the Masterplan has been assumed to be available for supplying the heat demand in the buildings.

The available potentials of municipal waste, solid and gaseous biomass identified in the Masterplan sum up to 3,600 GWh/yr. In order to supply the estimated heat demand in industry in 2050 around 3,000 GWh/yr of these fuels will be needed. Therefore, approximately 600 GWh/yr of municipal waste might be available for feeding into a potential district heating system. In the Masterplan a potential of solar thermal energy of around 1,200 GWh/yr is estimated. Due to the high uncertainty of these numbers in the context of the competition between solar thermal and photovoltaic collectors a maximum potential of 500 GWh/yr is assumed for this analysis.

The other important literature source for the estimation of the resource potentials in Frankfurt is a study on the available excess heat potentials in the city. (ECO.S and Fraunhofer ISE, 2018) analysed the potentials of excess heat in the wastewater treatment plants, in different industrial parks, in the different data centres spread around the city and in the river water. The following map shows the location of the excess heat potentials from industry, wastewater, wastewater treatment and data centres matched with new development areas in Frankfurt.

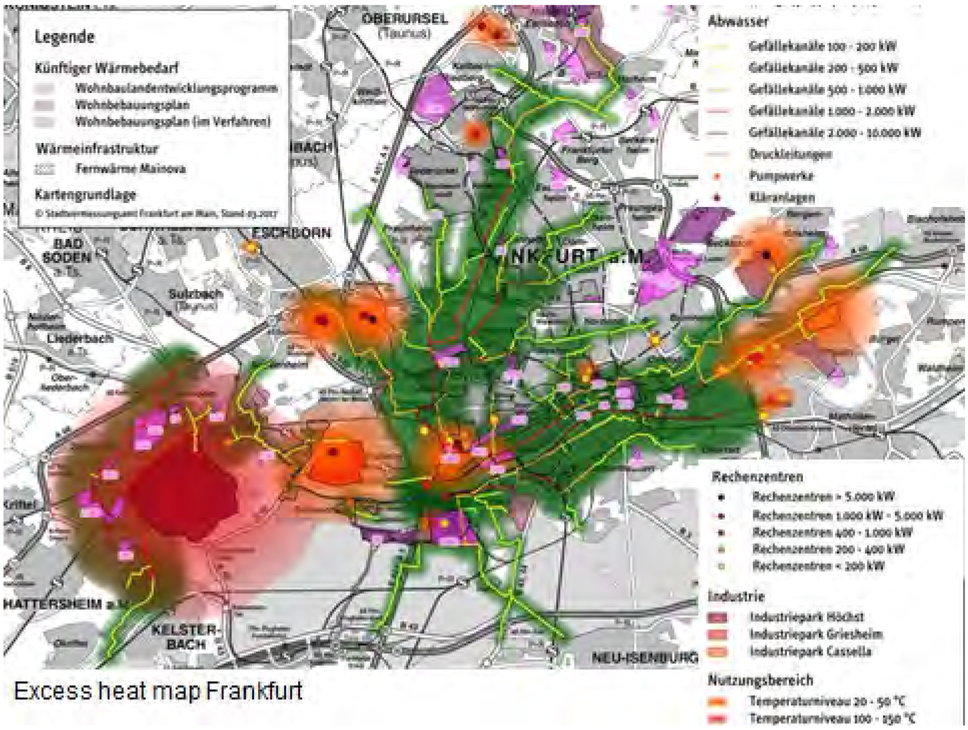


Figure 10: Map of the identified sources of excess heat in the city of Frankfurt (Source: (ECO.S and Fraunhofer ISE, 2018))

(ECO.S and Fraunhofer ISE, 2018) identified the maximum power and the indications of the temperature ranges and variations over time at which the excess heat is available. The data on the available maximum power has been directly used in the analyses. For the industrial parks and for the data centres average temperatures stable over the year have been defined. For the wastewater, the indications of the temperature variations in the study have been used to set up an hourly temperature profile. For the river water, a measured hourly temperature profile over the year was available for a station in the Nidda near to Frankfurt at (GDB, 2020). The following Table 4 shows the estimated available resources that were used in further analyses.

In the Table 4, the maximum theoretical energy potentials for the different resources are stated. These are calculated using the maximum power together with the theoretical availability over the year. In the analyses with the calculation module **"CM - District heating supply dispatch"** (Hotmaps Dispatch Wiki, 2019), the practical availability of the different resources is taken into account. This includes the matching of demand and supply in each hour of the year with the goal of minimising the total system costs (see chapter 6.1.2.4 for the results of the dispatch calculations). In the calculation of heat pumps using river water as a heat source, this also includes the shutdown of the heat pumps in case that a defined minimum threshold temperature is not met. The modelling, therefore, yields the practical availability and maximum energy potentials of the different resources.

For the scenario calculations, we selected different technology combinations for decentral and district heating supply. A description of these technology combinations is given in chapter 6.1.

Table 4: Overview of potentials for renewable energy, municipal waste and excess heat used in the analyses (Source: own calculation)

	Temperature [°C]	Max. Power [MW]	Availability [h/yr]	Max. Energy [GWh/yr]
Excess heat				
Wastewater	18	100	Temperature profile	876
Industrial park Höchst	30 – 150	22	8,760	193
Industrial park Griesheim	12 – 130	6	8,760	36
Industrial park Cassella	15 – 30	11	8,760	96
Data centres	30 – 40	80	8,760	701
River water	5 - 20	260	Temperature profile	2,278
Renewables				
Solar thermal			Radiation profile	500
Near-surface geothermal			8,760	270
Municipal waste			8,760	600

4.2 Description of existing heating and cooling

Heat demand

The fuel mix for the heat supply for the city has changed in the last 30 years. Industry in Frankfurt has a long tradition in producing own energy for process heating and electricity. Therefore, district heating (DH) always dominated the fuel mix. But also, in this sector, the share has increased by 10%. In the office sector, there is now also a dominance of DH in the fuel mix for heat supply. This is because of a replacement of heating oil and natural gas (+20%). Only households rely on natural gas - but according to city policies, a lot of new housing areas could be connected to DH. Thus, the share of DH increased from 5 to 12%.

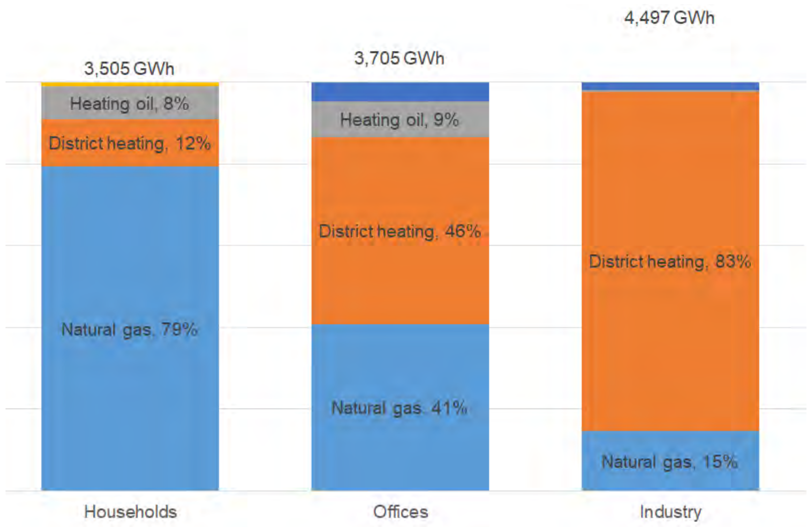


Figure 11: Shares of different energy carriers in the final energy demand for heating in the different sectors in the city of Frankfurt in 2017 (Source: (ifeu and Energiereferat, 2018))

The generation of the district heating is mainly done by two companies: Mainova for offices and households and Infraserv for the industrial sector.

There are different temperature levels for the systems. In the centre of the city, Mainova is operating a steam-based supply system, the rest of the DH from Mainova is based on hot water. Industry supplies steam on two different temperatures and pressures. The CO2 footprints of the different systems have been calculated by ifeu (ifeu and Energiereferat, 2018). The following Figure 12 shows the result of the calculation for the year 2017.

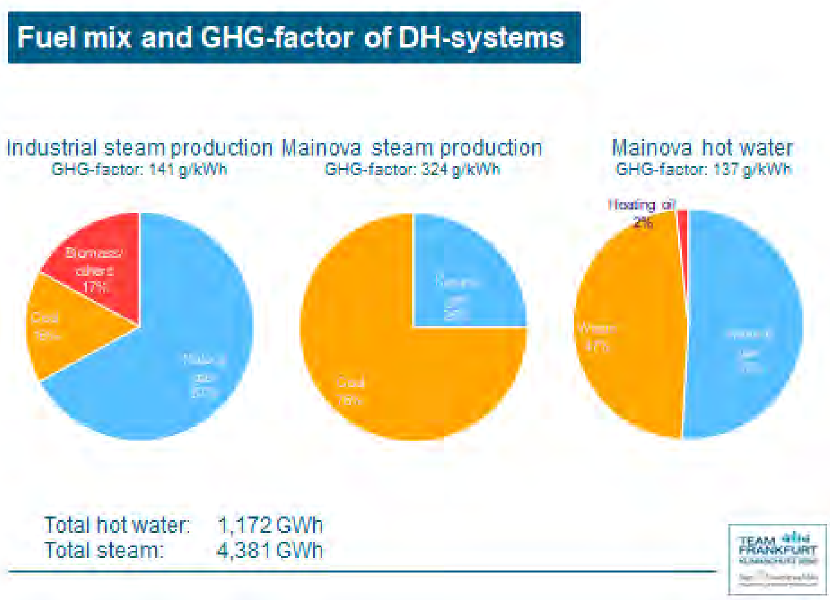


Figure 12: Share of the fuel input for the generation of district heat in the city of Frankfurt and the related Greenhouse Gas (GHG) emission factors (Source: (Energiereferat, 2020b))

Figure 13 shows the use of renewable energy and excess heat in the generation of heat in the city of Frankfurt in the year 2017. It shows that waste currently has a large share of the “renewable” generation both in industry as well as in other parts of the city. Other renewable energies still play a minor role.

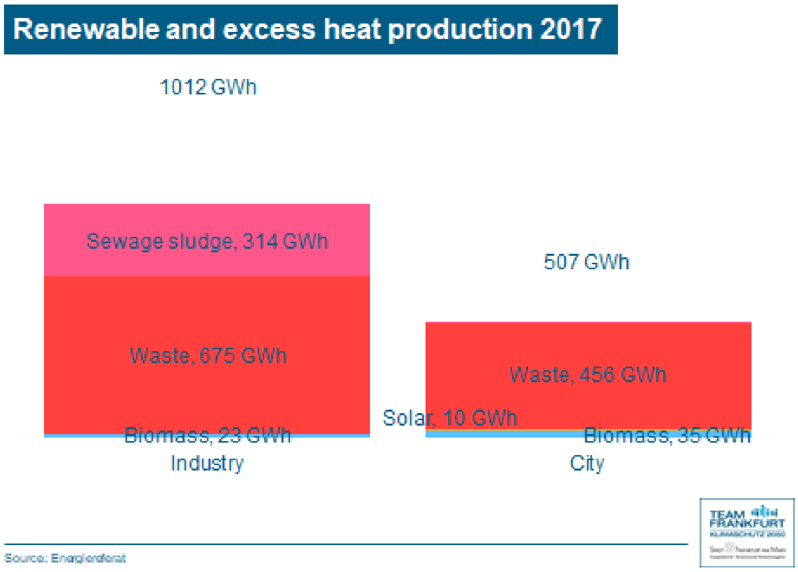


Figure 13: Generation of renewable heat in Frankfurt in the year 2017 (Source: (Energiereferat, 2020b))

Cooling demand

Only a small amount of the cooling demand of the city is metered. Besides the airport, no district cooling system is in operation. The demand of the airport was 130 GWh of cold in 2017. In addition to this, no concrete figures can be given. Just estimations are available.

As an average Trade, commercial and service operations use around 8 % of the electrical energy for cooling (ambient and process cooling) (City of Frankfurt and Fraunhofer IBP, 2015). In addition to that, the cooling demand for data centres and server farms, located in Frankfurt have to be taken into account. Industrial cooling demand is not considered:

Electricity demand of office sector in Frankfurt 2017:

2,978 GWh - electricity demand of airport (585 GWh) - electricity demand data centres (1,087 GWh) = 1,306 GWh

With the figures above another electricity demand for cooling would be 104 GWh.

A very relevant link between the heating and the cooling systems in Frankfurt can be the use of the excess heat of cooling data centres in the city. The potentials for excess heat from data centres are taken into account in the scenario calculations shown in chapter 6.1.

4.3 Data for economic calculation

The economic calculations for this heating strategy reflect socio-economic criteria: the depreciation time was set to the lifetime of the technologies and an interest rate of 3% was used. This interest rate includes inflation on the one hand and also a supplement for the investment risk on the other hand.

In the following, we describe the relevant data of costs and prices related to the heating system, which are used in the calculation of the scenarios presented in chapter 6.

4.3.1 Data for decentral heat supply technologies

In order to calculate the costs of supplying space heating and hot water in the buildings via decentral supply technologies, the following data are used: investment costs as a function of the device size (larger devices usually have lower costs per power), fixed operation and maintenance (O&M) costs, the thermal efficiency and the lifetime of the devices and the price of the energy carrier used by the device. The following Table 5 shows these data for the different technologies taken into account in the analysis except for the energy carrier prices. Those are described in chapter 4.3.5.

Table 5: Investment and O&M costs, thermal efficiency and lifetime of decentral heat supply technologies applied in the scenario calculations (Source: Invert/EE-Lab database for Germany (TU Wien, e-think, 2015))

	power [kW_{th}]		invest [EUR/kW_{th}]		O&M fix	thermal	LD [yr]
	from	to	from	to	[EUR/kW_{th}*yr]	efficiency [-]	
Oil boiler	10	200	460.7	186.0	9.9	0.976	20
Natural gas	10	200	290.5	117.3	6.2	0.976	20
Biomass_Automatic	10	200	2055.3	291.6	17.4	0.93	20
Biomass_Manual	10	200	919.8	336.3	13.8	0.93	20
Wood stove	10	200	919.8	336.3	13.8	0.93	20
HP Air-to-Air	10	200	419.7	227.6	21.9	3.41	12
HP Air-to-Water	10	200	445.9	278.5	21.9	3.41	18
HP Brine-to-Water	10	200	2065.7	1430.4	16.5	4.59	20
Solar thermal	3	200	1027.7	653.0	11.3	1	30
Electric heater	10	200	51.9	51.9	1.0	1	30

4.3.2 Data for district heating supply and storage technologies

In Frankfurt currently two types of district heating systems exist: a steam network in the centre of the city and various hot water networks in other parts of the city. In the modelling also these two different types of systems are distinguished due to the different technologies that can be used to supply heat into both types of systems. The following Table 6 and Table 7show the costs, efficiencies and lifetimes of district heating supply and storage technologies applied in the scenario calculations with the **"CM - District heating supply dispatch"** (Hotmaps Dispatch Wiki, 2019), Table 6 shows the data of the technologies modelled in potential hot water networks, Table 7 shows the data of the technologies modelled in a potential future steam network. The data are based on experiences in past projects performed by TU Wien and e-think.

Table 6: Technology data used for the calculations of the hot water district heating network - Investment and Operation and Maintenance (O&M) costs, thermal efficiency and lifetime of supply and storage technologies (Source: own estimations based on experiences in various projects)

	thermal efficiency	investment costs [EUR/kW$_{th}$]	OPEX fix [EUR/kWyr]	OPEX var [EUR/kWh]	Coldstart Costs [EUR/Start]	Lifetime [yr]	Minimum Output Power Factor [0-1]
HP – River Water	0.2 - 4.6	580	34	0	1,000	20	0.05
HP – Waste water	2.8 - 4.2	440	34	0	1,000	20	0.05
HP – EH Servers	2.8 - 3.8	510	34	0	1,000	20	0.05
HP – Industrial HT EH	4.4 - 5.4	750	34	0	1,000	20	0.05
Solar Thermal	1	1,448	0.005	0	1,000	20	0.05
HP – Industrial LT EH	3.2 - 4.2	750	34	0	1,000	20	0.05
Natural Gas Boiler	0.95	60	4	0	1,000	20	0.05
HP – near-surface Geothermal	2.2 - 3.2	750	34	0	1,000	20	0.05

	storage capacity [MWh]	hourly stoarge losses [-]	maximum unloading power [MW]	maximum loading power [MW]	un-/loading efficiency	investment costs [EUR/MWh]	OPEX fix [EUR/MWh]	lifetime [yr]
weekly storage	2,500	0.001	50	50	0.97	2,500	0	25
seasonal storage	30,750	0.001	50	50	0.97	2,500	0	25

HP ...... Heat Pump
HT ...... High Temperature
LT ...... Low Temperature
EH ...... Excess Heat

Table 7: Technology data used for the calculations of the steam district heating network - Investment and Operation and Maintenance (O&M) costs, thermal and electrical efficiency and lifetime of supply technologies (Source: own estimations based on experiences in various projects)

	thermal efficiency [-]	electrical efficiency [-]	invest costs [EUR/kW$_{th}$]	OPEX fix [EUR/kW$_{th}$yr]	coldstart costs [EUR/Start]	Life-time [yr]	must run [0-1]	minimum output power factor [0-1]
Waste incineration plant	0.83	0	750	54	1,000	20	0.7	0.05
Natural Gas Boiler	0.95	0	60	4	1,000	20	0	0.05
Waste incineration power plant	0.6	0.2	3,389	102	1,000	30	0.7	0.05
SNG Boiler	0.95	0	60	4	1,000	20	0	0.05

SNG ...... Synthetic Natural Gas

4.3.3 Costs of district heating network construction

Besides the costs for the supply of heat to the district heating grid, the costs for the distribution of heat via the grid have to be calculated for determining the overall costs of heat supply via district heating. The costs for the heat distribution mainly consist of the investment costs for the network infrastructure. For calculating the investment costs in the network the Hotmaps **"CM - District heating potential: economic assessment"** (Hotmaps Wiki, 2019b) builds on a concept developed by (Persson and Werner, 2011) as well as (Persson et al., 2019). The concept is based on the following relations: 1) a relation of the effective width with the plot ratio, 2) a relation between the effective width, the distributed heat demand and the average pipe diameter, and 3) a relation between the average pipe diameter and the overall investment costs in the network construction. These relations have been derived based on the analysis of a number of existing district heating projects around Europe. A detailed description of the CM for assessing the heat distribution costs and how these relations are used in the module is given in (Fallahnejad et al., 2018).

For the analyses in Frankfurt the relations 1 and 2 are used as given in (Persson and Werner, 2011) as well as (Persson et al., 2019). For the relation between the average pipe diameter and the overall investment costs in the network construction experiences from the Germany and Switzerland as well as from Mainova have been used in order to adapt the data derived by (Persson et al., 2019).

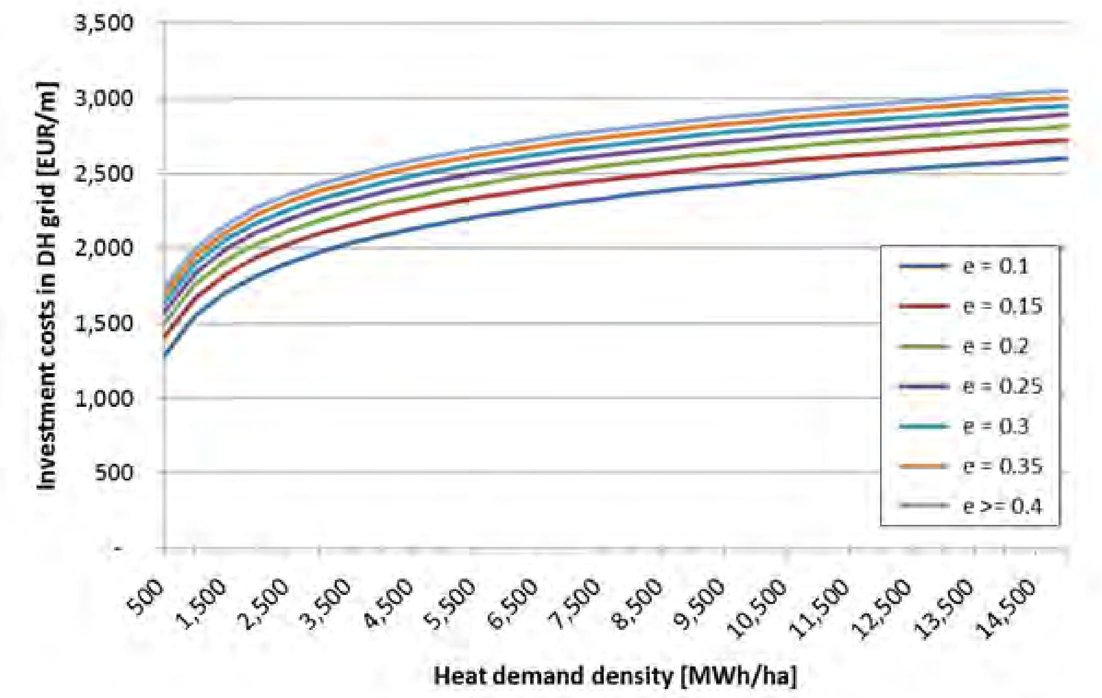


Figure 14: Investment costs in network construction per meter of trench length (flow and return pipes) for different plot ratios e in relation to the heat demand density to be supplied (Source: own calculation based on (Persson et al., 2019))

Figure 14 shows the resulting investment costs per meter of trench length (flow and return pipes) for the range of heat demand density relevant in Frankfurt and for different plot ratios e. Plot ratio hereby is defined as the fraction between building gross floor area (GFA) and corresponding land area (LA) in a defined raster element, both measured in [m²]. In the calculations for this strategy, a raster element is defined as a land area of 100 x 100 m.

4.3.4 Costs of renovation measures in buildings

The costs and effects of applying renovation measures in the existing building stock in the city are calculated using the Invert/EE-Lab model. For each typical building currently existing in the city (see chapter 4.1.1 for a description of the current building stock) a set of 9 renovation packages is developed. Each renovation package hereby leads to different relative savings and consists of a combination of the following single measures: insulation of roofs, insulation of exterior walls, insulation of basements and change of windows. While for reaching ambitious savings measures on each part of the building surface are required, packages for reaching less ambitious savings only consist of selected measures. The compilation of the packages is done by identifying the combination of single measures with the lowest investment costs for reaching a certain saving target for a building.

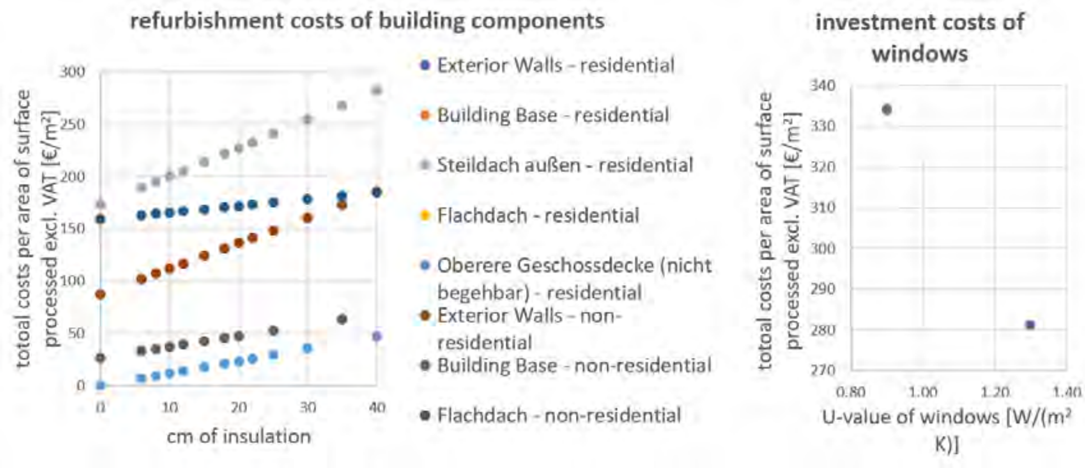


Figure 15: Investment costs for renovating different parts of the building surface depending on the thickness of insulating and u-value of windows respectively (Source: own calculations based on (BMVBS, 2012))

Figure 15 shows the investment costs for renovation measures on the different parts of the building surface depending on the thickness of insulation and the u-value of the windows, respectively. The basis of the values is a detailed analysis of past renovation projects in Germany (BMVBS, 2012). The data sample of the German study was high enough to derive cost functions for the different measures showing the correlation between the ambition of the measures and the related costs.

A more detailed description of the approach of compiling the renovation packages can be found in the article “The costs and potentials for heat savings in buildings: refurbishment costs and heat saving cost curves for 6 countries in Europe” (Hummel et al., 2020).

The costs and effects on the heat demand of all different renovation packages in all different typical buildings are used for the identification of least-cost combinations of renovation packages in the buildings of the city for reaching certain predefined saving targets. Hereby, the additional costs are taken into account, which is the difference between the costs of the renovation measure and the costs of only maintaining the selected part of the building surface. The results of this calculation are presented in chapter 6.1.2.

4.3.5 Prices of energy carriers and CO2 emission allowances

In order to calculate the cost-effectiveness of different alternatives for heating supply and demand reduction, the prices of energy carriers play an important role. For the calculations in the course of this strategy process, we use price data from the Horizon 2020 SET-Nav (SET-Nav, 2020). These data form also the default data on energy carrier prices of the Hotmaps database (Hotmaps Wiki, 2018b).

In the project SET-Nav, scenarios of the entire European energy systems for the years 2030 and 2050 have been developed, which are in line with the long-term European climate targets. This included modelling of the heating and electricity systems in Europe as well as the transport grid for heat and electricity.

Table 8: Overview of the four different price scenarios (Source: SET-Nav project (Resch et al., 2019))

Scenario name	description
Directed vision	EU/state directed shared vision strong EU policy framework
National champions	utilities & incumbents regulatory capture low transition costs
Diversification	heterogeneous actors coordination (beyond markets) digitalization (diverse heterogeneous actors) regulatory change disrupt incumbents
Localization	local resources resistance to big infrastructure developments experimentation & diversity (many niches) digital winners-take-all

While prices for fossil energy carriers were taken from the IEA World Energy Outlook 2016 (the IEA 450 ppm scenario)(IEA, 2016), the hourly prices for electricity were derived with an electricity market model, Enertile (Fraunhofer ISI, 2020) for 4 different settings regarding political and regulatory framework conditions. The price scenarios were calculated using a cap for the carbon emissions from electricity and district heating generation based on the PRIMES EUCO30 scenario from the European Commission 2016 (734 Mt in 2030, 146 Mt in 2040 and 60 Mt in 2050)[2]. Table 9 gives a general overview of the four different price scenarios.

Table 9: Average yearly retail prices for end consumers of relevant energy carriers in the year 2050 in Germany, including taxes, excl. VAT (Source: SET-Nav project, (SET-Nav, 2019))

Energy Carrier	Retail price [EUR/MWh]
Electricity	321.0
Biomass solid	38.5
Natural gas	65.0

The following Figure 16 Figure 17 show the average yearly retail prices for electricity, solid biomass and natural gas for residential and commercial end consumers as well as the hourly

[2] A detailed description of the scenarios can be found in (Resch et al., 2019)

electricity wholesale prices both for the year 2050. The electricity wholesale market prices do not include charges for the electricity grid. Therefore, in the calculations, we add 40 EUR/MWh of grid charge on top of the prices.

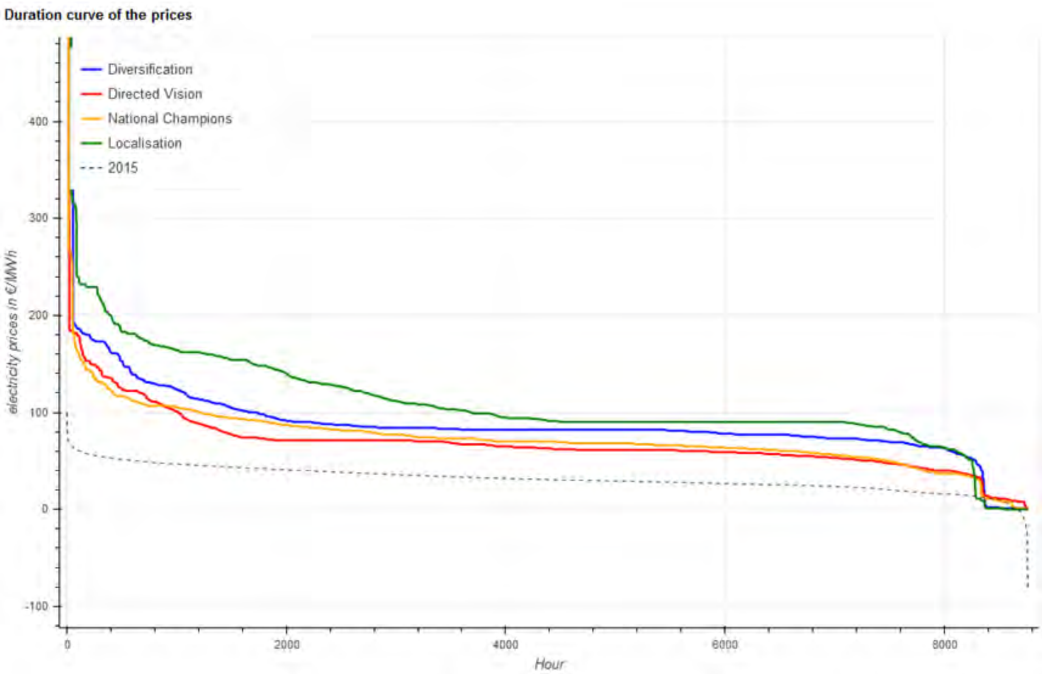


Figure 16: Duration curve of wholesale electricity prices for 4 scenarios for 2050 and historic 2015 prices in 2015 for Germany used in the scenario calculations (Source: Enertile (Fraunhofer ISI, 2020), SET-Nav project (Resch et al., 2019))

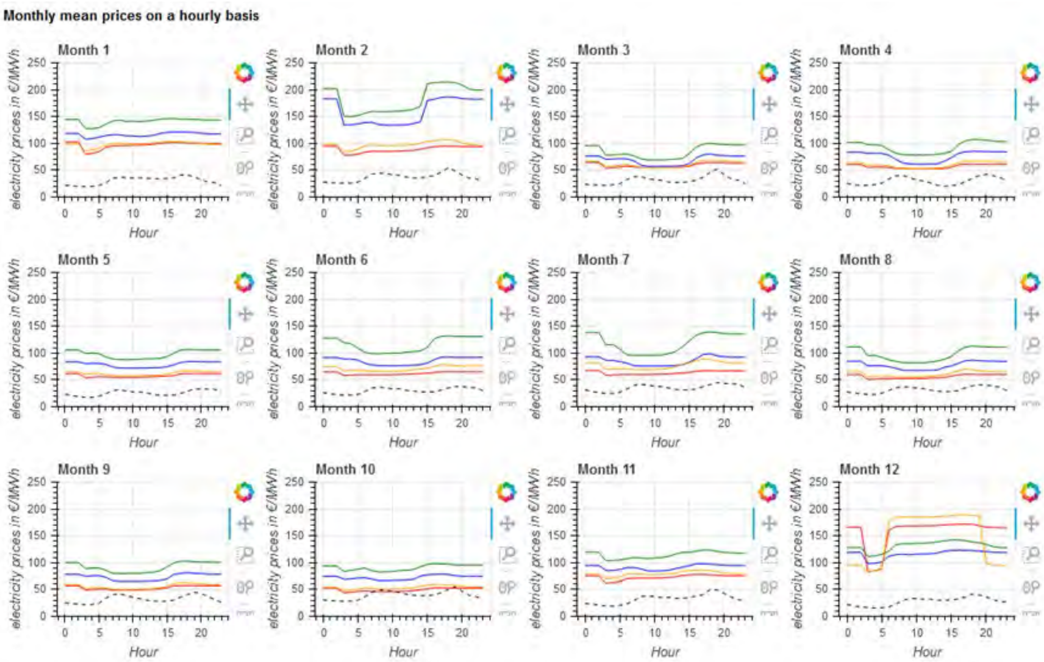


Figure 17: Monthly mean prices on hourly basis of wholesale electricity prices for 4 scenarios for 2050 and historic prices in 2015 for Germany used in the scenario calculations (Source: Enertile (Fraunhofer ISI, 2020), SET-Nav project (Resch et al., 2019))

The following Table 10 shows the mean electricity wholesale prices as well as the CO2 shadow prices[3] in the year 2050 in Germany for the four electricity price scenarios as described before. The CO2 shadow price is used in the calculations for Frankfurt to determine the costs of CO2 from fossil emissions.

Table 10: Mean electricity wholesale prices and CO2 shadow prices in the year 2050 in Germany for the four electricity price scenarios (Source: SET-Nav project (Resch et al., 2019, p. 7))

Scenario	Name	Mean electricity price [EUR/MWh]	CO_2 Price [EUR/t_{CO2}]
Price 1 (P1)	Directed Vision	67.99	183
Price 2 (P2)	National Champions	72.30	139
Price 3 (P3)	Diversification	86.65	199
Price 4 (P4)	Localisation	108.89	296

5 Drivers and Barriers

5.1 Drivers

Many initiatives to achieve the goal of CO2 reduction come from the public sphere. A current example is the "Fridays for Future" movement. More than any other movement, it has succeeded in sensitising politicians, the press and the public opinion to the theme of climate protection.

- Frankfurt has a lot of examples showing good solutions for the building sector. These projects have mostly been carried out by the local housing association (ABG-Holding Frankfurt or KEG). These good, partly prize-winning examples are shown and promoted at an internet platform: www. klimaschutzstadtplan-frankfurt.de.
- The municipality itself is also an important driver through exemplary resolutions, municipal statutes, subsidy programs for energy-efficient housing, voluntary commitments to CO2 reduction and offering free consultancy service for investors via Energiereferat.
- National subsidy programs from German bank of reconstruction (KfW) and BAfA for an energy-efficient building standard, renewable energies and energy-efficient heat production.
- Energy advice given by a local association, financed by the city of Frankfurt, for private households and building owners. Energiepunkt (Energiepunkt FrankfurtRheinMain.e.V., 2020)
- Solutions for an energy-efficient and/or renewable heat supply are often developed by the local utility Mainova in collaboration with the housing companies. These solutions can also be found on the website: Klimaschutzstadtplan-frankfurt.de.

[3] The shadow prices of CO2 are the result of the optimisation calculation with the Enertile model. For the different framework and technology settings different CO2 prices result from the calculation.

5.2 Barriers

Although there is a large commitment in society, that CO2 and energy saving measures and the use of renewable energies have to be undertaken rapidly, the process of implementing is working much too slow. As long as there is no obligation to choose the environmentally friendliest solution for construction or energy supply, the majority of the people will choose the cheapest solution with a minimum of investment, risk and work.

There could be written a long list of barriers and reasons why a specific climate-friendly solution is not realised - but in the end, the reason why is mentioned above.

International studies show clearly, which instrument would help the climate and renewable energies (besides a legal obligation): high pricing of CO2 emissions worldwide[4]. This would help dramatically to make investments in CO2 reducing technologies more economically favourable. At the moment fossil energies are much too cheap.

The following barriers have been identified to be crucial to reach the goal of climate neutrality by 2050:

- Lack of energetic refurbishment of buildings: Increase the refurbishment rate from 1% to 3%
- Too high costs for DH - Exemption of district heating from infrastructure costs which are a barrier when expanding the DH -system.
- Lack of renewable energy and excess heat in the heating system
    - Reduce temperature of the heating systems in the buildings below 45°C
    - make renewable energies competitive
    - find solutions for the use of excess heat
        - Legal Obligation for not wasting heat
        - Secure the investment of energy service company (ESCO) in excess heat facility (in the event that the company providing the waste heat goes bankrupt)

6 Local heating and cooling strategy

6.1 Assessment of scenarios

In order to identify technically and economically sound solutions for future heating systems in Frankfurt, a set of scenarios is calculated and assessed regarding costs and CO_2 emissions. The outcomes then form the quantitative basis for formulating a heating strategy for the city. In the following chapters, the scenarios, as well as the results of the different analysis steps,

[4] The Massachusetts Institute of technology (MIT) has developed an online tool, En-ROADS ("En-ROADS Climate Scenario," 2020), to calculate the impact of different CO2-saving measures - with this tool the statement above can be proofed.

are described. The method for the development of the scenarios is described in chapter 2 of this document.

6.1.1 Definition of scenarios and sensitivities

For a first analysis, various sensitivities for each of the different parts of the heating demand and supply systems in the city are calculated:

- Seven different levels of savings in demand for space heating in the city via virtually applying different renovation packages to different buildings in the city.
- 228 different sensitivities for the expansion of the district heating grids in the city varying the following input parameters: heat demand density maps (developed in the previous step), share of heat demand connected to district heating in the regions where district heating is available, grid cost ceiling of district heating (= the maximum distribution costs in each of the connected regions)
- Seven different sensitivities of decentral supply costs in the city varying the following input parameters: heat savings in the buildings according to the saving scenarios developed in the first step
- Two different portfolios of a potential district heating systems for the city based on different renewable energy sources, waste incineration and biomass boilers. Different sizes of potential district heating networks are analysed. These are calculated for 4 different electricity and CO2 price scenarios and three different temperature levels in the supply line of the heat distribution grid in potential hot water networks.

Table 11: Overview of sensitivities calculated with the different modules in the course of the strategy process

Main parameters varied	*range of variation of parameter*
Energy demand for space heating and hot water generation	
target of savings in heat demand for space heating	10% - 70% in steps of 10%
Decentral heating supply costs	
savings in heat demand for space heating	10% - 70% in steps of 10%
District heating (DH) distribution costs	
savings in heat demand for space heating	30%, 50%, 60%, 70%
share of heat demand connected to DH in areas with DH grid	50%, 70%, 90%
maximum grid costs [EUR/MWh] in regions connected to DH	16 - 54 in steps of 2 EUR/MWh
District heating (DH) supply costs	
total heat demand supplied by DH	depending on the saving and DH expansion scenario; calculations done for 643 & 883 GWh/yr for the steam net and 2.153, 1.510 & 1.367 GWh/yr for the hot water net
capacities of installed technologies	2 different portfolia; see respective chapter for more details
electricity wholesale and CO_2 prices	4 different prices scenarios, see chapter 4.3.5
supply line temperatures in the district heating grid	3 different temperature profiles in the hot water network from 55 - 86 °C (median Temperature)

All sensitivities are calculated for the year 2050. The citywide scenarios are then compiled from a selection of those sensitivities.

The Table 11 gives an overview of the sensitivity calculations in the course of the strategy development and it shows the parameters and range in which these have been varied in the different modules.

6.1.2 Scenario results

6.1.2.1 Heat demand density maps 2050

A heat demand density map for the city's current situation has been developed based on the data of the building stock in the city and building type-specific demand data from Invert/EE-Lab (see chapter 4.1). Potential changes in the heat demand density in the city have been developed by virtually applying different renovation measures to each of the buildings in the city. These heat-saving measures have been chosen in a way that the overall costs of renovation towards a predefined overall saving target for the city were minimised, i.e. buildings providing cheaper renovations are renovated first and more ambitiously. In the following Figure 18, the heat demand density map of the current situation is shown together with heat demand density maps for three different saving scenarios: 35%, 46% and 53% savings of heat demand in the city.

Figure 18: Heat demand density maps of Frankfurt for 2017 (top left), 2050 with 35% savings (top right), 2050 with 46% savings (bottom left) and 2050 with 53% savings (bottom right) (Source: own calculations)

Currently, the useful energy demand for space heating and hot water generation in residential and service buildings in the city of Frankfurt is 5,663 GWh/yr [5]. The average heat demand density in the city currently is around 561 MWh/ha*yr, the highest heat demand density in the city centre is 14,865 MWh/ha*yr.

As can be seen in the Figure 18, the application of renovation measures in the city would lead to decreased heat demand densities especially in the central parts of the city. In the

[5] See details on the bottom-up estimation of heat demand and heat demand density in chapter 4.1.1

surroundings of the city, the heat demand density is already low in the current situation. The average heat demand density in the three saving scenarios decreases to 367 MWh/ha*yr, 305 MWh/ha*yr and 261 MWh/ha*yr. The maximum heat demand density in the city in all scenarios is 14,865 MWh/ha*yr. It is not decreasing due to the fact that all buildings located in this 100 x 100 m area are not cost-efficient to renovate in none of the calculated scenarios.

The following Figure 19 shows the costs of reaching different levels of heat savings in the buildings of the city of Frankfurt. For different levels of overall savings between 5% and 53% the annualised investment costs per MWh of saving and the total annual investment costs in MEUR/yr are shown. The figure shows that the average costs per savings (blue line) increase only slightly until savings of around 35% of the overall heat demand, which would cost around 90 EUR/MWh. Reaching savings of 53% of the overall heat demand becomes remarkably more expensive of around 125 EUR/MWh. This gives an indication that an economically interesting level of heat savings might be in the range of 30 - 40% of total heat demand.

In order to identify a meaningful level of heat savings in the city not only the costs for the savings are relevant, but also the costs for heat supply and the availability of resources. A comparison of these parameters is done in the scenario assessment section in chapter 6.1. In this comparison, the total annualised heat-saving costs are used to calculate the overall costs occurring in different scenario settings. In the figure, these values are shown in the orange line.

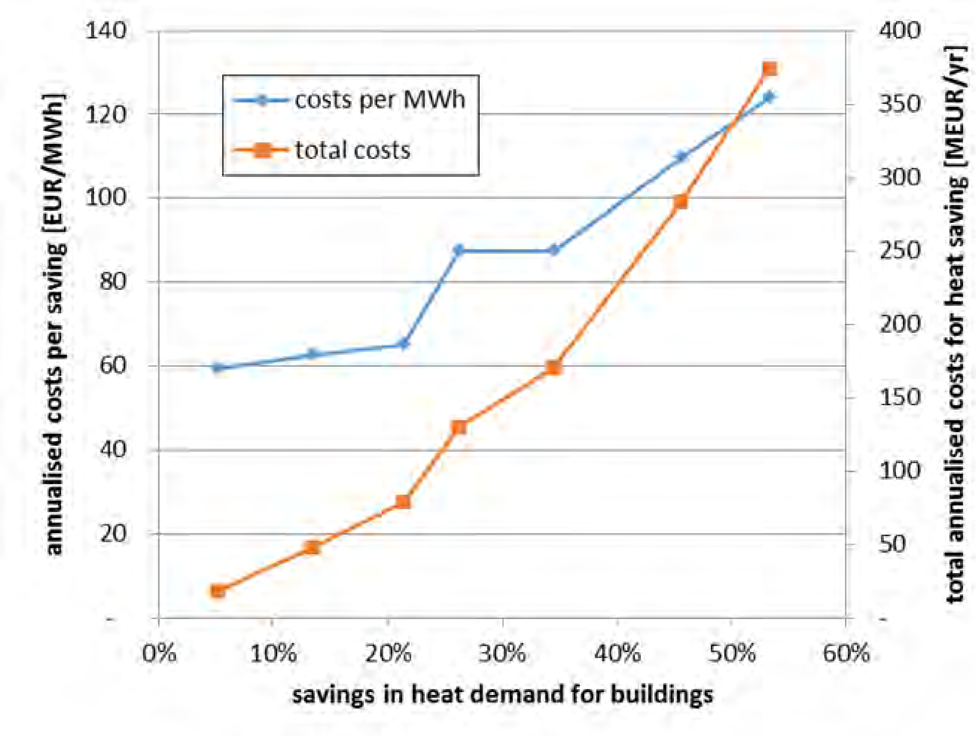


Figure 19: Annualised investment costs per saved heat (left axis) and total annualised investment costs (right axis) for reaching different overall savings of heat demand in building in the city of Frankfurt (Source: own calculations)

As already described in chapter 4.3.4 and 6.1.1, different renovation targets are calculated. However, these refer to the total heating demand and still have to be adjusted for the additional hot water production. The following Table 12 shows the relationship between a renovation scenario, the calculated savings and the savings that can be achieved by considering space heating and hot water production.

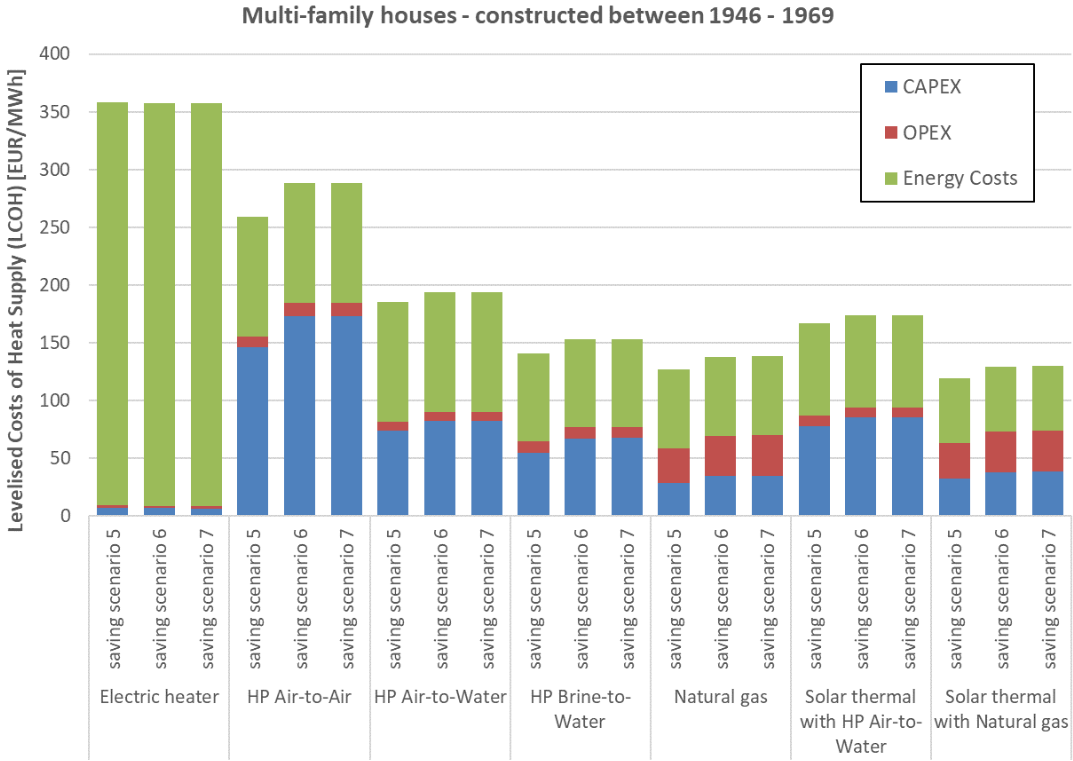
Table 12: Savings in demand for space heating and savings in total heat demand (space heating + domestic hot water) for the calculated renovation-scenarios. (Source: own calculations)

scenario name	savings in demand for space heating	saving in total heat demand (space heat + domestic hot water)
renovation scenario 1	8%	5%
renovation scenario 2	20%	13%
renovation scenario 3	29%	21%
renovation scenario 4	36%	26%
renovation scenario 5	46%	35%
renovation scenario 6	60%	46%
renovation scenario 7	69%	53%

In order to reach 35% of savings (at lowest costs), 44% of buildings gross floor area is renovated in the calculations, to reach 46% of savings, 63%, and to reach 53% of savings, 74% of buildings gross floor area is renovated. To reach 35% of savings, mainly row houses, health and education buildings are renovated in the model, smaller shares of the other types of buildings. In the majority of buildings measures below the standards for renovation are applied. To reach savings of 46% also large parts of the multifamily buildings and hotels and restaurants are renovated, while in the other types of buildings mostly the buildings constructed before the 1980s are renovated. Then to reach 53% of savings also large parts of the office buildings have to be renovated and also the ambition of the measures increases. At the same time the costs for the measures also remarkably increase.

6.1.2.2 Costs of decentral supply

The costs of heat supply (Levelized costs of heat - LCOH) via decentral technologies have been calculated with the **"CM - Decentral heating supply"** (Hotmaps Wiki, 2019c). For each building type and construction period distinguished in the calculation of the current heat demand (see chapter 4.1), heat supply costs in the year 2050 have been calculated. Hereby, costs have been calculated for different levels of refurbishment in these buildings according to the saving scenarios developed in the first step of the analysis (see description of methodology in chapter 6.1.1). The following Figure 20 shows the LCOH for heat supply from different technologies for three saving scenarios (35%, 46% and 53% savings in overall heat demand) for two exemplary building types and construction periods: multi-family houses (MFH) constructed between 1946 and 1969 (top) and office buildings constructed between 1980 and 1989 (bottom).



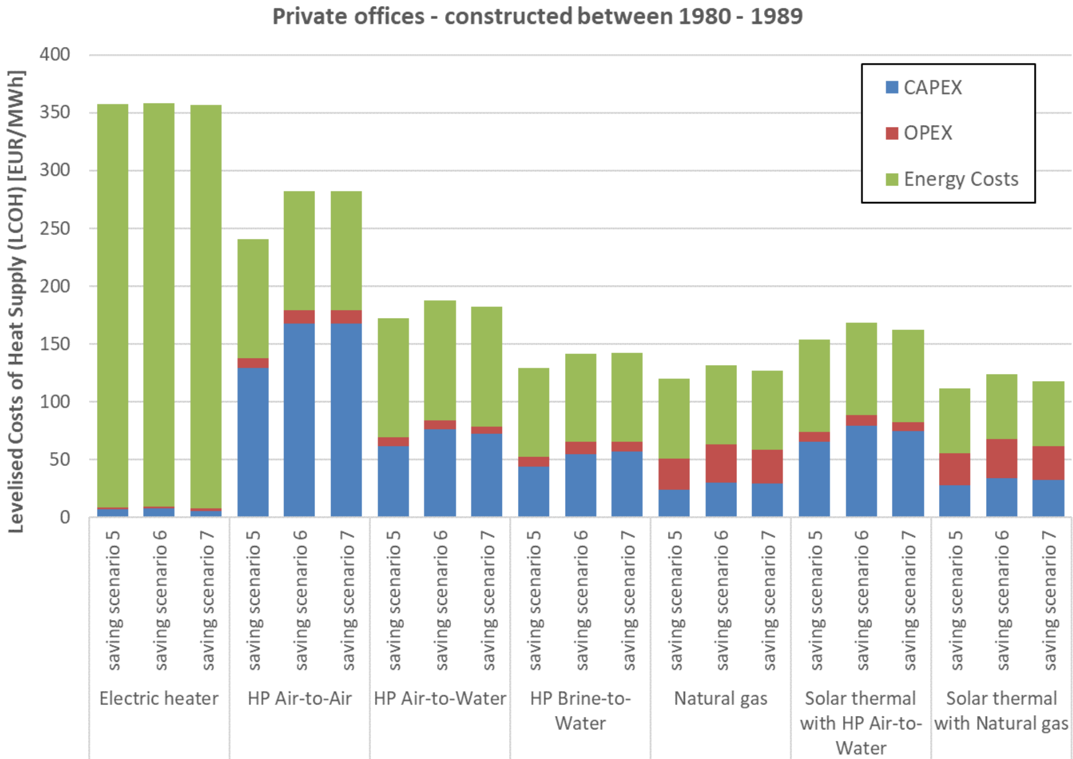


Figure 20: Levelized costs of heat supply from decentral technologies in 2050 for three different scenarios of heat savings in the buildings (35%, 46% and 53% savings in overall heat demand), top for multi-family houses constructed between 1946 and 1969, bottom for offices built between 1980 and 1989 (Source: own calculations)

Most buildings in the construction period between 1946 and 1969 are economically feasible to renovate in many heat-saving scenarios. Decreasing heat demand in the buildings affects the heat supply costs: smaller device capacities usually lead to higher specific investment costs and many technologies have a certain minimum capacity available on the market. This often leads to increased LCOH with decreased heat demand in the buildings, especially for small buildings or flat-wise heat supply. However, it is also possible that LCOH decrease with decreased heat demand. This is the case when the maximum needed power decreases strongly after renovation. In the figure, this effect is shown especially in office buildings in renovation scenarios with higher heat savings (bottom figure - saving scenario 7). LCOH for heat supply from decentral technologies in MFH constructed between 1946 and 1969 are calculated to 119 and 358 EUR/MWh, with a combination of solar thermal and natural gas being the cheapest supply option and electric heaters being the most expensive. The supply with heat pumps leads to LCOH between 140 and 288 EUR/MWh in those buildings. For office buildings constructed between 1980 and 1989 LCOH between 111 and 358 EUR/MWh have been calculated. This is similar to the costs calculated for Multi-family houses.

The LCOH for each building type, construction period and supply technology are used to calculate average cost of decentral heat supply in the different heat-saving scenarios. For this the overall heat demand and related supply costs in all buildings of the city are calculated. The following mix of technologies has been assumed: 65% heat pumps, 12% electric heaters, 10% solar thermal and rest biomass. This results in weighted average costs of decentral heat supply in the year 2050 for the different saving scenarios of 175 (no savings), 179 (23% savings) and 183 EUR/MWh (37% savings). However, it has to be noted that a decrease of the supply line temperatures in buildings after renovation is not taken into account in these calculations. Decreased supply temperatures would lead to higher COPs for heat pumps, which would decrease the LCOH for these technologies. Therefore, LCOH of decentral heat supply might not increase as strongly as reflected in these values.

6.1.2.3 Sensitivity of economic district heating expansion

With the **"CM - District heating potential: economic assessment"** (Hotmaps Wiki, 2019b) several scenarios for the expansion of district heating (DH) in the city have been calculated. The module calculates the location, the investment and the heat distribution costs as well as the delivered energy of a potential DH system under different technical and economic framework conditions. The following Figure 21 shows the annualised investment costs into the DH grid over the average grid costs per distributed heat (left side) and the share of DH on the overall heat demand in buildings over the average grid costs per distributed heat (right side). Scenarios have been calculated for various different levels of heat savings in the buildings, different shares of heat demand connected to DH in DH areas and different maximum grid cost ceilings.

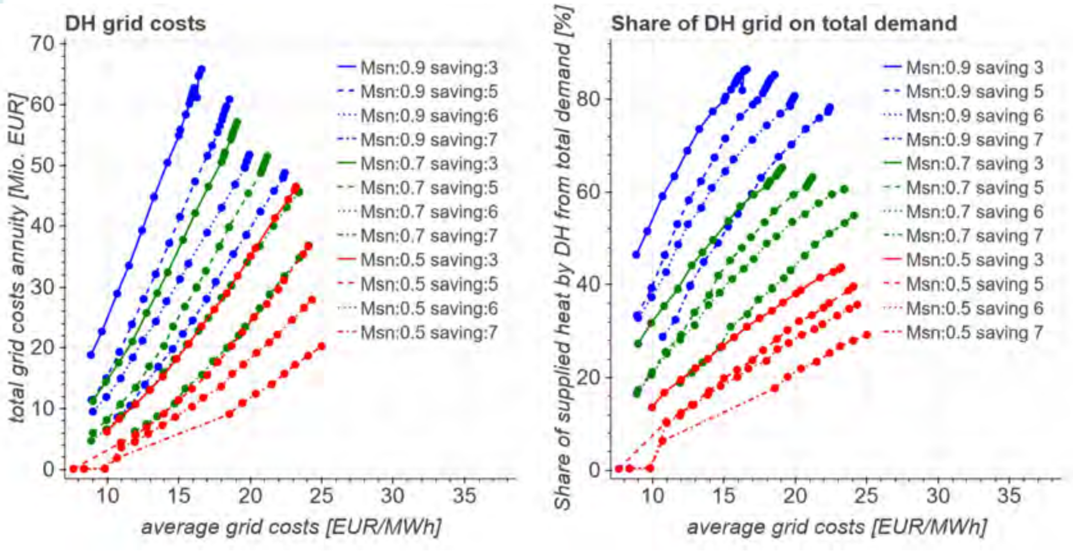


Figure 21: Annualised investment costs into the district heating (DH) grid (y-axis) over the average grid costs per distributed heat (x-axis) (left side) and share of DH on overall heat supply in the city (y-axis) over the average grid costs per distributed heat (x-axis) (right side) for several scenarios with different levels of heat saving[6] in the buildings, different shares of buildings' heat demand connected to DH in DH areas (Msn) and different maximum grid cost ceilings. (Source: own calculations)

Figure 21 shows the high sensitivities of the average grid costs per distributed heat [EUR/MWh] to the heat demand density/amount of heat savings in the city (solid vs. dashed vs. dotted lines) and to the share of heat demand that is connected to DH in areas where a DH grid would be built (red vs. green vs. blue lines). Assuming e.g. savings in the heat demand of buildings of 35% (savings 5) and that district heat should be supplied at heat distribution costs of 30 EUR/MWh on average: in case that 50% of the heat demand is connected in areas where a DH grid is constructed would allow a total share of 28% DH in the city, while if 90% of the heat demand in DH areas is connected this would allow for a share of around 82% of total heat demand to be supplied by DH. This shows the remarkable importance of increasing the share of buildings connected to DH in areas where DH networks are constructed for decreasing the costs of DH distribution.

6.1.2.4 District heating portfolios and related costs

In the city of Frankfurt, different district heating systems are currently in place. In the centre of the city, a steam network operated by Mainova supplies large parts of the buildings' energy demand. In several other parts of the city, various hot water systems are in operation, the majority of them are operated by Mainova. The following Figure 22 shows the areas of the city where the district heating systems from Mainova are located.

[6] See chapter 6.1.2.1 for a description of the different heat-saving/renovation scenarios and especially Table 12 for the share of heat savings in the related renovation scenarios 3, 5, 6 and 7

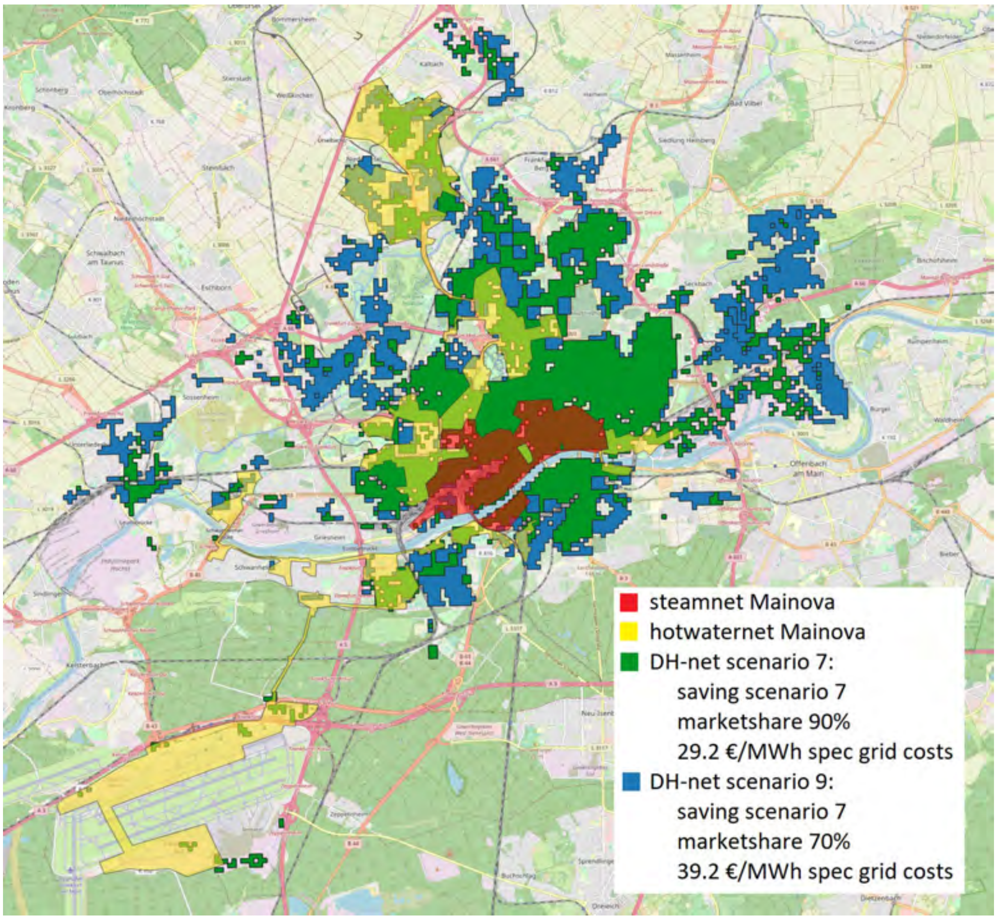


Figure 22: Current and potential future areas of district heating in the city of Frankfurt - area of current steam network (dark red), area of current hot water networks from Mainova (orange), two different scenarios calculated within this strategy (green and blue) (Source: own calculations)

Figure 22 also shows potential district heating areas for two of the various scenarios calculated with the **"CM - District heating potential: economic assessment"** (Hotmaps Wiki, 2019b) (see chapter 6.1.2.2). It can be seen that areas potentially interesting for district heating in the future are overlapping with the currently existing district heating areas. This accounts especially for the area of the current steam network, as this is located in areas with high heat demand densities in the current situation and also in the different heat-saving scenarios.

Due to the different technical options for supplying hot water and for supplying steam these two potential district heating systems in Frankfurt in the year 2050 are modelled separately. The heat demand potentially supplied by district heating networks according to the calculations described in chapter 6.1.2.2 is split into a heat demand in a steam network and a heat demand in hot water networks. This split is derived according to the following approach: It is assumed that a steam network in 2050 would also be located where the current steam network is located. In all other areas potentially interesting for district heating hot water networks would be set up. The demand supplied by the hot water networks is the difference between the overall identified demand potentially supplied by district heating in the respective scenario minus the demand supplied by the steam network. The steam network hereby will supply the majority of the heat demand in the area of the current steam network. Depending on the underlying heat-saving scenario (see chapter 6.1.2.1) different heat demands will be located in the respective area. Figure 23 shows the decrease of the heat demand in the area of the current steam network in the different calculated saving scenarios together with the current heat supply to the existing steam network.

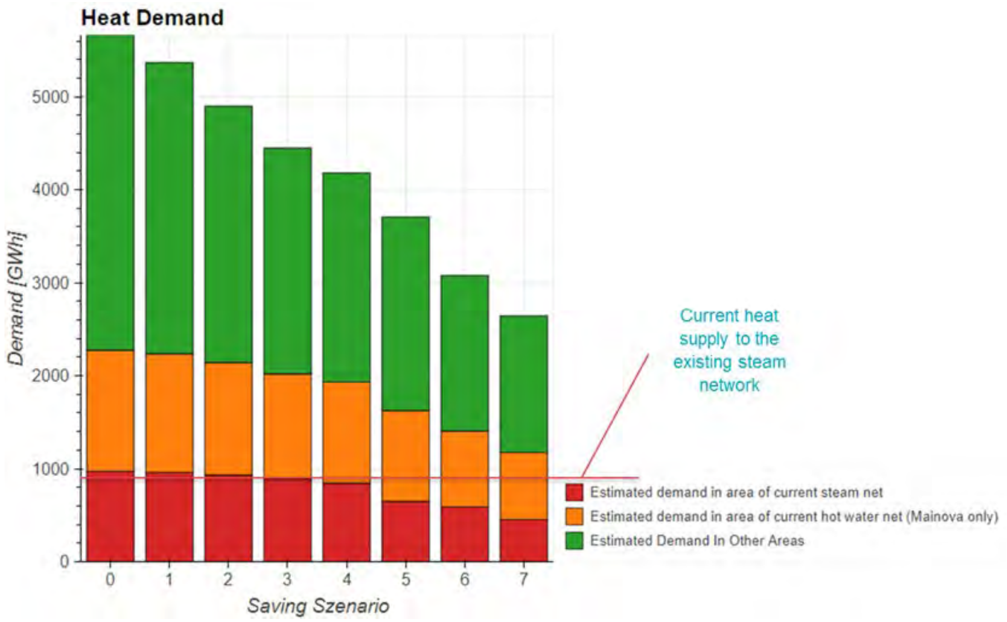


Figure 23: Estimated heat demand (space heating + hot water generation) in the city of Frankfurt in the year 2050 for different scenarios of heat savings split into the areas of the current steam network (red), the areas of the current hot water networks of Mainova (orange) and the rest. (Source: own calculations)

For the supply of heat to the steam network a limited set of technologies is available when underlying the goal of nearly no CO2 emissions in the system. Looking at the identified resource potentials (see chapter 4.1.4) only municipal waste is able to supply heat at temperatures needed for steam generation. For the analyses in this strategy, it is assumed that a waste incineration plant will supply base load to the steam network and the residual load will be supplied by a gas boiler fuelled with synthetic natural gas (SNG).

For the supply of heat to the hot water networks various different technologies and heat sources are available in Frankfurt. The following technologies and heat sources have been taken into account in the compilation of district heating (DH) portfolios for the hot water networks (see also chapter 4.1.4 for further details on the existing potentials): various different heat pumps for using the different sources of (excess) heat in the city (excess heat in the different industrial parks, excess heat from data centres, excess heat in the wastewater treatment plants, the heat contained in the Main river and heat from near-surface geothermal sources), solar thermal collectors, a weekly heat storage and a natural gas boiler for covering peak load. In order to meet the identified potential district heating demands all of these sources need to be used in potential future hot water networks. However, depending on the implemented heat savings, on the share of the heat demand connected to the district heating system and on the size of the heat storages different sizes of installed peak load capacities are needed.

Based on the analysis of the costs of potential DH systems, costs of decentral supply in the city and eventually meaningful amounts of heat supplied by DH three different sizes of heat networks have been modelled for both the steam and the hot water networks: 650 GWh/yr, 580 GWh/yr and 450 GWh/yr of total heat supply to the steam network and 2,500 GWh/yr, 1,800 GWh/yr, 1,400 GWh/yr and 1,100 GWh/yr of total heat supply to the hot water networks.

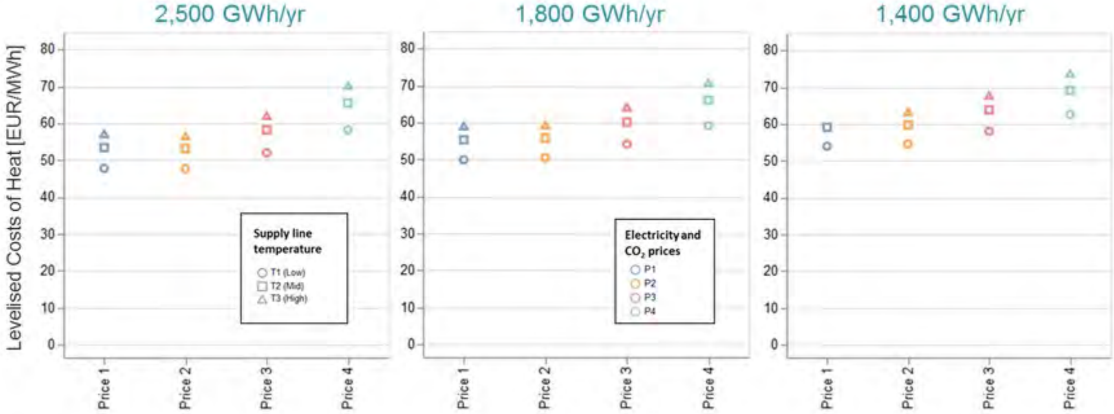


Figure 24: Levelized costs of heat supply to the hot water network in [EUR/MWh] for three sizes of the networks (in terms of overall heat supply), different scenarios for electricity wholesale and CO2 prices (P1 - P4)[7] as well as supply line temperatures (T1 - T3)[8] (Source: own calculations)

For the dispatch of the supply to the steam network the sensitivity to 4 different price assumptions for the electricity wholesale and the CO2 price in 2050 are calculated. For the hot water network, additionally three sensitivities to potential supply line temperatures have been analysed. Figure 24 and Figure 25 show the resulting levelized costs of heat supply (LCOH) to the district heating networks under different sensitivities.

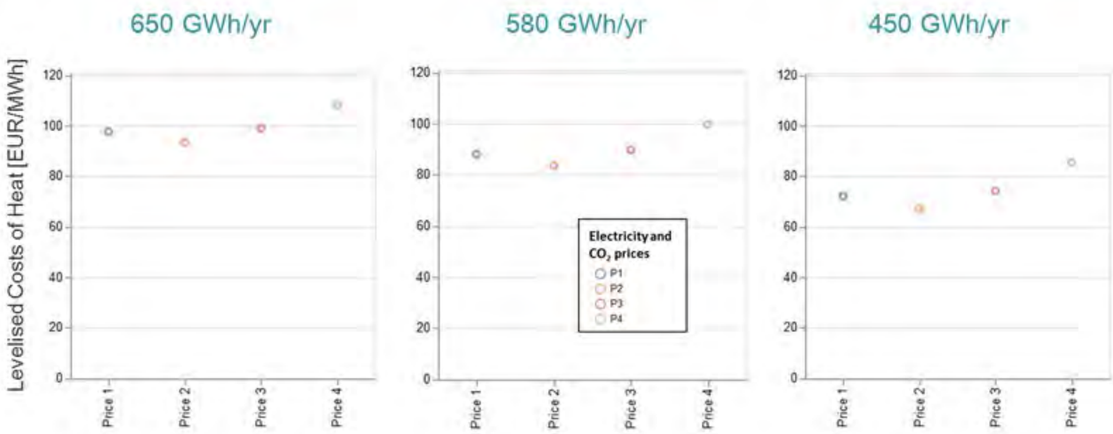


Figure 25: Levelized costs of heat supply to the steam network in [EUR/MWh] for three sizes of the networks (in terms of overall heat supply) and different scenarios for electricity wholesale and CO2 prices (P1 - P4) (Source: own calculations)

Figure 25 shows the remarkable sensitivity of the LCOH to the electricity wholesale and CO2 prices. While the portfolio of the hot water networks is mainly sensitive to the electricity wholesale prices due to the extensive use of heat pumps, the portfolio of the steam network is only sensitive to the CO2 price due to the CO2 emissions in the waste incineration. Additionally, the portfolio of the hot water network shows a sensitivity of the LCOH to the average supply line temperature due to higher efficiencies of the heat pumps with decreasing

[7] See chapter 4.3.5 for a description of the energy carrier and CO2 prices in the price scenarios P1-P4.

[8] See the annex of the document for a description of the assumed supply line temperatures T1 to T3.

supply temperatures. For the modelled combination of capacities in the hot water networks the LCOH decrease around 10 EUR/MWh for a decrease of the supply line temperatures from around 90°C to around 60°C (yearly average). A slight increase of the LCOH with decreasing size of the district heating systems can be observed. This is due to a remarkable decrease of the full load hours of several of the installed technologies like the heat pump in the river water and the natural gas peak boiler. The figure also shows that the LCOH for steam supply are remarkably higher than the LCOH of the hot water supply especially in case of higher heat demand (580 - 650 GWh/yr). This is due to the high prices of synthetic natural gas (SNG) estimated for this analysis. The figure shows as well that a decrease in the demand for steam can remarkably reduce the LCOH because less SNG is needed. The reason that price scenario 2 leads to the cheapest LCOH in the steam system is that price scenario 2 contains the lowest CO2 prices of all price scenarios.

The following Figure 26 and Figure 27show the load duration curves for the steam and for the hot water networks for two different sizes of the networks. They show the split of capacities used in each hour of the year ordered by the total power needed in each hour.

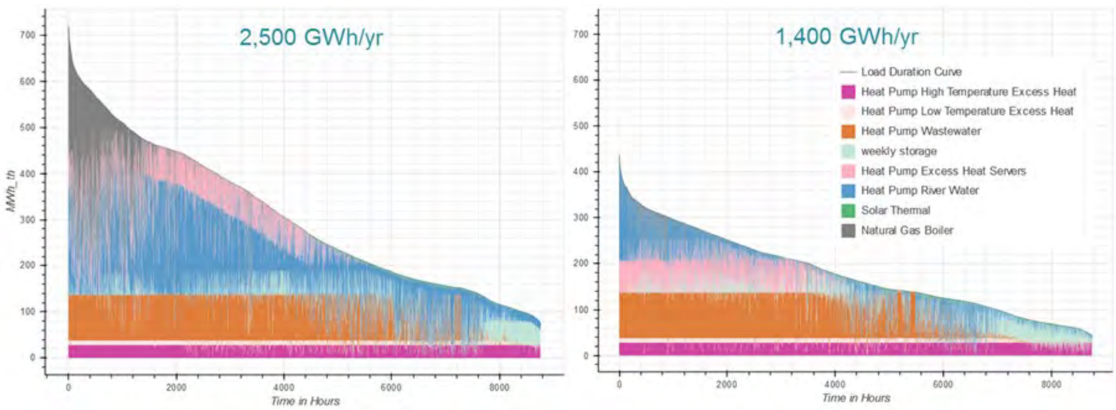


Figure 26: Load duration curves for the hot water networks for an annual heat supply to the network of 2,500 GWh/yr (left side) and 1,400 GWh/yr (right side) - split into the different supply technologies (Source: own calculations)

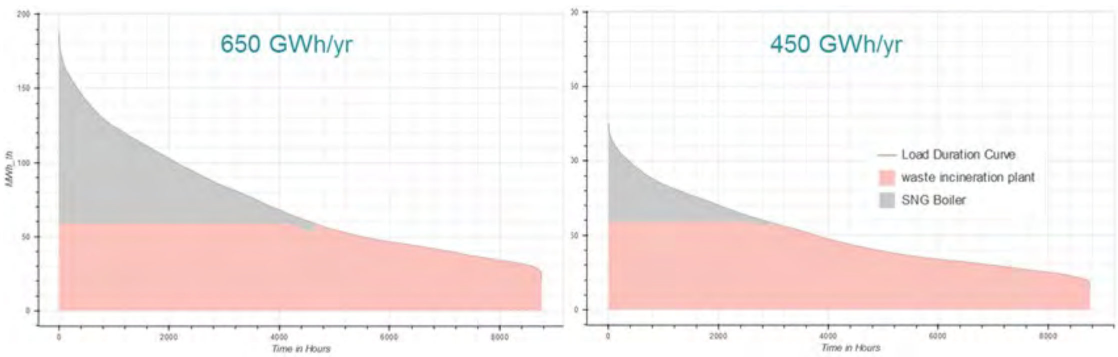


Figure 27: Load duration curves for the steam network for an annual heat supply to the network of 650 GWh/yr (left side) and 450 GWh/yr (right side) - split into the different supply technologies (Source: own calculations)

These figures show that large amounts of heat demand in potential district heating (DH) systems in the city of Frankfurt can be supplied with the available potentials of renewable and excess heat sources. This is especially true for the supply to hot water DH systems. For the supply of steam only municipal waste is an option. However, in large DH systems, the highest loads in winter cannot be supplied with the available capacities. A reduction of the demand for peak load fuels (e.g. natural gas or SNG) can be reached with decreasing the heat demand in the DH systems and consequently with decreasing the heat demand in the city. In the hot water network with a size of 2,500 GWh/yr around 310 GWh/yr of natural gas is needed for supplying peak loads. This is reduced to 100 GWh/yr in a system of 1,800 GWh/yr and to 30 GWh/yr in a system of 1,400 GWh/yr. Thus, with a reduction of the overall system size of 30% a reduction of peak fuel needs of 70% is reached, a reduction of the system size of 40% leads to a reduction of peak fuels of 90%. In the steam network a reduction of the system size from 650 GWh/yr to 450 GWh/yr (30%) leads to a reduction of SNG demand from 195 to 62 GWh/yr (70%).

The results also show that even with a strong reduction of heat demand in the city remarkable capacities of peak load boilers need to be provided in the hot water network for the coldest days of the year. This is due to the fact that remarkable heat pump capacities are not usable on the coldest days: the river water heat pumps cannot be used below a certain threshold temperature of the heat source, in this case 3°C of the river water temperature. In hot water networks of 2,500 GWh/yr of heat supply a peak load boiler capacity of 300 MW needs to be available. In a network of 1,800 GWh/yr 200 MW are needed and in a system of 1,400 GWh/yr still 100 MW of peak load boilers are required. These are, however, only used in a very low number of hours over the year. In the scenario of 2,500 GWh/yr these reach 775 full load hours, in the system of 1,800 GWh/yr they reach 430 h/yr and in the 1,400 GWh/yr they reach 290 h/yr.

In the steam system, a further reduction of the peak fuel demand might be reached with a storage of municipal waste from summer to winter. In the hot water network, an increase of storage capacity could help to decrease the peak fuel demand.

Although the calculations cover sensitivities for different combinations of technologies, different temperatures in the supply line of the hot water networks and different electricity wholesale and CO2 prices, other main influencing parameters have not been varied over the scenarios as e.g. future potential prices of SNG or the investment costs and efficiencies of the technologies. This has to be taken into account in the interpretation of the results.

6.1.2.5 Overall city scenarios

Based on the analyses of the sensitivity of costs in the different parts of the heating demand and supply system a set of scenarios has been selected for comparing indicators for the entire city. For three different levels of heat savings in the buildings, different settings of potential district heating systems have been compiled in order to see their effects. This covers different overall amounts of heat supplied to the district heating grids, different market shares of district heating in areas where district heating is available and additional seasonal heat storage in the hot water networks of the city. The following Table 13 shows the definition of the different scenarios.

Table 13 and Figure 28 show important indicators for the entire city for the defined scenarios. These indicators are the utilisation rate of the identified resource potentials [GWh/GWh], the total annual CO2 emissions [tCO2/yr], total annual heating system costs [MEUR/yr], the final energy demand [MWh/yr], the heat demand for heat pumps [MWh/yr] and the shares of district heating (DH) and heat savings [%].

Table 13: Overview of scenarios in the different calculation modules combined to overall city scenarios (Source: own assumptions)

Scenario nr.	1	2	3	4	5	6	7	8	9
Scenario Name	Low savings / very high DH	Low savings / high DH	Mid savings / high DH	Mid savings / low DH	Mid savings / high DH / additional storage	High savings / high DH	High savings / mid DH	High savings / low DH	High savings / mid DH / additional storage
Savings in heat demand of the buildings	35%	35%	46%	46%	46%	53%	53%	53%	53%
Decentral supply	Mainly heat pumps, some solar thermal, biomass and electric boiler	= scenario 1	= scenario 1	= scenario 1	= scenario 1	= scenario 1	= scenario 1	= scenario 1	= scenario 1
District heating network - steam net	Market share in DH ares (MS) = 90% Yearly Supply to the DH system (YS) = 650 GWh/yr	= scenario 1	MS = 90% YS = 590 GWh/yr	MS = 90% YS = 590 GWh/yr	MS = 90% YS = 590 GWh/yr	MS = 90% YS = 450 GWh/yr	MS = 90% YS = 450 GWh/yr	MS = 90% YS = 450 GWh/yr	MS = 90% YS = 450 GWh/yr
District heating network - hot water net	MS = 90% YS = 2,500 GWh/yr	MS = 90% YS = 1,800 GWh/yr	MS = 90% YS = 1,800 GWh/yr	MS = 70% YS = 1,100 GWh/yr	MS = 90% YS = 1,800 GWh/yr	MS = 90% YS = 1,800 GWh/yr	MS = 90% YS = 1,400 GWh/yr	MS = 70% YS = 1,100 GWh/yr	MS = 90% YS = 1,400 GWh/yr
District heating supply - steam net	Waste incineration, synthetic natural gas for peak load, medium price	= scenario 1	= scenario 1	= scenario 1	= scenario 1	= scenario 1	= scenario 1	= scenario 1	= scenario 1
District heating supply - hot water net	Mix of different excess heat, solar thermal, weekly storage, natural gas for peak load, medium distribution temperature, medium price	= scenario 1	= scenario 1	= scenario 1	= scenario 1 with additional seasonal storage	= scenario 1	= scenario 1	= scenario 1	= scenario 1 with additional seasonal storage

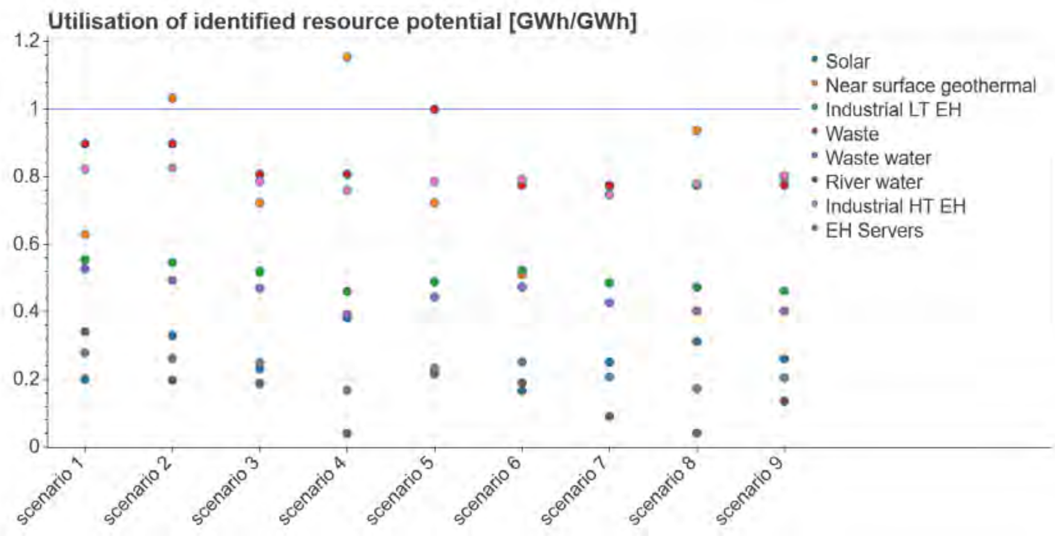


Figure 28: Utilisation of identified resource potentials in 2050 in the city of Frankfurt in the different scenarios (Source: own calculations)

Figure 28, on the utilisation ratio, shows how much of the identified resource potentials in the city are used in different scenarios. It can be observed that not all of the selected scenarios can be supplied only by resources from the city. In scenario 2 and scenario 4 the local potentials for near-surface geothermal energy are not enough to cover the needed energy. Near-surface geothermal energy is only assumed to be used in decentral supply. A shift from brine/water heat pumps to air-source heat pumps could also lead to scenarios where the utilisation ratios of all resources are below 100%. However, for the air as a heat source, there is no resource potential identified and therefore no limit of the resource defined in the calculations. Decentral air source heat pumps are assumed to have a share of around 60% on the total heat demand supplied by decentral technologies in the scenarios. Therefore, high shares of decentral supply in the scenarios might be unrealistic due to high resulting amounts of air source heat pumps.

At the same time, high shares of decentral heat supply also lead to higher overall system costs. The following Figure 29 shows the total annual costs of the heating system in Frankfurt in 2050 for the different calculated scenarios.

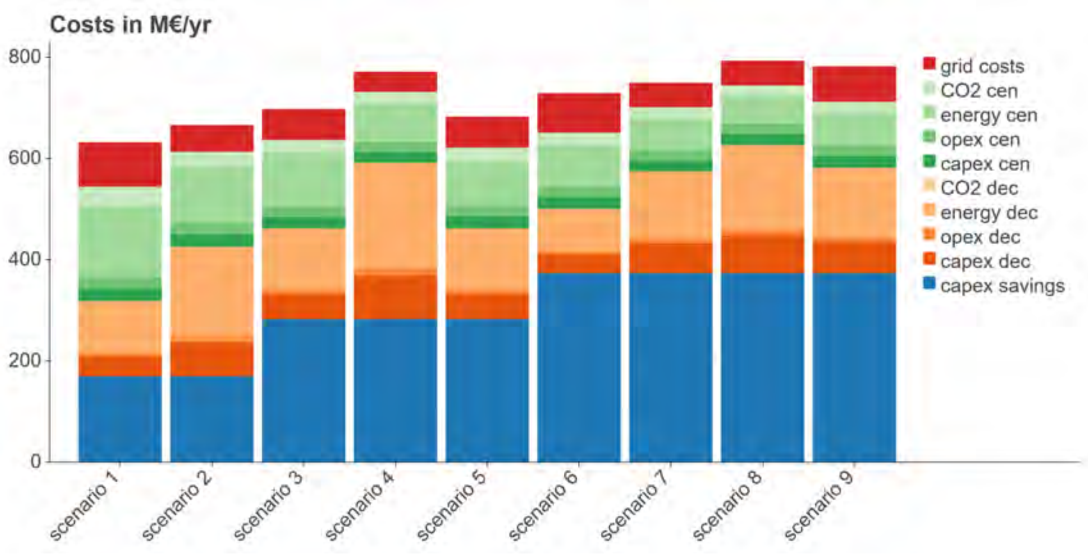


Figure 29: Annual heating system costs for the city of Frankfurt in 2050 for the defined scenarios split into costs for heat savings (savings), decentral supply (dec), district heating supply (cen) and district heating grid (grid) as well as revenues from electricity generation (revenues) (Source: own calculations).

In Figure 29, the scenarios with higher shares of district heating lead to lower overall systems costs (e.g. scenario 3 vs. 4 and 7 vs. 8). The reason is the lower levelized costs of heat (LCOH) from district heating supply compared to the LCOH from decentral supply. The figure also shows that a remarkable part of the yearly costs results from the renovation of the buildings in order to reduce heat demand (blue bars). The share of these costs increases with increasing levels of heat savings (see especially in scenarios 6 - 9).

In Figure 29, scenario 1 would be the cheapest scenario. However, scenario 1 leads to remarkably higher fossil CO_2 emissions compared to the other scenarios. The following figure shows the fossil CO_2 emissions for all calculated scenarios.

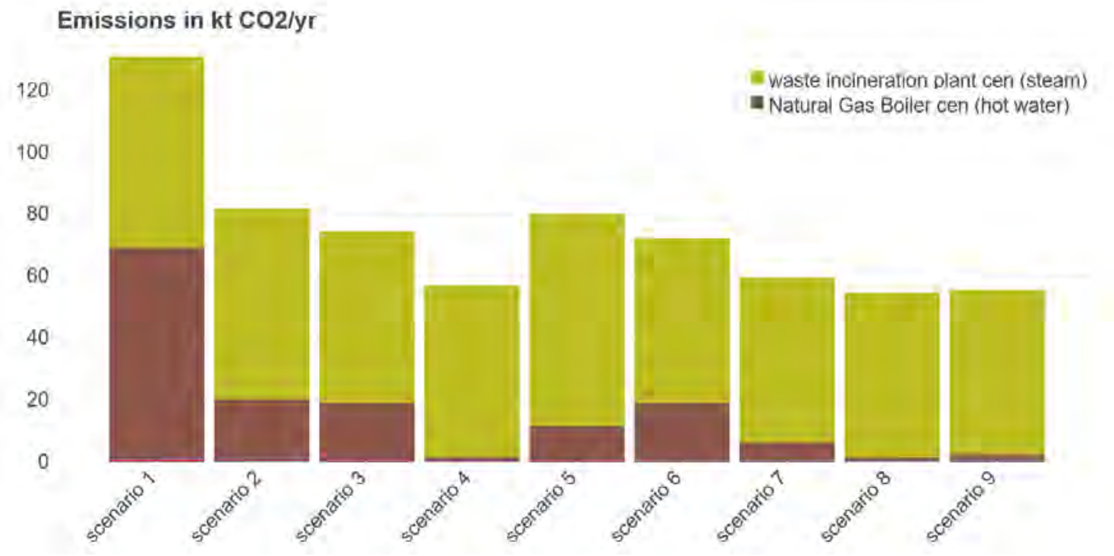


Figure 30: Total annual CO2 emissions for the city of Frankfurt in 2050 for the defined scenarios distinguished between the different supply technologies (Source: own calculations)

Figure 30 shows that scenarios 1, 2, 3, 5 and 6 lead to fossil CO_2 emissions above 60 kt/yr for heating in the city. Apart from scenario 1, the majority of the emissions result from the incineration of municipal waste (green bars) for the supply of steam to the DH steam network in the city centre. The other part of the fossil emissions in the scenarios origin from the natural gas peak load boilers in the hot water networks of the city. The emissions from these boilers account for the majority of the emissions in scenario 1, in the other scenarios the emissions from these boilers are reduced remarkably. This is due to the fact that the total heat demand in the hot water DH systems is lower in the other scenarios. As described in chapter 6.1.2.4 on the DH supply dispatch the demand for peak load fuels can be reduced remarkably by reducing the overall heat demand in the hot water networks. For the supply of peak load in the steam system, SNG is used and no emissions for the SNG incineration are assumed.

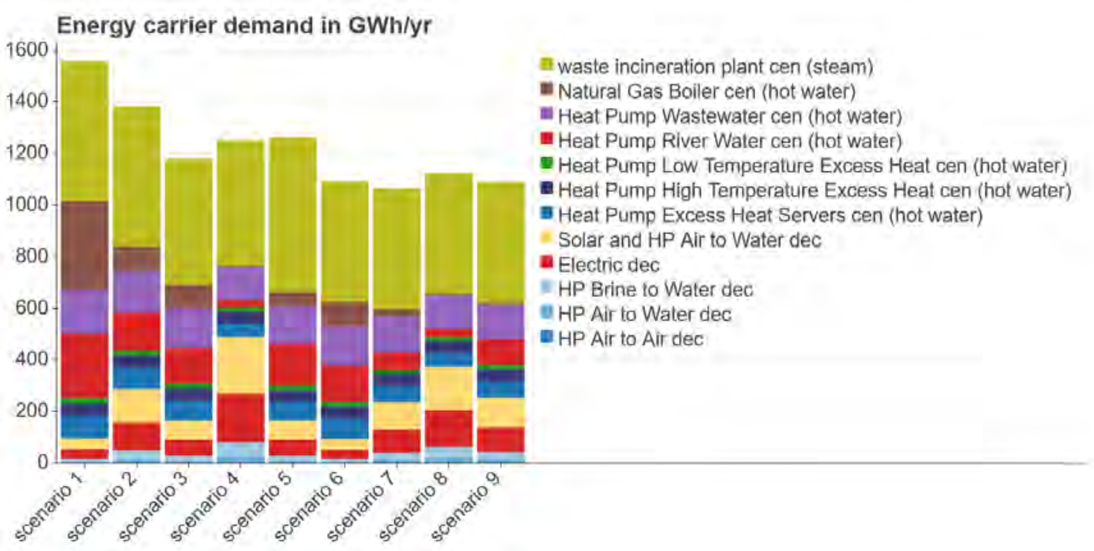


Figure 31: Total energy carrier demand for space heating and hot water generation (energy carriers used in the buildings plus energy carriers used in the district heating supply plants) in the city of Frankfurt in 2050 in the different scenarios distinguished between the different supply technologies (Source: own calculations)

Figure 31 shows the demands for energy carriers in the different calculated scenarios. For decentral heat supply these reflect energy carriers used in the buildings and for district heating supply these reflect the energy carriers used in the supply plants of the district heating systems. Solar thermal energy and ambient heat used in heat pumps is not reflected in the figure. The latter is shown separately in the subsequent Figure 32.

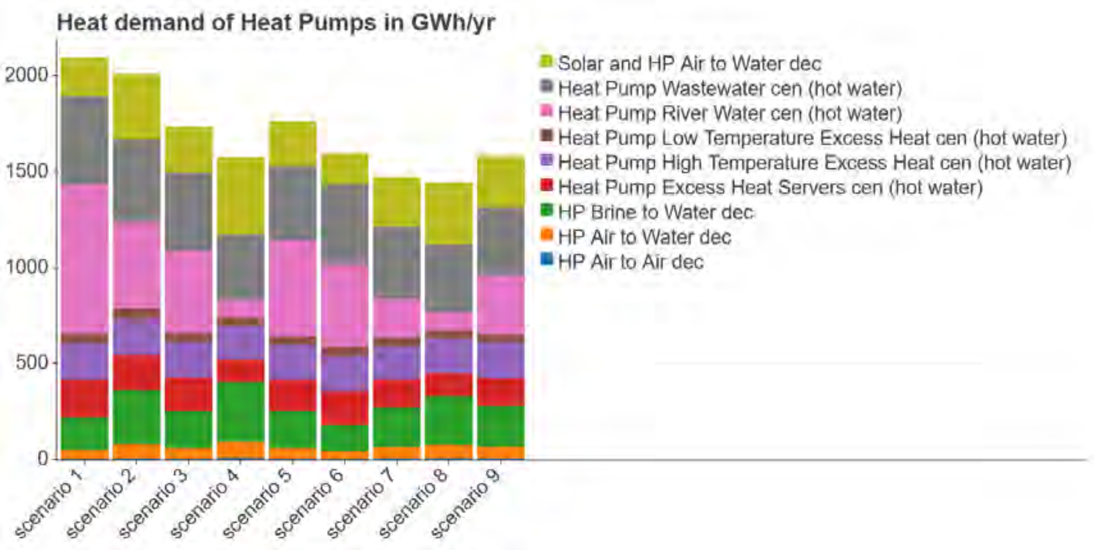


Figure 32: Heat demand of heat pumps in 2050 in the city of Frankfurt in the different scenarios (Source: own calculations)

Figure 31 and Figure 32 show that large parts of the heat demand in Frankfurt would be supplied by heat from different sources used with different types of heat pumps. Depending on the share of district heating and the share of heat savings different heat sources are the most important for the supply of the heat demand in the city. Besides the electricity and heat demand in heat pumps also municipal waste and (synthetic) natural gas are important energy carriers, at least in the scenarios with lower heat savings (scenarios 1- 5).

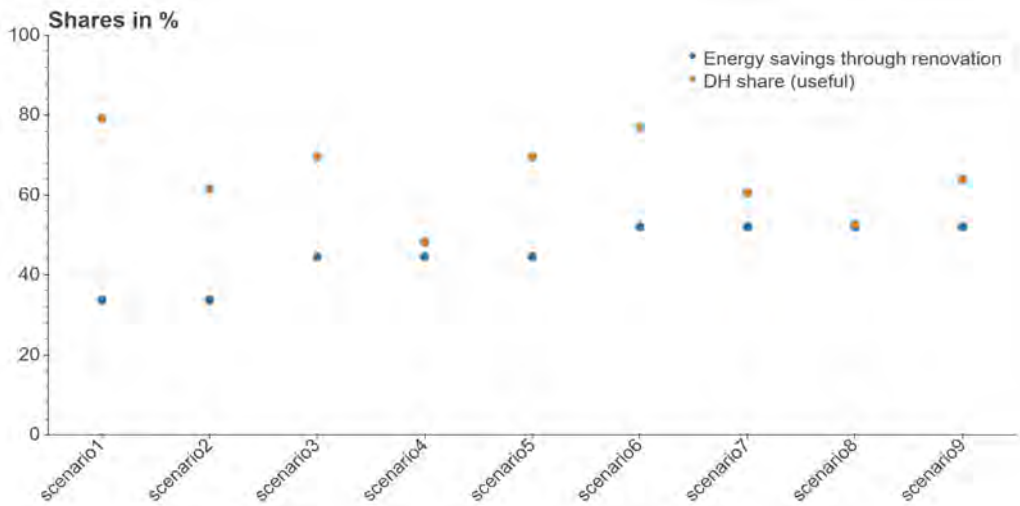


Figure 33: Shares of district heating (DH) and heat savings in the city of Frankfurt in 2050 in the different scenarios (Source: own calculations)

Figure 33 shows the shares of heat savings through buildings renovation (on the total heat demand for space heating and hot water generation) and the share of district heating on the overall heat demand in the buildings.

6.1.3 Conclusions and recommendations from the scenario assessment

Developing this strategy, a high number of calculations have been carried out. This included the collection of a remarkable number of input parameters and the variation and combination of various different of those input parameters. The results of the different analyses have been presented in the previous chapters. Based on these calculations the following conclusions and recommendations are derived.

Reaching a low carbon heating system in the city of Frankfurt is based on two important pillars: the saving of heat demand in the buildings and the supply of the remaining heat demand by energy derived from renewable or excess heat sources. Thus, the availability and the costs of the different options in these two fields are crucial.

In the city of Frankfurt, significant amounts of energy are demanded for industrial production. In the future, the entire local biomass, as well as large parts of the municipal waste potentials, will be needed to supply that heat demand. For the supply of heat demand in buildings, only a small share of the municipal waste potential will be available. This will be needed to supply steam to the district heating steam network in the city centre. However, apart from the municipal waste, a broad variety of local energy sources are available to be used for providing space heating and hot water.

The amounts of identified heat sources to be used with heat pumps together with solar thermal energy will be able to supply large amounts of the heat demand in the buildings in Frankfurt in 2050. However, the calculations have shown that remarkable potentials are not available in times of high heat demand due to cold climatic conditions. Therefore, peak load capacities with very low full load hours will be required in the future heating system of Frankfurt.

The calculations have also shown that a reduction of the overall heat demand in the buildings in the city of Frankfurt also leads to a remarkable reduction of the amounts of necessary peak fuels. Due to the non-availability of biogenic peak fuels, this will most probably also lead to a reduction in the related emissions. This shows the importance of the reduction of the heat demand in the buildings in the city for avoiding fossil emissions for heating.

The results of the calculations show that a reduction of the heat demand in the buildings of the city between 40 and 50% compared to not renovating the buildings will be needed in order to cut down emissions nearly entirely. The calculations also show that the costs for the savings become very high for saving higher shares of the heat demand and that available local resource potentials might be sufficient for supplying the remaining heat demand nearly entirely. In order to reach savings of 53% of the heat demand in the buildings, nearly 75% of the buildings in the city will need to be renovated. Therefore, an ambitious renovation policy should be implemented tackling all buildings in the city. This renovation policy should be based on detailed identification of cost-efficient levels of heat saving in the different buildings and draw special attention to remarkably increase the rate of yearly renovated buildings in the city. This is essential in order to reach heat-saving targets in the coming 30 years.

For the supply of the heat demand in the city, a share of district heating between 60 and 80% seems to be meaningful. On the one hand, district heating allows for the use of large potentials of heat sources in the city that would be difficult or impossible to be used without district heating. This applies especially to the industrial excess heat, excess heat in wastewater treatment plants, excess heat from data centres and from the river water. If these heat sources could not be used, far more ambitious heat savings would be needed also leading to remarkably higher costs. On the other hand, the calculations show remarkably higher costs for decentral supply compared to the costs of supply via district heating for all scenarios.

The results of the district heating grid cost analyses show a strong sensitivity of the costs to the share of buildings connected to the grid in areas where district heat is available (market share) and the amount of heat savings in the area. Also, high shares of district heating in the city will only be possible with high shares of heat demand connected to the district heating system in areas where district heating is available. Therefore, in areas where a district heating system is constructed measures to reach a high share of buildings connected to the grid should be foreseen and prioritized.

As discussed before, the supply of peak load in district heating without fossil CO2 emissions is a challenge in both the steam as well as the hot water district heating networks due to missing biogenic peak fuels. One option is the reduction of the overall heat demand in the city as described before. The remaining peak load can be provided with natural gas and CCS. The costs of this have only been indirectly taken into account in the different CO2 price scenarios. Also, it is not clear if such an option is accepted in the city of Frankfurt. Another option is the supply via synthetic natural gas. Here it is expected that prices will be very high due to the low efficiency of the generation process and the high competition with industrial users.

In the hot water network also the use of heat storage is an option to reduce the needs peak load capacity and fuel. The energy potentials from the identified heat sources would be sufficient to supply the entire heat demand of the buildings in the city in various saving scenarios. However, in order to better understand this potential, the costs related to large multi-weekly and seasonal storage with low full load hours in Frankfurt should be analysed in more detail as a next step. Looking at the difference between the costs of decentral and the costs of district heating supply there might be an economic potential for taking into account relevant multi-weekly heat storage in the city.

In order to reduce the need for peak load capacities and fuels and the related fossil emissions in the steam network, a reduction of the heat demand in the steam network seems appropriate. This can be obtained by heat savings in the buildings in the area of the steam network and also by disconnecting heat demand from the network. The steam network could be transformed into a hot water network starting from the outside of the current steam network. Also, buildings in the city centre could be partly disconnected from the network and only supplied with base load. The peak load of these buildings could then be supplied decentrally via ground source heat pumps.

In the calculations of the supply of heat to the district heating system, different temperatures of the supply line have been taken into account. The results show that the heat supply costs are lower for lower supply line temperatures. At the same time, the costs for the district heating distribution will be higher with lower supply line temperatures due to higher amounts of water distribution for supplying the same amounts of heat in the network. The latter has not been taken into account in the calculations. Therefore, based on the results of this strategy it is not possible to identify a meaningful temperature level of the hot water district heating grids in the city of Frankfurt. Further investigations have to be performed.

Many sensitive input parameters have been varied in sensitivity analyses. However, a remarkable number of input parameters has not been varied in the calculations and are based on estimations and experiences from other cases and countries. Therefore, further analyses have to be undertaken in order to strengthen the conclusions.

The calculations in this strategy have been performed with an interest rate of 3% and a depreciation time equal to the lifetime of each technology and component. This reflects socio-economic calculations and lowest costs mean the lowest costs for the general public. Based on socio-economically meaningful scenarios business cases have to be developed in which potential investors could find economically interesting investment opportunities.

6.2 Heating and cooling strategy roadmap

The overall Strategy, based on the scenario calculations will be to continue the policy of energy saving in the building sector and try to establish more renewable and excess energies for the heating of the buildings:

- Engaging house owners to refurbish their building to the lowest energy demand possible, to retrofit the heating system in the dwellings, so that temperatures in the system can drop under 45°C.
- Convince investors that they build new constructions more ambitious than foreseen in national standards e.g. using the passive house standard and install a heating system operating at low temperatures.
- Try to establish a rule for data centres to cool the systems with water and make this available for district heating on a temperature level of 65°C.
- Convince politicians, the utility and building owners that they expand the existing DH system, connect themselves to the system and establish a city law that all buildings have to connect to the DH system in defined areas.
- Decarbonise the heating system of the city step by step to zero carbon in 2050.

All these actions have to be accompanied by consulting and subsidy measures and also political decisions. E.g. all public buildings should have to be connected to the DH grid or renewable heating systems to show the city society that the municipality itself is a frontrunner (passive house refurbishment has already been implemented).

Table 14: Concrete steps in the near future

Year	Measure	Who	CO2-savings per year
2020	Increase the cooperation with Mainova - defining a roadmap to implement the strategy developed during the Hotmaps project - maybe modifying the strategy in one or the other point	Mainova, Energiereferat, e-think	-
2021	Establish energy managers in integrated city development areas - co-financed by KfW programme 432	Energiereferat - spatial planning department	
2021	Decision of the strategy developed in Hotmaps by the local government	Energiereferat, local parliament	
2021	Decision by local parliament that municipal buildings have to connect to dh-system if available	local parliament	

2022	Replacement of coal fired power plant with gas turbine	Infraserv	500 kt
2022	Local statute for dh connection in existing areas	local parliament, Mainova, Energiereferat	
2023	First project using excess heat from data centres for heating a new development area (outcome of excess heat study from Energiereferat)	Mainova, investor, Telehouse	1000 t
2025	Replacement of coal fired power plant with natural gas plant	Mainova	

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8 Annex

In this section we present assumptions on input data used in the calculation of the scenarios that are not described in the other parts of this document.

8.1 A1) Temperature sensitivity of heat pumps

As described in chapter 2.2.2 the modelling of the generation of heat in the district heating systems takes into account the sensitivity of the COP of heat pumps towards changes in the temperatures of the heat source, the flow and the return of the district heating system. This sensitivity is based on the formula and values described in (Totschnig et al., 2017) and (Gumhalter, 2019). The following table shows the values used for the different modelled heat pump systems together with the fade out and shut off temperatures, the source temperatures and the nominal temperatures for flow and return.

Table 15: Specifications of heat pumps as used in the district heating supply dispatch model (Source: (Totschnig et al., 2017) and (Gumhalter, 2019))

	COP source tempe-rature sensitivity (1/°C)	COP flow tempe-rature sensitivity (1/°C)	COP return tempe-rature sensitivity (1/°C)	min shutoff source tempe-rature (°C)	fade out tempe-rature where power reduction starts (°C)	source tempe-rature (°C)	nominal flow tempe-rature (°C)	nominal return tempe-rature (°C)
HP – River Water	0.0578	-0.0247	-0.0136	3	6	10	70	50
HP – Waste water	0.0578	-0.0247	-0.0136			10	70	50
HP – EH Servers	0	-0.0247	-0.0136			30	65	45
HP – Industrial HT EH	0	-0.0247	-0.0136			80	100	70
HP – Industrial LT EH	0	-0.0247	-0.0136			40	65	45
HP – near-surface Geothermal	0	-0.0247	-0.0136			15	65	45

HP ...... Heat Pump
HT ...... High Temperature
LT ...... Low Temperature
EH ...... Excess Heat
COP ...... Coefficient Of Performance

The technology (type and working medium) of the heat pump for each of the sources as defined in the table is chosen based on the temperatures in which the heat pumps should operate. The operating points of each of the heat pumps are defined separately for each of the sources and for each flow and return temperature scenario of the district heating systems (see chapter 8.2). This is done using median values of the yearly flow and return temperature profiles.

8.2 A2) Flow and return temperatures in the district heating system

For the district heating system (hot water system) three different flow and two different return temperature scenarios are calculated to investigate the influence of these temperatures on the COP of the heat pumps and subsequently on further indicators of the heat supply to the district heating system and the entire heating system in the city. The following figures show the modelled flow and return temperatures in function of the ambient temperature in the city.

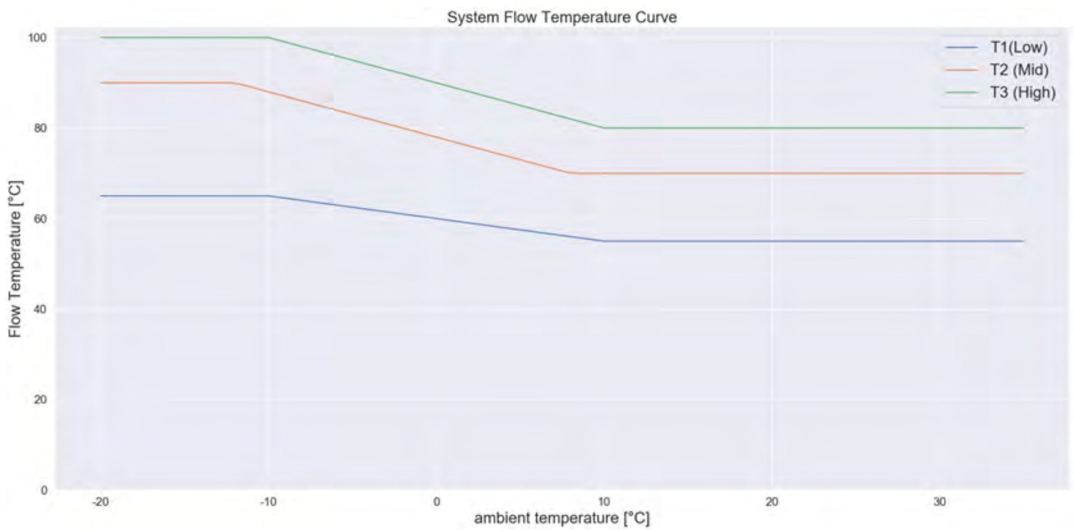

Figure 34: Flow temperature in the district heating systems in function of the ambient temperature used in the dispatch model

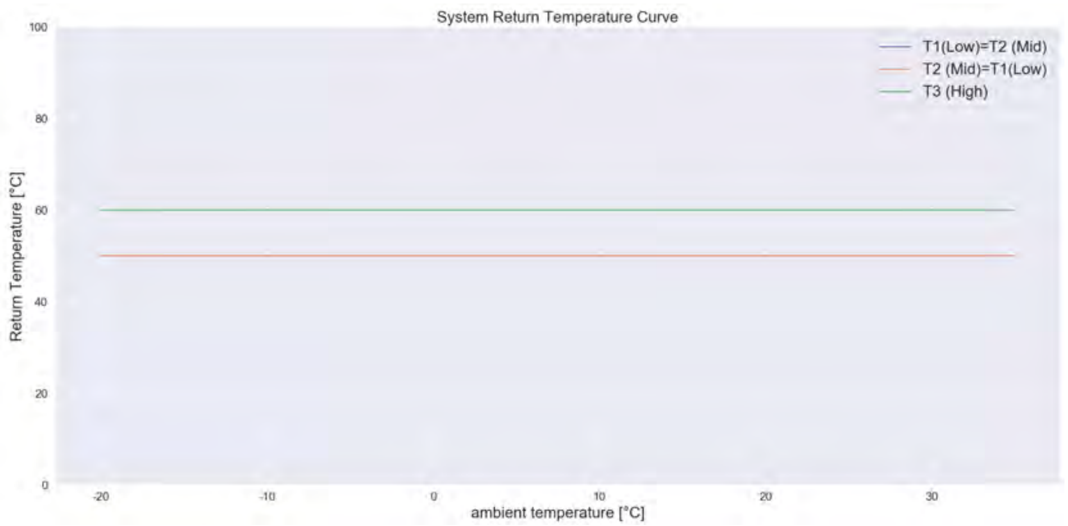

Figure 35: Return temperature in the district heating systems in function of the ambient temperature used in the dispatch model

These relations together with the hourly profile of the ambient temperature (see chapter 8.3) are used to calculate the hourly temperature profiles of the district heating flow and return lines.

8.3 A3) Temperature and solar irradiation profiles

In order to derive the hourly temperature profiles of the district heating flow and return line the ambient temperature for each hour of the year in the city is needed. These data as well as the hourly solar irradiation data have been taken from (EU PVSEC, 2017) for the location of Frankfurt. Furthermore, hourly temperatures of the river water as well as of the outlet of the wastewater treatment plant were needed to model the sensitivity of the COP of the heat pumps. These data have been taken from (GDB, 2020) and (ECO.S, 2018). The following figures show these values for each hour of the year.

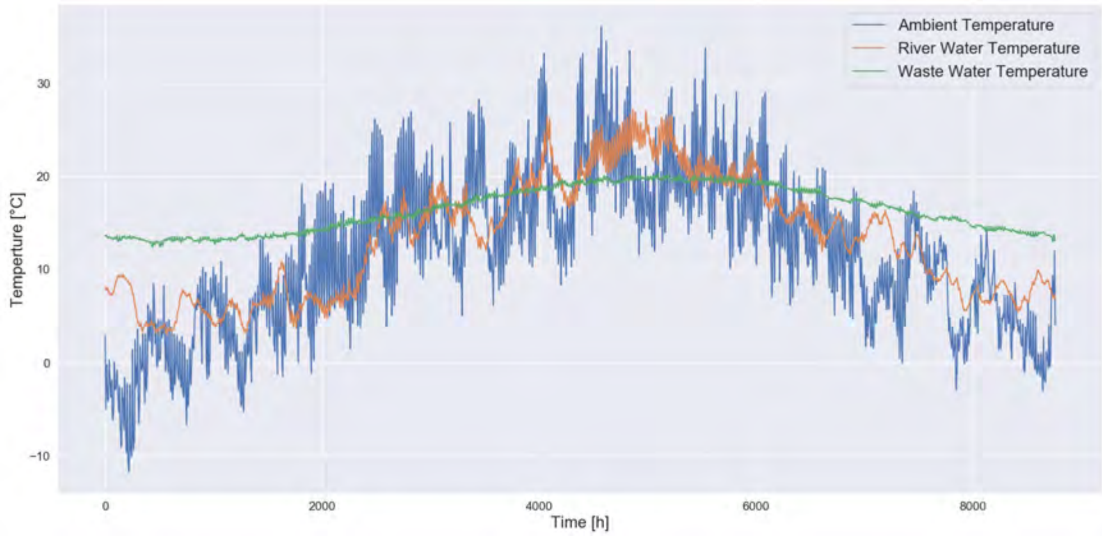

Figure 36: Temperature profiles for ambient air, river water and the outlet of the wastewater treatment plant used in the dispatch model (Source:(GDB, 2020), (ECO.S, 2018), (EU PVSEC, 2017))

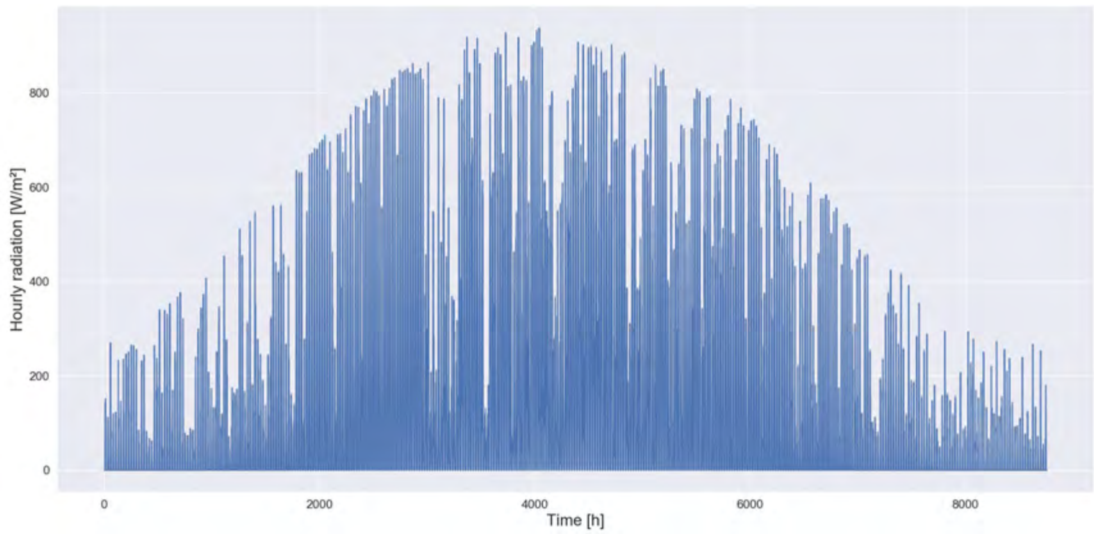

Figure 37: Solar irradiation profile used in the dispatch model (Source: (EU PVSEC, 2017))

8.4 A4) Load profiles of the district heating system

An important input parameter for the calculation of the heat supply to the district heating system is the projected hourly demand profile of the system. For the calculations described in this document the following methodology has been applied: The basis is an hourly profile of heat supply to the current district heating system in Frankfurt provided by Mainova (Mainova, 2017). This profile has been divided into two separate profiles, one profile representing the demand corresponding to space heating and one profile representing the demand for hot water in buildings. For this step the split of space heating and hot water demand over the year as described in chapter 4.1.1 has been used together with hourly profiles of space heating demand and hot water demand in the respective NUTS3 region from the Hotmaps database (Fallahnejad, 2019). The last step was to scale each of the profiles to the overall demand for space heating and hot water generation according to each of the calculated scenarios. With this approach it was possible to account for the change in the characteristics of the load profiles of district heating supply with decreasing share of space heating on the overall load. The following figures show the resulting load duration curves for the overall heat demand (space heating plus hot water) for the calculated sizes of the district heating systems both for the steam as well as for the hot water district heating systems.

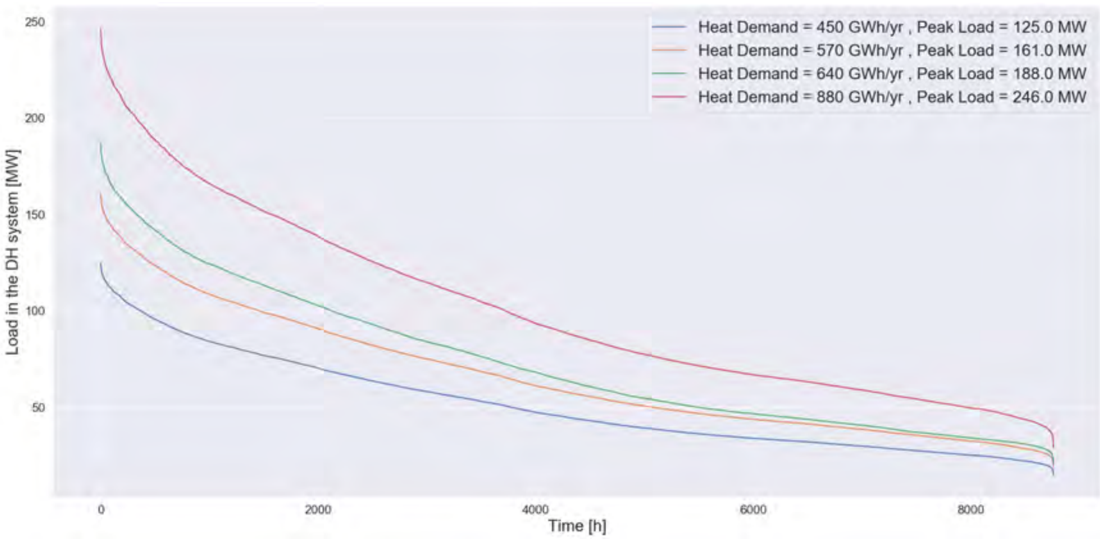

Figure 38: Load duration curves of the district heating system (steam net) for the different total heat demands supplied by the DH system used in the dispatch model (Source: own calculation based on data from (Mainova, 2017) and (Fallahnejad, 2019))

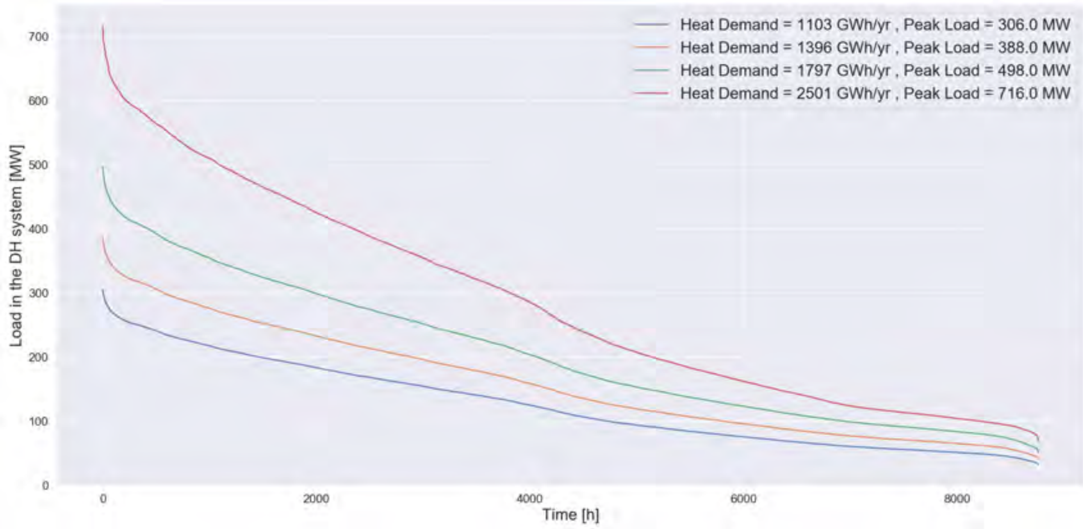

Figure 39: Load duration curves of the district heating system (hot water net) for the different total heat demands supplied by the DH system used in the dispatch model (Source: own calculation based on data from (Mainova, 2017) and (Fallahnejad, 2019))