Max-Julian Gerlach

The role of district heating for the decarbonisation of the buildings sector

A model-based analysis of district heating potentials in Germany towards climate neutrality 2045 in light of recent legislative changes

Master's thesis | Berlin | 02. Juni 2023

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Publisher:

Aalborg University
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Version: 1.0

Duration: 01.02.2023 – 02.06.2023

Pages: 128

Appendices: 5

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Preface

This master thesis is written by Max-Julian Gerlach in order to obtain a degree from the master program Sustainable Energy Planning and Management at Aalborg University. It took place during the 4th semester of the studies from February to June 2023. District heating and the heating transition is an important and challenging topic for the following years as the political and societal discussion during 2023 have shown. Therefore, it is even more important to contribute to the transition of the buildings sector in scientific way.

I would like to take this opportunity and express my gratitude to my supervisor Anders N. Andersen. During these four months, he has inspired me to strive for more and provided me with valuable insight and feedback in order to stay on track. Also, in times of frustration, he was able to guide me towards accomplishing this work.

Furthermore, I would like to thank BBH Consulting and especially, Lars Dittmar and Frederik Seehaus. Through this cooperation, I was able to get a direct insight into the heating transition taking place at the moment and get to understand the complexity of the challenges that concern the heating transition. I want to express my gratitude to everyone in the team of Roland Monjau that has always been there with an open ear to answer my plenty question. Moreover, Lars and Fred managed to find time in their busy schedules to discuss the obstacles I was facing and provide me with constructive feedback that not only improved my work, but also helped to get a better understanding of the topic. I also want to thank Devendra Malla for the exchange and discussions for continuously motivating me.

Finally, I want to express my gratitude to my family and friends who have always supported me throughout the adventures in the past years that I had the privilege to experience. Especially, my parents, Christa Meyer-Gerlach and Axel Gerlach have always been there for me and strengthened me in my decisions and paths that I have taken. It is important to have a strong background that gives enough stability to strive for exciting adventures. Furthermore, I want to thank my girlfriend Daniela Rendon Alonso, who has supported me the best she can from the distance and always cheered me up to keep going in times of struggle. Moreover, I want to thank my friends for reminding me of the good sides in life, when the day consists mainly of working on the thesis.

Reading guide

The introduction can be found in Chapter 1 and is followed by the problem analysis in Chapter 2. Based on the formulated problem, a research question is developed and a research design presented in Chapter 3. The theories which form the basis of the thesis and their application are explained in Chapter 4. Next, in Chapter 5 the methods used throughout the thesis are presented. This is followed by the results of the various analysis conducted in Chapter 6. The results as well as other relevant aspects regarding the research question are then discussed in Chapter 7. Finally, Chapter 8 concludes the results of the analysis and discussion and further recommendations for research are presented in Chapter 9.

Abstract

The buildings sector in Germany has missed its greenhouse gas emission reduction target for two years in a row with the majority of the emissions relating to the use of fossil fuels for heating. Therefore, urgent action is required and new support schemes for district and individual heating have been introduced. While DH currently accounts for 14% of the heat demand, other countries have reached a share of more than 60%. This thesis therefore aims to answer the question which role district heating can play for German municipalities larger than 10,000 inhabitants in order to supply heat in an economically feasible way and reach climate neutrality in 2045 in light of the new support scheme BEW while considering the different potentials for renewable and waste heat?

The research design is based on the theories Multi-Level Perspective, which explains the transition of the heating sector and Choice Awareness, which explains how radical technological change towards renewable district heating can be implemented. In combination with the guidelines for municipal heat planning, this also leads to the selection of the methods. Besides data gathering, the heat demand and existence of district heating as well as the potential for renewable and waste heat for urban areas are analysed. This is followed by a cluster analysis and an energy system analysis in order to assess the feasibility of district heating.

The heat demand in urban areas with existing district heating is overall higher compared to areas with potential district heating. Furthermore, the heat demand is expected to decrease by around 35% until 2045, while the district heating distribution capital costs are doubled over the same time. Currently, on average around 90% of the heat demand can be covered by 4th Generation district heating. While waste heat and ambient heat from lakes is only available in less than 25% of urban areas, ambient heat from river and wastewater are the most promising heat sources in addition to solar thermal.

The cluster analysis showed the no optimal number of clusters could be determined based on the selected input variables. Therefore, max and min cluster are derived based on statistical criteria where the max cluster represents a large and a medium-sized urban area with all available renewable and waste heat potentials in urban areas with existing and potential district heating respectively. On the other hand, the min cluster represents a medium-sized and a small urban area with no heat potentials in urban areas with existing and potential district heating respectively.

While district heating is more feasible compared to individual heating for both the max and min cluster currently, it is only more feasible in 2045 for urban areas with existing district heating. On the other hand, establishing new district heating is only feasible in 2045 if sufficient waste heat potentials are available, but otherwise individual heating is more feasible. In general, waste heat is the cheapest heat potential available and otherwise large-scale heat pumps in combination with solar thermal and heat storage are used if available. Furthermore, combined infrastructure planning has the potential to reduce the costs of district heating and make it more feasible than individual heating.

Therefore, it can be concluded that district heating is feasible for urban areas with existing district heating, while the establishment of new district heating towards climate neutrality 2045 is uncertain and depends significantly on the time of investment or combined infrastructure planning.

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BEG	*Bundesförderung effiziente Gebäude* (Federal funding for efficient buildings)
BEW	*Bundesförderung effiziente Wärmenetze* (Federal funding for efficient heating networks)
CAPEX	Capital expenditures (investment costs)
CCS	Carbon capture and storage
COP	Coefficient of performance
DH	District heating
DHDCC	District heating distribution capital costs
DHW	Domestic how water
FEC	Final energy consumption
FLH	Full load hours
GEG	*Gebäudeenergiegesetz* (Buildings Energy Act)
GIS	Geographic information system
HD	Heat demand
KGS	*Klimaschutzgesetz* (Federal Climate Change Act)
LCOH	Levelized costs of heating
MLP	Multi-Level Perspective
OPEX	Operation expenditures (operation and maintenance costs)
PTES	Pit thermal energy storage
RE	Renewable energy
SH	Space heating
SHD	Specific heat demand (heat density)
TCS	Trade/Commerce/Services
UA	Urban area
WACC	Weighted average cost of capital

1 Introduction

Climate change is the single most serious problem facing the world. According to a recent survey in the EU, more than nine in ten persons believe that climate change is a serious problem (European Commission, 2021). While almost all countries in the world have adopted the Paris Agreement and therefore vowed to limit global warming to well below 2 °C and pursue further efforts to confine the increase to 1.5 °C above pre-industrial levels (UNTC, 2016), the reality looks quite different. The latest report of the Intergovernmental Panel on Climate Change, published in March 2023 projects that the measures taken so far can only limit the increase in temperature to 3.2 °C by 2100 and therefore clearly miss the targets of the Paris Agreement. As global warming has already reached 1.1 °C on average over the last ten years, urgent action is required. In order to limit the temperature increase to 1.5 °C, global greenhouse gas (GHG) emissions would have to be cut by half until 2030. (IPCC, 2023)

While Germany has managed to reduce its GHG emissions between 1990 and 2020 by 40%, further ambitious action is required to meet the target of reducing GHG emissions by 65% by 2030 compared to 1990 levels on the way to climate neutrality in 2045 (Presse- und Informationsamt der Bundesregierung, 2022). Overall, the efforts so far have mainly focused on the transformation of the electricity sector, while other sectors such as the buildings and transport sector have been neglected and missed their emission reduction targets for two years in a row.

The GHG emissions of the buildings sector can mainly be attributed to the heating of the buildings through fossil fuels (Deutsche Energie-Agentur (dena), 2022). Therefore, an urgent transition towards renewable energy (RE) is needed. According to research, the main levers for the transition will be individual heat pumps (HP) and the extension and transition of district heating (DH) (Institut für Energie- und Umweltforschung (ifeu) et al., 2023). Therefore, the government has planned the introduction of municipal heat planning and a minimum share of 65% RE for individual heating. These measures are furthermore flanked by support schemes for individual heating systems and DH. (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen (BMWSB), 2022)

Through municipal heat planning, municipalities will have to identify areas that are suitable for DH and decide if the existing DH network should be extended and transformed or a new DH should be established. While the feasibility of DH in the past mainly depended on the heat density, municipalities also have to take the potential for RE into account, as this can significantly influence the feasibility of DH. Moreover, there are various advantage of DH, such as the integration of waste heat or the provision of flexibility to the electricity grid. However, it also requires high investments and depends on the acceptance of the society (Institut für Energie- und Umweltforschung (ifeu) et al., 2023).

While the share of DH compared to the total heat demand in Germany is rather low with around 14%, other countries such as Denmark have reached share of 65%. Therefore, this thesis aims to identify the role that DH can play for municipality in the transition towards climate neutrality in 2045. Therefore, the feasibility of DH will be compared to individual heating while taking local difference in terms of RE and waste heat potentials into account.

2 Problem analysis

In the following, the GHG emissions and targets in Germany and the buildings sector are analysed. Next, a brief description of the proposed legislative changes and the possible pathways for the transition of the buildings sector are presented.

2.1 GHG emissions and targets in Germany

As one of the largest economies in Europe and the world, Germany is the biggest emitter of GHG emissions in Europe and one of the 10 largest emitters of GHG emissions in the world. (The World Bank Group, 2020) Germany has been working to reduce its GHG emissions since the 1990s and has made significant progress as shown in Figure 1 below. Overall, Germany managed to reduce its GHG emissions by more than 40% since 1990 from 1,251 Mt CO_2e to 746 Mt CO_2e in 2022. This reduction was achieved through a combination of measures, including an increased use of renewable energy, improved energy efficiency, and reduced emissions from the industrial sector. (Umweltbundesamt (UBA), 2023)

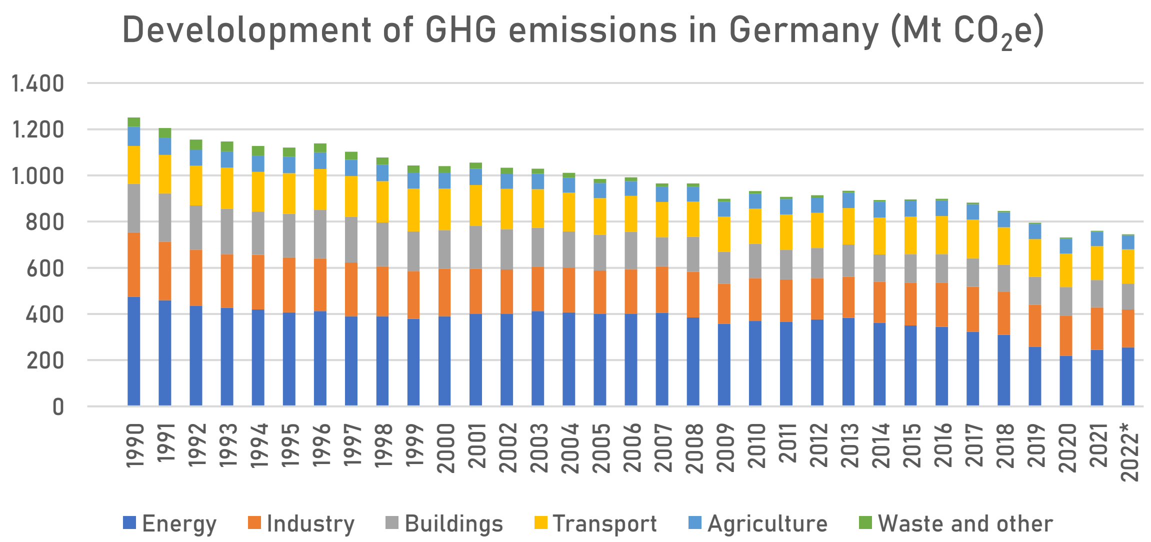


Figure 1: Development of GHG emissions in Germany between 1990 and 2022 by sector in Mt of CO_2e. Value for 2022 is preliminary. (Umweltbundesamt, 2023)

The contribution of the different sectors to the GHG emissions has remained mostly constant with the exception of the transport sector increasing its share from 13% in 1990 to 20% in 2022. Furthermore, the energy sector managed to decrease its share from 38% in 1990 to 30% in 2020 but has recently grown again to 34% in 2022. This can mainly be attributed to the increased use of coal power plants due to the boycott of Russian gas and the increased natural gas prices. Therefore, the energy sector still remains the major source of emissions in Germany. Next, the industry and transport sectors follow with a share of 22% and 20% respectively in 2022. The buildings sector contributed around 15% to the GHG emissions in 2022, while the agriculture sector only accounted for a share of 8%. (Umweltbundesamt (UBA), 2023)

Despite this progress, Germany still faces significant challenges in meeting its GHG emissions reduction targets. Germany has made various commitments to reduce its GHG emissions and its targets became more ambitious over the years. To deliver on the goals of the Paris Agreement, Germany and the EU made the commitment in 2019 to reach netzero emissions by 2050. Following a constitutional complaint in 2021, the German *Klimaschutzgesetz* (Federal Climate Change Act; KSG) has further been tightened and now aims for climate neutrality in 2045. This also meant increasing the GHG emission reduction target for 2030 from 55% to 65% and setting a GHG reduction target of 88% by 2040. (Presse- und Informationsamt der Bundesregierung, 2022)

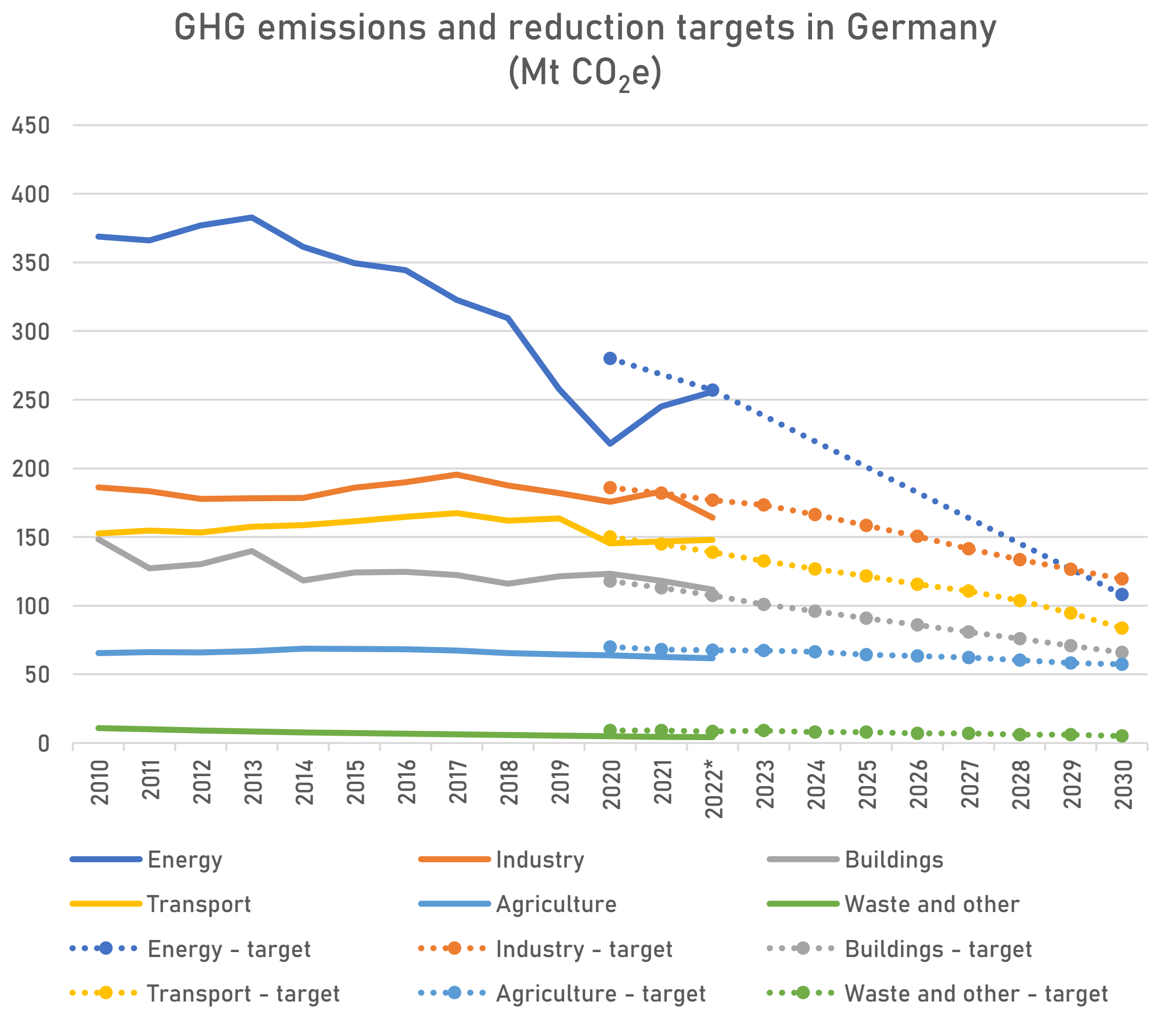


Figure 2: Development of GHG in Germany between 2010 and 2022 and reduction targets according to the Klimaschutzgesetz between 2020 and 2030 by sector in Mt of CO_2e. Value for 2022 is preliminary. (Umweltbundesamt, 2023)

In the KSG, binding reduction targets for each sector for 2030 are defined, as shown in Figure 2 above. Based on the current emissions levels in 2022, the energy sector needs to achieve the highest reduction of 58% to reach 108 Mt CO_2e in 2030. This is followed by the transport and buildings sector which need to reduce their emissions by 43% and 40% respectively. The industry will also need to achieve emission reductions of 28%, while agriculture and waste and others only need to reduce emissions by less than 10%. In total the GHG emissions in Germany still need to be reduced by 40% compared to now in order to reach the target in 2030. This means that the yearly average rate of emission reduction has to increase from less than 2% for the period since 2010 to 5% for the period between 2023 and 2030. (Umweltbundesamt (UBA), 2023)

The *Expertenrat für Klimafragen* (Council of Experts on Climate Change), which is responsible for monitoring the progress towards the climate targets, lamented that the transport and buildings sectors missed their respective reduction targets 2022 for the second year in a row. Moreover, the buildings sector profited from mild weather and heat savings due to the limited availability of natural gas and thus the gap could have been significantly greater. The other sectors on the other hand managed to reach their targets, although the emissions of the energy sectors have increased sharply. If the overall rate of emission reduction stays at the current level, this would lead to a gap of 190 Mt CO_2e in 2030. Therefore, significant action is required to reach the GHG reduction targets in 2030. A more detailed report estimating the impact of the current policies and comparing it to the climate targets was to be released by the end of March 2023, but was delayed and could therefore not be considered in this report. (Expertenrat für Klimafragen, 2023)

As seen above, especially the buildings and transport sectors are crucial to focus on for the reduction of GHG emissions in Germany. However, these sectors pose a significant challenge in terms of decarbonisation and have not received the same attention as the energy sector, which has largely been the focus of the climate and energy policy in the past years.

For the building sector, the GHG emissions can be mainly attributed to the heating of buildings through fossil fuels. One of the main challenges is the long investment horizon and as buildings are designed and constructed to last for various decades, retrofitting them to become more energy-efficient can be a time-consuming and expensive process. Furthermore, the amortization of the investments can take some time and the payback time might even extend beyond the planned stay at the building.

Another challenge in the buildings sector is the ownership structure of the buildings. The majority of buildings are rented out and tenants usually have no influence on investment decisions regarding the retrofitting of heating systems. On the other hand, there might also be little incentive for building owners to invest in retrofitting of heating systems, as the reduction in variable costs would mostly benefit the tenant and the rent cannot always be increased accordingly.

Lastly, fossil-based heating systems provide another challenge to the building sector and are connected to the other challenges. Many buildings are still heated by oil or gas-based systems with a long lifetime and the replacement with renewable systems can be capital intensive and might require previous retrofitting. In the following, the building sector in Germany will be analysed in more detail in the following. (Burkhardt and Blesl, 2023)

2.2 Buildings sector in Germany

In 2021, around 19 million residential buildings existed in Germany, consisting of 13 million single-family houses and three million two-family houses and multi-family houses each. Additionally, there are around two million non-residential buildings, which are relevant for the *Gebäudeenergiegesetz* (Buildings Energy Act; GEG) and thus are either heated or cooled. The total number of housing units in residential buildings is around 42 million in addition to the one million housing units in non-residential buildings, leading to a total of around 43 million housing units in Germany. (Deutsche Energie-Agentur (dena), 2022)

The heating systems for housing units are dominated by gas-fired units which accounted for almost 50% of the installed systems in 2020, as shown in Figure 3 below. This is followed by oil-fired units which make up 25% and 14% of housing units which are connect to DH. Even though, HPs have been installed in a lot of new buildings from 2007 onwards, they currently only account for less than 3% of the installed heating systems. Overall, the structure of heating systems is very static and only changes by 0.2% to 0.3% yearly despite the high share of renewable energies in new residential buildings. (Bundesverband der Energie- und Wasserwirtschaft (BDEW), 2022; Deutsche Energie-Agentur (dena), 2022)

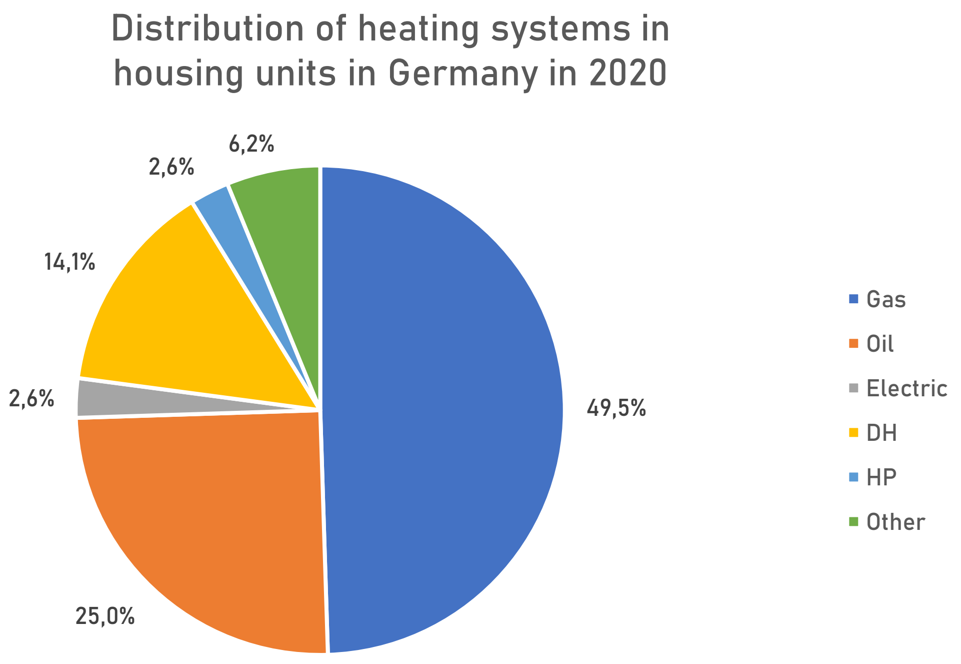


Figure 3: Distribution of heating systems in housing units in Germany in 2020. (BDEW, 2022)

The average age of heating systems in Germany is 17 years, indicating that plenty of units will have to be replaced in the coming years, considering a lifetime of around 20 to 30 years. Already now, 40% of the heating systems are older than 20 years and 25% are older than 25 years. Therefore, it is important to channel the new investments for the replacement of the heating systems into renewable energy sources. When looking at the age structure of residential buildings, it can be observed that 67% of the existing buildings were constructed before 1979. The majority of these buildings are therefore in need of energetic retrofitting. Therefore, retrofitting of buildings and replacement of heating system should be thought together as this can significantly affect the available options and costs. (Bundesverband der Energie- und Wasserwirtschaft (BDEW), 2022)

However, the rate of retrofitting in Germany has stagnated at around 1% per year since 2010. In order to reach the climate targets in 2030, the efforts would need to be strengthened and the rate of retrofitting would have to increase to at least 2% to 2,5% per year. Furthermore, the depth of retrofitting would also need to increase and reach on average the standard *Effizienzhaus 55*, which only requires 55% of the primary energy demand of a reference building defined in the GEG. (Umweltbundesamt (UBA), n.d.)

The final energy consumption (FEC) of the buildings sector amounted to 907 TWh in 2021, which is around 38% of the total FEC in Germany of 2.403. Out of this around 817 TWh, so 90% of the FEC of the buildings sector and 34% of the total FEC relate to space heating (SH) and domestic hot water (DHW), which makes heating the most important energy use for the buildings sector. Different from the KSG, the FEC is commonly grouped into the sectors industry, trade/commerce/services (TCS), transport and households. Households (residential buildings) make up 64% of the FEC of the buildings sector, while TCS and industry (non-residential buildings) make up 30% and 6% respectively. The FEC of heating in residential buildings is 98% and 76% in non-residential buildings, where lighting also plays a significant role. Therefore, as already previously mentioned the heating demand is the most important energy demand in the buildings sector. As the heating systems are mainly dominated by fossil-based systems, as shown in Figure 4 below, a transition to RE is an important measure to reduce GHG emissions. (Deutsche Energie-Agentur (dena), 2022)

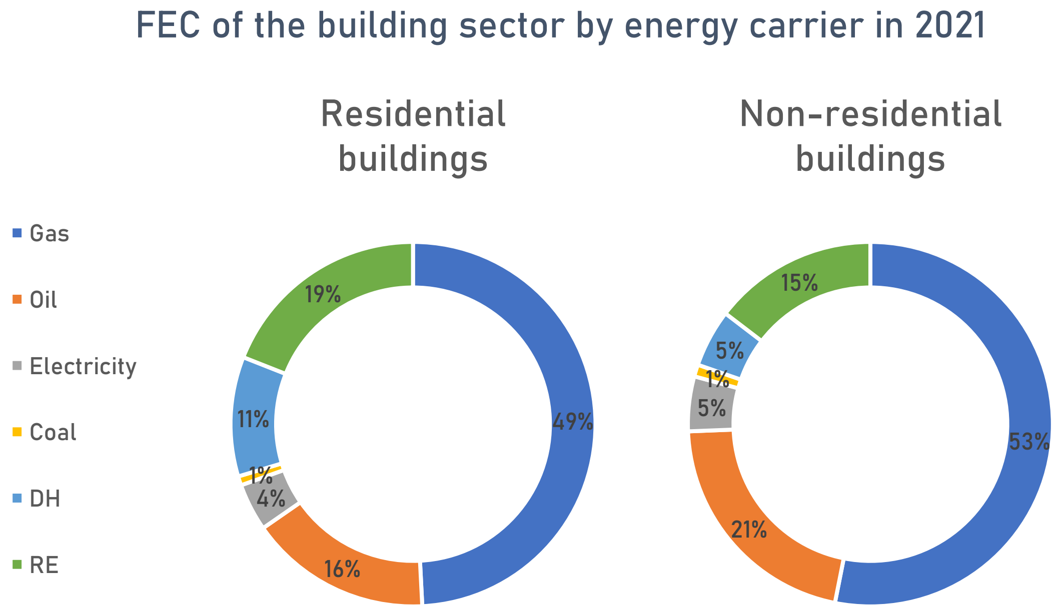


Figure 4: FEC of the buildings sector by energy carrier divided into residential and non-residential buildings for 2021. (Deutsche Energie-Agentur (dena), 2022)

The share of energy carriers in the FEC is very similar to the distribution of heating systems shown above, it shows however the share of RE of the FEC. For residential buildings the RE share of the FEC has almost doubled from 10% in 2008 to 19% in 2021. On the other hand, the share of oil has decreased from 31% to 16%. Looking at non-residential buildings, the RE share also increased significantly from 3% in 2008 to around 15% in 2017 and has stayed almost constant since. This was accompanied by a decrease of the DH share from 16% to only 5% in 2021. The RE share only accounts for the direct use of energy carriers in the buildings sector and not for the RE share in electricity or DH. This can therefore mainly be attributed to the use of biomass, biogas and solar thermal energy. Overall, the share of RE in the buildings sector is around 18%. (Deutsche Energie-Agentur (dena), 2022)

While there have been some positive trends in the recent years, the share of RE in the buildings sector is still rather low. Furthermore, the rate of retrofitting is lacking behind and the GHG emissions have missed the reduction target in the past years. The government has acknowledged these shortcomings and released a *Sofortprogramm* (Climate Action Programme) for the buildings sector, as required by the KSG. The most important measures that are planned or have been implemented will be explained in the following. (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen (BMWSB), 2022)

2.3 Recent and proposed policy and regulation for the buildings sector

Overall, the measures of the Sofortprogramm consist of the continuation and extension of existing measures as well as the introduction of new measures and focuses on the retrofitting of buildings, increase of energy efficiency and promotion of RE in the heating sector. Furthermore, municipal heat planning should play a more important role. The government expects that the recently introduced and proposed measures will lead to additional GHG emission reductions of 156 to 161 Mt CO_2e and will therefore be able to close the existing cumulated GHG emissions gap between 2022 and 2030 of around 152 Mt CO_2e. While the reduction targets will still not be reached until 2026, overachievements from 2028 onwards will lead to compliance with the GHG budget for the entire period until 2030. (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen (BMWSB), 2022)

2.3.1 Support schemes for buildings and DH

Prior to the regulatory changes, the government has already introduced new support schemes for buildings (*Bundesförderung effiziente Gebäude*, BEG) and heating networks (*Bundesförderung effiziente Wärmenetze*, BEW). These are supposed to flank the regulatory changes and provide financial incentives for the heating transition. (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen (BMWSB), 2022)

The BEG combines previous support schemes and focuses on increasing energy efficiency and promoting new RE heating systems. The scheme therefore supports individual measures on the building envelope, the optimisation of existing heating systems and the installation of system technology with 15% of the investment costs. The installation of new RE heating system is even supported with up to 40% of the investment costs depending on the technology. Furthermore, the BEG also contains a component that supports the retrofitting of existing buildings through a loan repayment subsidy depending on the efficiency standard. (Bundesamt für Wirtschaft und Ausfuhrkontrolle (BAFA), n.d.)

The BEW on the other hand supports the establishment of new DH with a high RE share and the transformation of existing fossil-fuel based grids. The scheme therefore mainly focuses on the DH as a whole instead of individual measures, but still provides support for individual measures in appropriate cases. The funding programme is divided into four modules which build on each other as shown in Figure 5 below. Module 1 provides support for the development of transformation plans and feasibility studies which lead to a GHG-neutral DH in 2045 and covers 50% of the costs up to 2 million EUR. The investments into HPs, geothermal, solar thermal, biomass boilers, heat storage or system components for existing DHs with a transformation plan or new DHs with a feasibility study is covered by module 2. There are various requirements, which limit among others the grid temperature and the share of biomass depending on the length of the grid. Overall applicants can receive 40% subsidy of the investment costs up to 100 million EUR. Module 3 provides investments subsidies for individual measure in existing DHs with transformation plans and has the same conditions as module 2. Additionally, HPs and solar thermal units supported through module 2 or 3 can receive operating funding for a period of up to 10 years depending on a profitability analysis. (Bundesamt für Wirtschaft und Ausfuhrkontrolle (BAFA), n.d.)

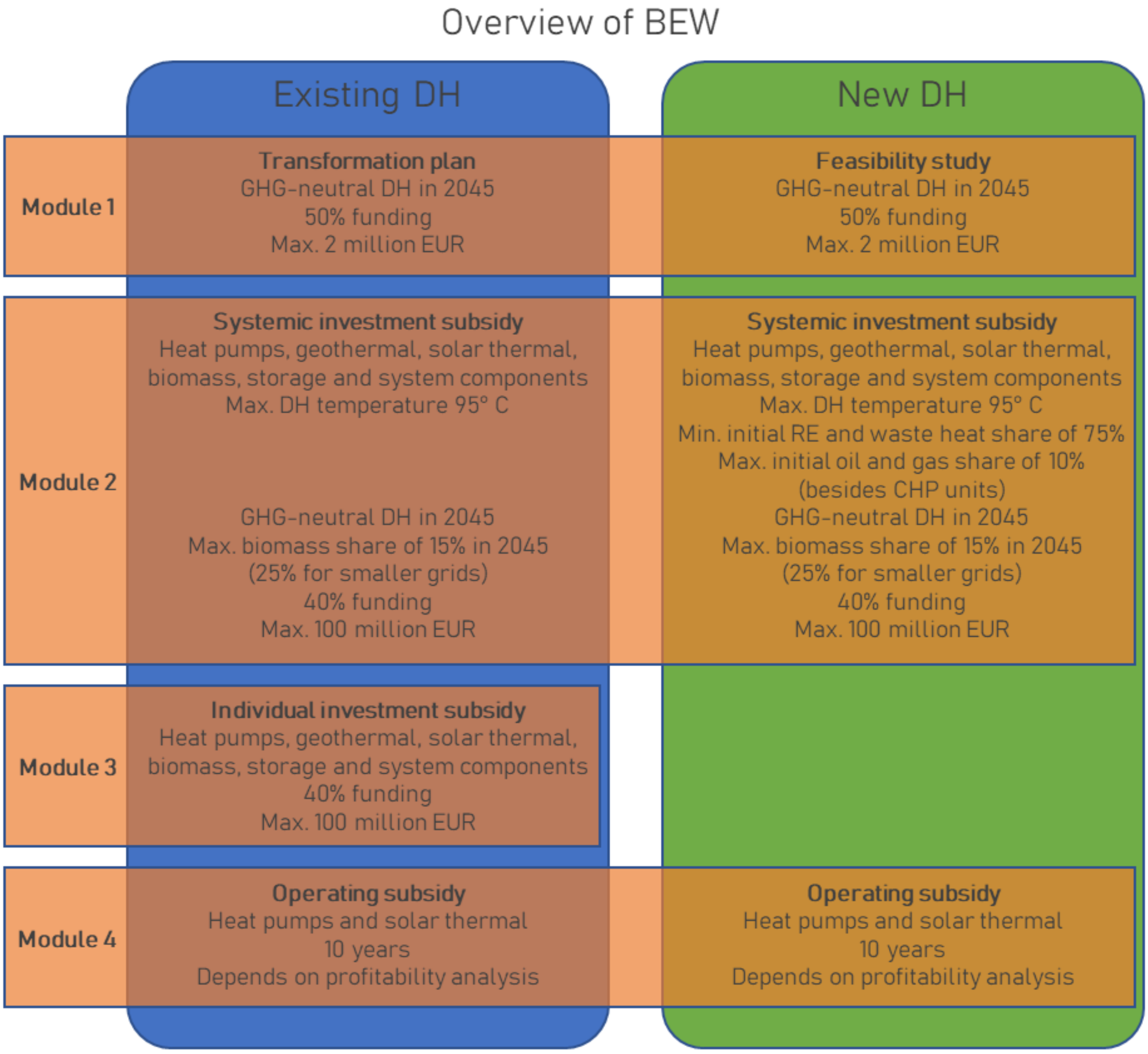


Figure 5: BEW funding scheme divided into modules for new and existing DH with requirements and funding amount (Bundesamt für Wirtschaft und Ausfuhrkontrolle (BAFA), n.d.)

2.3.2 Amendment of the Gebäudeenergiegesetz (GEG)

The amendment of the GEG has been heavily debated among the government and society. The final draft of the government from April 2023 establishes that every new heating system installed from 2024 onwards has to use at least 65% RE and the use of fossil fuels for heating systems will be forbidden by 2045. In order to achieve the required 65% RE various options exist. The connection to DH, HPs, electric heating systems, hybrid heating systems and solar thermal automatically comply with the requirement. Furthermore, H_2-ready gas heating systems can be used, if the use of 65% hydrogen from 2035 onwards can be guaranteed by the distribution grid operator. Additionally, existing buildings are also allowed to use biomass heating systems or gas heating systems in connection with the certified use of renewable gases. In order to ensure a socially acceptable transition, the installation of new heating systems is supported to varying degrees. The BEG should be adjusted to support the installation of new heating systems with 30% for all technologies. On top of that additional support can be received e.g., for the replacement of very old heating systems or for older people. (Bundesministerium für Wirtschaft und Klimaschutz (BMWK) and Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen (BMWSB), 2023)

According to the coalition agreement it is further intended to increase the energy efficiency standard for new buildings to *Effizienzhaus 40*[1] from 2025 onwards by another amendment of the GEG. Furthermore, the EU Commission has proposed to introduce minimum energy performance standards in the revision of the Energy Performance of Buildings Directive. This would mean that the 15% of the building stock with the worst energy performance in each EU member state will have to be retrofitted by 2027 or 2030 for non-residential and residential buildings respectively. The directive is currently negotiated in trilogues and would most likely be implemented through another amendment of the GEG. (Bundesministerium für Wirtschaft und Klimaschutz (BMWK) and Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen (BMWSB), 2023)

2.3.3 Municipal heat planning

In order to better coordinate the activities of the stakeholders involved in the heating transition, the government intends to implement a new municipal heat planning law. A final draft of the government has been expected for some time and is currently discussed in the government. A discussion paper from July 2022 describes the main advantage of a municipal heat planning law in providing predictability for public and private investments, as municipal heat plans determine the priority of the available heat supply technologies for the different parts of the municipality. It furthermore serves as a connection between the legal regulations (e.g., GEG) and support schemes (e.g., BEG and BEW) and can thus accelerate the heating transition and make it more efficient. (Bundesministerium für Wirtschaft und Klimaschutz (BMWK), 2022)

Based on the discussion paper, municipalities with more than 10,000 or 20,000 inhabitants will be required develop municipal heat plans within 3 years of the entry into force of the proposed law (expected before 2024). The municipal heat plans should be a legally binding planning and control instrument for the heating transition and should be updated every five years. The development of the municipal heat plan should involve the relevant stakeholder and consist of an inventory analysis, potential analysis, target scenario and an action strategy. (Bundesministerium für Wirtschaft und Klimaschutz (BMWK), 2022)

The proposed measures of the government therefore focus on the retrofitting of buildings and the increase of energy efficiency. In terms of technology the measures support the transformation of DH, the establishment of new DH with a high share of RE as well as the promotion of RE for individual heating, especially HPs. However, according to research projects, this is still not enough to steer towards a climate neutral buildings sector in 2045. In the following possible pathways to reach climate neutrality for the buildings sector in 2045 are therefore described.

[1] Accordingly, an Effizienzhaus 40 only requires 40% of the primary energy demand of a reference building defined in the GEG

2.4 Pathways towards a carbon neutral buildings sector

Despite the recently introduced and proposed policies, the buildings sector still faces various challenges. A comparison of the major scenarios for climate neutrality in Germany shows that the rate of retrofitting is expected to increase to 1.5% for the period until 2030. For heating systems, the majority of scenarios expect the installation of 6 million HPs by 2030 and 15 million HPs by 2045. Furthermore, the share of DH is expected to increase to 15% in 2030 and 30% in 2045. It is therefore clear that the main focus lies on the installation of HPs and the extension of DH. Overall, the time till 2030 will be extremely important to set the buildings sector on a pathway towards climate neutrality. (Lübbers et al., 2022)

Larger municipalities will soon have to conduct municipal heat planning and will face the challenge of deciding which role DH should play in the heat supply of the buildings sector. As individual heating has been predominating the heating supply since, it is also assumed to be the default for many municipalities. Furthermore, DH involves various stakeholders and involves more planning than individual heating systems. However, it is expected that DH will be the primary solution for densely populated urban areas, as there are spatial or noise constraints for the installation of HPs or other RE technologies. Therefore, existing DH has to be transformed to RE and new DH has to be established. (Burkhardt and Blesl, 2023; Institut für Energie- und Umweltforschung (ifeu) et al., 2023)

The transition of existing DH faces various challenges. Probably the most obvious challenge is to increase the share of RE from currently 17% to 100%. As heat cannot easily be transported over long distances, the transition to RE depends significantly on the local potentials or other renewable energy carriers. Natural gas has long been considered as bridging technology for the transition of DH and is a major component of existing DH due to the low costs and security in supply. However, due to the Russian invasion of Ukraine and the following sanctions, gas has become scarce and prices have increased significantly and changed the perspective of many municipalities and utilities. (Burkhardt and Blesl, 2023; Institut für Energie- und Umweltforschung (ifeu) et al., 2023)

While hydrogen will play a significant role in the transition to a carbon neutral society overall, various studies showed that the use of hydrogen in the buildings sector is economically unattractive. Furthermore, the green hydrogen that will be available will be needed more urgently in other sectors such as industry, maritime or aviation. The transition of existing DH therefore depends on RE such as solar thermal, geothermal or ambient heat sources in combination with large scale heat pumps. However, the availability of most RE sources varies significantly between municipalities and thus there is no one-size-fits-all solution for the transition of existing DH. (Burkhardt and Blesl, 2023; Institut für Energie- und Umweltforschung (ifeu) et al., 2023)

Moreover, the majority of existing DH operates at temperatures above 100 °C, which makes the integration of RE, mainly through large-scale HPs, difficult or significantly reduces their efficiency. While there are also low-emission technologies such as biomass, geothermal or waste-to-energy that can provide heat at current temperature levels, their availability and capacity are limited. Therefore, existing grid temperatures have to be lowered, which often not only requires a conversion of the grids, but also adjustments at the end customers. (Burkhardt and Blesl, 2023; Institut für Energie- und Umweltforschung (ifeu) et al., 2023)

To facilitate the transition of DH and establish new DH, significant investments are required, which can easily reach more than 100 million EUR even for medium-sized DH with high costs already occurring during the planning and concept phase. This is especially a problem for smaller municipalities, which often have limited resources. Therefore, it is important to use synergies with other municipal infrastructure measures such as road construction. This requires good planning but has the potential to reduce costs by 30%. Additionally, there is the risk of low connection rates, which decreases the profitability of DH. Furthermore, due to the increase in energy efficiency in the buildings sector, the profitability of DH might decrease over time and thus requires early investments in DH and high connection rates. (Burkhardt and Blesl, 2023; Institut für Energie- und Umweltforschung (ifeu) et al., 2023)

On the other hand, DH also provides the opportunity to access heat sources such as waste heat, geothermal or ambient heat from rivers or lakes. While waste heat is basically available for free, ambient heat from water sources can lead to higher efficiency compared to air, especially in winter when the heat demand is highest. Furthermore, DH can provide additional flexibility to an increasingly smart and fluctuating RE based electricity system compared to individual heating systems through a larger storage capacity of heat. (Burkhardt and Blesl, 2023; Institut für Energie- und Umweltforschung (ifeu) et al., 2023)

Besides the recently introduced and proposed policies, there is still the potential for further measures. This could include the setting of RE quotas or emission limits for DH or the mandatory connection to DH if it is available. Furthermore, the exemption of HPs from fees and taxes would significantly increase the profitability of DH, as it will rely to a large extent on HPs. It also remains to be seen, what impact the energy crisis has on the development of DH. (Burkhardt and Blesl, 2023)

As DH will play an important role in a carbon neutral buildings sector in Germany, its share is expected to reach 30% in 2045. While this is a significant increase, DH plays a more significant role in other European countries with shares above 50%. In Denmark for example, DH has reached a share of around 65% in residential housing units. This has been achieved among others through municipal heat planning, mandatory connection, the non-profit principle and the same approximate price for customers irrespective of heat densities. Therefore, there seems to be further potential also for DH in Germany. (Johansen and Werner, 2022)

3 Research question

Based on the problem formulation the research question is formulated and its scope and delimitations are discussed. The research design concludes this chapter by explaining the approach to answer the research question.

3.1 Problem formulation

Based on the previous problem analysis, the following problem can be formulated. Germany aims to reach climate neutrality by 2045 and reduce its GHG emissions by 65% by 2030 compared to 1990 levels. Therefore, specific reduction targets for each sector have been introduced. Especially the transport and buildings sector are lacking behind and have missed their targets for two years in a row. Focusing on the buildings sector, the emissions mainly relate to provision of SH and DHW for buildings. The heating systems are however mainly based on fossil fuels and the RE share of the FEC in the buildings sector is only 18%. Furthermore, the rate of retrofitting to increase energy efficiency is stagnating at 1% and would need to be further increased.

In order to bring the buildings sector back on track, the government has recently introduced and proposed further measures. These mainly focus on the promotion of RE, the increase of retrofitting and the transformation and extension of DH. However, there are still various challenges to achieve a carbon neutral buildings sector. Especially DH is seen as the main technology for densely populated urban areas. However, the transformation of existing DH is a major challenge, as this depends significantly on the availability of local RE potentials. Furthermore, the majority of existing DH network operate at high temperatures above 100 °C, which makes the integration of RE sources difficult and reduces their efficiency. The establishment of new DH is furthermore very capital intensive and requires large investments in infrastructure. There are however also opportunities for a better integration of waste heat and fluctuating RE electricity production. While research projects expect a DH share of 30% in a climate neutral Germany 2045, other countries, such as Denmark have reached a DH share of 65%. As large municipalities will soon be required to conduct municipal heat planning, this raises the question for municipalities what role DH plays for them and leads to the formulation of the following research question.

3.2 Research question

Which role can district heating play for German municipalities larger than 10,000 inhabitants in order to supply heat in an economically feasible way and reach climate neutrality in 2045 in light of the new support scheme BEW while considering the different potentials for renewable and waste heat?

In order to answer the research question the following sub-research questions were developed:

1. *How is the heat demand, existence of district heating and the potential for renewable and waste heat distributed among German municipalities larger than 10,000 inhabitants?*
2. *Can municipalities be clustered to determine the potential of district heating towards climate neutrality 2045 while taking the local differences into account?*
3. *Is district heating feasible compared to individual heating from a business economic perspective towards climate neutrality 2045 while considering the BEW support scheme and the local differences?*

3.3 Scope and delimitations

As the research questions can be answered in various ways, due to the available resources and time limitations the following scope and delimitations are defined. Firstly, as the research focuses on the time horizon towards 2045, only RE are considered. This ensures the achievement of climate neutrality and is in line with the BEW. Therefore, fossil fuels and carbon capture and storage (CCS) are not included in this research. While existing DH include waste-to-energy, which may rely on CCS to achieve climate neutrality this is not included in the thesis either. It is assumed that the availability of waste for waste-to-energy is reduced in the future, as more waste will be recycled and thus also no new waste-to-energy plants are constructed. Furthermore, it is assumed that the overall share of waste-to-energy in a future carbon neutral is rather low compared to RE and can therefore be excluded. Furthermore, hydrogen is not considered for the heating sector, as according to studies mentioned above, it will be more urgently needed in other sectors, which is also in line of with the view of the government in Germany.

The heat demands considered in this thesis are limited to residential and TCS within the buildings sector and thus do not consider the heat demand of industry. This is due to the fact that industrial processes often require high-temperature heat, which cannot be supplied by DH. While high-temperature HPs could supply certain industrial processes, this is beyond the scope of this thesis and is therefore not included.

Sector coupling is an important aspect of a future smart energy systems, which will be required in order to achieve climate neutrality. However, this thesis focuses on the heat supply and demand within the buildings sector and does not include any forms of sector coupling besides the use of waste heat, as it would significantly increase complexity. As, it is acknowledged that especially the integration with a fluctuating RE based electricity market has advantages and synergies, this is taken into consideration through spot market prices. Furthermore, cooling is also beyond the scope of this thesis, even though it is acknowledged that it will play a more significant role in the future and provides the potential for synergies with DH and it would be advisable to conduct municipal heat planning for both heating and cooling.

In the energy system analysis, the hydraulics and the seasonal temperature differences between the supply and return flow are not specifically taken into account due to their complexity. As a simplification only the supply flow is taken into account to calculate the coefficient of performance (COP) of the HPs. Furthermore, the DH network is included in the form of a simplified single node network, as the actual layout of the DH in the various municipalities would be too complex to take into account and is beyond the scope of this thesis.

The economic feasibility assessment is based on a business economic perspective only and considers the total system costs. Therefore, tariffs for electricity and other commodities are taken into account, while taxes are not taken into account and only the net values are used. While the BEG and BEW support scheme are included, other forms of support, such as the *Kraft-Wärme-Kopplungs-Gesetz* for CHP units, are not taken into account. Furthermore, socio-economic aspects, such as externalities or employment effects are also beyond the scope of the thesis and therefore excluded.

3.4 Validation

While previous studies have been conducted regarding the development of Germany overall towards climate neutrality in 2045, which also include the heating sector, these have focused on a more general analysis on a national level (Lübbers et al., 2022). On the other hand more specific research projects regarding the current and future development of the heat density as well as the estimation of potentials for renewable and waste have been conducted on a European level and identified potential DH areas (Flensburg University et al., n.d.; TU Wien et al., n.d.). However, these studies have only focused on a few exemplary municipalities as show cases where the potential for DH has been determined and otherwise not combined the heat demand and RE potentials for municipalities. This is also in line with the studies that have been conducted in Germany with a more specific focus on the heating transition (Burkhardt and Blesl, 2023; Fraunhofer ISE and Fraunhofer IEE, 2022; Institut für Energie- und Umweltforschung (ifeu) et al., 2023; Papadis et al., 2022). These focus on exemplary show cases, often with high potentials for RE, but do not provide answers regarding the overall role of DH in Germany based on a bottom-up approach. Moreover, the focus is often on policies and other measures to support the transition of the heating sector. Lastly, so far, no study has explicitly focused on the comparison of DH and individual heating for a transition towards climate neutrality while also taking the local differences into account.

On the other hand, given the current and planned legislative proposals, especially municipal heat planning, municipalities will soon need to start their planning and therefore be required to decide the role of DH for them. While natural gas often was considered as cheap and rather clean transition technology, there has been a shift in perspective due to the Russian war in Ukraine and the following energy crisis. Municipalities therefore already need to investigate the potential of RE source to determine the feasibility of DH towards climate neutrality 2045. Thus, it would significantly help municipalities to orient themselves in possible clusters that answer the question of the role of DH more generally. Especially, for municipalities with little RE potential, there are no studies to orientate themselves with. Therefore, this research aims to bottom-up clustering of municipalities while taking their heat demand and potential for RE into account and determine the potential of DH in comparison to individual heating. While the research is limited to municipalities above 10,000 inhabitants in accordance with the proposed heat planning law, this still accounts for around 70% of the heat demand in the buildings sector (Bundesministerium für Wirtschaft und Klimaschutz (BMWK), 2022). This research can therefore still contribute significantly to the transition of the buildings sector.

3.5 Research design

In order to answer the above-mentioned research question and sub-research questions the following research design is established. The development of the research design is based on an iterative process, where all stages of the research follow a reflective process. Therefore, the strategy can be reconsidered and adjusted if unexpected parameters arise while keeping the overall objective in mind. (Farthing, 2016)

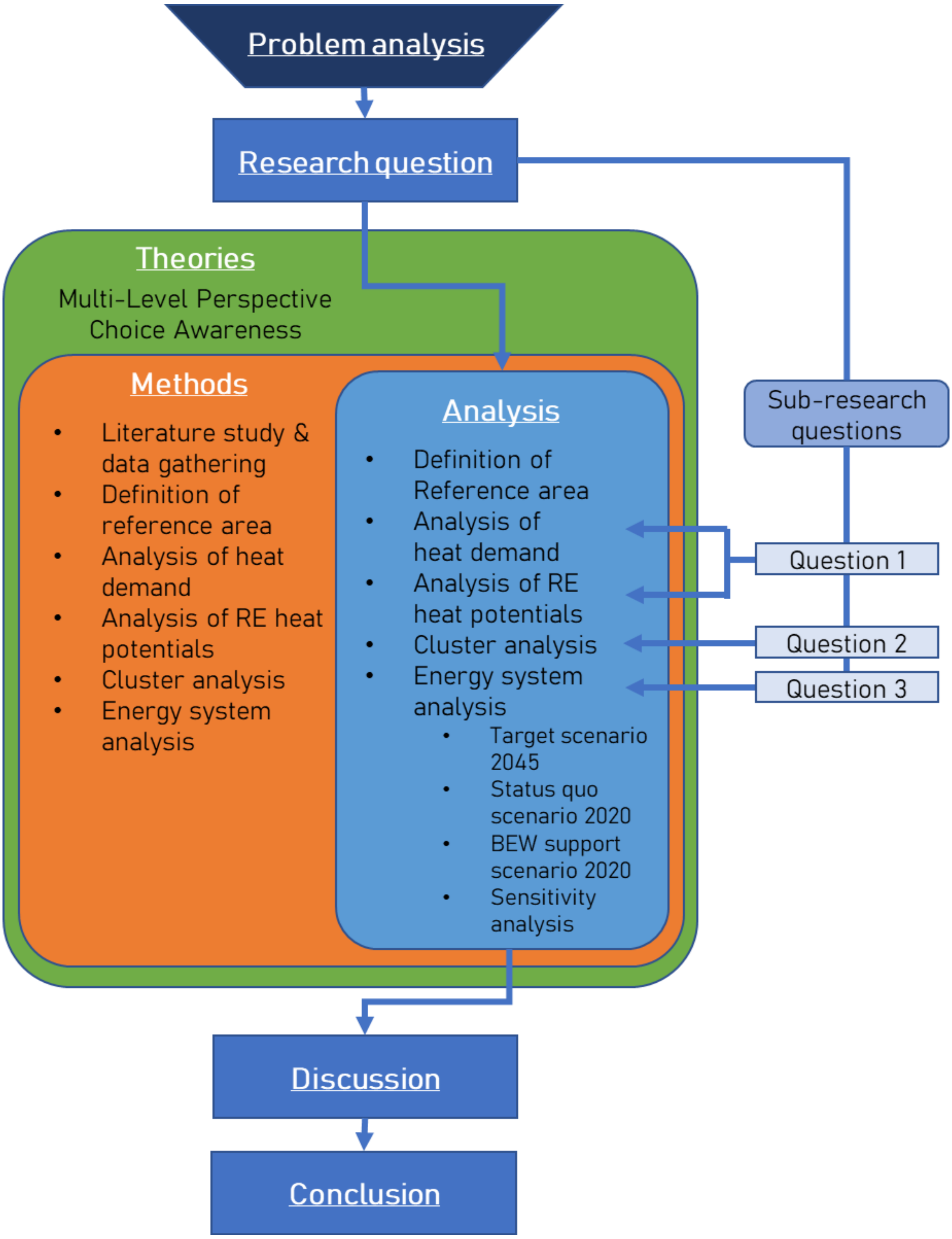


Figure 6: Flow chart of the proposed research design in order to answer the research question

The framework for the research design is established by the research and sub-research questions as shown in Figure 6 above. The flowchart represents the strategy for the research and includes all relevant stages that are needed to answer the research question. The different stages of the research design also structure the chapters of this report. The problem analysis (Chapter 2) formulates the starting point of this research and leads to the formulation of the research question (Chapter 3) and the respective sub-research questions. The Multi-Level Perspective and Choice Awareness form the theoretical framework (Chapter 4) of the thesis. They are well suited as the MLP explains the emergence of transitions, such as the heating transition towards climate neutrality 2045 and Choice Awareness on the other hand provides a strategy for developing scenarios to determine the role of DH. The application of the theories also influences the choice of methods (Chapter 5), which include literature study and data gathering, scenario design, a geospatial analysis of the heat demands and RE potentials and a subsequent cluster analysis. This then forms the basis of an energy system analysis. The structure of the analysis (Chapter 6) and thus also the methods is influenced by the respective sub-research questions which are answered in the different sections of the analysis. Afterwards, the results of the analysis are discussed (Chapter 7) and further aspects that could not be included in depth in the analysis are discussed qualitatively. This is followed by the conclusion (Chapter 8), which gives an answer to the research question and sums up the different results obtained. Lastly, based on the results and discussion, recommendations (Chapter 9) for further research are formulated, although this is not included in the flow chart of the research design, as it does not contribute to answering the research question.

4 Theories

In the following the theories Multi-Level Perspective (MLP) and Choice Awareness are explained, as they form the basis of this thesis. Furthermore, their interpretation and application in the context of this thesis will be explained.

4.1 Multi-Level Perspective (MLP)

MLP was developed by Frank Geels in the early 2000s. The theory is widely used in social sciences for the conduction of transition studies and has been verified and elaborated through case studies in various fields. The origins relate to evolutionary economics, the sociology of innovation and neo-institutional theory. MLP is continuously evolving through the interaction and discourses within social sciences (e.g., integration of agency and transition pathways). According to the theory, transition is the result of the alignment of developments that take place on multiple levels. MLP has been used for the analysis of a wide range of future sustainable transitions, such as the transition of the heating sector. (Geels, 2020, 2019)

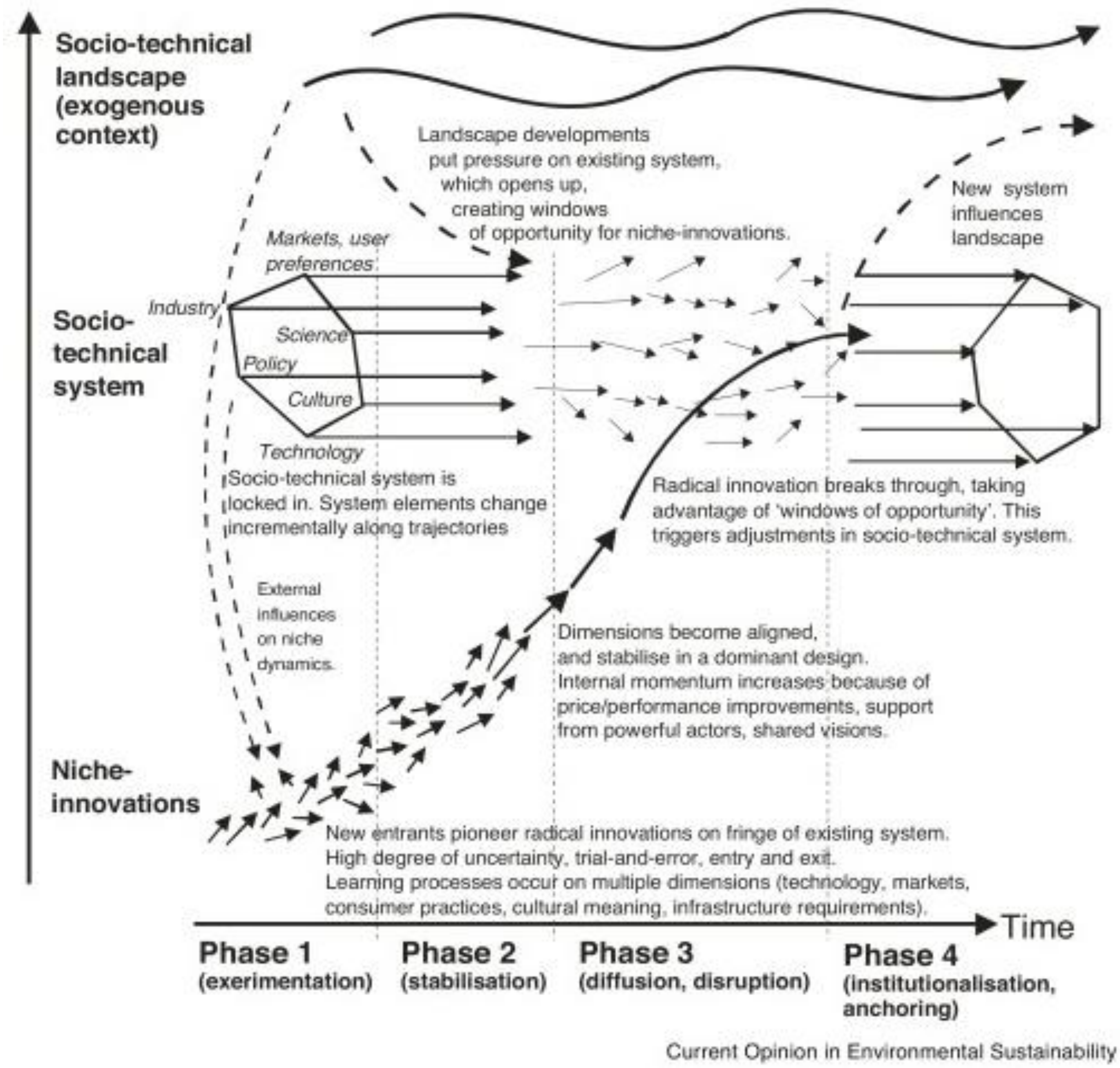


Figure 7: Illustration of Multi-Level Perspective (MLP) on socio-technical transitions with its different phases and regimes. (Geels, 2019)

As shown in Figure 7 above, MLP consists of three distinct levels of analysis i) niche-innovations, ii) socio-technical system/regime and iii) socio-technical landscape that influence each other in different ways. The physical, macroeconomic, political and cultural trends that frame our day-to-day life are defined by the socio-technical landscape, which is the overarching context where society interacts within. This can be broken down further into slow changing aspects such as political ideologies or demography and external shocks such as accidents or war as is the case with Ukraine. As these developments are external to the niche and regime actors, they cannot be directly influenced and changed by them. Nevertheless, the landscape is not detached from society and can be influenced by human agents through various aggregated actions, such as globalisation or urbanisation. (European Environment Agency, 2018; Gandenberger et al., 2020)

The interplay of the established industrial, market, technological, scientific, regulatory, market user preferences and institutional structures are described by the socio-technical system. The perceptions and actions of incumbent actors such as politicians, companies and users further consolidate the socio-technical regime. As these actors share common values and practices this leads to economic, social and political lock-in mechanisms as well as path dependence and subsequently innovation is minimal. However, changes still happen in the socio-technical system, even though these are relatively predictably and go along stable trajectories. (European Environment Agency, 2018; Gandenberger et al., 2020)

The development and emergence of radical novelties that differ from the established regimes level can only occur in a protected space such as is the case with research and demonstration projects in the Niche-innovations level. Thus, niche actors such as start-ups or inventors can develop radical innovations without the influence of the current socio-technical system. However, if the current regime is too stable and there are no windows of opportunity, even radical novelties that are ready to be used in a social-technical system may remain in the niche level for a long time. (European Environment Agency, 2018; Gandenberger et al., 2020)

Transitions are therefore dynamic processes, where landscape developments are destabilizing the current socio-technical system and create windows of opportunity. These are then used by emerging niche innovations, where the diffusion of these innovations disrupts the existing regimes and results in the formation of new regimes. These processes of transition usually take 20 to 30 years from the emergence of radical new thoughts until the formation of new regimes and can be divided into four phases. (European Environment Agency, 2018; Geels, 2019)

In Phase 1, novel ideas are further developed into radical novelties through experimentation and trial-and-error learning. This includes among others a high degree of uncertainty and high rates of failure. During Phase 2, the innovations become established in niche markets and developed into dominant designs. This stabilisation is driven among others through learning experiences and expanding social networks. Phase 3 involves all three levels and is characterized by the entrance of radical innovations into the established regime. The diffusion is enabled on one hand by niche-internal drivers such as support from influential actors or price improvements and on the other hand by using windows of opportunity created due to continuous pressure from landscape developments. During Phase 4, the new innovations become part of the established socio-technical system and subsequently modify or replace the old regime by a new one and can change among others the view of normality and user habits. (European Environment Agency, 2018; Geels, 2019)

4.2 Choice Awareness

Choice Awareness has been developed by Henrik Lund in the context of implementing radical technological change in an existing energy system. It builds on the perception of no choice or a Hobson's choice and incorporates elements of discourse and power theories. The theory furthermore contains specific strategies on how to create awareness and achieve a collective decision-making process towards a radical technological change. (Lund, 2014)

Starting point of Choice Awareness is the distinction between a *true* choice and a *false* choice. While a true choice is a choice between at least two real options, a false choice describes a situation where the only choice exists between choosing or not choosing an option and therefore creates the perception of choice. Lund observed in various decision-making processes in the field of energy planning that the society often ends up with the perception of a choice. Existing organisations often aim to go ahead with their business as usual and thus try to eliminate other alternatives to leave only a false choice. However, for the achievement of political targets, radical technological changes are needed and therefore Choice Awareness. (Lund, 2014)

Radical technological change refers to the change of more than one of the five dimensions of technology, which are technique, knowledge, organization, product and profit. This is for example the case when changing a fossil-based energy system to RE. These changes often imply a threat to existing organisations, because of which these organisations try to protect their interests and established technologies. Therefore, alternatives would have to be proposed by external actors, as the existing organisations have no interest them. Furthermore, it is then attempted to eliminate the possible alternatives through discourse and power dynamics to leave no choice but the continuation of the existing technology. (Lund, 2014)

The first thesis of Choice Awareness therefore stipulates that when society aims to achieve objectives that include radical technological change, the implementation will be influenced by existing organisations. The existing organisations will try to exclude alternatives from the debate or assess different alternatives based on methods that favour the existing technologies and present radical new technologies as infeasible. This will result in the perception that society only has the choice to continue with the existing technologies. Therefore, it is important to raise choice awareness and enable different choices throughout the political decision-making process, which is the core of the second thesis. (Lund, 2014)

The second thesis of Choice Awareness stipulates that by raising the awareness that alternatives and choices do exist, society will ultimately benefit, as its objectives can be achieved. As shown in Figure 8 below, the strategies to promote choice awareness include the description of concrete alternatives in debates, the inclusion of relevant political objectives in the feasibility study and the description of policies and measures that can support the advance of new technologies. This can further be supported by changes in the democratic decision-making infrastructure to also include representatives of new technologies. (Lund, 2014)

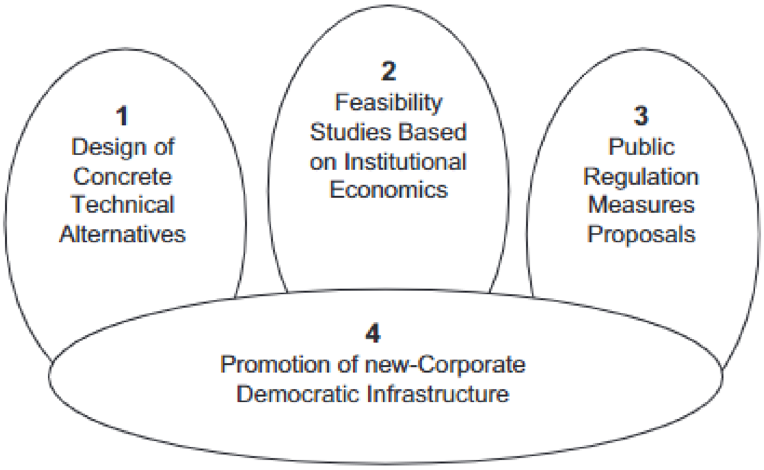


Figure 8: Strategies for the raising of Choice Awareness in political decision-making (Lund, 2014)

The first strategy consists of the design of concrete technical alternatives. Hereby it is important to consider that the alternatives are equally comparable with key parameters such as their capacity, include suitable combinations of energy savings, efficiency improvements in supply as well as RE and have the same direct costs. The socioeconomic feasibility study is the second strategy and is based on institutional economics instead of neoclassical economics. While a cost-benefit analysis often follows the idea of a free market and only focus on business economics, a socio-economic feasibility study takes into account political objectives and thus also includes aspects such as employment, externalities and balance of payment. In this regard, it is also important to set a long time horizon to find solutions independent of existing technologies and analyse technical, institutional and political sensitivities. (Lund, 2014)

The third strategy is the proposal of public regulation measures that support the implementation of the socio-economic preferred solution. Oftentimes the existing public regulation presents barriers to the implementation of radical technological change. Therefore, it is important to analyse these barriers based on a comparison between a business economic and socio-economic feasibility study. This can then be used to suggest specific public regulation measures, such as changes in taxes or subsidies, which will support the implementation of the preferred solution. Finally, the proposal of a new corporate democratic infrastructure is the last strategy. As existing organisations are usually well represented in the democratic decision-making process, it is important to identify further institutional barriers for organisation of potential future technologies. Eventually this may be the key to reach better Choice Awareness and lead to the success of the other strategies. (Lund, 2014)

4.3 Application of MLP and Choice Awareness

MLP provides a good overview of the current societal system and its various levels. The continuous high levels of GHG emissions keep exerting pressure on the current regime and demand responses of the various dimensions. The politicians are therefore in need to provide answers and solutions for the transition of the society. On the other hand, the Russian invasion of Ukraine has been an external shock on the existing regime that led to a drastic change in energy policy. While cheap natural gas was seen as an important bridging technology towards the transition to a carbon neutral society, natural gas has become scarce and expensive and led to a search for alternatives. These circumstances created a window of opportunity among other for the transition of the buildings and heating sector.

At the same time, new innovations in the form of RE and new DH have been waiting for this window of opportunity. Even though HPs have existed for a long time, they have primarily existed on a niche level. This is especially true for large-scale HPs, but also for smaller units which have only be used more widely in other countries such as Sweden. DH has existed for a long time as technology as well but has rather been a niche technology in Germany compared to other countries such as Denmark. Furthermore, the combination of new generation DH with lower temperatures and RE as well as waste heat is a radical innovation that needs the current window of opportunity for its uptake.

There is therefore a high potential for a transition to a renewable heat supply system in the buildings sector. This is where Choice Awareness comes to play, as the decision towards this transition will be significantly influenced by municipalities and utilities. Through the above-mentioned pressures, municipalities and utilities have to take action. Historically DH has relied heavily on fossil fuels and the replacement and transition to a renewable heating system would require significant investments. While some municipalities and utilities tend to delay the transition and continue with their current system, there is also the choice for a radical technological change. Furthermore, the same is true for areas where previously no DH existed. Instead of continuing to rely on the gas infrastructure to heat each house individually, there is the choice to establish DH, which would also describe a radical technological change.

While the MLP is more used for the description of a transition, Choice Awareness contains specific strategies to create radical technological change. Based on the strategies presented above, the focus of this thesis lies mostly on the development of alternatives and the conduction of the feasibility study. However, there are important differences compared to the methods suggested by the Choice Awareness strategies.

While alternatives are developed in the form of scenarios for DH with RE, no concrete alternatives are developed, as no specific case is looked into, such as a specific municipality. Furthermore, important parameters, such as the installed capacity are determined through the energy system modelling, which is part of the feasibility study and not set beforehand. However, overall comparability is still ensured.

Regarding the feasibility study, the focus is on the business economic perspective in terms of the overall system costs and therefore effects on employment and externalities are not included. Nevertheless, the overall political objectives are taken into account in the design of the alternatives. The feasibility study furthermore suggests various sensitivity analyses, while they are more limited in this thesis and only focus on technical sensitivities.

Furthermore, the proposal of new regulation is only indirectly discussed in the discussion section and the proposal of new corporate democratic infrastructure is not included in the thesis. Overall, MLP and Choice Awareness are extensive theories that touch upon various aspects. Due to the scope and time frame of this thesis, not all aspects could be included and led to the deviations mentioned above. However, the fundamental ideas of the theories are still applied to the thesis.

5 Methods

The methods used in order to answer the research question are presented in the following. Besides the general method of literature study and data gathering, the methods overall follow the guidelines for municipal heat planning (Deutscher Verein des Gas- und Wasserfaches (DVGW) and AGFW, 2022; Klimaschutz- und Energieagentur Baden-Württemberg (KEA-BW), 2020). This is combined with the first two strategies of Choice Awareness, which also function as methods. Therefore, the assessment of the heat demand and RE and waste heat potentials as well as the clustering of municipalities is regarded as scenario design. The development of a target scenario for 2045 and further scenarios through an energy system analysis together with a sensitivity analysis is then regarded as the feasibility study.

5.1 Literature study and data gathering

The conduction of various literature studies is relevant for different sections of the report. In the first place, the literature study was used to collect broad information about the topic and area of research. Subsequently this was further narrowed down and more specific information was searched for the problem analysis that led to the formulation of the research question. Furthermore, a literature study was used for the validation of the research question, where specific literature was searched that had a similar focus to this study. The collection of relevant data for the project also required a literature study. Hereby, it was attempted to create coherence among the sources used and focus on databases and technology catalogues. Next to that, the literature study was used for the discussion section to validate the results of the analysis and discuss further aspects that are beyond the scope, but still important to consider for an answer to the research question.

Overall, a wide range of different sources were used for the literature study. Depending on the aim of the literature study, the most important search engines used in order to access peer-reviewed articles include Aalborg University Library and Google Scholar. Furthermore, Google Search was used to access publicly funded studies by research institutes in Germany. Furthermore, legal and policy documents from the relevant ministries and governmental bodies were used. Next to that, news outlets and further website were used for additional information. Overall, significant attention was paid to actuality and the quality of literature used, as due to the actuality of the topic literature might be outdated rather quickly. This is especially true if various sources were available for the sought-after information.

Regarding the data gathered for the analysis of the research, the focus was on publicly available data bases and projects with a high quality that could provide the desired information. This mainly includes the European research project sEEnergies and Hotmaps as well as the Technology Catalogue from the Danish Energy Agency. In case no sufficient and qualitative data could be obtained, assumptions were formulated based on a discussion with experts from BBH Consulting.

Limitations

The limited access to literature as well as data provides the main limitation to the literature study and collection of data. While some data was restricted due to a paywall, others were restricted due to access limitation for public offices. Furthermore, some data was not available at the required resolution or degree of detail or quality, which could lead to inaccuracies of the analysis. Lastly, some information was also unavailable due to confidentiality and could therefore not be used. Nevertheless, the overall quality of literature and data available for this research is considered high and missing information could be filled with other sources.

5.2 Definition of reference area

As this research aims to answer a more general question regarding the role of DH, it is important to define the area of study and thus the reference area. In line with the guidelines for municipal heat planning, it is important to take the local circumstances into account for the assessment. Therefore, the analysis of the heat demand and renewable and waste heat potentials will be carried out in the geographic information system (GIS) QGIS 3.28. This way the local differences can be taken into account.

While the research question focuses on municipalities, as smallest political entities in Germany, which would carry out municipal heat planning, it is often not sensible to base the analysis for the potential of DH on municipalities as a spatial unit. While larger cities almost only consist of urban settlements, smaller municipalities also contain large parts of agricultural fields, forests or other land use forms, where it does not make sense to investigate the potential of DH. Therefore, instead the concept of urban areas (UA) based on the sEEnergies (Flensburg University et al., n.d.) project is used. The data availability for UA is significantly higher compared to municipalities which is another advantage to use this as reference area instead of municipalities.

In order to assess the impact of using UAs instead of municipalities, the spatial distribution of municipalities with more than 10,000 inhabitants is compared to UA with more than 10,000 inhabitants. For the municipalities, the dataset VG250 31.12. (Bundesamt für Kartographie und Geodäsie (BKG), 2022a) is used, while for UA the dataset UA heat demands (Flensburg University et al., n.d.) is used. Both datasets contain the outline of the respective area as polygons in a Geographic information system (GIS) and also contain data on population among others. Therefore, the datasets are filtered to only represent municipalities with more than 10,000 inhabitants and subsequently compared to each other.

Limitations

Due to the use of UAs instead of municipalities as reference area, the results of the analysis might deviate and thus lead to different conclusions. As the areas are compared beforehand the possible difference are attempted to be minimalized. Overall, it is considered that the UAs are sufficiently comparable to municipalities and that therefore the results are also valid for municipalities.

5.3 Analysis of heat demand and infrastructure

The first step of municipal heat planning on the way to the development of a target scenario for 2045 regards the analysis of the heat demand and infrastructure. This concerns the current heat demand as well as the development of the heat demand in the future and the infrastructures which are needed. While there are various approaches to collect data regarding the heat demand, there often is a trade-off between data availability and accuracy of the heat demand. Ideally, heat demand data for each building would be used to aggregate the data for the heat demand, however this would be beyond the scope of this thesis and these data are not publicly available due to privacy reasons. Therefore, aggregated data based on models are used to determine the specific heat density (SHD). Furthermore, it is recommended to distinguish the heat demand between residential and TCS, as they represent different load profiles. (Deutscher Verein des Gas- und Wasserfaches (DVGW) and AGFW, 2022; Klimaschutz- und Energieagentur Baden-Württemberg (KEA-BW), 2020)

The input data used for the analysis of the heat demand and infrastructure in UAs is based on the EU funded project sEEnergies, which provides various GIS datasets, as shown in Table 1 below. The datasets consist of different shape types, units and reference years and areas and therefore need to be further processed for a homogenous analysis.

Table 1: Overview of sEEnergies datasets (Flensburg University et al., n.d.) used including their description, unit, reference year (scenario) and reference area.

Name of dataset	Description	Unit	Reference year	Reference area	Used for
BL2015 HD100 total	Raster file with total SHD (Residential + TCS)	GJ/ha	BL2015	Ha	Define DH potential areas
Peta5 0 1 DHDCC 2015 res and ser	Raster file with DHDCC based on the total SHD	Ct/GJ	BL2015	Ha	Define DH potential areas
BL2050 HD100 total	Raster file with total SHD (Residential + TCS)	GJ/ha	BL2050	Ha	Define DH potential areas
BL2050 DHDCC	Raster file with DHDCC based on the total SHD	Ct/GJ	BL2050	Ha	Define DH potential areas
Peta5 0 1 HD res	Raster file with Residential SHD	GJ/ha	BL2015	Ha	Determine the residential share of the heat demand
D5 1 District Heating Areas	Urban areas with information about existing and potential DH among others	Various (existing DH / potential DH)	Various (2017 for DH)	UA	Distinguish urban areas according to existing and potential DH

The datasets contain among others the SHD as well as the DH distribution capital costs (DHDCC) per ha for the EU, as well as information regarding the existence of DH. The latest data available shows the SHD for 2015, which is still considered reasonably current as the measures towards a heating transition have been limited until now. Furthermore, the dataset already includes a baseline scenario for the development of the SHD and DHDCC in 2050, which is assumed as development also for 2045, as no other data is available on this level of granularity. The DHDCC are calculated based on the linear heat density, the effective width and the average installation costs of district heating pipes. More information regarding the methods is explained in Persson et al. (2021).

Overall, the potential for DH increases with increasing SHD and decreasing DHDCCC. However, other factors such as the supply and return temperature also significantly influence the potential of DH, as this in turn impacts the insulation for pipes, the diameter of the pipes and the installation costs. In order to use a coherent approach and ensure comparability among the UAs, the classification for DH based on the sEEnergies project is used. (Persson et al., 2021) While the initial classification also shows criteria for 3rd generation DH, this research solely focuses on 4th generation DH, as this enables a better integration of renewable and waste heat and is considered necessary for future DH as mentioned in Section 2.4 above. Furthermore, the classification only considers SHDs and is therefore extended to also include DHDCC based on the criteria in the same report and is shown in Table 2 below.

Table 2: Overview of criteria for the classification of 4th generation DH. Modified from (Persson et al., 2021)

Nominal density class	**Mapped density class**	**Mapped distribution cost class**	**Interpretation**
> 20 TJ/km² > 5.6 GWh/km²	> 200 GJ/ha > 56 MWh/ha	< 25 EUR/GJ < 9 ct/kWh	Potential for 4th Gen DH

As a first step the total heat demand for the whole UA is calculated based on the aggregation of the SHD for each ha, so the heat demand for each ha inside the UA. Next, the area that is suitable for 4th Gen DH in each UA is calculated based on the above-mentioned classification. Therefore, the raster files were first clipped to only match the outline of the UAs and subsequently filtered to only show areas which fulfil the above-mentioned criteria. While the Total heat demand for 4th Gen DH was determine likewise by summing up the SHD for each ha, the average DHDCC was calculated by taking the average of the DHDCC for the identified potential areas. Lastly, the raster fields were counted to determine the total area of 4th Gen DH. All calculated heat demands and DHDCC were then converted to GWh and MWh respectively for easier handling and comparison and also represents the required input format for the subsequent modelling. Based on the calculated information also the share of 4th Gen DH compared to the total area of the UA and the share of the total heat demand of 4th Gen DH compared to the total heat demand of the UA were determined.

In order to calculate the share of residential heating, the raster with the residential SHD only was used to calculate the total residential heat demand for each UA. This was then divided by the total heat demand for each UA to determine the share of residential heating. As the data was only available for 2015, the share of residential heating could only be determined for 2015 and was assumed to stay constant till 2045. Furthermore, information regarding the current existence of DH within an UA was extracted from the dataset D5 1 District Heating Areas. Therefore, the polygons with DH areas were overlapped with the UA through the join attributes by location function and the information about currently existing DH transferred to the UA layer.

Overall, the following parameters were calculated based on the input data, which are considered relevant information regarding the heat demand, infrastructure and the potential development according to the guidance for municipal heat planning. These data were added for each UA to the overall layer containing the dataset of UA in QGIS.

- Total heat demand UA 2015 [GWh/a]
- Total heat demand UA BL2050 [GWh/a]
- Total heat demand 4th Gen DH in UA 2015 [GWh/a]
- Total heat demand 4th Gen DH in UA BL2050 [GWh/a]
- Average DHDCC 4th Gen DH in UA 2015 [EUR/MWh]
- Average DHDCC 4th Gen DH in UA BL2050 [EUR/MWh]
- Heat demand share 4th Gen DH in UA 2015 [%]
- Heat demand share 4th Gen DH in UA BL2050 [%]
- Area share 4th Gen DH in UA 2015 [%]
- Area share 4th Gen DH in UA BL2050 [%]
- Residential heat demand Share in UA 2015 [%]
- Existing DH in UA 2016 [yes/no]

Limitations

The limitations relate mainly to the available datasets, which are based on modelling data on a European level and therefore the local accuracy of the data might be limited. As this research aims to draw more general conclusions regarding the role of DH and is not intended for the development of specific municipal heat plans, the data available are considered sufficiently accurate.

Another limitation is the baseline scenario for 2050, which is based on the European reference scenario from 2016. This describes a business-as-usual scenario and therefore is not in line with reaching climate neutrality in 2050 on a European level. However, the overall reduction of the heat demand in the buildings sector between 2015 and 2050 for the baseline scenario 2050 is comparable with the heat demand reduction in the climate neutrality scenarios for Germany in 2045 (Lübbers et al., 2022). Therefore, it assumed that the use of the baseline scenario 2050 rather presents a conservative estimate regarding the development of the heat demand. It is however unclear if significantly higher rates of retrofitting can be reached in more ambitious scenarios. As it was beyond the scope of this thesis. It is therefore recommended for to conduct further research with alternative scenarios and validate the results obtained by this thesis.

The criteria for determining the potential of DH in this thesis are limited to the SHD and the DHDCC, which are based on average values on models. Furthermore, a wide range of other factors, such as temperature difference between the supply and return flow, the type of materials used for insulation and pipes and the costs for installation based on the surface among others. Therefore, in reality, it is more complex to determine the potential of DH in certain areas. However, as mentioned in the scope and delimitations, this research focuses on the overall role of DH and therefore does not consider the layout or hydraulics of DH. Therefore, it is considered acceptable for the scope of the study to estimate the potential DH area based on the SHD and DHDCC.

5.4 Analysis of renewable and waste heat potentials

According to the guidelines for municipal heat planning, the local potentials of various RE sources and waste heat should be evaluated. This includes biomass (including biogas), geothermal, solar thermal, ambient heat (including surface water) as well as waste heat (industry, data centers and wastewater among others). As there is no one-size-fits-all solution for DH, it is important to consider all options in order to determine if there is a potential for DH. The above mentioned RE and waste heat potentials are therefore assessed for each UA based on the datasets in Table 3 below.

Table 3: Overview of considered RE and waste heat source including unit, reference area and source

Name of heat source	Name of dataset	Unit	Reference area	Source
Biomass	UA heat sources	TJ/a	UA	(Flensburg University et al., n.d.)
Geothermal	UA heat sources	Existing/ Not existing	UA	Flensburg University et al., n.d.)
Industrial waste heat	D5 1 Industry Dataset	GJ/a	Point	Flensburg University et al., n.d.)
Wastewater	Europäische Kommunal-abwasser-Richtlinie	m^3/a	Point	(Umweltbundesamt (UBA), n.d.)
Lake	DLM250	m^3	Polygon	(Bundesamt für Kartographie und Geodäsie (BKG), 2022b)
River	3.9 Mittlerer jährlicher Durchfluss und Durchflussvariabilität	m^3/s	Polygon	(Bundesanstalt für Gewässerkunde (BfG), n.d.)
Solar thermal	potential_solarthermal_collectors_open_field	MWh/a	ha	(TU Wien et al., n.d.)

In order to obtain the respective RE or waste heat potential in terms of capacity or annual energy production, the input data still had to be converted and matched to the UA, if they were based on a different reference area. For biomass, the potential considered in this research only regards waste biomass for which the potential has already been calculated as part of the sEEnergies project. The data was therefore merged with the overall data on UA based on the matching of the UA and finally the data was converted from TJ/a to TWh/a for easier comparison and input for the modelling. The potential for geothermal heat has also already been determined by the sEEnergies project. However, the information is only provided in the form of the existence of high temperature groundwater, high heat flow densities, hot sediment aquifers, Neogene basins and other potential reservoirs. The values are therefore not quantified but only indicate if geothermal potential exists or not. It was assumed that if one of the options has been fulfilled that there is geothermal potential. This is the only potential which is not quantified and it is only assessed if the potential exists or not.

For RE and waste heat sources with reference area of points or polygons (all water sources and industrial waste heat), the first step consisted of the calculation of potential capacity for each point or polygon, thus each water body, wastewater treatment plant or industrial site. The industrial waste heat potential has already been calculated as part of the sEEnergies project and considers industrial sites from the sectors chemicals, iron and steel, non-ferrous metals, non-metallic minerals, paper and printing as well as refineries. For these processes the annual waste heat potential from fuel combustion is quantified for different temperatures (95 °C, 55 °C and 25 °C respectively) at the current rate of internal heat recovery and the maximal rate of internal recovery. As this thesis focuses on 4th Gen DH and the potential towards 2045, the waste heat at 55 °C with a maximum rate of internal heat recovery is used as potential. As the data has been calculated in the form of annual waste heat potential and as the input for the model is required as the hourly capacity, it is assumed that the above-mentioned industries operate continuously and that therefore the heat available is equally distributed throughout the year. The annual waste heat potential in TJ/a is therefore converted to MW for easier comparison and input for the modelling.

On the other hand, the potential heat available from water sources had to be calculated. The dataset for rivers and wastewater contained information regarding the volumetric flow rate of the water source. Therefore, Equation 1 was used to calculate the potential of ambient heat that could be extracted.

Equation 1: Potential heat that can be extracted from a water source (Gaudard et al., 2019)

$$Q_h = c \times \rho \times \Delta T \times Q_v$$

where

Q_h	*Heat flow rate [kW]*	
c	*specific heat capacity [kJ Kg $^{-1}$ °K $^{-1}$]*	*≈ 4.2 kJ Kg $^{-1}$ °K $^{-1}$ for water*
ρ	*density [kg m $^{-3}$]*	*≈ 1000 kg m $^{-3}$ for water*
ΔT	*Temperature difference [°K]*	
Q_v	*Volumetric flow rate [m ^{3} s $^{-1}$]*	

For wastewater, the input first was converted from m^3/a to m^3/s, while it was assumed that the annual flow rate is constant in each second as simplification due to limited data availability. Next, wastewater with flow rates less than 0,01 m^3/s were disregarded, as the extraction of such small quantities is not considered feasible for a DH. As wastewater usually has a temperature above 10 °C throughout the year, it is assumed that the wastewater can be cooled by 5 °C to extract heat from it.

Larger rivers have high flow rates and provide significant potentials for heat extraction. However, there are seasonal and annual variations of the flow rates based on the type of river and the overall weather conditions. Furthermore, there is rather strict regulation regarding the extraction or addition of heat in natural water bodies (Papadis et al., 2022) and therefore only 5% of the minimum average flow rate is used as potential heat source. In order to ensure economic feasibility, only flow rates above 0,1 m^3/s are considered. This way, it can also be ensured that enough water should be available as heat source during times of low water and that the change in river temperatures downstream of the point of extraction is limited to a maximum of 1 °C. This gives enough flexibility to cool the extracted water by 3 °C as this usually only represents a small fraction of the flow rate. In case the river temperature reaches less than 4 °C, this would mean that less heat can be extracted from the river in order to prevent the water from freezing or that heat would have to be used for defreezing. However, most larger rivers in Germany have a temperature above 5 °C and can therefore be used all year long for heat extraction.

For lakes only information regarding the surface area was available, because of which the potential could not be calculated and had to be estimated based on other studies.

Furthermore, there is no specific regulation for the use of lakes as heat source, besides the Bodensee, but it assumed that authorities are rather strict depending on the type of water body or may even forbid it. Therefore, as a first step, lakes in protected areas are exclude from the dataset by using the dissolve function in QGIS. Based on previous studies conducted regarding the heat potential of lakes (Kammer, 2018), only lakes larger than 50 ha are assumed to be available for heat extraction as these are also covered by the water framework directive. As no information regarding the depth or volume of lakes is available, the heat potential is assumed based on a study from Gaudard et al. (2019), where the heat potential of lakes in Switzerland is calculated. According to the study around 1 MW of heat can be extracted per 50 ha of lake. This represents a rather conservative estimate, as it is the lower end of the range from potentials in Switzerland. However, the lakes considered in Switzerland have a sufficient depth to provide constant temperatures that also allow heat extraction in winter times. It therefore needs to be evaluated if the potential for heat extraction is also true for the specific lake in Germany. In order to calculate the potential heat capacity of a lake the potential per area is therefore multiplied with the area of the lake.

After the determination of the capacity for each point and polygon, they were matched to the respective UA by various tools in QGIS. Overall, based on previous studies it is assumed that 1 MW of heat can be transported economically feasible for 1 km (Böhnisch et al., 2001) and the maximum distance is set to 10 km, as in reality few projects with a distance of more than 10 km have been realized due to the limited feasibility. The points and polygons are matched with the UA through the join attributes by nearest function, where a maximum distance of 10 km is set and multiple outputs are allowed. Subsequently the distance of the point or polygon to the UA is compared with the potential capacity and all heat potentials where the distance in km is higher than the capacity in MW were excluded. It is assumed that a point source (industrial waste heat or wastewater) will only be used by one UA, while a polygon (river or lake) can be used by multiple UAs. Therefore, for heat potentials from points that have been allocated to multiple UAs, it was allocated only to the UA with the shortest distance and the potential was deleted from the other UAs. Lastly, for all UAs with multiple heat potentials of the same source (e.g., two wastewater treatment plants), the values are summed for each UA with the exception of rivers. As the polygons for rivers contain different segments of a river and in various municipalities one river flows into another river, the highest value is taken, which would correspond to the joined river. If the sum was taken, the potential might be overestimated, as the potential of the smaller rivers is already included in the segment of the joined river.

For solar thermal, the input consisted of a raster file with the potential output per ha only considering agricultural and open areas and limiting the collector area to 25% of the available space. In order to present a more conservative estimate, this number is further reduced to use only 10% of the area available. It is assumed that the available potential for DH in the context of this study consist of the solar potential within a 1 km zone around the outline of the UA. Hereby, it was assumed that areas that are shared by various UA are divided equally among them. Therefore, first the vertices of the UA are extracted in order to create Voronoi polygons, which are grouped for each UA. Then a buffer of 1 km around the outline of the UA is created which the Voronoi polygons are clipped to. The sum of the raster within the buffer is then calculated by zonal statistics and matched to the corresponding UA by the join attribute by location function.

Overall, the following parameters were calculated based on the input data, which are considered relevant information regarding the potentials for RE and waste heat according to the guidance for municipal heat planning. These data were added for each UA to the overall layer containing the dataset of UA in QGIS.

- Biomass potential [GWh/a]
- Geothermal potential [yes/no]
- Ambient heat potential from lakes [MW]
- Ambient heat potential from rivers [MW]
- Ambient heat potential from wastewater [MW]
- Waste heat potential from industry [MW]
- Solar thermal potential [GWh/a]

Limitations

While the majority of renewable and waste heat potentials were included, some waste heat potentials, especially from data centers and future electrolysers or power-to-X units still provide significant potentials for waste heat. Therefore, some UA might have still higher waste heat potentials. Moreover, further low temperature waste heat source such as supermarket were not included and provide further potential. However, due to the scope if the research the potentials could not be included. Nevertheless, it is assumed that the major renewable and waste heat sources are included and the results are still robust enough to draw overall conclusions. Furthermore, there are currently only a limited number of locations in Germany where large scale units with significant waste heat potentials are planned.

The potential for geothermal heat could not be quantified and might therefore lead to deviations as there are significant difference between the UA and their respective potentials. Overall, a quantification would be possible, but is beyond the scope of this thesis as it would require significant resources and time. While some areas might have larger potentials for geothermal heat, which might be enough to cover significant parts of their heat demand this is not taken into account, as all areas with geothermal potential only receive an average capacity, as described in more detail in Section 5.6. Therefore, depending on the role of geothermal heat, the analysis should be update if more widely available data regarding local geothermal heat potentials are available.

Lastly the analysis of heat potentials overall is based on various assumptions, as for some heat source no specific regulations and guidelines exists, as they are rather novel technologies. There are some uncertainties especially regarding the heat potentials of lakes, as depths of around 10m are required to ensure constant temperatures for a continuous operation and heat extraction. As this information was not available for lakes in Germany, there is some uncertainty whether the identified lakes can provide the calculated potential. Therefore, overall conservative assumptions are taken and the calculated potentials are considered reasonable.

5.5 Cluster analysis

In order to find general conclusions regarding the role of DH, the aim is to group the UA into clusters. There are various methods for the classification of municipalities and the comparison of UA. Most of these approaches have been applied in social sciences for demographics or education. Based on literature, the most promising and commonly used method is a cluster analysis in order to derive a classification of municipalities. The advantage of a cluster analysis is the possibility to use a variety of input parameters and that the areas which are most similar to each other are clustered, while the differences between the clusters are maximised. Cluster analysis has also been previously applied for the identification of energy cities. (Gleich and Staudinger, 2013; Saks and Giar, 2022; Wall et al., 2016)

Within cluster analysis there are a lot of different approaches and ways to obtain clusters. Overall, the approach most commonly followed consists of using hierarchical clustering with Ward's-linkage and using the elbow criterion to determine the number of clusters (Backhaus et al., 2021). This approach is also applied in this thesis and implemented through GeoDa 1.20 as it covers all functions necessary and provides the possibility to work with GIS files as input, which were created for the analysis of the heat demand and RE potential. In the following the approach used is described in more detail.

A cluster analysis consists of 5 steps as shown in Figure 9 below. The first step in a cluster analysis is to determine the variables that will be used to group a set of objects. This is followed by the assessment of the similarities or differences between the objects that will be measured. The third step is the selection of the clustering method and is important, as there is a wide range of clustering algorithms, which may lead to different result. Then the number of clusters has to be decided upon based, which is often a trade-off between manageability (small number of clusters) and homogeneity (large number of clusters). The last step consist of the interpretation of the formed clusters and its content. (Backhaus et al., 2021)

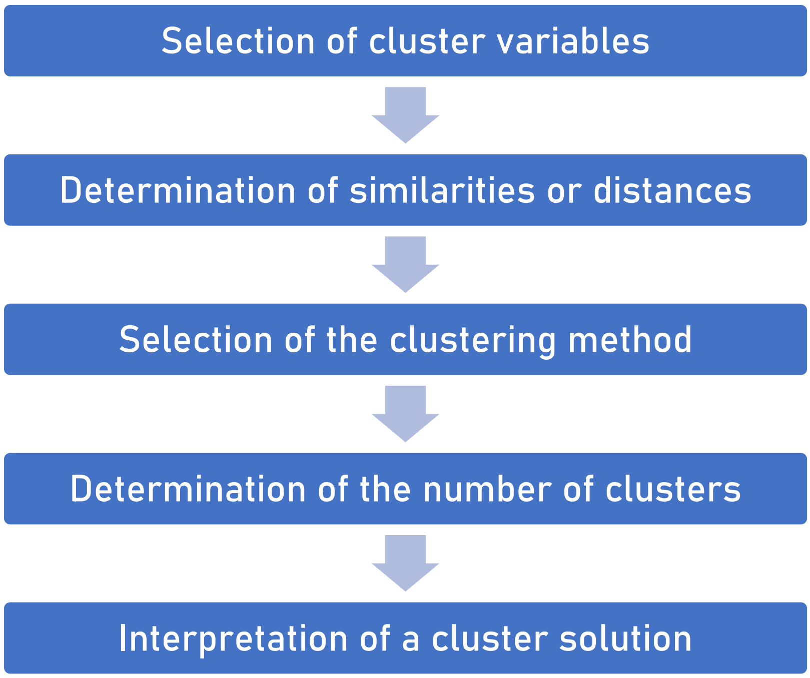


Figure 9: Overview of different process steps of a cluster analysis (Backhaus et al., 2021)

The first step in a cluster analysis consists of the choice of the relevant variables for the clustering. Hereby it is important that the variables are not correlated and thus convey the same information. The potential variables are therefore analysed for their correlation based on the add-on in Microsoft Excel to exclude variables with high correlation. Furthermore, the variables should be highly relevant for the objective of the cluster analysis and observable as well as measurable in reality. Therefore, based on the previous analysis the following variables could be considered for the clustering, as shown in Table 4 below.

Table 4: Overview of potential variables considered for clustering based on the previous analyses

Heat demand	**RE and waste heat**
Total heat demand UA 2015 [GWh/a]	Biomass potential [GWh/a]
Total heat demand UA BL2050 [GWh/a]	Geothermal potential [yes/no]
Total heat demand 4th Gen DH in UA 2015 [GWh/a]	Ambient heat potential from lakes [MW]
Total heat demand 4th Gen DH in UA BL2050 [GWh/a]	Ambient heat potential from rivers [MW]
Average DHDCC 4th Gen DH in UA 2015 [EUR/MWh]	Ambient heat potential from wastewater [MW]
Average DHDCC 4th Gen DH in UA BL2050 [EUR/MWh]	Waste heat potential from industry [MW]
Heat demand share 4th Gen DH in UA 2015 [%]	Solar thermal potential [GWh/a]
Heat demand share 4th Gen DH in UA BL2050 [%]	
Area share 4th Gen DH in UA 2015 [%]	
Area share 4th Gen DH in UA BL2050 [%]	
Residential heat demand Share in UA 2015 [%]	

As the variables consist of different units, the variables first have to be normalized through standardization. This ensures that the variables are comparable as the mean of the standardized variable is 0 and the variance as well as the standard deviation are 1. (Backhaus et al., 2021)

The second step of the cluster analysis concerns the determination of similarity or differences and provides the direct input for the clustering. Hereby, the raw data matrix is transformed into a distance or similarity matrix which contains the distance or similarity values between each variable. In this thesis the Euclidean distance is used as measure of distance. Therefore, the higher the distance value, the more the variables are different from each other. (Backhaus et al., 2021)

The selection of the clustering algorithm is an important step, as there is a wide range of different options, which have a significant impact on the formation of clusters. Generally, the distinction can be made between partitioning clustering methods, such as k-means and hierarchical clustering methods. As hierarchical procedures are of great importance for practical applications, a hierarchical procedure is also chosen for this thesis. The hierarchical clustering algorithms can further be distinguished into agglomerative methods, such as single-linkage and divisive methods, such as Ward's-linkage. The difference is that the agglomerative method links the objects with the smallest distance, while the divisive method links the objects that increases the variance in the resulting cluster the least. Compared to other algorithms, Ward's-linkage is widely and frequently used and usually assigns the objects to clusters correctly. Therefore, Ward's-linkage is also chosen for this thesis. The output of the clustering algorithm is a dendrogram which shows the objects on one axis and the distance between an object and another object or cluster on the other axis. (Backhaus et al., 2021)

The next step is the determination of the number of clusters. The dendrogram presents different options for clustering, but as the optimal number of clusters is not known beforehand, it needs to be evaluated based on statistical criteria. Overall, this process describes finding a balance between a few clusters, which are homogenous to each other and heterogenous within and many clusters, which are homogenous within and heterogenous to each other, but more difficult to handle. The elbow criterion is widely used to easily determine the optimal number of clusters. This is done by plotting the development of the heterogeneity measure and the number of clusters in a diagram, which is also called a scree plot. The elbow is the point, where there is a significant jump in heterogeneity and thus presents a good balance. (Backhaus et al., 2021)

However, if no clear elbow point can be determined, there is also the possibility that the optimal number of clusters cannot be determined. In that case a number of clusters could be chosen based on the needs of the user or it could be that there is no group structure in the dataset. Due to the limitations of this thesis, no further elaborate analysis could be conducted regarding the structure of the dataset and other ways to identify the optimal amount of cluster, if the number of clusters could not be determined by the elbow criterion. Therefore, clusters will then be determined based on a statistical analysis of the respective criteria to form clusters that could cover a wide range of possibilities within the dataset.

The last step regards the interpretation of the formed clusters, where it is useful to compare the clusters with the original dataset by calculating t-values and F-values. While t-values can be used to characterise the clusters and describe if a variable is over- or underrepresented in a cluster, the F-values can be used to assess the homogeneity of a cluster in comparison to the dataset and shows the dispersion of the variable within a cluster. The equations for the calculation of the t-values and F-values are shown in Equation 2 and Equation 3 below. (Backhaus et al., 2021)

Equation 2: Calculation of t-values for each variable in a cluster in comparison to the original dataset (Backhaus et al., 2021)

$$t_{v,c} = \frac{\bar{x}_{v,c} - \bar{x}_v}{s_v}$$

where

$t_{v,c}$	*t-value of variable v in cluser c*
$x_{v,c}$	*average of variable v in cluster c*
x_v	*average of variable v in the survey population*
s_v	*average of variable v in the survey population*

Equation 3: Calculation of F-values for each variable in a cluster in comparison to the original dataset (Backhaus et al., 2021)

$$F_{v,c} = \frac{s_{v,c}^2}{s_v^2}$$

where

$F_{v,c}$	*F-value of variable v in cluster c*
$s^2_{v,c}$	*average of variable v in cluster c*
$s^2_{v,c}$	*average of variable v in the survey population*

As the number of clusters is unknown beforehand, it would be beyond the scope of the thesis to aim to investigate all clusters. Instead, the aim is to use a min/max approach where the cluster with the highest potentials and the cluster with the lowest potentials are used for further analysis. This way the range of possible solutions can be investigated and overall conclusions can be drawn. If some clusters are excluded from the min/max approach these were considered in the form of a sensitivity analysis to be able to derive general conclusions.

The selection of input variables for the formation of clusters is based on the previous analysis and corresponding literature (Deutscher Verein des Gas- und Wasserfaches (DVGW) and AGFW, 2022; Klimaschutz- und Energieagentur Baden-Württemberg (KEA-BW), 2020) as well as the discussion with BBH Consulting, which has high expertise in the planning and transition of DH (BBH Consulting, 2023). The standardization, calculation of distance values and computation of the Ward's-linkage algorithm are conducted through GeoDa, which provides as output the dendrogram as well as the within-cluster sum of squares, which is needed for the elbow criterion. The scree plot is then calculated in Excel in order to determine the elbow point. In case clusters are found, the further analysis of the t-values and f-values is also conducted in excel.

Limitations

Overall, it might be more difficult to find clusters in smaller datasets, as there could be less overlap of data, especially if a large number of variables is used. In this case there are however other methods such as a Principal Component Analysis or Uniform Manifold Approximation and Projection, which can reduce the dimensions. Furthermore, there is a wide range of clustering algorithms, which can significantly impact the results of the identified clusters (scikit-learn developers, 2023). This is also dependent on the input data and their pre-processing. Additionally, there are also other methods for the identification of the number of clusters, such as the Calinski/Harabasz's criterion or the Silhouette method.

While Ward's-linkage and the elbow criterion are commonly used in literature, there might be other algorithms and methods that are more suitable to the dataset. This might significantly impact the outcome of the cluster analysis and can thus also influence the overall results. Due to the structure of the research design, it is intended to minimize this impact and it is assumed that the general conclusions regarding the role of DH are still valid with the chosen clustering method. Due to the scope of the project, there were no further resources for the evaluation of other clustering algorithms and methods for the identification of the optimal number of clusters. It would therefore be recommended to investigate different clustering algorithms and methods for the identification of the number of clusters and assess how this changes the outcome of the cluster analysis.

5.6 Energy system analysis

According to the guidance for municipal heat planning, the next step is the development of a target scenario for 2045. Hereby, modelling tools are a crucial part to evaluate the complex developments that take place on various levels. Especially in order to determine the feasibility from an economic as well as technological perspective, an energy system analysis is a widely used method. (Martins et al., 2021)

5.6.1 Selection of modelling tool

As there is a wide range of modelling tools, it is important to choose a tool that suits the needs of this project. One of the requirements is that the model needs to be able to optimize the installed capacities of various energy conversion units to find the most cost-efficient energy system. Furthermore, it is an advantage if the model can also optimize the energy system flows. Lastly, it is an important requirement that the model has the ability to implement a DH solution and is flexible for various configurations, so a modular approach is preferable. This way, it is easy to change parameters and configure the model to the respective clusters. This will also ensure that the model can optimize the flows of heat, electricity as well as other commodities and provides the potential to show the effect of sector coupling. Other requirements include an hourly time resolution and a spatial resolution for UA or municipalities. Furthermore, it is advantageous if the model has an easy interface for the exchange of data and outcomes with other programs, e.g., for visualization or further processing.

The Open Energy Modelling Framework (oemof) has already been used for different kind of analysis and is well suited for the modelling of the energy sector, in a smart city context. One of the advantages is that it is open source as well as modular and can therefore be tailored to the needs of the users. According to Martins et al. (2021) it is one of the best tools available for the assessment of energy transitions in urban areas. Overall, oemof can fulfil all of the above-mentioned requirements and is therefore chosen as modelling tool for this analysis. BBH Consulting has developed its own distribution of oemof for the assessment of the feasibility of DH system, which is used for this thesis and is therefore already set-up to match the objectives of this study. (BBH Consulting, 2023; Hilpert et al., 2018)

Oemof and its toolbox is written in python, which provides further flexibility to adjust the model according to the needs of the user. From the oemof toolbox, the energy system analysis is conducted based on the solph package. Oemof.solph is based on a graph structure of buses and components that are connected by directed edges which represent the flow of energy. This provides the necessary flexibility to adjust solph according to the needs of the users and model different sectors together at the same time. The various components of solph are shown exemplary in Figure 10 below. (Krien et al., 2020)

The graphs are then converted by soph into an optimisation model through pyomo, which is then passed onwards to an external solver. The solver then optimises the linear or mixed integer linear problem for minimal costs that can be determined as economic, environmental or technical. Additionally, further constraints such as investment constraints or CO_2 limits can be defined and included in the optimisation. Further information regarding the principles of oemof and solph are well documented and available online. (Flensburg University et al., n.d.; Krien et al., 2020)

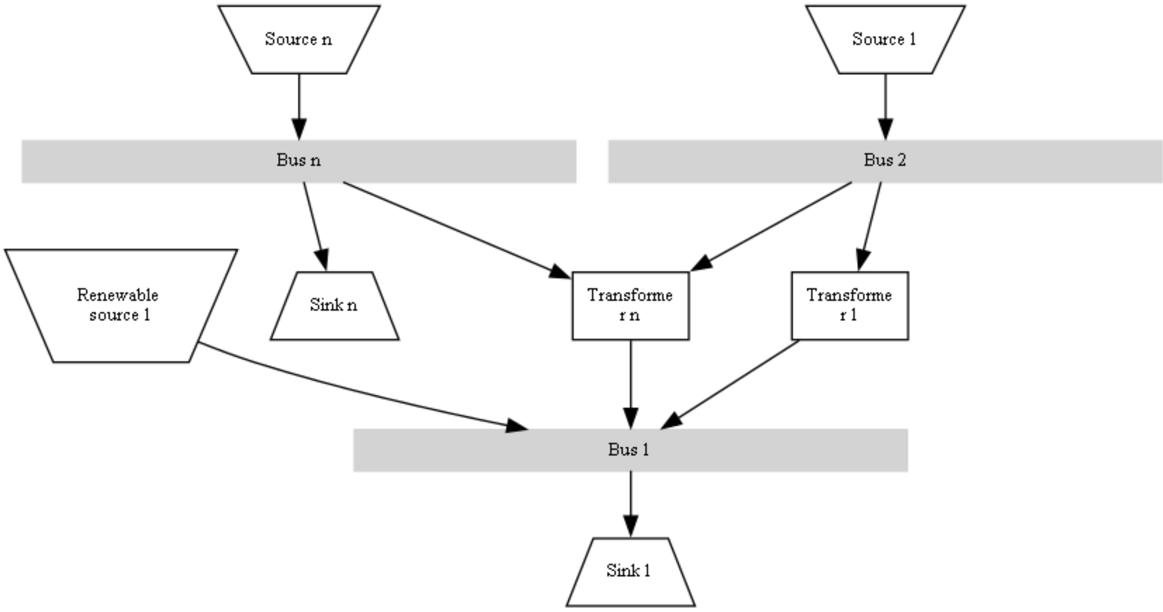


Figure 10: Schematic overview of the components and structure of oemof

For this thesis the BBH Conuslting distribution of oemof.solph 0.45 is used together with Gurobi 10.0.01 as external solver. The BBH Consulting distribution is set up in a way that the input data are set in an excel table, which is then read into the model through python. The model is solely run as an optimization model in order to find the most cost-efficient heating system for the target scenario 2045. Besides the determination of the role of DH in 2045, it is relevant to also calculate the most cost-efficient scenario currently to determine the transition pathway and if the same technologies that will be cost-efficient in 2045 are also cost-efficient now. Furthermore, the impact of the BEW support scheme is evaluated to assess if this makes the most efficient technologies of 2045 more feasible today, or if it promotes the establishment of DH. An overview of the scenarios that are analysed is shown in Figure 11 below.

Based on the research question and the min/max approach discussed above, the max cluster is used to determine the best available technologies, while the min cluster is used to determine the feasibility of DH compared to individual heating. As a reference technology for individual heating, an air HP is chosen, which according to studies (Fraunhofer ISE and Fraunhofer IEE, 2022; Lübbers et al., 2022; Papadis et al., 2022) is expected to be the default individual heating solution in the future.

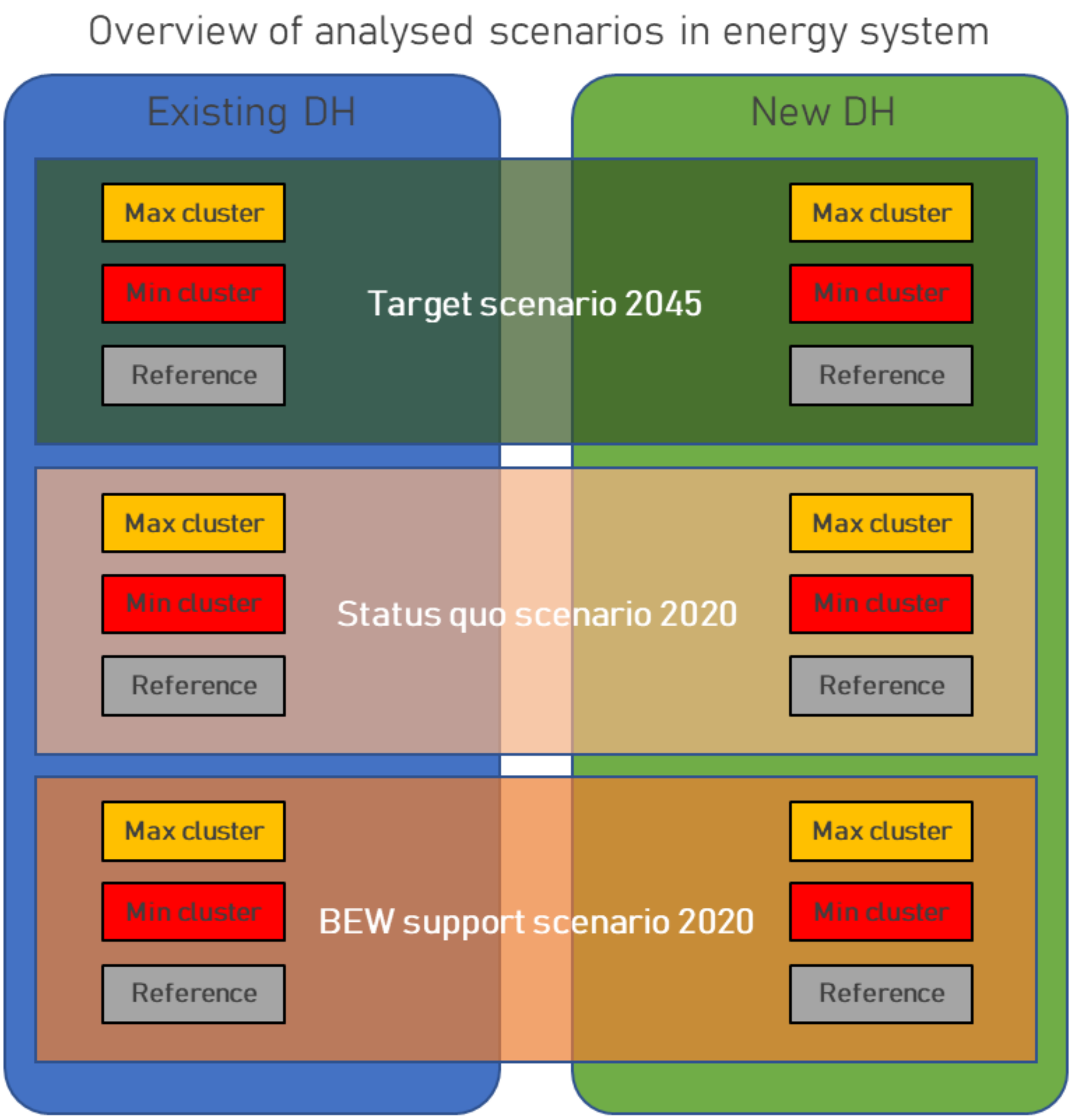


Figure 11: Overview of analysed scenarios and clusters in the energy system model

5.6.2 Input parameter

For the development of the target scenario for 2045, various aspects such as the development of the gross domestic product, the population, refurbishment rates, development of RE and heat and electricity demand among other aspects have to be evaluated. The assumptions for this are included in the data for BL2050, presented in Section 5.3 and therefore form the basis of the target scenario 2045. Another important aspect are the available technologies, DHDCC and potentials in each UA. As mentioned beforehand, only RE sources are considered in line with the guidelines for municipal heat planning. Furthermore, it is important to set equal framework conditions for the comparison of different UA and municipalities to ensure a fair comparison. Therefore, it is intended to limit the variety of sources used in order to ensure higher comparability and cohesion among them. An overview of the different input types and their source is provided in Table 5 below. (Fraunhofer ISE and Fraunhofer IEE, 2022)

Table 5: Overview of input data for the energy system optimization including reference area and source

Type of input data	Name of dataset	Reference area	Source
Hourly air temperature and global radiation for extremely cold weather year 2015 and 2045	Testreferenzjahre TRY	Potsdam	(Deutscher Wetterdienst (DWD), 2017)
Average daily river temperature for period between 1995-2012 (reference period)	CXX359	Rhine river, Karlsruhe	(Landesanstalt für Umwelt Baden-Würtember (LUBW), 2023)
Average commodity prices for 2045 and 2020	Bottom-Up Studie zu Pfadoptionen einer effizienten und sozialverträglichen Dekarbonisierung des Wärmesektors	Germany	(Fraunhofer ISE and Fraunhofer IEE, 2022)
Hourly spot market prices for 2045	Hourly price forward curve	Germany	(BBH Consulting, 2023)
Temperature dependent standard load profile for Residential SH heat demand	load_profile_residential_heating_generic	Germany	(TU Wien et al., n.d.)
Temperature dependent standard load profile for Residential DHW heat demand	load_profile_residential_shw_generic	Germany	(TU Wien et al., n.d.)
Temperature dependent standard load profile for TCS SH heat demand	load_profile_tertiary_heating_generic	Germany	(TU Wien et al., n.d.)
Temperature dependent standard load profile for TCS DHW heat demand	load_profile_tertiary_shw_generic	Germany	(TU Wien et al., n.d.)
Technical and financial data for heat storage	Technology Data for Generation of Electricity and District Heating	Denmark	(Danish Energy Agency, n.d.)
Technical and financial data for heat storage	Technology Data for Energy Storage	Denmark	(Danish Energy Agency, n.d.)
Technical and financial data for individual HPs (reference technology)	Technology Data for Individual Heating Plants	Denmark	(Danish Energy Agency, n.d.)
Technical and financial data for DH grids	Technology Catalogue for Transport of Energy	Denmark	(Danish Energy Agency, n.d.)
RE and waste heat potential	See Section 5.3	UA	See Section 5.3
Heat demand and share of residential heating	See Section 5.4	UA	See Section 5.4

Share of SH and DHW on residential and TCS heat demand 2015	Space heating and cooling and domestic hot water	Germany	(TU Wien et al., n.d.)
Requirements and conditions of BEW Funding scheme	Merkblatt Module 1 bis 4: Technische Anforderungen	Germany	(Bundesamt für Wirtschaft und Ausfuhrkontrolle (BAFA), 2023)

As the data from the Technology Catalogue has different price years, these are adjusted according to the European inflation in order to match the price year 2022, which is set for this report. The adjustment is based on the Harmonised Index of Consumer Prices of the EU. (Eurostat, 2023)

Furthermore, the target scenario for 2045, as well as the status quo scenario 2020 and the BEW support scenario 2020 are calculated. However, the dataset only provides data for 2015 and 2050 respectively. As the previous target for climate neutrality was 2050, it is assumed that this is still true for climate neutrality in 2045 and the data is therefore comparable. Likewise, it is assumed that the values for 2015 can still be used for the current status as there has not been so much progress since 2015.

The input of the potentials of the renewable and waste heat sources is based on the analysis in the previous section. As all parameters, except geothermal have been quantified, it is assumed that if there is a potential for geothermal, it would be around 5 MW as this is average size of projects that have been realised in Germany (Bundesverband Geothermie, 2023).

For solar thermal energy the potential is given in MWh/a and in order to calculate the hourly production the following Equation 4 is used.

Equation 4: Calcuation of solar thermal heat production (Sydfalster Varmeværk, n.d.)

$$Y = A \cdot I_s \cdot \left(n_0 - \frac{a_1 \cdot (T_m - T_a)}{I_s} - \frac{a_2 \cdot (T_m - T_a)^2}{I_s} \right)$$

where

Y	*Solar thermal heat production [W]*	
A	*Solar collector area [m ^{2}]*	
I_s	*Global radiation [W m $^{-2}$]*	
n_0	*Intercept (maximum efficiency) [dimensionless]*	*≈ 0,817*
a_1	*First-order coefficient [W m $^{-2}$ °C $^{-1}$]*	*≈ 2,205 W m $^{-2}$ °C $^{-1}$*
a_2	*First-order coefficient [W m $^{-2}$ °C $^{-1}$]*	*≈ 0,0135 W m $^{-2}$ °C $^{-1}$*
T_m	*Average temperature difference [°C]*	*≈ 50 °C*
T_a	*Ambient temperature [°C]*	

The weather data are required for the calculation of the load profile for the residential and TCS heat demand, distinguished between SH and DHW. Furthermore, the ambient temperatures and the global radiation are required for the calculation of the hourly solar thermal production. As Potsdam is the reference location for representative energy assessments, it is also chosen as reference location for this study. Furthermore, for a correct dimensioning of the energy system, the extreme cold test reference year is chosen. (Deutscher Wetterdienst (DWD), 2019)

For the water bodies and wastewater no reference locations exist and the data availability is limited. As the Rhine is the largest river in Germany and has good data availability, it is chosen as reference for the river temperature based on the reference period form 1995 – 2012. Furthermore, as there is no further data available, it is assumed that the average lake temperature is equal to the river temperature and that the wastewater temperature is 5 °C above the river temperature. The temperatures of the water bodies are required for the calculation of the COP of the HPs.

The standard load profiles used are weather, day and season dependent and are therefore matched to the weather data of Potsdam and the according days and seasons of the respective year. Next, the load profiles are normalized, so they can be scaled to the heat demand that has been determined in the previous analysis. Furthermore, it is assumed that the reduction in heat demand can solely be attributed to SH in accordance with scenarios for the development of the heat demand (Kranzl et al., 2019).

The average commodity prices are acquired from one source for consistency. In order to reflect the possibility of stabilization and flexibilization of DH for the electricity grid, also the hourly spot market prices are included in the analysis. However, in order to ensure consistency, the hourly spot market prices are adjusted to match the average prices. Therefore, the overall level of the spot market prices is increased by adding the difference between the average prices, which would represent the tariffs and profits of the utilities. However, for the sale of electricity this is still assumed to be the spot market price.

As the scenarios regard different years, the interest rate is another important parameter to consider in the modelling. As this research regards the feasibility of DH from a business economic perspective, the weighted average costs of capital (WACC) are used, as is suggested by the AGFW (n.d.) and BEW.

After entering all input data in the input data table in excel, the model is run in python and an output table including the hourly production per energy conversion unit, installed capacity and system costs is generated by oemof. In order to compare the different scenarios and clusters among each other, the levelized costs of heating (LCOH) are calculated according to Equation 5 below based on the system costs.

Equation 5: Calculation of levelized costs of heat (LCOH)

$$LCOH = \sum_{t=0}^{n} \frac{(CAPEX_t + OPEX_t) \times (1 + i_t)^{-t}}{Q_t \times (1 + i_t)^{-t}}$$

where

$LCOH$	*Levelized cost of heat [EUR/MWh ≙ 10 ct/kWh]*
$CAPEX_t$	*Total capital expenditures in year t [EUR/a]*
$OPEX_t$	*Total operational expenditures in year t (including commodities) [EUR/a]*
i_t	*Interest rate in year t (WACC) [dimensionless]*
Q_t	*Total heat produced in year t [MWh/a]*
t	*Analysed year from baseline t=0 [a]*
n	*Number of years in analysed time period [dimensionless]*

5.6.3 Sensitivity analysis

According to Choice Awareness, there is a wide range of sensitivity analyses that can be conducted including technical, institutional and political sensitivities. As the energy system analysis focuses on a long-time horizon towards 2045 and includes various assumptions, this could lead to uncertainties. Therefore, the sensitivity analysis is used to substantiate the results of the analysis and show the degree of uncertainty. (Lund, 2014) While it is recommended to conduct various types of sensitivity analyses due to the time and resource limitations of this research only a technical sensitivity analysis is conducted. Furthermore, the sensitivity analysis is used to cover aspects that could not be included in the min/max approach for the cluster analysis. This way it is also used as a mean to reduce the number of clusters that have to be investigated while still be able to draw conclusions that are applicable to more clusters.

The technical sensitivity describes the links between technology and economy and therefore includes economic parameters such as CAPEX or the interest rate and technical parameters such as the efficiency or capacity. Due to the scope of this thesis and the clustering approach, the sensitivity analysis mainly focuses on the potentials for renewable and waste heat sources that are defined by the clusters. On the other hand, economic parameters are evaluated as part of the sensitivity. This focuses mainly on the WACC and the potential to reduce the DHDCC as this is related with higher uncertainties.

Limitations

The selection of the modelling tool provides a significant limitation, as different tools can lead to different outcomes. This is mainly related to the features included in the model as well as the underlying assumptions and calculations used. Overall, as the selection of the modelling tool is guided by relevant criteria and a review of literature, it is assumed that the modelling tool chosen is suitable. However, the reliability of the results could be further increased if the analysis is also conducted with another modelling tool.

Another limitation represents the input data. While it is intended to use coherent sources for all input parameters, this is not always possible due to the limited data availability. Therefore, most of the economic and technical input data are based on Danish data, while the weather data relate to more specific locations in Germany. However, there are also regional differences in Germany and thus the different data sources might not match to each other and could therefore lead to deviations in the results of the analysis. Overall, it is intended to pay attention to the data quality of the sources used and ensure geographical similarity of data. Therefore, even though some of the data is based on Denmark, it is considered acceptable as the costs or spot market prices in Germany and Denmark are rather similar. Nevertheless, it would be recommended to increase the data quality over time for municipal heat planning and agree on a common data basis to conduct the analysis regarding transition of the buildings sector.

Furthermore, there is some uncertainty regarding the development of the commodity prices, as this depends significantly on the development of RE sources in general and the demand of other sectors. Additionally, the prices of the commodities are influenced by tariffs and other political decisions such as taxes or the design of the market, which can significantly affect the preference between different commodities. Therefore, it is ensured that the average commodity prices are based on the same source and are thus based on the same underlying assumptions and scenarios. However, especially the hourly spot market prices for 2045 should be regarded with some uncertainty.

Finally, only one type of sensitivity analysis is conducted. Especially due to the uncertainty regarding the underlying assumptions, it would be recommended to include another sensitivity analysis. Another aspect is that the technical sensitivity included only focuses on the potentials for renewable and waste heat and some economic input parameter. While this represent the most important sensitivities for the scope of the research, it would also be relevant to investigate further sensitivities, such as different commodity prices. As both other sensitivities and the inclusion of more parameters is beyond the scope of this thesis it is recommended for further analysis in order to increase the robustness of the results obtained.

6 Analysis

In the following the development of the heat demand as well as the potentials for renewable and waste heat are presented. Subsequently clusters are formed based on the heat demand and potentials for existing and potential DH areas. The clusters are then used as input for an energy system analysis to develop the target scenario 2045 and also evaluate the current feasibility of DH and the impact of the BEW funding. Furthermore, the difference in renewable and waste heat potentials and economic parameters are evaluated through sensitivities.

6.1 Definition of reference area

As mentioned in the methods section, due to data availability and the focus on assessing the role of DH, it is more useful to use UA as reference area instead of municipalities. Nevertheless, it will be evaluated how this could potentially impact the results. Therefore, Figure 12 below shows the spatial difference between using municipalities or UA.

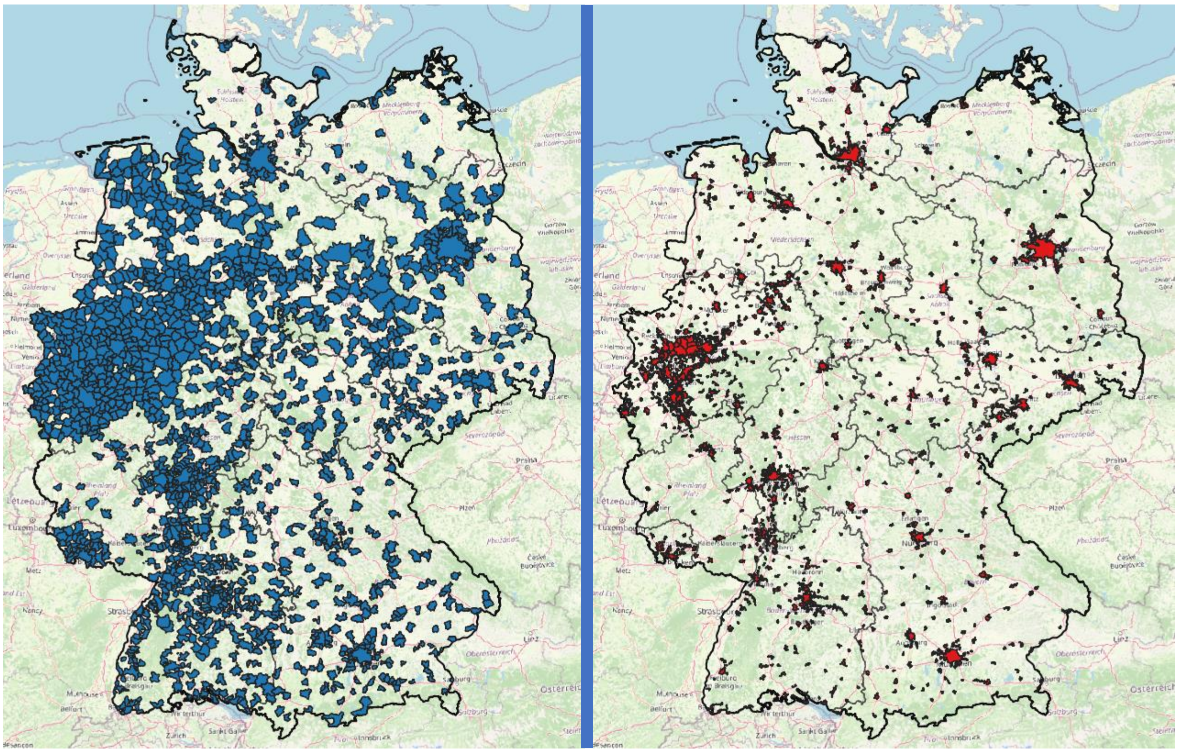


Figure 12: Overview of municipalities (left) and UA (right) with more than 10,000 inhabitants in Germany (Scale 1:5,000,000) Geobase: Open Street Map

Overall, it can be observed that the municipalities cover a significantly larger area. On one hand the municipalities are larger than UA and also encompass agricultural areas and forests among others. On the other hand, a municipality can also consist of multiple smaller urban areas, where each of them has less than 10,000 inhabitants. Based on the 11,123 municipalities in Germany, 1,602 have more than 10,000 inhabitants. This still represent around 75% of the population and around 70% of the heat demand in the buildings sector according to the BMWK (2022). In contrast to that, 1,016 out of 22,772 UA have more than 10,000 inhabitants. This corresponds to 65% of the population covered by the UA and around 58% of the total population. However, still 73% of the heat demand of all UA is covered by the UA above 10,000 inhabitants. It should also be noted that the UA as defined by the sEEnergies project do not always reflect the actual municipal boundaries and therefore can stretch over 2 municipalities. Therefore, in total around 500 municipalities are disregarded from the analysis as their biggest UA has between 3000 and 10,000 inhabitants. However, the majority of the heat demand is still covered and shows little deviation to the use of municipalities.

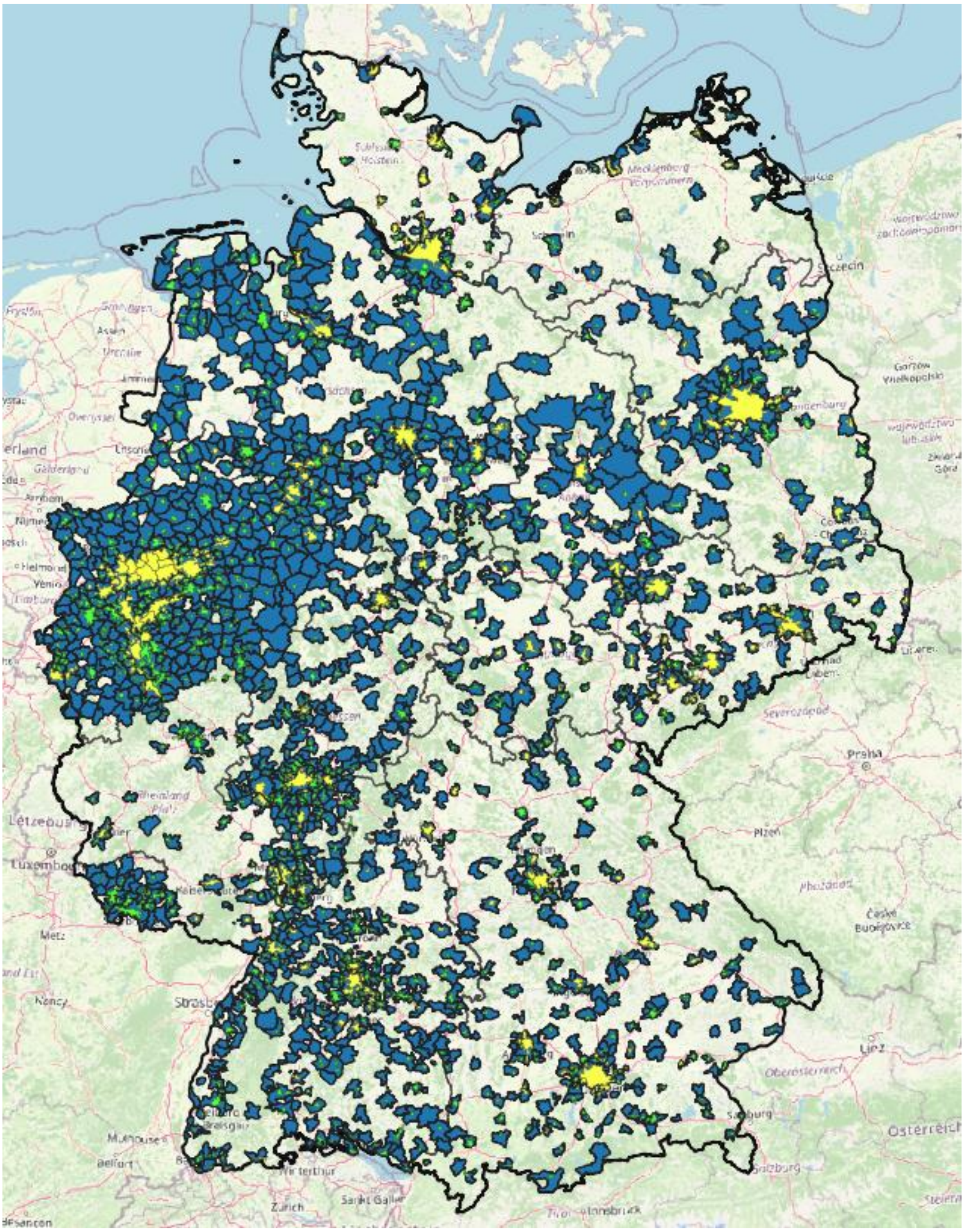


Figure 13: Overview of municipalities (blue) and UA with more than 10,000 inhabitants distinguished into UA with existing DH (yellow) and potential DH (green) (Scale 1:5,000,000) Geobase: Open Street Map

In general, the smaller the UA, the lower the feasibility of DH, however as proven in Denmark, DH can also be feasible in smaller areas. However, this is beyond the scope of this thesis and also not the focus of the politically wanted expansion of DH. Furthermore, some UA, such as Ulm or Lahr/Schwarzwald are not included in the UA dataset by sEEnergies and are therefore missing. Figure 13 above shows the direct comparison between municipalities and UA. As there is a significant difference between the transformation of existing DH and the establishment of new DH, as explained in the methods section, the results section is divided between existing and potential DH for each analysis step. Therefore, the difference between the two UA in terms of population are analysed in more detail. Out of the 1,016 UA that are analysed within this thesis, 223 UA have an existing DH representing 37% of the population and 42% of the heat demand in all UA, while 793 have the potential for DH representing 27% of the population and 31% of the heat demand in all UA. Therefore, a little more than 20% of UA above 10,000 inhabitants have DH. In this regard it is interesting to look at the distribution of DH based on the size of UA, as shown in Figure 14 below.

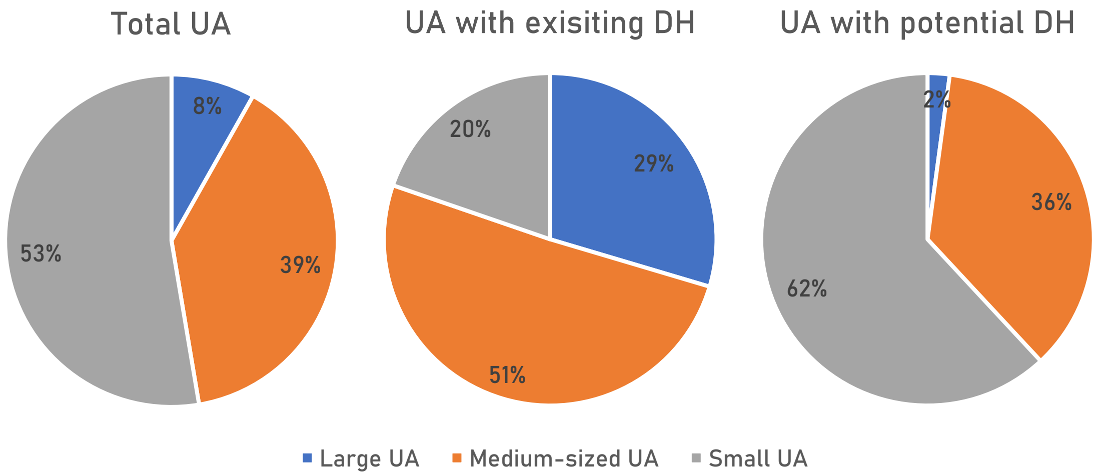


Figure 14: Overview of the distribution of large, medium-sized and small UA among total UA, UA with existing DH and UA with potential DH

Overall, 53% of the UA consist of small UA between 10,000 and 20,000 inhabitants, while only 8% of the UA are large UA with more than 100,000 inhabitants. Out of the 83 large UA 80% have existing DH, leaving 17 with potential for DH. Looking more generally at UA with existing DH, only 20% of DH is installed in small UA, indicating that oftentimes DH has been more economically feasible in large UA. For UA with potential DH the picture is the opposite and the largest potentials lie with small UA and medium-sized UA which make up 62% and 36% respectively of 793 UA. This shows that for potential DH areas, the major question is whether DH is feasible in small UA compared to individual heating and for existing DH areas, how the transformation towards renewable and waste heat in medium-sized and large UA can take place.

6.2 Existing DH areas

6.2.1 Development of heat demand and district heating distribution capital costs

Based on the various calculations in QGIS, the following results could be obtained regarding the current heat demand and DHDCC as well as the future heat demand and DHDCC for 2050. Figure 15 below shows the reduction of heat demand for 4th Gen DH between 2015 and BL 2050.

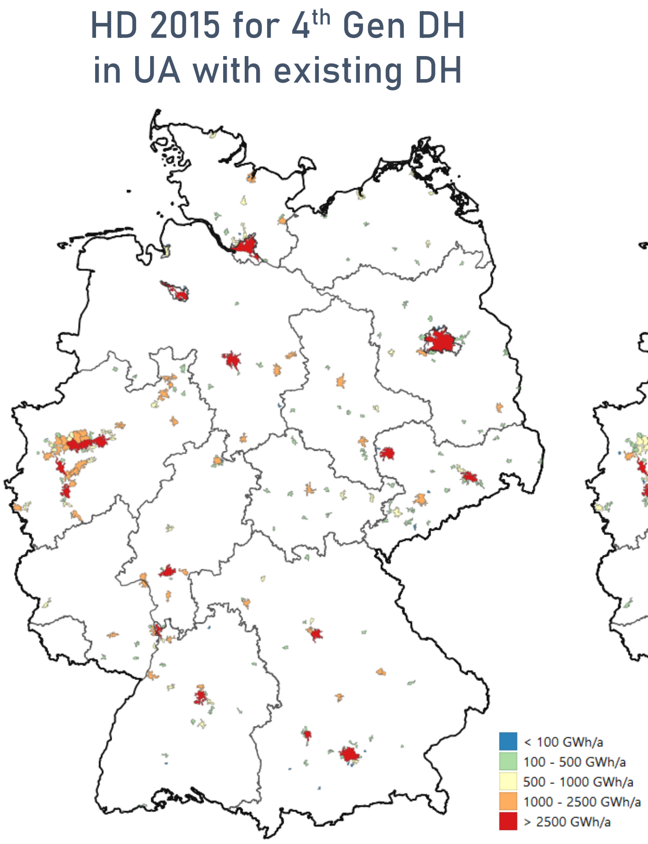


Figure 15: Overview of the reduction of the heat demand (HD) for 4th Gen DH between 2015 and BL2050 in UA with existing DH

Overall, it can be observed that the highest heat demand is in the largest UA, but that also smaller UA have DH. In general, the heat demand for 4th Gen DH is declining in all UA between 2015 and BL2050. The geographical distribution of the heat demands, DHDCC and shares in each UA with existing DH is shown in Appendix I: Geographical distribution of heat demands in UA with existing DH. The changes for the different parameters are shown in more detail in Table 6 below.

Table 6: Statistical overview of the development of the total heat demand, heat demand for 4th Gen DH and DHDCC for 4th Gen DH between 2015 and BL2050 in UA with existing DH

	Total heat demand 2015	Total heat demand BL2050	Heat demand 4G DH 2015	Heat demand 4G DH BL2050	DHDCC 4G DH 2015	DHDCC 4G DH BL2050
Unit	GWh/a	GWh/a	GWh/a	GWh/a	ct/kWh	ct/kWh
Average	1,124.9	716.4	1049.8	605.3	2.0	5.0
Max	25,252.0	16,762.5	24,278.6	15,268.1	3.1	6.9
3. Quartile	1,143.5	729.8	1,056.3	607.5	2.3	5.4
Median	449.1	278.2	418.6	214.9	2.0	4.9
1. Quartile	232.3	148.7	200.2	101.1	1.8	4.6
Min	60.2	41.7	45.6	13.7	1.3	3.3

The average values for the heat demand are significantly impacted by the high values of larger UA, such as Berlin and are closer to the third quartile than the median, while for the DHDCC the average is very close to the median. In general, both the total heat demand as well as the heat demand for 4th Gen DH are reduced by around a third or more, while the DHDCC is more than doubled. Table 7 below furthermore shows the development of the share of 4th Gen DH compared to the total heat demand and the area of the UA as well as the share of residential heat demand in 2015.

Table 7: Statistical overview of the development of the share of the heat demand for 4th Gen DH and the share of the area for 4th Gen DH between 2015 and 2050 as well as the share of residential heat demand in 2015 for UA with existing DH

	4th Gen DH share of total heat demand 2015	4th Gen DH share of total heat demand BL2050	4th Gen DH share of total area 2015	4th Gen DH share of total area BL2050	Share of residential heat demand 2015
Unit	%	%	%	%	%
Average	90	75	53	35	61
Max	97	95	79	67	94
3. Quartile	93	85	59	42	65
Median	92	79	52	35	62
1. Quartile	87	69	47	26	56
Min	68	27	29	5	34

Similar to the total heat demand and the heat demand of 4th Gen DH, also the share of DH of the total heat demand decreases. However, the decline is not as sharp and for BL2050, 4th Gen DH still makes up 75% of the heat demand on average. Looking at the area, 4th Gen DH would only cover around 50% of the UA in 2015 and would still reduce to 35% for

BL2050. In most UA the share of residential heat demand of the total heat demand is around 60%, there are however also exceptions with a significantly higher and lower share.

Overall, it can be observed that likewise to the total heat demand, also the heat demand of 4th Gen DH is decreasing. Furthermore, both its share of the total heat demand and the area are also decreasing, while on the other hand the DHDCC are more than doubling. This indicates that while DH might be preferable and more suitable currently, it is not expected that the current network would significantly increase or otherwise might not be economically feasible anymore in 2045.

6.2.2 Renewable and waste heat potential

According to the guidelines and studies, the potentials for heat from biomass, geothermal, industrial waste heat, wastewater, lakes, rivers and solar thermal were evaluated for each UA. However, the potentials among the UA vary significantly, as shown in Figure 16 below. While some UA, have a range of different RE sources available to supply their heat demand, other areas have very little RE potential. The geographical distribution for each renewable and waste heat potential for UA with existing DH is shown in Appendix III: Geographical distribution of renewable and waste heat potentials in UA with existing DH.

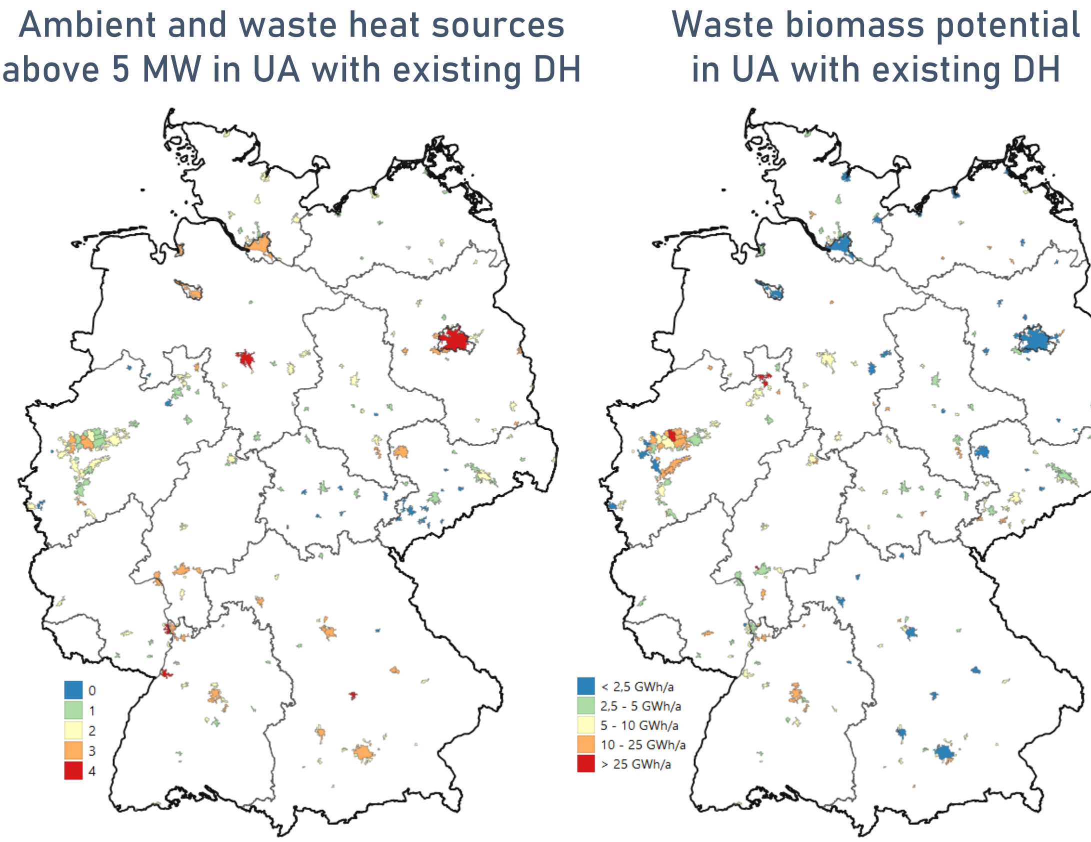


Figure 16: Overview of the number of ambient and waste heat source above 5 MW (left) and waste biomass potential (right) in UA with existing DH

A more detailed overview of the potentials is given in Table 8 below. Here it can be observed that all UA have a significant potential for solar thermal, which could almost be enough to cover the heat demand of most UA. However, it has to be noted that the solar thermal strongly varies throughout the season, providing most heat during summer and least during winter, when the heat demand is the highest. Therefore, it can only be used feasibly in combination with a heat storage. In general, literature suggests that solar thermal can supplement renewable heating, but is not seen as sole heating technology.

Table 8: Statistical overview of the renewable and waste heat potential in UA with existing DH

	Biomass	Geo-thermal	Lake	River	Waste-water	Industrial waste heat	Solar thermal
Unit	GWh/a	Yes/no	MW	MW	MW	MW	GWh/a
Average	7.0	0.6	2.5	95.9	8.3	4.0	212.2
Max	42.0	1.0	226.9	603.0	216.5	192.4	1064.3
3. Quartile	9.2	1.0	0.0	43.4	8.6	0.0	273.5
Median	5.6	1.0	0.0	8.7	2.6	0.0	173.2
1. Quartile	2.7	0.0	0.0	0.6	0.0	0.0	109.3
Min	0.0	0.0	0.0	0.0	0.0	0.0	2.4

Furthermore, almost all UA have waste biomass potential, which is however very low compared to the heat demand. On the other hand, less than 25% of UA with existing DH have potentials for industrial waste heat or ambient heat from lakes. Overall, rivers seem to be the most promising ambient heat source that is widely available (at least 75% of UA) and has the highest values of the ambient heat sources.

While solar thermal could provide most UA with sufficient heat, it is not available throughout the year and therefore is not suitable as base load unless it is used in combination with a heat storage. Therefore, especially rivers and wastewater have potential for UA, although the potential might not be enough. Therefore, the distribution among the UA has to be evaluated to identify, if the potentials are balanced out between the UA, so that the ones with no potentials from rivers, have potentials from other types of renewable heat.

6.2.3 Cluster analysis

In order to find a more general answer regarding to the role of DH in a carbon neutral heating scenario 2045, it is intended to cluster the UA. This way the heat demand and DHDCC as well as the potentials for renewable and waste heat can be characterised together. As a first step for the cluster analysis, the correlation between the potential input parameters is assessed, as shown in Table 9 below.

Table 9: Overview of the correlation between potential input parameters for the cluster analysis of UA with existing DH consisting of the heat demand (HD), DHDCC, shares and RE and waste heat potentials

	HD 2015	HD BL2050	HD DH 2015	HD DH BL2050	DHDCC DH 2015	DHDCC DH BL2050	HD DH Share 2015	HD DH Share BL2050	Area DH Share 2015	Area DH Share BL2050	Res HD share 2015	Biomass potential	Geothermal potential	Potential lakes	Potential rivers	Potential wastewater	Potential waste heat	Solar thermal potential
HD 2015	1,00																	
HD BL2050	1,00	1,00																
HD DH 2015	1,00	1,00	1,00															
HD DH BL2050	1,00	1,00	1,00	1,00														
DHDCC DH 2015	-0,30	-0,30	-0,30	-0,30	1,00													
DHDCC DH BL2050	-0,35	-0,34	-0,35	-0,35	0,67	1,00												
HD DH Share 2015	0,31	0,30	0,31	0,31	-0,36	-0,59	1,00											
HD DH Share BL2050	0,35	0,34	0,35	0,34	-0,69	-0,79	0,87	1,00										
Area DH Share 2015	0,14	0,13	0,15	0,15	0,02	-0,30	0,74	0,53	1,00									
Area DH Share BL2050	0,33	0,32	0,34	0,34	-0,59	-0,68	0,85	0,91	0,76	1,00								
Res HD share 2015	0,05	0,05	0,05	0,05	0,35	0,31	-0,20	-0,33	-0,07	-0,25	1,00							
Biomass potential	-0,13	-0,13	-0,13	-0,13	-0,05	0,05	0,01	-0,01	-0,04	-0,01	-0,03	1,00						
Geothermal potential	0,03	0,03	0,03	0,04	0,06	-0,13	0,07	0,03	0,22	0,11	-0,05	-0,14	1,00					
Potential lakes	0,07	0,06	0,07	0,07	-0,22	-0,29	0,30	0,29	0,13	0,28	0,04	0,03	-0,20	1,00				
Potential rivers	0,05	0,05	0,05	0,06	-0,10	-0,10	0,01	0,07	0,00	0,05	-0,08	0,06	0,10	-0,06	1,00			
Potential wastewater	0,58	0,57	0,58	0,57	-0,17	-0,20	0,21	0,22	0,08	0,21	0,04	-0,16	-0,04	0,17	0,00	1,00		
Potential waste heat	0,06	0,06	0,06	0,06	-0,17	-0,12	0,11	0,12	-0,10	0,06	-0,02	0,15	-0,10	0,29	-0,03	0,09	1,00	
Solar thermal potential	0,45	0,45	0,44	0,43	-0,10	-0,10	-0,02	0,06	-0,14	-0,03	0,00	-0,11	-0,09	-0,13	-0,02	0,20	-0,01	1,00

It can be observed that all total heat demands for UA are positively correlated with each other. Furthermore, there is a high positive correlation between the heat demand share and the area share for UA. Therefore, only one of these criteria should be chosen for the cluster analysis. The second aspect that is important to consider is that the criteria should be relevant regarding the outcome of the cluster analysis. As the aim of the cluster analysis to investigate the role of DH in 2045, the criteria that are therefore considered important, while also considering the correlation are shown in Table 10 below.

Table 10: Overview of chosen criteria for the cluster analysis of UA with existing DH

Heat demand	RE and waste heat
Total heat demand 4th Gen DH in UA BL2050	Biomass potential
Average DHDCC 4th Gen DH in UA BL2050	Geothermal potential
Residential heat demand share UA 2015	Ambient heat potential from lakes

	Ambient heat potential from rivers
	Ambient heat potential from wastewater
	Waste heat potential from industry
	Solar thermal potential

Based on the above-mentioned criteria the cluster analysis is conducted. The resulting dendrogram is shown in Appendix V: Dendrogram of the cluster analysis for UA with existing and potential DH. Subsequently, a scree plot is created to find the optimal number of clusters. However, as observable in Figure 17, no clear elbow point can be seen. Therefore, there is no clear suggestion as to how many clusters should be formed.

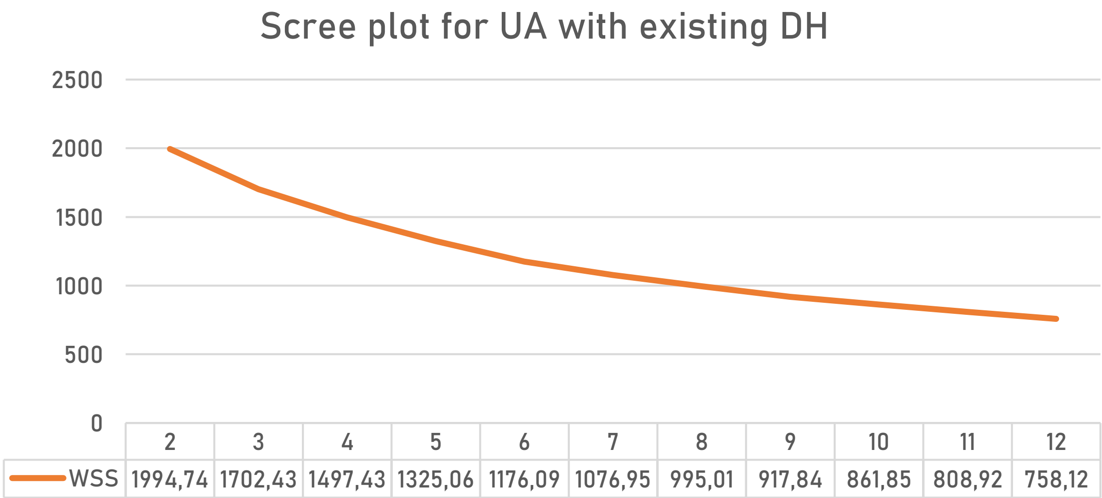


Figure 17: Scree plot for the clustering of UA with existing DH based on the within-cluster sum of squares (WSS) and the number of clusters in order to identify the optimal number of clusters (elbow point)

As no clear number of clusters could be determined, the clusters are determined based on other statistical criteria instead. In order to ensure a general conclusion regarding the role of DH, the sensitivity analysis is therefore extended if necessary. Overall, the approach is still followed to establish a max and a min cluster, where the max cluster is used to assess which renewable and waste heat potentials are most cost-efficient and the min cluster to assess if DH is cost-efficient compared to individual heating.

Therefore, based on the data analysis of the heat demand and the RE potentials in Section 6.2.1 and 6.2.2, the max and min cluster are derived and shown in Table 11 below.

Table 11: Overview of the max and min cluster for existing DH based on statistical criteria

Criterium	Unit	Max cluster		Min cluster	
Total heat demand 2015	GWh/a	1,144	3. Quartile	232	1. Quartile
4th Gen DH share of heat demand 2015	%	93	3. Quartile	87	1. Quartile
4th Gen DH heat demand 2015	GWh/a	1,064	Calculated	202	Calculated
Total heat demand BL2050	GWh/a	730	3. Quartile	149	1. Quartile
4th Gen DH share of heat demand BL2050	%	85	3. Quartile	69	1. Quartile
4th Gen DH heat demand BL2050	GWh/a	621	Calculated	103	Calculated
DHDCC DH 2015	Ct/kWh	1.8	1. Quartile	2.3	3. Quartile
DHDCC DH BL2050	Ct/kWh	4.6	1. Quartile	5.4	3. Quartile
Res heat demand share 2015	%	62	Median	62	Median
Biomass potential	GWh	42	Max	0	Min
Geothermal potential	Yes/no	1	Max	0	Min
Potential lakes	MW	227	Max	0	Min
Potential rivers	MW	603	Max	0	Min
Potential wastewater	MW	216	Max	0	Min
Potential waste heat	MW	192	Max	0	Min
Solar thermal potential	GWh	1,064	Max	2.4	Min

The max cluster is mainly based on the heat demand of the third quartile, so it represents an exemplary UA with a higher heat demand. This is highly negatively correlated with the DHDCC and therefore the values of the first quartile are used for the DHDCC. Furthermore, to establish the most cost-efficient technologies, the maxima for each renewable and waste heat potentials are used. For the min cluster, the opposite approach is used and it therefore consists mainly on the first quartile for the heat demand and the minima for the RE potentials. In the following the max and min cluster are therefore assessed through an energy system analysis in order to determine the role of DH in a climate neutral buildings sector.

6.2.4 Energy system analysis

In order to determine the role of DH towards climate neutrality in 2045, first the cost-efficient heat system for 2045 is analysed for both the max and min cluster and compared to individual heating. Subsequently, the cost-efficient heat system is analysed for the status quo scenario in 2020 and the BEW support scenario for 2020 in order to determine the current feasibility of DH and the impact of the BEW funding.

6.2.4.1 Set-up of energy system model

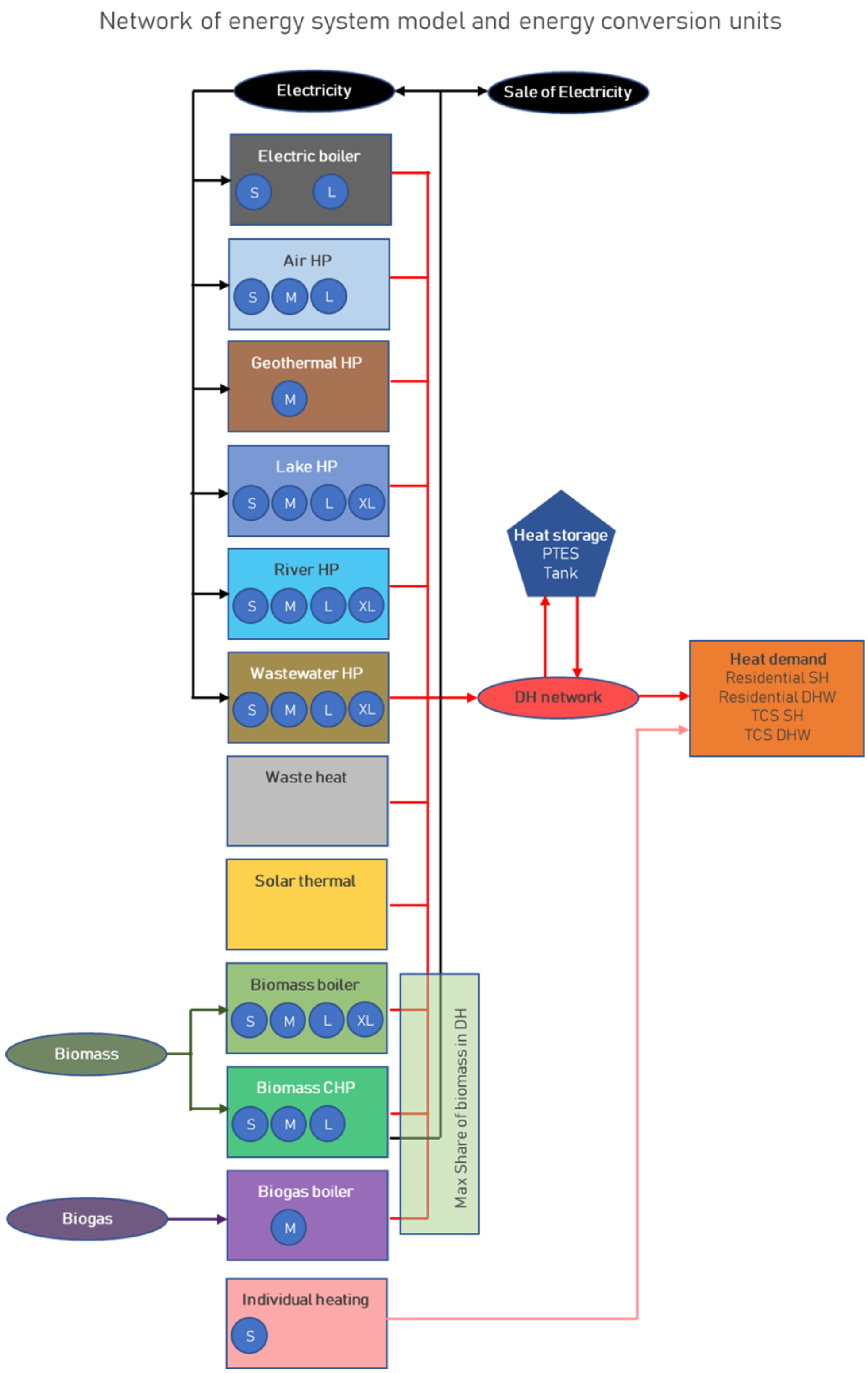


Figure 18: Schematic overview of energy system model and included energy conversion units with the available investment sizes

The energy system model is an investment optimization model that decides to invest in the most cost-efficient technologies based on the available technologies with the aim to reduce the overall system costs. The technologies that are considered include the technologies covered within the BEW scheme and therefore any fossil-fuel technologies are disregarded. The input for the model consists of the heat demand, which is further divided into residential and TCS as well as SH and DHW for each of them. In order to meet the heat demand, the standard technologies which are always available consist of an air source HP, an electric boiler and a biogas boiler. Further technologies are also available depending on the potentials for renewable and waste heat available in the respective cluster. A general overview of the energy system model and the included energy conversion units are shown in Figure 18 above.

In the following the input parameters of the model are presented starting with the general input parameters, as shown in Table 12 below.

Table 12: Overview of general input parameters for the energy system model based on

Input parameter	Unit	Value
WACC	%	8
Price year	-	2022
Supply temperature of DH	°C	60
Heat losses of DH	%	10
BEW support	%	40
BEG support (individual heating)	%	30
Max biomass share 2045	%	100
Max biomass share 2020	%	100
Max biomass share 2020 BEW	%	25
Share of DHW of residential heat demand	%	12.5
Share of DHW of TCS heat demand	%	4.7

The WACC for DH and the reference technology is set to 8%. For DH, this value is recommended by the AGFW (AGFW, n.d.) and is also used as default value for economic calculations as part of the BEW (Bundesamt für Wirtschaft und Ausfuhrkontrolle (BAFA), 2023). This enables the DH operator to have a profit that is similar to other monopolies such as the electricity grid. For the reference technology, it is assumed that a loan will be needed for the investment and 8% therefore is reasonable including the inflation and corresponding risks. The price year is set to the year 2022 and the price of the input data that is available from different years is therefore adjusted according to the inflation in the EU (Eurostat, 2023).

Furthermore, in accordance with the definition of 4th Gen DH (Thorsen et al., 2018), it is assumed that the supply temperature of the DH is 60 °C. The supply temperature is only needed for the calculation of the COP of heat pumps as well as the average temperature difference for solar thermal. As mentioned in the scope and delimitations, no hydraulic model including the supply and return temperature is used to analyse the heat flows and costs of the DH. The heat loss for 4th Gen DH is assumed to be 10% according to the Technology Catalogue by the Danish Energy Agency (n.d.). While this depends on local circumstances and specific grid temperatures as well as pipes used among others, due to the limitations of the research an average value was chosen for the energy system analysis.

Furthermore, various parameters are set by the BEW and BEG support scheme. Overall, the support for investments in DH and energy conversion units as well as heat storage is 40% according to the BEW, while electric boilers, biogas boilers and biomass CHPs are excluded, as mentioned in Section 2.3. However, the operational funding of the BEW for HPs was not included, as the implementation would have been more difficult as it requires a profitability gap calculation. Therefore, the operational funding for solar thermal was also not included for consistency. For individual heating, the BEG supports investment costs by 30%, which is therefore used for an air HP as reference technology as well. Moreover, the BEW sets limitation regarding the use of biomass and sets the share for newly established DH to 25% of the heat production. This value is also assumed for the calculation of the impact of the BEW for existing DH.

For the determination of the different load profiles for residential and TCS as well as SH and DHW, the share of DHW based on the overall heat demand is furthermore set based on the distribution in Germany. While the share of residential heat demand is determined for each cluster, the share for DHW is set as a constant, as this information is only available on a national level.

Furthermore, it should be mentioned that based on the input from the clustering, it is assumed that DH will be used to cover all of the heat demand for 4th Gen DH, which would equal a connection rate of 100%. This way the maximum potential of DH is evaluated.

In Table 13, Table 14 and Table 15 below, the temperatures, technical and economic parameters of the considered renewable and waste heat sources are shown.

Table 13: Overview of temperatures of considered renewable and waste heat sources

Temperatures	**2045**			**2020**		
Unit	°C			°C		
	Max	Average	Min	Max	Average	Min
Ambient air (hourly)	32	10	-10	36	10	-11
Industrial waste heat	60			60		
Geothermal heat	44			44		
Lake (daily)	22	13	5	22	13	5

River (daily)	22	13	5	22	13	5
Wastewater (daily)	27	18	10	27	18	10

The temperatures for the considered heat sources are used for the calculation of the COP of HPs as well as for the calculation of the hourly solar thermal production. Even though the data for industrial waste heat indicates a temperature of 55 °C, the heat is also available at higher temperatures and it is therefore assumed that approximately the same amount of heat is also available at 60 °C and no further HP is needed. As the river and lake temperature are not below 5 °C, they can be used throughout the whole year for heat production without limitations to their capacity.

Table 14: Overview of technical parameters of RE sources

RE Source	Min capacity	Max capacity	Efficiency	Lifetime
Unit	MW_{th}	MW_{th}	%	a
Solar thermal	0	Depending on cluster	Calculated	30
Industrial waste heat	0	Depending on cluster	n/a	n/a
Ambient heat air	0	indefinite	n/a	n/a
Geothermal heat	0	Depending on cluster	n/a	n/a
Ambient heat lake	0	Depending on cluster	n/a	n/a
Ambient heat river	0	Depending on cluster	n/a	n/a
Ambient heat wastewater	0	Depending on cluster	n/a	n/a

The maximum capacity of the considered heat sources depends on the specific cluster and the potentials that are determined. Only ambient air is assumed to be available indefinitely. As solar thermal describes the energy conversion unit, it also includes a lifetime and an efficiency which is calculated for every hour according to Equation 4. The other inputs only describe the ambient heat potentials and not the HP which uses the ambient heat.

Table 15: Overview of economic parameter of RE sources

RE Source	CAPEX 2045	CAPEX 2020	CAPEX 2020 with BEW	OPEX 2045	OPEX 2020
Unit	T EUR/MW_{th}	T EUR/MW_{th}	T EUR/MW_{th}	EUR/MWh_{th}	EUR/MWh_{th}
Solar thermal	47	51	31	0.06	0.04
Industrial waste heat	0	0	0	0	0

Ambient heat air	0	0	0	0	0
Geothermal heat	0	0	0	0	0
Ambient heat lake	0	0	0	0	0
Ambient heat river	0	0	0	0	0
Ambient heat wastewater	0	0	0	0	0

For the economic parameters, only solar thermal as energy conversion unit has capital expenditures (CAPEX) and operational expenditures (OPEX) defined. As the heat exchangers are included in the costs for the HPs, there are no costs related to the other heat sources itself.

The technical and economic parameters of the considered commodities are shown in Table 16 and Table 17 below.

Table 16: Overview of technical parameters of commodities

Commodity	**Min supply**	**Max supply**
Unit	MWh	MWh
Biogas	0	indefinite
Biomass	0	Depending on cluster
Electricity	0	indefinite

Concerning the technical parameters only biomass is limited depending on the potential of waste biomass in the respective cluster. While it is therefore assumed that electricity and biogas is available through a grid connection or other means of transportation, it is assumed that only local waste biomass is available and that no biomass can be imported from other regions, as they will require their own biomass.

Table 17: Overview of economic parameter of commodities

Commodity	**Price 2045**			**Price 2020**		
Unit	EUR/MWh			EUR/MWh		
	Max	Average	Min	Max	Average	Min
Biogas	124			66		
Biomass	85			45		
Electricity for DH (hourly)	330	147	103	387	197	69

Electricity sale for DH (hourly)	230	47	3	224	34	-94
Electricity for individual heating	248			288		

In order to ensure consistency, the average prices of the commodities both for 2045 and 2020 are based on the same source (Fraunhofer ISE and Fraunhofer IEE, 2022). Furthermore, as DH operators use significantly larger amounts of electricity, it is available at reduced costs compared to individual heating, as larger amounts can be bought at lower prices and the tariffs are lower. Moreover, in order to reflect the potential benefit and synergy of DH with an increasingly fluctuating electricity market, the electricity prices are included as hourly values based on the historic values and the projected values for 2045 (Danish Energy Agency, 2023; ENTSO-E, 2022). Therefore, the hourly spot market prices are increased, so that their average matches the average yearly price. This difference would then represent the profits, tariffs and fees. However, as this would not apply to the sale of electricity by CHP units, the spot market prices are used for the sale of electricity. The variation of the different electricity prices is shown in Figure 19 below.

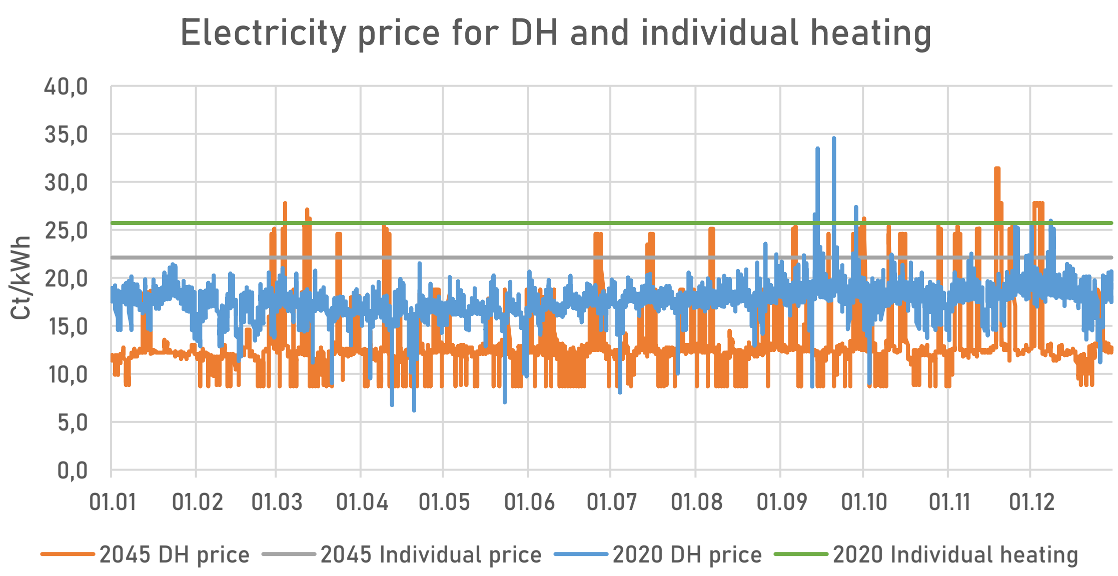


Figure 19: Overview of the development of electricity prices for different years and consumers

While the volatility of the electricity price is expected to increase over time, the overall electricity costs are expected to decline over time. Furthermore, it can be seen that the price for DH is considerably cheaper on average than the price for individual heating. Generally, it should be mentioned that there is a lot of uncertainty regarding the future development of the electricity price, especially for a long-term time horizon such as 2045. The future electricity price will depend on many various parameters such as the installation of new RE source and a possible redesign of the electricity market as discussed currently in the EU and Germany.

In the following the technical and economic input parameters for boilers based on the Technology Catalogue of the Danish Energy Agency (n.d.) are shown in Table 18 and Table 19.

Table 18: Overview of technical parameters of boilers

Boiler	Min capacity	Max capacity	Efficiency	Lifetime
Unit	MW_{th}	MW_{th}	%	a
Small electric boiler	1.0	indefinite	99	20
Large electric boiler	10.0	indefinite	99	20
Small biomass boiler	5.3	indefinite	114	25
Medium biomass boiler	39.7	indefinite	115	25
Large biomass boiler	79.5	indefinite	115	25
Medium biogas boiler	0.5	indefinite	104	25

While the capacity for small, medium and large boilers is not handled consistently, the nomenclature of the Technology Catalogue of the Danish Energy Agency (n.d.) is used for comprehensive referencing. There is no medium electric boiler, small biogas boiler and large biogas boiler in the Technology Catalogue, because of which they are also not included here. It is however assumed that the presented units cover a wide enough range of capacity.

Table 19: Overview of economic parameter of boilers

Boiler	CAPEX 2045	CAPEX 2020	CAPEX 2020 with BEW	OPEX 2045	OPEX 2020
Unit	T EUR/MW_{th}	T EUR/MW_{th}	T EUR/MW_{th}	EUR/MWh_{th}	EUR/MWh_{th}
Small electric boiler	153	177	177	1.18	1.06
Large electric boiler	71	82	82	1.18	1.06
Small biomass boiler	699	813	488	4.46	3.20
Medium biomass boiler	535	581	349	4.43	3.19
Large biomass boiler	475	518	311	4.42	3.18
Medium biogas boiler	59	71	71	1.18	1.30

Table 20 and Table 21 below show the technical and economic parameters that are used for the CHPs based on the Technology Catalogue of the Danish Energy Agency (n.d.).

Table 20: Overview of technical parameters of CHPs

CHP	Min capacity	Max capacity	Electrical efficiency	Heat efficiency	Lifetime
Unit	MW_{el}	MW_{el}	%	%	a
Small biomass CHP	0.1	indefinite	14	98	25
Medium biomass CHP	6	indefinite	28	83	25
Large biomass CHP	25	indefinite	29	83	25

In contrast to the other units, CHPs are also used for the production of electricity and are therefore based on the electrical capacity. Furthermore, electricity is the primary output and therefore, the units are optimized for the production of electricity instead of the production of heat. Furthermore, there are no biogas CHPs in the Technology Catalogue, because of which they are not included here.

Table 21: Overview of economic parameter of CHPs

CHP	CAPEX 2045	CAPEX 2020	CAPEX 2020 with BEW	OPEX 2045	OPEX 2020
Unit	T EUR/MW_{el}	T EUR/MW_{el}	T EUR/MW_{el}	EUR/MWh_{el}	EUR/MWh_{el}
Small biomass CHP	6,828	7,442	4,465	11.08	10.91
Medium biomass CHP	3,764	4,174	2,504	5.36	5.29
Large biomass CHP	3,457	3,872	2,323	5.24	5.17

The technical and economic parameters for HPs based on the Technology Catalogue of the Danish Energy Agency (n.d.) are shown in Table 22 and Table 23 below.

Table 22: Overview of technical parameters of HPs

HP	Min capacity	Max capacity	Lorenz Efficiency	Lifetime
Unit	MW_{th}	MW_{th}	%	a
Small air HP	0.2	indefinite	51	25
Medium air HP	1.5	indefinite	58	25
Large air HP	5	indefinite	62	25
Medium geothermal HP	4.3	indefinite	54	30
Small lake HP	0.2	indefinite	51	25

Medium lake HP	1.5	indefinite	58	25
Large lake HP	5	indefinite	62	25
Extra-large lake HP	20	indefinite	65	25
Small river HP	0.2	indefinite	51	25
Medium river HP	1.5	indefinite	58	25
Large river HP	5	indefinite	62	25
Extra-large river HP	20	indefinite	65	25
Small wastewater HP	0.2	indefinite	51	25
Medium wastewater HP	1.5	indefinite	58	25
Large wastewater HP	5	indefinite	62	25
Extra-large wastewater HP	20	indefinite	65	25

As there is no data in the Technology Catalogue of the Danish Energy Agency (n.d.) for lake, river and wastewater HPs, it is assumed that the input parameters are equal to air HPs. Furthermore, it is assumed that the large sea water HP can also be used for other water sources and its therefore included as extra-large HP for lakes, rivers and wastewater. As part of the calculation of the COP, the Lorenz efficiency is used, which describes the actual efficiency of the HP compared to the maximal possible technical efficiency. The Lorenz efficiency increases with increasing capacities and is also obtained from the Technology Catalogue of the Danish Energy Agency (n.d.).

Table 23: Overview of economic parameter of HPs

HP	CAPEX 2045	CAPEX 2020	CAPEX 2020 with BEW	OPEX 2045	OPEX 2020
Unit	T EUR/MW$_{th}$	T EUR/MW$_{th}$	T EUR/MW$_{th}$	EUR/MWh$_{th}$	EUR/MWh$_{th}$
Small air HP	1,569	1,681	1,009	3.17	3.17
Medium air HP	1,009	1,121	672	3.15	2.58
Large air HP	897	1,009	605	1.99	1.99
Medium geothermal HP	2,801	3,197	1,918	6.91	6.71
Small lake HP	1,569	1,681	1,009	3.17	3.17
Medium lake HP	1,009	1,121	672	3.15	2.58
Large lake HP	897	1,009	605	1.99	1.99

Extra-large lake HP	448	560	336	1.97	1.40
Small river HP	1,569	1,681	1,009	3.17	3.17
Medium river HP	1,009	1,121	672	3.15	2.58
Large river HP	897	1,009	605	1.99	1.99
Extra-large river HP	448	560	336	1.97	1.40
Small wastewater HP	1,569	1,681	1,009	3.17	3.17
Medium wastewater HP	1,009	1,121	672	3.15	2.58
Large wastewater HP	897	1,009	605	1.99	1.99
Extra-large wastewater HP	448	560	336	1.97	1.40

Next, the technical and economic parameters of heat storages based on the Technology Catalogue of the Danish Energy Agency (n.d.) are shown in Table 24 and Table 25 below.

Table 24: Overview of technical parameters of heat storages

Heat storage	Min capacity	Max capacity	Inflow efficiency	Outflow efficiency	Heat loss	Lifetime
Unit	MWh_{th}	MWh_{th}	%	%	%	a
Storage tank	45	indefinite	99	99	0.008	40
PTES	4,500	indefinite	85	85	0.004	20

While further storage tanks are included in the Technology Catalogue of the Danish Energy Agency (n.d.), only the large storage tank is included, as it is the only one suited for DH. Besides the storage tank, a pit thermal energy storage (PTES) is included for larger scale storage of heat and is mainly used in combination with solar thermal. Furthermore, only the roundtrip efficiency is given, which is then divided equally into the inflow and outflow efficiency. The heat loss is also given in percent per day and is thus converted to represent the loss per hour. Moreover, it is assumed that the heat storage is filled at the beginning of the energy system analysis, as it is assumed that the storage would rather be filled towards the end of the year for a seasonal storage and during the night for a daily storage. In order to ensure an equal balance, it is also required that the storage is filled again to the initial level at the end of the optimization.

Table 25: Overview of economic parameter of heat storages

Heat storage	CAPEX 2045	CAPEX 2020	CAPEX 2020 with BEW	OPEX 2045	OPEX 2020	Investment relation
Unit	T EUR/ MWh_{th}	T EUR/ MWh_{th}	T EUR/ MWh_{th}	EUR/ MWh_{th}	EUR/ MWh_{th}	MW_{th}/ MWh_{th}
Storage tank	3.493	3.493	2.096	0.15	0.20	0.0166
PTES	0.550	0.683	0.410	0.29	0.39	0.0067

In contrast to other energy conversion units, the CAPEX is based on the capacity of the heat storage in MWh. As a corresponding input and output capacity also needs to be installed, this is assumed to be equal for both inflow and outflow. It is calculated based on the standard inflow/outflow divided by the standard capacity of the heat storage.

Finally, in Table 26 and Table 27 below the technical and economic parameters for individual heating are shown. This is the reference technology compared to DH and consist of an air HP. While the Technology Catalogue of the Danish Energy Agency (n.d.) contains data for air HPs for both single-family house and apartment complex, it contains different parameters and is not directly comparable to the other energy conversion units. As the ratio of single-family houses and apartment complexes is not defined, the different parameters are compared to the small air HP for DH. As the parameters for the small air HP for DH are in between the values for the air HP for the single-family house and apartment complex respectively, it is therefore used as reference technology.

Table 26: Overview of technical parameters of individual heating

Individual heating	Min capacity	Max capacity	Lorenz Efficiency	Lifetime
Unit	MW_{el}	MW_{el}	%	a
Air HP	0	indefinite	51	25

Table 27: Overview of economic parameter of individual heating

Individual heating	CAPEX 2045	CAPEX 2020	CAPEX 2020 with BEW	OPEX 2045	OPEX 2020
Unit	T EUR/MW_{th}	T EUR/MW_{th}	T EUR/MW_{th}	EUR/MWh_{th}	EUR/MWh_{th}
Air HP	1,569	1,681	1,009	3.17	3.17

Next to the general parameters mentioned above, there are also some more specific input parameters for the energy system modelling. This concerns the heat demand, DHDCC and potentials of the respective clusters. However, as the DHDCC obtained from the sEEnergies project is calculated for a WACC of 3% and a lifetime of 30 years, this is recalculated to a WACC of 8% and a lifetime of 40 years in accordance with the input parameter and the Technology Catalogue. Furthermore, for existing DH areas, part of the

DH system already exists and therefore only partly new DH has to be established and the remaining DH has to be modernized. Based on projections of the AGFW, the heat distributed in existing DH by existing pipes in 2050 is 29%, while the remaining 71% can be attribute to the installation of new pipes and to a small share also to new connections within existing DH areas (AGFW, 2018). It is therefore assumed that for existing DH only 71% of the DHDCC for new DH are required. The newly calculated DHDCC that are used as inputs are shown in Table 28 below.

Table 28: Overview of scneario dependet parameter for existing DH

Input Parameter	Unit	2045	2020	2020 with BEW
DHDCC Max	Ct/kWh	5.4	2.1	1.3
DHDCC Min	Ct/kWh	6.3	2.7	1.6

6.2.4.2 Target scenario 2045

For the target scenario 2045, the most cost-efficient heat scenarios for the max and min cluster are analysed. The installed capacity for the two clusters is shown in Table 29 below. The energy conversion units installed for the max cluster include a 192 MW industrial waste heat and a 73 MW biogas boiler as well as a PTES with a capacity of around 8 GWh, covering around 125,000 m^3 in order to meet the heat demand of 621 GWh. For the min cluster with a heat demand of only 103 GWh a 11 MW biogas boiler, a 25 MW air HP, 3.8 MW of solar thermal as well as a heat storage tank of around 1 GWh are installed.

Table 29: Overview of installed capacity for each energy conversion unit in the max and min cluster for UA with existing DH for the target scenario 2045

Energy conversion unit	Unit	Max	Min
Industrial waste heat	MW	192	-
Biogas boiler	MW	73	11
Air HP	MW	-	25
Solar thermal	MW	169	3,8
PTES	MWh	8,169	-
Storage tank	MWh	-	1,010

The heat production share for both clusters is shown in Figure 21 below. For the max cluster the heat demand is almost entirely covered by industrial waste heat, with only 2 GWh produced by the biogas boiler during peak demands. The PTES is also used as buffer for peak periods. For the min cluster, the heat demand is mainly covered by the air HP, while solar thermal and biomass only are responsible for 3% and 1% of the total heat produced respectively. While the solar thermal mainly produces heat in summer, the biogas boiler is also used to cover the peak demands. The heat storage tank is mainly used as daily storage to react to the fluctuating electricity prices and produce heat with the air HP during times of low electricity prices.

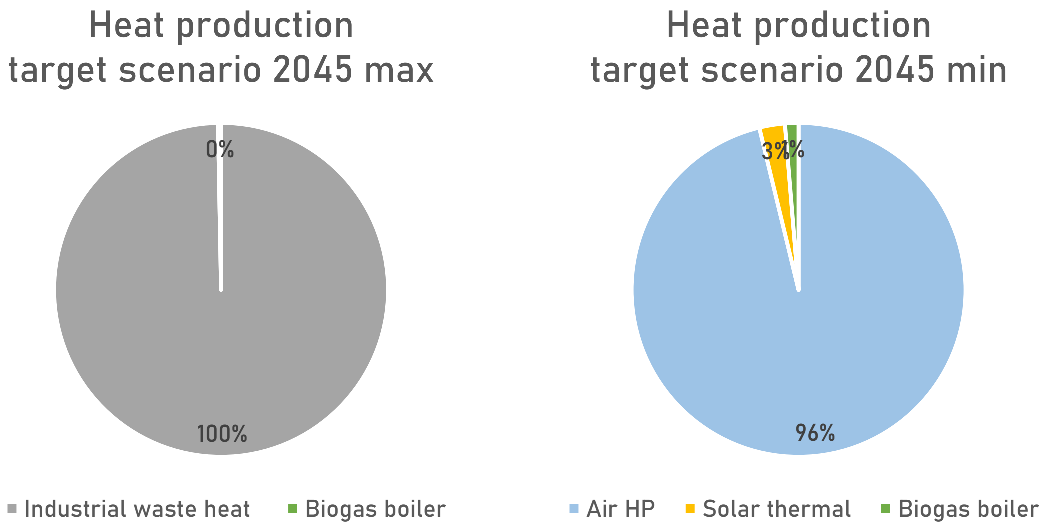


Figure 21: Heat production mix for UA with existing DH for max and min cluster for target scenario 2045

Looking at the total system costs, the max and min cluster describe the range for the LCOH for the DH system and is shown in Figure 20 below. Compared to the reference scenario both the max and min cluster are below the reference price for individual heating of 15.1 ct/kWh. However, the min cluster has costs of 13.6 ct/kWh and is therefore only slightly lower than the reference price. On the other hand, the max cluster only has costs around 6.1 ct/kWh due to the significant use of free waste heat. The costs for the heat production between the scenarios ranges between 0.8 ct/kWh and 7.3 ct/kWh and therefore show a wide range and potentially significant influence on the LCOH. On the other hand, the difference between the DHDCC in the max and min cluster is only 0,9 ct/kWh and therefore rather small.

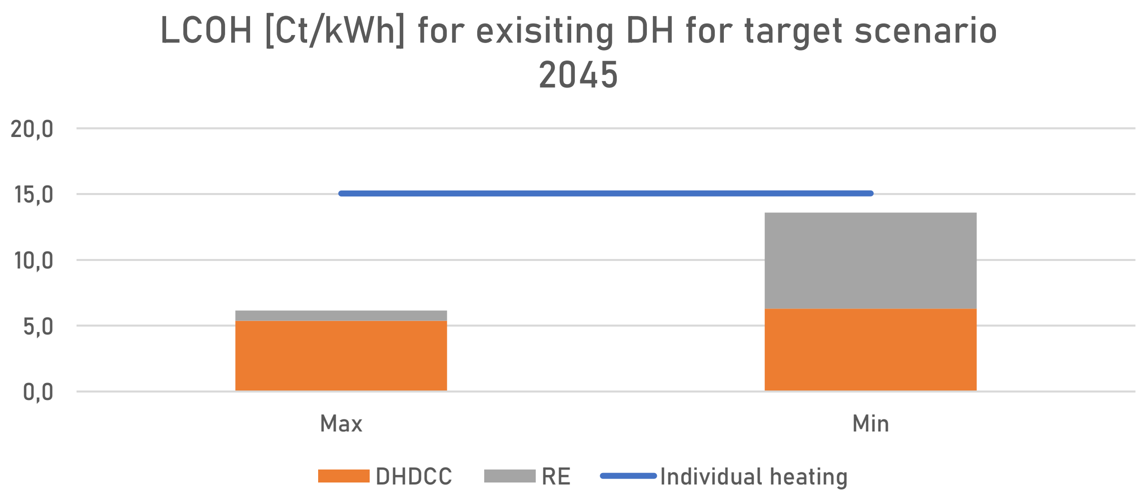


Figure 20: LCOH for UA with existing DH for max and min cluster as well as reference for target scenario 2045

Therefore, it can be concluded that DH is overall feasible and the most cost-efficient heating solution for UA with already existing DH towards climate neutrality 2045. Next, it will be investigated if the same technologies are already the most cost-efficient currently and if the support of the BEW supports the transition towards 2045.

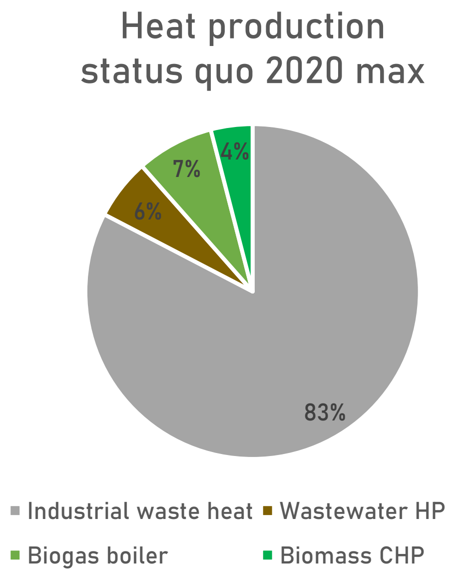
6.2.4.3 Status quo scenario 2020

The status quo scenario for 2020 is analysed to determine if DH is already cost efficient now and if the technologies that are invested into now are also the cheapest options in 2045. The installed capacity for the max and min clusters is shown in Table 30 below. Similar to the max cluster in 2045, the largest installed unit is industrial waste heat with 192 MW. As the heat demand in 2020 is significantly higher, the capacity of the biogas boiler and the PTES are increased to 132 MW and around 19 GWh respectively. Additionally, a wastewater HP with a capacity of 28 MW, a biomass CHP with a capacity of 6 MW and heat storage tank with a capacity of 1,8 GWh are installed. For the min scenario, the largest unit consists of a 91 MW biogas boiler and therefore only includes a 5 MW air HP. The solar thermal stays the same with 3.8 MW while the size of the heat storage tank is reduced to 243 MWh.

Table 30: Overview of installed capacity for each energy conversion unit in the max and min cluster for UA with existing DH for status quo scenario 2020

Energy conversion unit	Unit	Max	Min
Industrial waste heat	MW	192	-
Wastewater HP	MW	28	-
Biogas boiler	MW	132	91
Biomass CHP	MW	6	-
Air HP	MW	-	5
Solar thermal	MW	-	3,8
PTES	MWh	18,695	-
Storage tank	MWh	1,761	243

Looking at the heat production, there is a significant difference between the max and min cluster, as shown in Figure 23 below. While for the max cluster, waste heat still supplies the largest share of heat, similar to the target scenario 2045, the biogas boiler supplies the largest share of heat in the min cluster. Due to the higher heat demand, the waste heat cannot supply enough heat and the wastewater HP, the biogas boiler and the biomass CHP have a share between 4 – 7% each. All three units are used over the wintertime, where the heat demand is the highest and the CHP unit can supply cheap heat to the wastewater HP. The biogas boiler and both types of heat storage are mainly used to cover the peak demands. Regarding the min cluster, the air source HP produces significantly less heat and only supplies 16% of the heat. However, it is used almost all year long and reaches a capacity factor of 80%. Due to the limited capacity, solar thermal can only marginally contribute to the heat production.



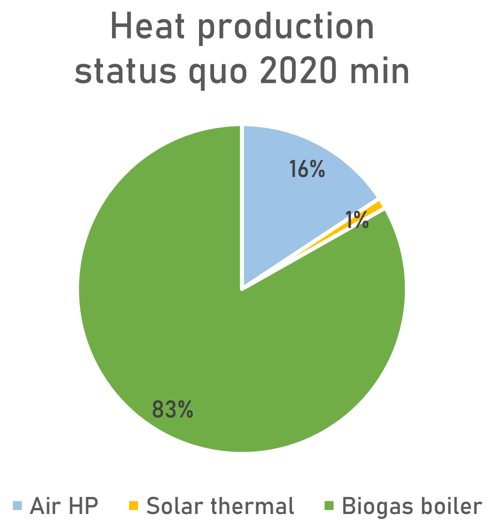


Figure 23: Heat production mix for UA with existing DH for max and min cluster for the status quo scenario 2020

Comparing the DH options with the reference technology, it can be seen in Figure 22 below that the LCOH for both the max and min cluster are clearly below the LCOH of the reference technology. With a LCOH of 17.7 ct/kWh the individual heating solution is more than two thirds more expensive than the min cluster with 10,4 ct/kWh. If all potential heat sources are available, this can be further reduced to 3.8 ct/kWh. Similar to the target scenario, the largest impact for the total LCOH can be attributed to the costs of renewable and waste heat production, while the DHDCC only ranges between 2.1 and 2.7 ct/kWh. Another similarity is that the availability of heat source shows a rather wide range between 1,7 and 7.7 ct/kWh.

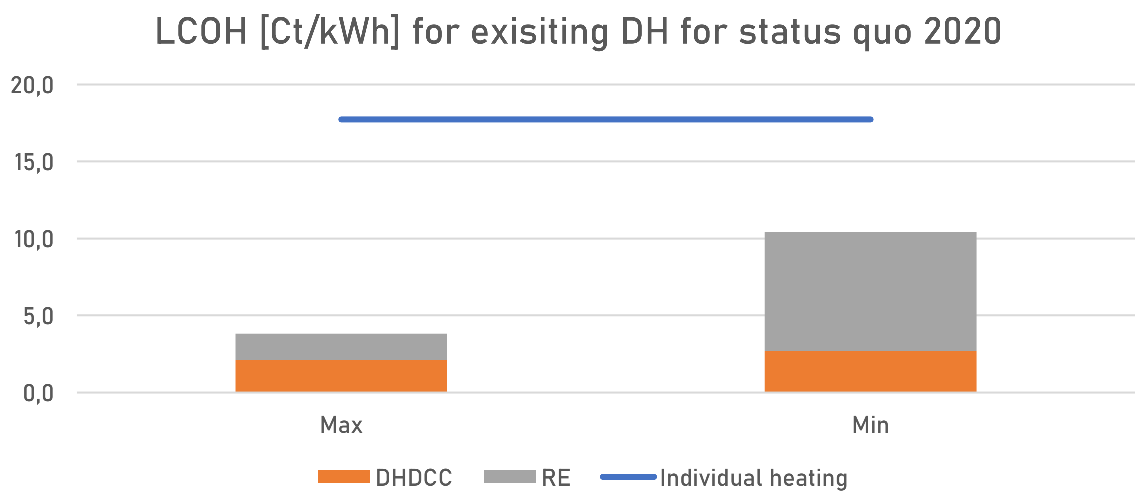


Figure 22: LCOH for UA with existing DH for max and min cluster as well as reference for status quo scenario 2020

Overall, it can be concluded that DH is even more feasible in the status quo than in the target scenario 2045. While the max cluster shows that similar technologies are used, with the additional use of wastewater and biomass, in the min cluster the use of biomass is currently more cost-efficient than an air HP, which is most cost-efficient in 2045. Therefore, there seems to be no additional need for support in case waste heat is available, while it will be evaluated if the BEW support shows a similar priority for technologies in 2020 as in 2045.

6.2.4.4 BEW support scenario 2020

Looking at the installed capacity for the BEW support scenario 2020, as shown in Table 30, the installed capacities shifted compared to the status quo for 2020. For the max cluster, the capacity of the wastewater HP and the biomass CHP and the heat storage tank have increased while the capacity of the biogas boiler is reduced by around one third to 83 MW. The capacity of the PTES stayed almost constant at around 19 GWh. For the min cluster, the capacity of the biogas boiler is likewise significantly reduced to 44 MW, while the capacity of the air HP is increased to 29 MW and is therefore slightly larger than the air HP capacity in the target scenario 2045. The solar thermal capacity stays constant as it is already at its maximum, while the heat storage capacity is also significantly increased to 1.6 GWh. Overall, as expected the capacity of the biogas boiler is therefore decreased, as it is not funded by the BEW[1]. Therefore, the BEW funding overall aligns the installed capacities more to the target scenario, while it also has to be taken into account that less capacities are required in 2045 in general, as the heat demand is also lower.

Table 31: Overview of installed capacity for each energy conversion unit in the max and min cluster for UA with existing DH for the BEW support scenario 2020

Energy conversion unit	**Unit**	**Max**	**Min**
Industrial waste heat	MW	192	-
Wastewater HP	MW	41	-
Biogas boiler	MW	83	44
Biomass CHP	MW	9	-
Air HP	MW	-	29
Solar thermal	MW	-	3,8
PTES	MWh	18,984	-
Storage tank	MWh	3,313	1,617

[1] Funding of biogas boilers as part of the BEW is possible, if it is only used as a peak boiler with less than 200h of runtime. Further additional requirements apply but depending on the case the biogas boiler of the status quo scenario could potentially receive funding. (Bundesamt für Wirtschaft und Ausfuhrkontrolle (BAFA), 2023)

Regarding the amount of heat production, which is shown in Figure 24 below, a similar shift can be observed for the min cluster as for the capacity. On the other hand, the shares of the max cluster have stayed almost constant and only changed by 1%. The effect on the

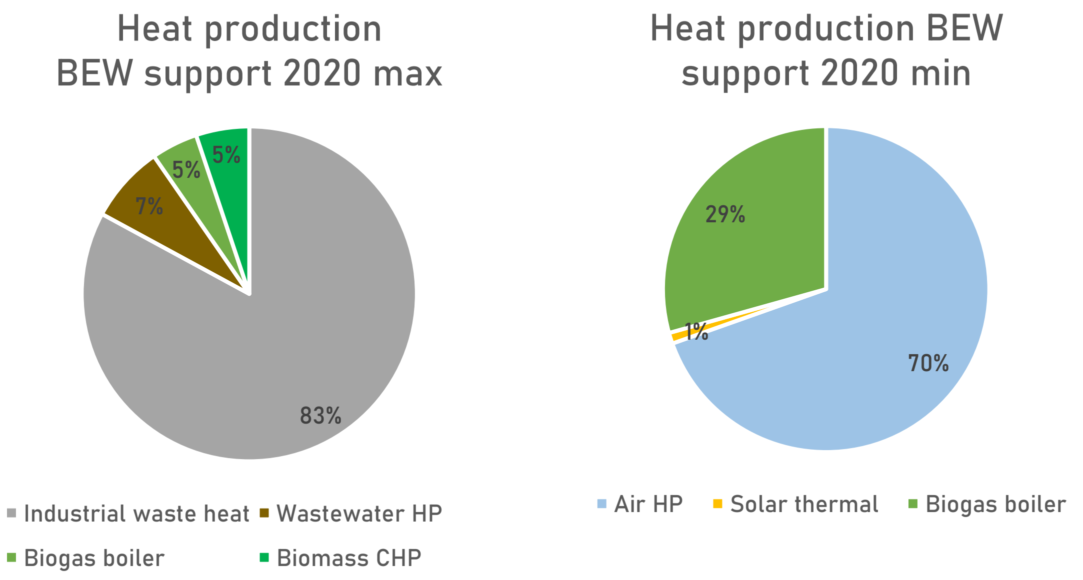


Figure 24: Heat production mix for UA with existing DH for max and min cluster for the BEW support scenario 2020

heat production is therefore rather marginal for the max cluster. Therefore, the changes for the min cluster are more drastic and the shares of the biogas boiler and air HP almost changed. The air HP now supplies 70% of the heat, while the share of the biogas boiler is reduced to 29%. This is significantly closer to the shares in the target scenario 2045.

While the BEW support reduces the investment costs for various technologies by 40%, the reference technology is also benefitting from the BEG, which reduces the investment costs by 30%. However, as shown in Figure 25 below, this has no effect on the overall feasibility of DH compared to individual heating and the profitability of DH is even increased.

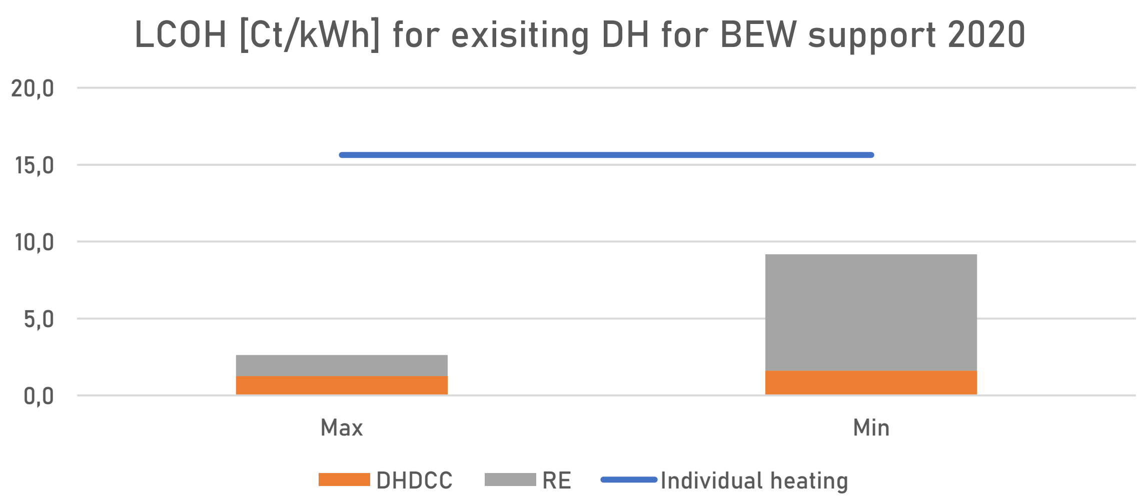


Figure 25: LCOH for UA with existing DH for max and min cluster as well as reference for the BEW support scenario 2020

Similar to both the target scenario and the status quo scenario, the biggest share of the LCOH of DH can be attributed to the renewable and waste heat production which ranges between 1.4 ct/kWh and 7.6 ct/kWh. The choice and availability of heat technologies therefore has a significant impact on the LCOH. As the DHDCC are also supported by the BEW, the costs are further reduced and only range between 1.3 ct/kWh and 1.6 ct/kWh.

DH would still be more cost-efficient than the reference technology without BEW support. However, the BEW support promotes technologies which are also used in the target scenario 2045 and reduces the share of biomass. This is more pronounced with the min cluster, while the changes in the max cluster are less extreme. As there is a wide range in the LCOH for the different available renewable and waste heat potentials, these are analysed in more detail as part of the sensitivity analysis.

6.2.4.5 Sensitivity analysis

As the LCOH for the max cluster is very low, this can mostly be attributed to the use of industrial waste heat. However, according to the analysis of the potentials only less than 25% of the UA with existing DH have waste heat potentials. Therefore, as a first step the different distributions of the renewable heat cluster as analysed. This therefore includes the different statistically determined RE potentials, which are shown in Table 8 in Section 5.2.2. The LCOH of the use of the max cluster in combination with the different RE clusters is shown in Figure 26 below.

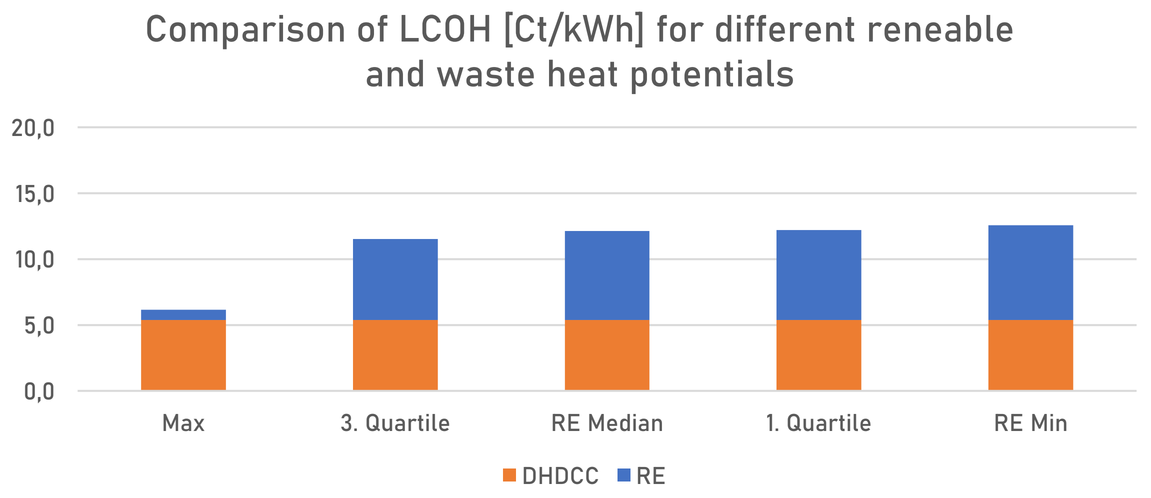


Figure 26: Comparison of LCOH for different renewable and waste heat cluster in UA with existing DH

While the LCOH for RE in the max cluster are very low, they are significantly higher in the other cluster and only range between 6.1 and 7.2 ct/kWh for the third quartile and RE min. Therefore, the costs for the heat supply are significantly higher in most UA with existing DH. Nevertheless, they are all still below the costs of individual heating and therefore DH is still more cost-efficient. For further comparison the installed capacities for the different clusters are shown below in Table 32.

Table 32: Overview of installed capacities for different renewable and waste heat clusters in UA with existing DH

Energy conversion unit	Unit	Max	3. Quartile	Median	1. Quartile	Min
Industrial waste heat	MW	192	-	-	-	-
Wastewater HP	MW	-	20	3	-	-
River HP	MW	-	58	20	-	-
Air HP	MW	-	72	126	144	153
Solar thermal	MW	-	210	217	171	3.8
Biogas boiler	MW	73	83	83	78	67
PTES	MWh	8,169	25,438	27,307	19,193	5,137
Storage tank	MWh	-	2,490	2,624	3,078	4,721

The installed capacities show that if no industrial waste heat is available, instead wastewater, river and air HPs as well as solar thermal in combination with large heat storages are installed. As the potentials for heat from wastewater and rivers decreases, this is replaced by additional air HP capacity.

As so far, no geothermal heat has been used in any of the scenarios or cluster, the impact on the availability of individual heat sources on the LCOH are investigated and shown in Figure 27 below. Hereby, it is assumed that in accordance with the min potential for RE, around 2.4 GWh of solar thermal are available, while the max potential is then used for the respective heat source.

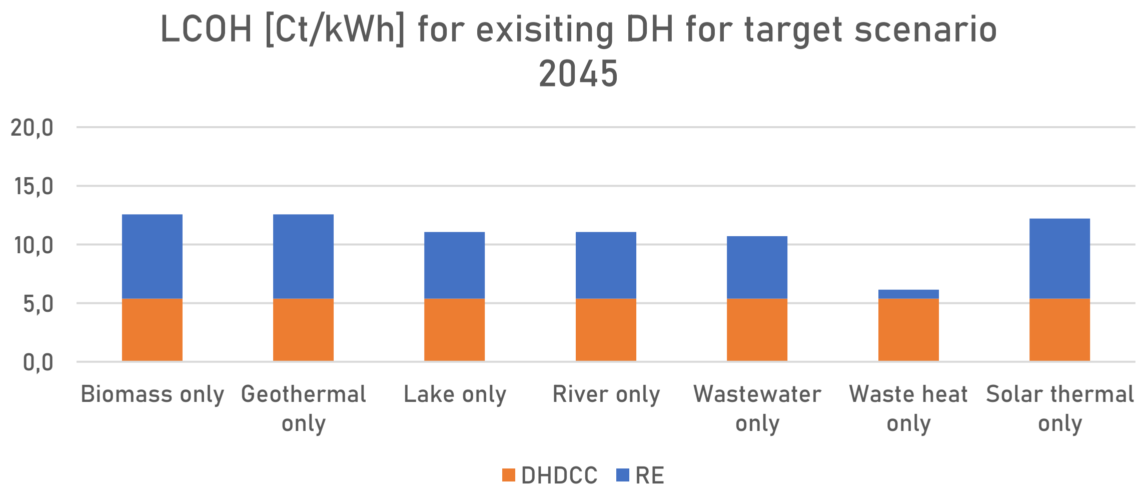


Figure 27: Comparison of LCOH for different renewable and waste heat sources in UA with existing DH

The highest LCOH are calculated for the case where only biomass or geothermal potentials are available. With a total LCOH of 12,6 ct/kWh, the LCOH is as high as for the max cluster with min RE potential. The next lowest LCOH is related to solar thermal only, which gives a slightly lower LCOH of 12,2 ct/kWh and therefore corresponds to the LCOH of the max with the first quartile RE potential. If only lake, river or wastewater sources are available, the LCOH can be further lowered to 11,1 ct/kWh or 10,7 ct/kWh respectively. The lowest LCOH can be attributed to the available of waste heat, which amounts to the same costs as the max cluster of 6,1 ct/kWh. The installed capacities of the different sensitivities are shown in Table 33 below in order to evaluate which energy conversion units are installed.

Table 33: Overview of installed capacities for different renewable and waste heat sources in UA with existing DH

Energy conversion unit	Unit	Biomass only	Geothermal only	Lake only	River only	Waste water only	Waste heat only	Solar thermal only
Air HP	MW	153	153	-	-	-	-	141
Lake HP	MW	-	-	156	-	-	-	-
River HP	MW	-	-	-	156	-	-	-
Wastewater HP	MW	-	-	-	-	155	-	-
Industrial waste heat	MW	-	-	-	-	-	192	-
Solar thermal	MW	3,8	3,8	3,8	3,8	3,8	-	219
Biogas boiler	MW	67	67	65	65	67	73	83
PTES	MWh	5.137	5.137	5.672	5.672	7.241	8.169	28.150
Storage tank	MWh	4.721	4.721	3.654	3.654	2.965	-	2.671

Overall, as suggested by the LCOH beforehand, it can be seen that no biomass units and geothermal HPs are installed. It seems that air HPs therefore provide a cheaper alternative for the heat supply in 2045. Furthermore, if available, wastewater, lake and river HPs are installed instead of air HPs, as their efficiency is higher to do higher temperatures in winter. This can also explain the slight reduction of LCOH in combination with the lower costs for larger units. Another observation is that the size of the PTES is dependent on the amount of solar thermal installed. Logically with large solar thermal capacity, also large PTES are required as seasonal storage to use the heat that is produced by solar thermal during summer in winter, where the heat demand is highest.

6.2.5 Sub conclusion

Based on the previous analysis, it can be concluded that the heat demand in UA with existing DH is reduced by around a third between 2015 and BL2050 and that the same also applies for potential areas for 4th Gen DH. The median heat demand for 4th Gen DH is even almost halved from 419 GWh/a to 215 GWh/a in BL2050. Furthermore, both the share of 4th Gen DH on the overall heat demand as well as the area in the UA is decreasing. On the other hand, the DHDCC are more than doubling from 2.0 to 5.0 ct/kWh on average.

The potential for renewable and waste heat is divided unequally among UA with existing DH. Overall, less than 25% of the UA have potential for waste heat or ambient heat from lakes, while still 50% have potential for geothermal heat and ambient heat from wastewater. On the other hand, 75% of UA have potential for waste biomass and ambient heat from rivers and all UA have potential for solar thermal. Furthermore, also the quantities of the potentials vary significantly between UA. Overall, the ambient heat potentials from rivers and wastewater are the most promising sources for most UA in combination with solar thermal.

The cluster analysis showed that based on the chosen variables, no clear elbow point and therefore no optimal number of clusters could be determined. Therefore, the clusters are determined based on other statistical criteria instead. The max cluster is therefore based on the third quartile of the heat demand and the first quartile of the DHDCC in combination with the maximum values for renewable and waste heat potentials. The min cluster is based on the opposite and therefore consists of the head demand of the first quartile and the DHDCC of the third quartile in combination with the minimum values for renewable and waste heat.

In UA with existing DH, DH is also feasible towards 2045 and provides the potential for a cost-efficient heat supply compared to an individual heating solution. This is the case for the max and min cluster and therefore, DH is feasible independent of the heat demand, DHDCC and RE potentials. As there are UA with a DHDCC that is still higher than that of the min cluster, there might be an exception where an UA is not feasible. However, this would have to be established based on an individual decision and local planning.

Looking at the different renewable and waste heat sources, it can be concluded that waste heat provides the cheapest heat supply with a LCOH of only 0.8 ct/kWh. This is followed by HPs using a water source, with a slight preference for wastewater compared to rivers or lakes. Otherwise, an air HP and if available solar thermal are used to cover the heat demand. Overall, there is always the need for a biogas boiler and PTES to cover the peak heat demand and in case no waste heat is available it is also feasible to install a heat storage tank to take advantage of the fluctuating electricity prices for the HP.

Looking at the status quo in 2020, it can be seen that DH is even more feasible currently, especially due to the lower DHDCC, as the SHD in 2020 are higher compared to 2045. While in the max cluster, waste heat is also mainly used to cover the heat demand, further energy conversion units are needed to cover the heat demand. This includes a wastewater HP, a biogas boiler and a biomass CHP. The heat supply is therefore similar to the target scenario in 2045. On the other hand, the most cost-efficient heat supply in 2020 in the min cluster consists mainly of a biogas boiler that is used in combination with an air HP.

With the addition of the BEW support for 2020 the feasibility of DH stays almost the same, as also individual heating is supported. While the heat supply is only marginally changed in the max cluster, it is significantly changed in the min cluster and the air HP is mainly used for the heat supply instead of the biogas boiler. Therefore, the BEW supports the installation of HPs which are also the preferred energy conversion unit in the target scenario besides waste heat.

6.3 Potential DH areas

6.3.1 Development of heat demand and district heating distribution capital costs

The development of the heat demand and DHDCC for potential DH areas follows a similar development as the one for existing DH aeras. The development of the heat demand for 4th Gen DH between 2015 and BL2050 is shown in Figure 28 below.

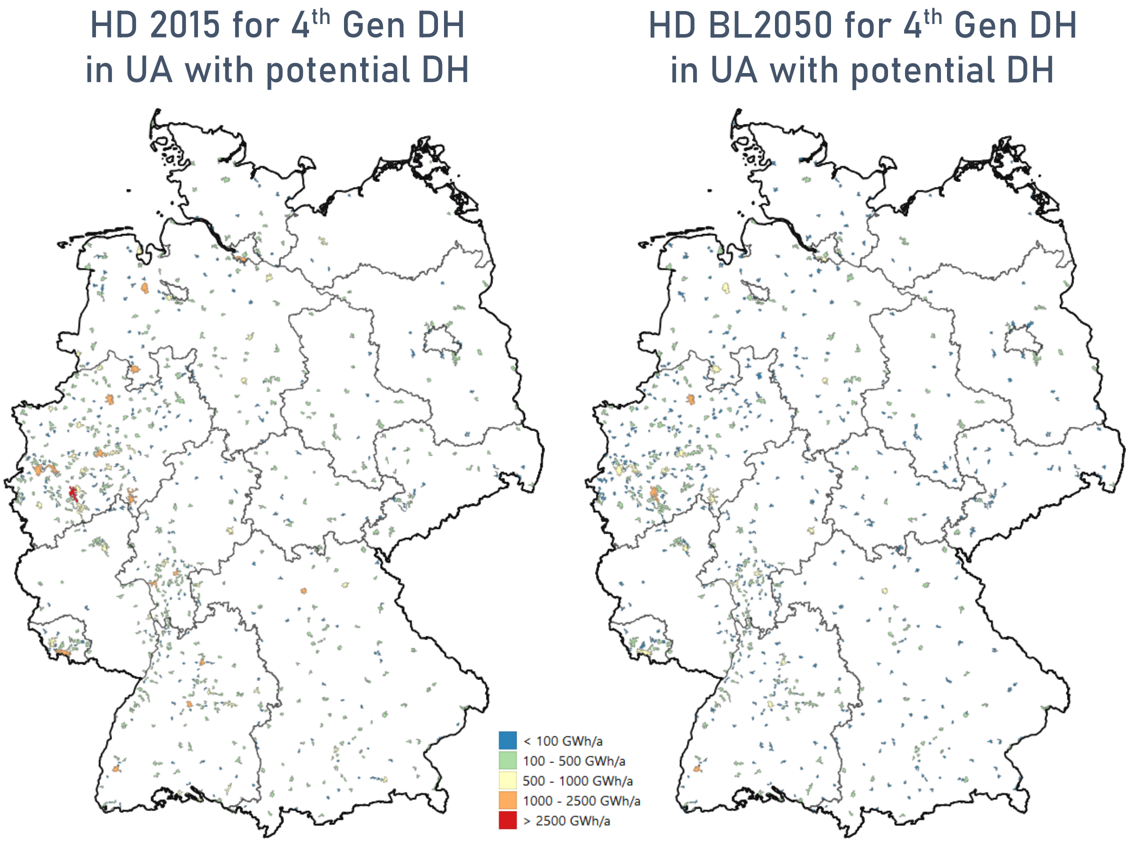


Figure 28: Overview of the reduction of the heat demand (HD) for 4th Gen DH between 2015 and BL2050 in UA with potential DH

As most of the larger UA already have DH, the potential for DH extends mainly to small and medium sized UA as already presented above. Also, for the potential DH areas, the heat demand is declining between 2015 and BL2050. This is also true for the overall heat demand and other parameters. The geographical distribution of the heat demands, DHDCC and shares in each UA with potential DH is shown in Appendix II: Geographical distribution of heat demands in UA with potential DH. A more detailed statistical overview of the development of the relevant parameter between 2015 and BL2050 is shown in Table 34 below.

Table 34: Statistical overview of the development of the total heat demand, heat demand for 4th Gen DH and DHDCC for 4th Gen DH between 2015 and BL2050 in UA with potential DH

	Total heat demand 2015	Total heat demand BL2050	Heat demand 4G DH 2015	Heat demand 4G DH BL2050	DHDCC 4G DH 2015	DHDCC 4G DH BL2050
Unit	GWh/a	GWh/a	GWh/a	GWh/a	ct/kWh	ct/kWh
Average	227.9	145.3	204.6	106.5	2.2	5.4
Max	3,051.2	1,994.7	2,887.8	1,748.9	3.8	7.5
3. Quartile	242.9	155.0	222.7	117.5	2.5	5.8
Median	147.6	94.6	129.7	66.2	2.2	5.3
1. Quartile	100.9	66.0	87.3	42.9	2.0	4.9
Min	48.7	33.9	24.2	4.3	1.3	3.2

Overall, the development and statistical analysis of the heat demand is similar to existing DH areas. The average values for the heat demand are significantly impacted by the high values of larger UA and are closer to the third quartile than the median. Likewise, both the total heat demand as well as the heat demand for 4th Gen DH are reduced by around a third or more, while the DHDCC is more than doubled. An interesting observation is however, that the third quartile of the potential DH areas is similar in values to the first quartile of existing DH for the heat demand. In general, it shows that as the UA tend to be smaller and have lower heat demands, also the DHDCC are slightly higher on average. The development of the share of 4th Gen DH compared to the total heat demand and the area of the UA as well as the share of residential heat demand in 2015 are shown in Table 35 below.

Table 35: Statistical overview of the development of the share of the heat demand for 4th Gen DH and the share of the area for 4th Gen DH between 2015 and 2050 as well as the share of residential heat demand in 2015 for UA with potential DH

	4th Gen DH share of total heat demand 2015	4th Gen DH share of total heat demand BL2050	4th Gen DH share of total area 2015	4th Gen DH share of total area BL2050	Share of residential heat demand 2015
Unit	%	%	%	%	%
Average	88	68	53	30	61
Max	98	95	85	71	94
3. Quartile	92	79	61	39	68
Median	89	70	54	29	60
1. Quartile	84	59	46	20	51
Min	42	11	15	1	29

The share of 4th Gen DH compared to the total heat demand is slightly lower as in existing DH areas, which can also be attributed to the overall lower heat demand and therefore a large share of area falling below the threshold that is suitable for 4th Gen DH. Furthermore, the range between the first and third quartile are bigger compared to the existing DH areas, suggesting that there is more variation between the different UAs. More broadly speaking the same trends with existing DH can be observed and both the share of the total heat demand and the DH area are decreasing between 2015 and BL2050. The average and median share of the residential heat demand compared to the total heat demand is also around 60% and therefore equal to existing DH areas, however, the there is a broader range between the first and third quartile.

It can be concluded that similar to existing DH areas, the analysed parameters are significantly decreasing between 2015 and BL2050, with the exception of the DHDCC which are significantly increasing. As the DH still has to be established, this suggests that the decision for DH should be taken as soon as possible, however it also raises the question how large the DH should be in the first place, as the heat demand and area will inevitably decrease over time.

6.3.2 Renewable and waste heat potential

The potentials for renewable and waste heat are varying significantly between the different UA, as is the case with existing UA. This can be seen exemplary for the potential of ambient heat sources above 5 MW and for waste biomass in Figure 29 below.

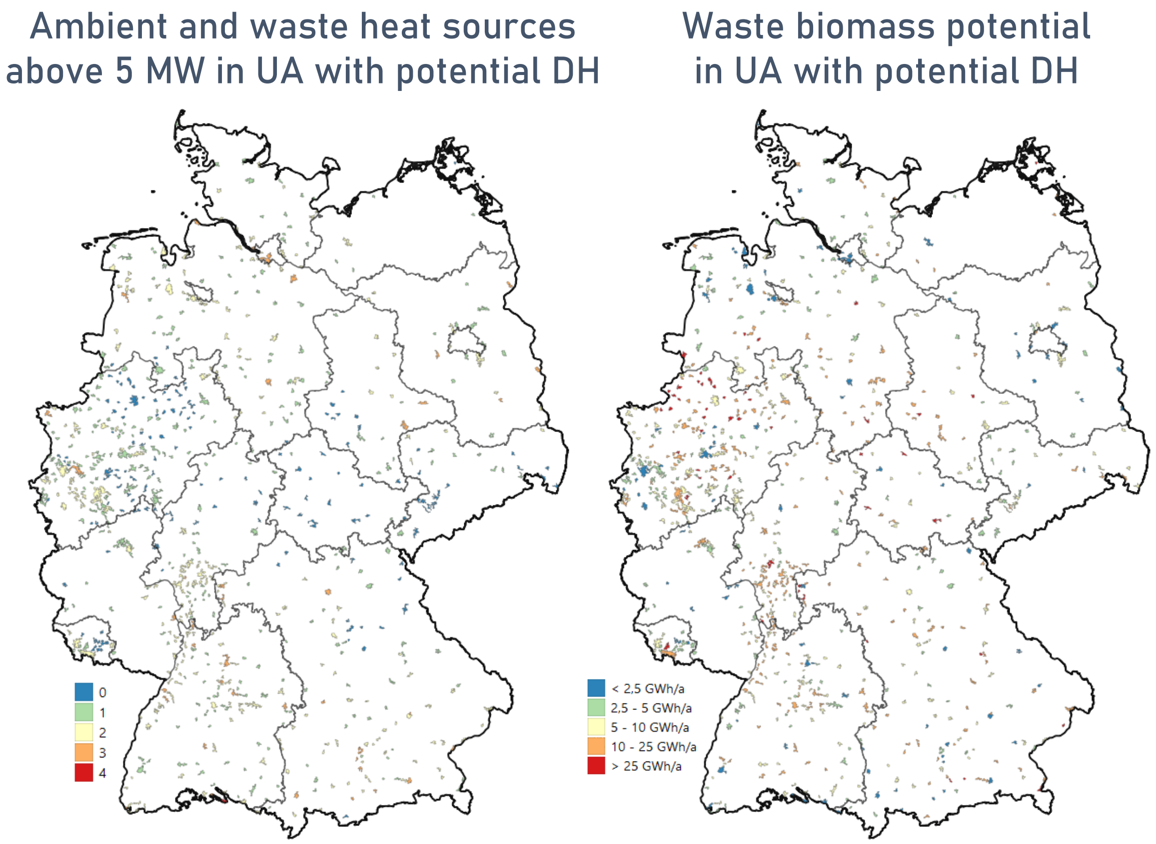


Figure 29: Overview of the number of ambient and waste heat source above 5 MW (left) and waste biomass potential (right) in UA with potential DH

Here it can be seen that in comparison to existing DH, there is overall less potential from ambient heat sources and that especially in central Germany little potential exists. However, there seems to be more potential for waste biomass, although the distribution is irregular. The geographical distribution for each renewable and waste heat potential for each UA with potential DH is shown in Appendix IV: Geographical distribution of renewable and waste heat potentials in UA with potential DH. A more detailed and statistical overview of the different potentials is given in Table 36 below.

Table 36: Statistical overview of the renewable and waste heat potential in UA with potential DH

	Biomass	**Geo-thermal**	**Lake**	**River**	**Waste-water**	**Industrial waste heat**	**Solar thermal**
Unit	GWh/a	Yes/no	MW	MW	MW	MW	GWh/a
Average	10.1	0.6	5.9	73.3	2.1	0.7	141.7
Max	154.2	1	942.9	654.6	45.9	86.7	539.9
3. Quartile	12.8	1	0.0	36.5	2.6	0.0	180.8
Median	7.4	1	0.0	2.9	1.3	0.0	129.6
1. Quartile	4.2	0	0.0	0.0	0.0	0.0	90.4
Min	0.0	0	0.0	0.0	0.0	0.0	0.0

Overall, the distribution of the potentials for potential UA is very similar to the distribution for existing DH areas. For the first quartile, only potentials for biomass and solar thermal exist, while there are no potentials for ambient or waste heat sources. While the potential from biomass is relatively low, solar thermal cannot be used throughout the year without seasonal storage. Also in the third quartile, there is still no potential for lake or industrial waste heat, indicating that only relatively few UA have access to these potentials. Overall river HPs in combination with solar thermal and biomass seems to be the RE sources that are most promising in terms of their availability and the amount of potential they can provide.

6.3.3 Cluster analysis

Similar to existing DH areas, the first step for the cluster analysis is the analysis of correlation between the potential input parameters, as shown in Table 37 below.

Table 37: Overview of the correlation between potential input parameters for the cluster analysis of UA with potential DH consisting of the heat demand (HD), DHDCC, shares and RE and waste heat potentials

	HD 2015	HD BL2050	HD DH 2015	HD DH BL2050	DHDCC DH 2015	DHDCC DH BL2050	HD DH Share 2015	HD DH Share BL2050	Area DH Share 2015	Area DH Share BL2050	Res HD share 2015	Biomass potential	Geothermal potential	Potential lakes	Potential rivers	Potential wastewater	Potential waste heat	Solar thermal potential
HD 2015	1,00																	
HD BL2050	1,00	1,00																
HD DH 2015	1,00	1,00	1,00															
HD DH BL2050	0,99	0,99	1,00	1,00														
DHDCC DH 2015	-0,26	-0,26	-0,27	-0,31	1,00													
DHDCC DH BL2050	-0,38	-0,36	-0,39	-0,41	0,40	1,00												
HD DH Share 2015	0,27	0,26	0,30	0,32	-0,17	-0,49	1,00											
HD DH Share BL2050	0,35	0,33	0,37	0,41	-0,53	-0,67	0,87	1,00										
Area DH Share 2015	0,11	0,10	0,15	0,17	0,05	-0,35	0,82	0,66	1,00									
Area DH Share BL2050	0,28	0,27	0,31	0,36	-0,49	-0,54	0,83	0,92	0,81	1,00								
Res HD share 2015	-0,15	-0,14	-0,15	-0,15	0,27	0,51	-0,25	-0,37	-0,13	-0,23	1,00							
Biomass potential	-0,08	-0,08	-0,07	-0,07	0,09	0,03	0,06	0,01	0,09	0,03	0,02	1,00						
Geothermal potential	-0,02	-0,03	-0,02	-0,01	0,00	-0,19	0,13	0,15	0,18	0,18	-0,11	-0,07	1,00					
Potential lakes	0,03	0,03	0,03	0,03	-0,04	-0,02	0,03	0,04	0,02	0,03	-0,02	-0,06	0,06	1,00				
Potential rivers	0,12	0,12	0,13	0,14	-0,17	-0,18	0,19	0,23	0,11	0,22	-0,01	-0,03	-0,08	0,00	1,00			
Potential wastewater	0,59	0,59	0,58	0,57	-0,10	-0,14	0,14	0,16	0,06	0,11	-0,08	-0,03	-0,10	0,07	0,08	1,00		
Potential waste heat	0,11	0,11	0,11	0,10	-0,01	-0,09	0,03	0,04	-0,11	-0,04	-0,10	-0,02	-0,02	-0,01	0,01	0,00	1,00	
Solar thermal potential	0,41	0,41	0,39	0,35	0,05	-0,01	-0,24	-0,16	-0,27	-0,24	-0,14	-0,06	-0,02	-0,08	-0,10	0,22	0,13	1,00

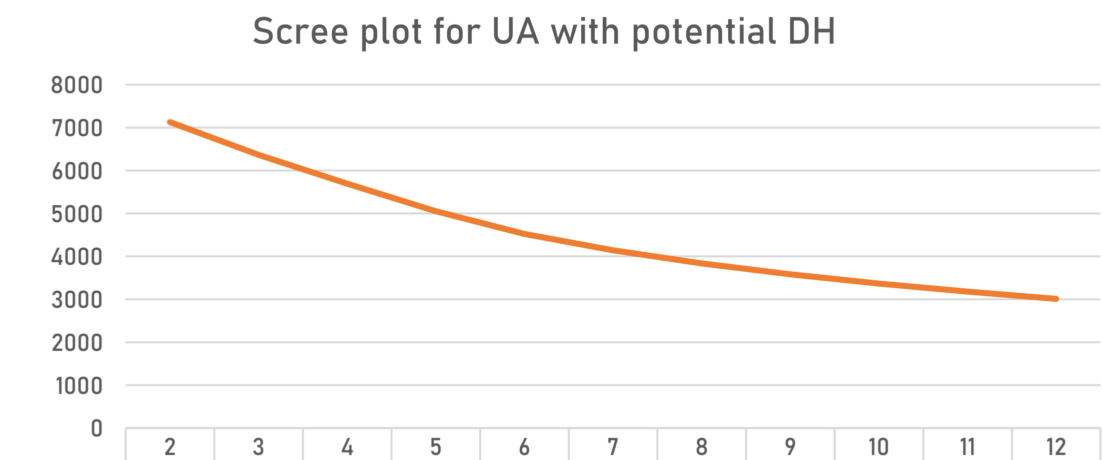
Overall, it can be observed that the correlation is very similar to existing DH areas. Thus, all heat demands for UA and the share of the heat demand with the share of the area are positively correlated to each other. Therefore, the same set of criteria are used for the cluster analysis and are shown in Table 38 below.

Table 38: Overview of chosen criteria for the cluster analysis of UA with potential DH

Heat demand	RE and waste heat
Total heat demand 4th Gen DH in UA BL2050	Biomass potential
Average DHDCC 4th Gen DH in UA BL2050	Geothermal potential

Residential heat demand share UA 2015	Ambient heat potential from lakes
	Ambient heat potential from rivers
	Ambient heat potential from wastewater
	Waste heat potential from industry
	Solar thermal potential

Based on the above-mentioned criteria the cluster analysis is conducted and the resulting dendrogram is shown in Appendix V: Dendrogram of the cluster analysis for UA with existing and potential DH. Subsequently, a scree plot is created to find the optimal number of clusters. However, as observable in Figure 30, no clear elbow criterium can be seen. Therefore, there is no clear suggestion as to how many clusters should be formed.



	2	3	4	5	6	7	8	9	10	11	12
WSS	7127,38	6362,23	5691,28	5050,28	4522,35	4139,83	3838,11	3579,66	3365,31	3177,39	3010,1

Figure 30: Scree plot for the clustering of UA with potential DH based on the within-cluster sum of squares (WSS) and the number of clusters in order to identify the optimal number of clusters (elbow point)

As no clear number of clusters could be determined, the clusters are determined based on other statistical criteria instead. Therefore, the same approach as for UA with existing DH is followed and based on the data analysis of the heat demand and the RE potentials in Section 6.2.1 and 6.2.2, the max and min cluster are derived and shown in Table 39 below. Likewise, in order to ensure a general conclusion regarding the role of DH, the sensitivity analysis is therefore extended if necessary.

Table 39: Overview of the max and min cluster for potential DH based on statistical criteria

Criterium	Unit	Max cluster		Min cluster	
Total heat demand 2015	GWh/a	243	3. Quartile	101	1. Quartile
4th Gen DH share of heat demand 2015	%	92	3. Quartile	84	1. Quartile
4th Gen DH heat demand 2015	GWh/a	224	Calculated	85	Calculated
Total heat demand BL2050	GWh/a	155	3. Quartile	66	1. Quartile
4th Gen DH share of heat demand BL2050	%	79	3. Quartile	59	1. Quartile
4th Gen DH heat demand BL2050	GWh/a	122	Calculated	39	Calculated
DHDCC DH 2015	Ct/kWh	2.0	1. Quartile	2.5	3. Quartile
DHDCC DH BL2050	Ct/kWh	4.9	1. Quartile	5.8	3. Quartile
Res heat demand share 2015	%	60	Median	60	Median
Biomass potential	GWh	154	Max	0	Min
Geothermal potential	Yes/no	1	Max	0	Min
Potential lakes	MW	943	Max	0	Min
Potential rivers	MW	655	Max	0	Min
Potential wastewater	MW	46	Max	0	Min
Potential waste heat	MW	87	Max	0	Min
Solar thermal potential	GWh	540	Max	0	Min

6.3.4 Energy system analysis

Next to the general parameters mentioned in Section 6.2.4 above, specific input parameters for the energy system modelling for UA with potential DH are shown in Table 40 below.

Table 40: Overview of scneario dependet parameter for potential DH

Input Parameter	Unit	2045	2020	2020 with BEW
DHDCC Max	Ct/kWh	8.1	3.3	2.0
DHDCC Min	Ct/kWh	9.5	4.1	2.5

Similar to UA with existing DH, the DHDCC are adjusted according to the WACC and lifetime, while the BEW funding is included for the BEW support scenario 2020. Overall, the DHDCC are higher compared to UA with existing DH, as the heat demands and SHD are lower in UA with potential DH. This effect is further amplified by a high WACC.

6.3.4.1 Target scenario 2045

For the target scenario 2045, the most cost-efficient heat supply technologies for the max and min cluster are analysed in the following. The installed capacity for the two clusters is shown in Table 41 below. The energy conversion units installed for the max cluster include a 64 MW industrial waste heat HP, which is sufficient to cover the heat demand of 122 GWh. For the min cluster the heat demand is only 39 GWh and therefore only a 9.6 MW air HP and a 4.2 MW biogas boiler in combination with a 395 MWh heat storage are needed. Therefore, the installed units in the max in min cluster for potential DH are similar to the units installed in existing DH.

Table 41: Overview of installed capacity for each energy conversion unit in the max and min cluster for UA with potential DH for the target scenario 2045

Energy conversion unit	**Unit**	**Max**	**Min**
Industrial waste heat	MW	64	-
Air HP	MW	-	9.6
Biogas boiler	MW	-	4.2
Storage tank	MWh	-	395

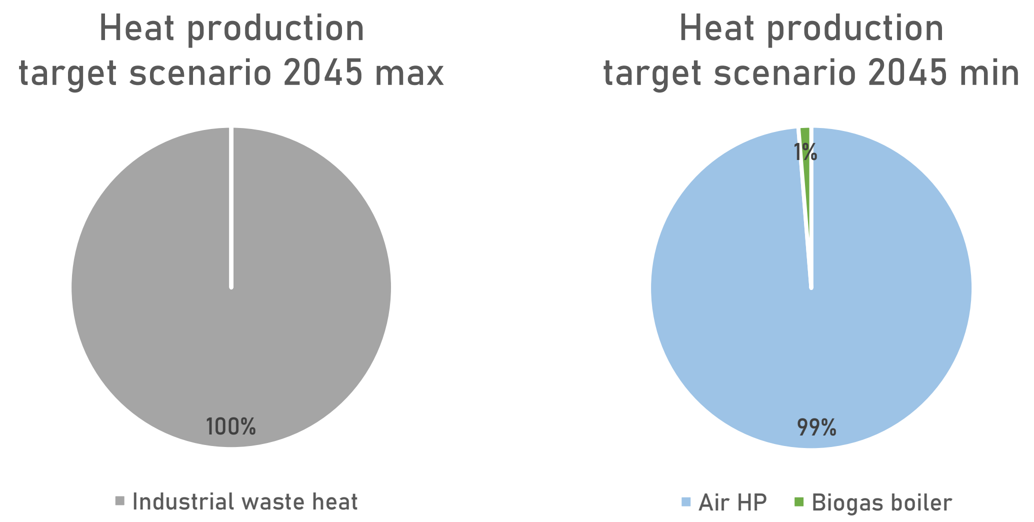


Figure 31: Heat production mix for UA with potential DH for max and min cluster for the target scenario 2045

The heat production for both clusters is shown in Figure 31 above. While the heat in the max cluster is solely supplied by industrial waste heat, the heat in the min cluster is almost only supplied by the air HP. The biogas boiler accounts for 1% of the produced heat and is only needed to cover the peak heat demand. The heat storage on the other hand is mainly used as daily storage to allow a use of the HP at times with low electricity prices and then discharge the heat at times of higher electricity prices.

Looking at the LCOH, the feasibility of DH for potential DH depends on the max and min cluster and is shown in Figure 32 below. While the max cluster only has a LCOH of 9.0 ct/kWh, the min cluster has a LCOH of 17.2 ct/kWh and is therefore higher than the LCOH for individual heating of 15.1 ct/kWh. The feasibility of DH therefore cannot be determined for all UA with potential DH. Overall, the DHDCC contribute significantly to the LCOH and make up around 55% of the LCOH for the min cluster and around 90% of the LCOH of the max cluster. Similar to existing DH, there is a wide range for the LCOH of RE heat production.

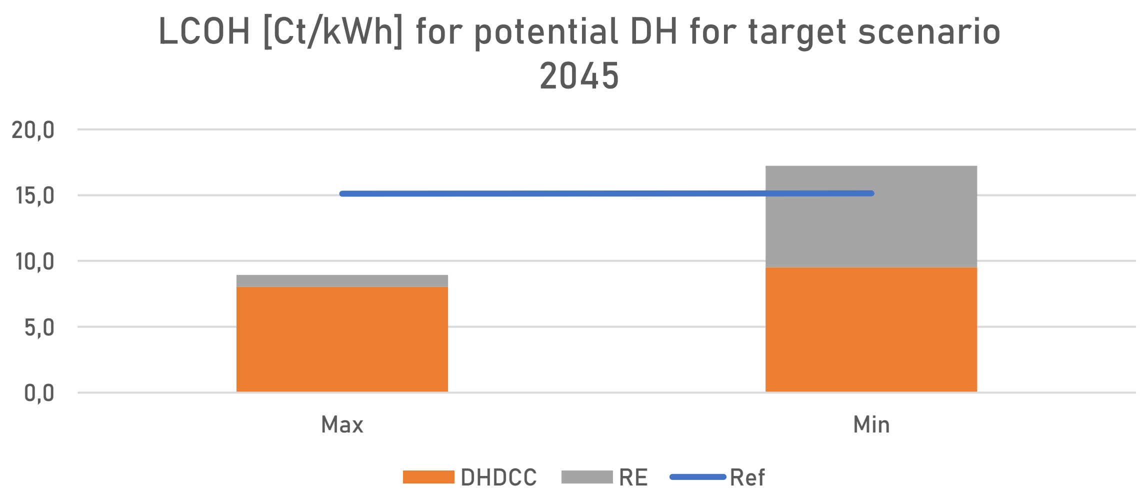


Figure 32: LCOH for UA with potential DH for max and min cluster as well as reference for target scenario 2045

As the sensitivity analysis for different renewable heat sources has shown, the costs for heat production in UA without waste heat is significantly higher. Using these values for the difference between the highest and lowest costs for the heat production besides waste heat has been around 2 ct/kWh for existing DH. As the difference between the min cluster and the reference is 2.1 ct/kWh, it is assumed that DH is not feasible in UA with DH potential without available waste heat sources.

6.3.4.2 Status quo scenario 2020

As the potential for DH in 2045 is rather low, it is interesting to determine if there is a potential for the establishment of new DH currently. The installed capacity for the max and min clusters is shown in Table 42 below. While for the max cluster 87 MW of waste heat and 24 MW of a biogas boiler are installed in order to meet the heat demand of 224 GWh, the min cluster consists only of a 42 MW biogas boiler in order to meet the heat demand of 85 GWh. This is therefore overall similar to the status quo scenario for existing DH. However, due to the lower heat demand, less capacity is required.

Table 42: Overview of installed capacity for each energy conversion unit in the max and min cluster for UA with potential DH for the status quo 2020

Energy conversion unit	Unit	Max	Min
Industrial waste heat	MW	87	-
Biogas boiler	MW	24	42

Looking at the heat production, there is a significant difference between the max and min cluster, as shown in Figure 33 below. As suggested by the installed capacity, the max cluster relies on waste heat to cover the majority of the heat demand and only needs the biogas boiler to cover peak demands. On the other hand, the biogas boiler supplies the total heat demand of the min cluster.

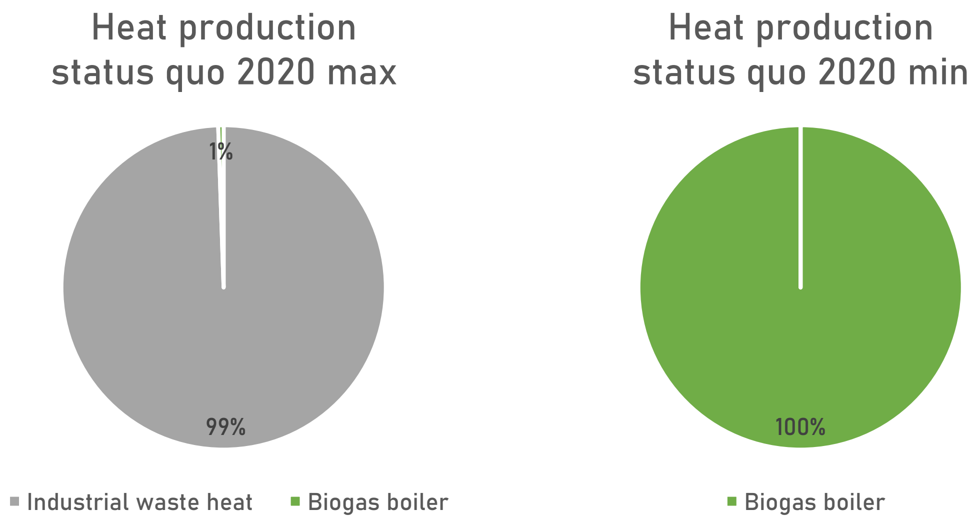


Figure 33: Heat production mix for UA with potential DH for max and min cluster for the status quo scenario 2020

In contrast to the target scenario 2045, DH is feasible in the status quo scenario for both the max and min cluster as shown in Figure 34 below. The LCOH of the min cluster is 12.1 ct/kWh and therefore significantly lower than the LCOH for individual heating of 17.7 ct/kWh. The max cluster even only has a LCOH of 3.7 ct/kWh and is therefore less than one fourth of the price for individual heating. Like in all previous scenarios, the range of LCOH for the renewable and waste heat production is still very large with only 0.5 ct/kWh for waste heat and 8.0 ct/kWh for the biogas boiler. Overall, compared to the target scenario 2045 the DHDCC are lower and only amount for a lower share of the total LCOH.

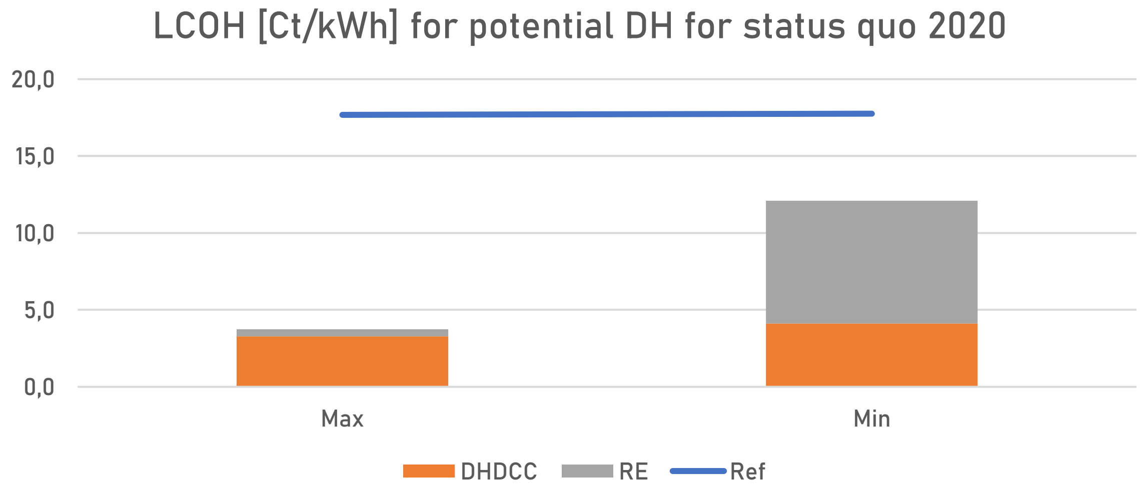


Figure 34: LCOH for UA with potential DH for max and min cluster as well as reference for status quo scenario 2020

Therefore, the establishment of new DH is currently the most cost-efficient heat supply option. However, while the max cluster also relies on the same heating technologies, this is very different for the min cluster, where the biogas boiler is the cheapest heating technology currently compared to the air HP in the target scenario 2045. It will therefore be investigated what impact the BEW support scheme has on the installation of energy conversion units.

6.3.4.3 BEW support scenario 2020

The installed capacities for the BEW support scenario 2020 are shown in Table 43 below. For the max cluster, the main installed energy conversion unit still consists of industrial waste heat, while the biogas boiler has been replaced with a PTES. The installed units for the min cluster have also changed significantly. While the installed capacity of the biogas boiler is reduced by more than 50% to 19 MW, an air HP with a capacity of 12 MW and a heat storage tank with a capacity of 662 MWh are installed. Overall, the capacity of biogas boilers in both clusters is therefore significantly reduced, as the biogas boiler is not funded by the BEW. Therefore, the clusters are more closely aligned with the target scenario 2045.

Table 43: Overview of installed capacity for each energy conversion unit in the max and min cluster for UA with potential DH for the BEW support scenario 2020

Energy conversion unit	Unit	Max	Min
Industrial waste heat	MW	87	-
Biogas boiler	MW	-	19
Air HP	MW	-	12
PTES	MWh	4,500	-
Storage tank	MWh	-	662

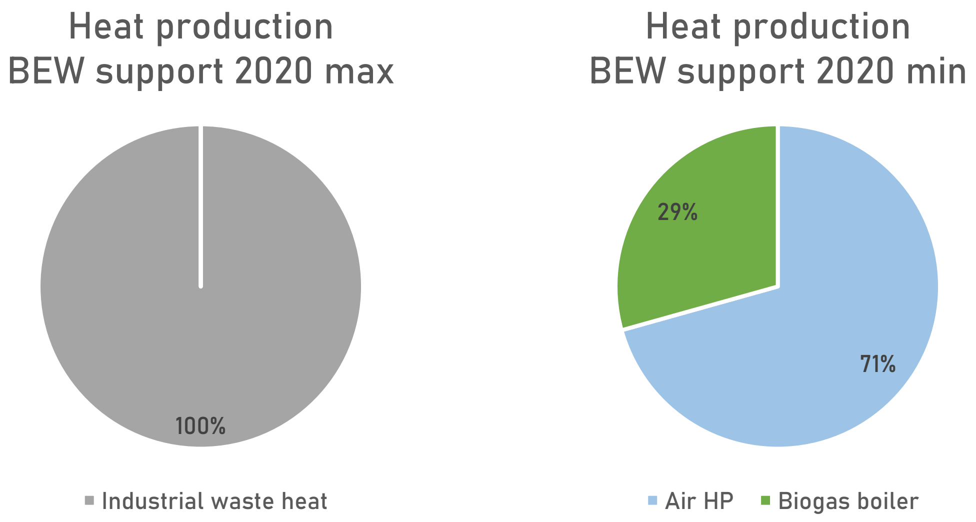


Figure 36: Heat production mix for UA with potential DH for max and min cluster for the BEW support scenario 2020

The amount of heat produced is shown in in Figure 36 above and shows a similar shift like the installed capacity for the min cluster. For the max cluster on the other hand, the heat is now solely supplied by waste heat, which is stored in the PTES to also cover the peak demands, when the capacity of waste heat is not sufficient. For the min cluster, similar to the BEW support scenario for existing DH, the air HP now contributes mainly to heat supply, while the share of the biogas boiler is significantly reduced. The heat storage furthermore enables the integration of the fluctuating electricity prices and therefore the air HP is running in hours of low electricity prices and the heat is stored accordingly to be used in hours of higher electricity prices. Therefore, the heat production is overall shifted towards the production in the target scenario 2045.

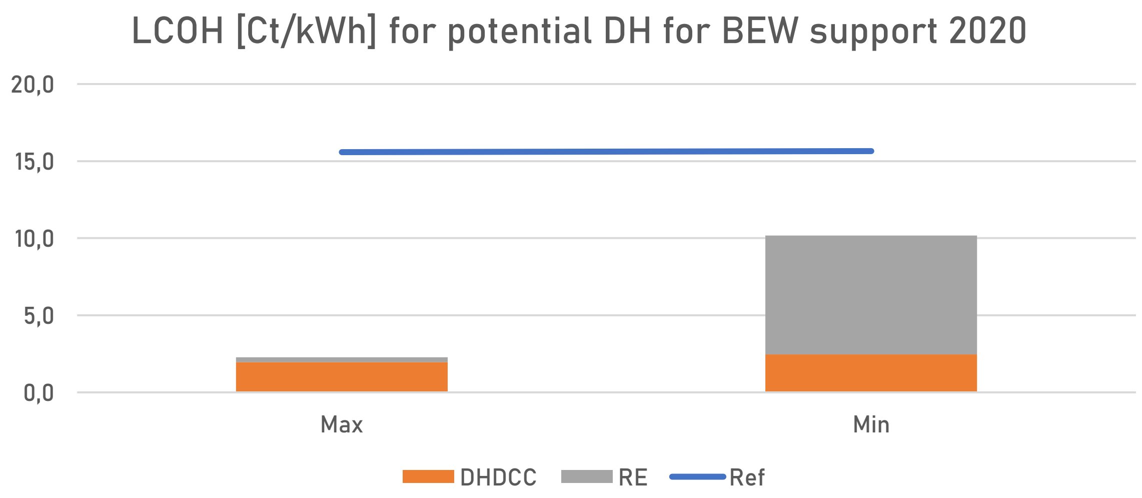


Figure 35: LCOH for UA with potential DH for max and min cluster as well as reference for BEW support scenario 2020

Concerning the LCOH for the BEW support scenario, a similar result is obtained as for the status quo scenario, as shown in Figure 35 above. Therefore, the BEW funding has no direct impact on the overall feasibility of newly established DH currently. While the LCOH of the DHDCC are significantly reduced by 40%, the costs for the heat production still range from

0.3 ct/kWh to 7.7 ct/kWh and therefore make up the most significant share of the LCOH in most UA with potential DH.

Overall, it can be concluded that DH would still be more cost-efficient than the reference technology without BEW support. However, the BEW support promotes technologies which are also used in the target scenario 2045 and reduces the share of biomass. However, in the target scenario 2045, establishing new DH is not feasible in UA where no waste heat is available, mostly due to the high DHDCC. As mentioned in Section 2.4, there is a signifcant potential for the reduction of DHDCC by the use of combined infrastructure planning, where new DH is installed when road works or other infrastructure measures are planned. This way, the DHDCC could be reduced by 30%, as the digging makes up a significant share of the DH installation costs (Burkhardt and Blesl, 2023). Furthermore, as DH operators in Denmark are not allowed to make profits, it is investigated if this could make establishing new DH more feasible. Therefore, the discount rate is reduced to the socio-economic discount rate of 3%.

6.3.4.4 Sensitivity analysis

The comparison of the LCOH for the min cluster with the sensitivity of combined infrastructure planning and a reduced discount rate is shown in Figure 37 below. Due to the reduction of the DHDCC by combined infrastructure planning, the LCOH can be reduced to 14.1 ct/kWh and is therefore lower than the LCOH for individual heating of 15.1 ct/kWh. Furthermore, a reduction of the discount rate to 3% also makes the min cluster for potential DH more feasible than individual heating. Hereby, especially the DHDCC are reduced by more than 50% from 9.5 ct/kWh to 4.9 ct/kWh, while the LCOH for the production of RE heat is reduced by around 20% from 7.7 ct/kWh to 6.2 ct/kWh. Likewise, also the LCOH of individual heating is reduced from 15.1 ct/kWh to 12.5 ct/kWh and only presents a reduction of around 17%, as the reduction relates to the investment costs only.

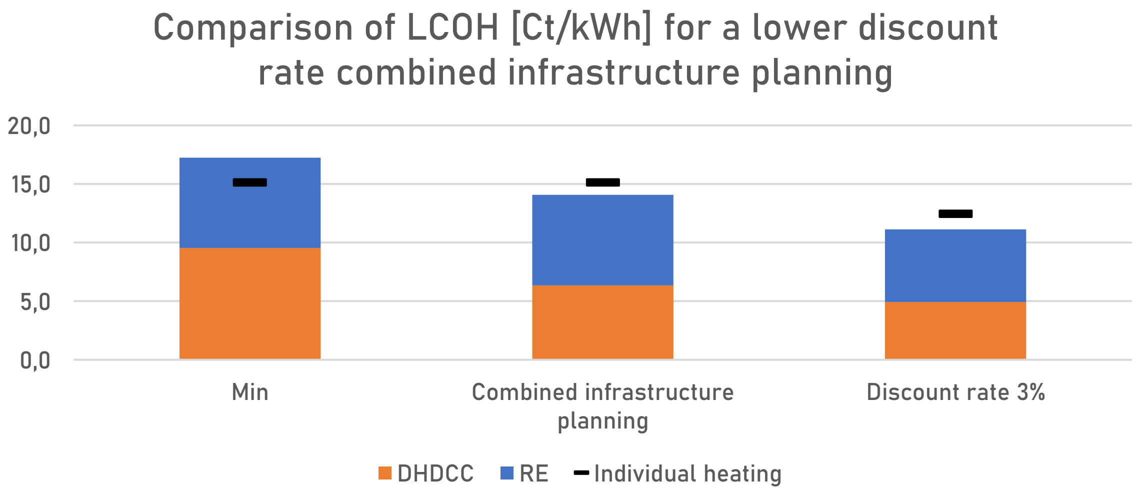


Figure 37: Comparison of LCOH for a lower discount rate and combined infrastructure planning in UA with potential DH

Therefore, both sensitivities provide potential for the feasibility of the establishment of new DH compared to individual heating independent of the available heat sources available.

6.3.5 Sub conclusion

The previous analysis has shown that overall, the heat demand in UA with potential DH is significantly lower compared to UA with existing DH, as UA with potential DH consist mainly of smaller UA. The median heat demand for 4th Gen DH in UA is similarly reduced by almost 50% from 130 GWh/a to 66 GWh/a in BL2050. Therefore, the heat demand for 4th Gen DH in UA with potential DH is only around a third of that in UA with existing DH. In general, the overall trends are similar to UA with existing DH and thus the heat demands as well as the heat demand and area shares of 4th Gen DH are decreasing significantly between 2015 and BL2050, while the DHDCC are more than doubling. As the heat demand is overall lower, the average DHDCC are also slightly higher with 2.2 and 5.4 ct/kWh on average in 2015 and BL2050 respectively.

The potential for renewable and waste heat shows a similar distribution to UA with existing DH. Therefore, only less than 25% of the UA have potential for waste heat or ambient heat from lakes, while 75% of the UA have potential for waste biomass and solar thermal. Based on the quantities, the most promising potentials are also based on ambient heat from rivers and wastewater as well as the use of solar thermal. However, the quantities are also varying significantly between the UA.

Similar to UA with existing DH, the cluster analysis showed that based on the chosen variables, no clear elbow point and therefore no optimal number of clusters could be determined. Therefore, the clusters are determined based on other statistical criteria instead and follow the same approach as for UA with existing DH. The max cluster is therefore based on the third quartile of the heat demand and the first quartile of the DHDCC in combination with the maximum values for renewable and waste heat potentials. The min cluster is based on the opposite and therefore consists of the head demand of the first quartile and the DHDCC of the third quartile in combination with the minimum values for renewable and waste heat.

The establishment of new DH in UA with potential DH in 2045 is only feasible for UA with sufficient waste heat potential. However, in other UA, the establishment of new DH is not feasible in 2045, as the LCOH for various RE potentials are higher than the LCOH for individual heating of 15.1 ct/kWh. However, looking at the status quo scenario 2020, establishing new DH is the most cost-efficient option independent of the renewable or waste heat used. This is also the case for the scenario with BEW support and therefore the overall feasibility of establishing new DH towards climate neutrality is unclear and seems to depend significantly on the time when the DH is installed. Therefore, further research with a more comprehensive analysis would be required to determine at which point in time, the investment into establishing new DH is not feasible anymore.

Overall, for the target scenario 2045, the DHDCC makes up the largest share of the LCOH. Therefore, the feasibility is significantly influenced by the DHDCC. The sensitivities have shown that through combined infrastructure planning, which reduces the DHDCC by 30%, establishing new DH will become feasible independent of the RE source available. Furthermore, the discount rate has a significant impact on the results, as the installation of new DH is very capital intensive. By using a socio-economic discount rate of 3%, it is shown that DH is more cost-efficient that individual heating. Therefore, DH models as the one in Denmark, where DH operators are not allowed to make profits also could have significant effects on the overall feasibility of DH compared to individual heating.

Similar to existing DH, the difference in DHDCC between the max and min cluster in all scenarios is rather low, while the difference of LCOH for the production of RE ranges significantly. In general, the energy conversion units used are also similar to existing DH and consist of waste heat for the max cluster and the use of an air HP and a biogas boiler for the min cluster. Overall, there is less need for storage as the heat demand are overall lower in UA with potential DH compared to UA with existing DH. However, in case a HP is installed, also a heat storage tank is installed to react to the fluctuating electricity prices.

While the establishment of new DH is already feasible for the status quo scenario 2020, the energy conversion units installed for the min cluster are not aligned with the target scenario. With the support of the BEW this is changed towards an air HP and therefore more aligned to the units installed in the target scenario 2045. Overall, the feasibility of establishing new DH towards a climate neutral building sector in 2045 is therefore uncertain and depends on the time of investment or the reduction of DHDCC by combined infrastructure planning.

7 Discussion

In the following the results obtained by the analysis are compared to literature and the reliability of them is discussed. Furthermore, additional factors that influence the role of DH, which could not be included in the analysis are discussed. This includes among others, the acceptance of DH as well as the investment costs.

7.1 Comparison with literature

Overall, literature agrees that limited data is available regarding DH in Germany. Furthermore, the data quality of those data available is significantly lower and outdated compared to other energy sectors. Most data available is based on surveys among district heating operators and therefore does not form a complete dataset. (Fraunhofer ISE et al., 2020; Fraunhofer ISE and Fraunhofer IEE, 2022) Therefore, it is more difficult to assess the reliability of the results.

7.1.1 Potential of DH

Based on the analysis conducted, around 20% of the 1,016 UA with more than 10,000 inhabitants have existing DH. However, based on the most recent study available (Blesl et al., 2023), 1,660 out of 2,923 municipalities with more than 5,000 inhabitants have existing DH. This would mean that 55% of the municipalities already have existing DH. Furthermore, according to the study, all large UA and around 80% of the medium-sized UA have existing DH, while according to the analysis conducted here only 80% of the large UA and less than 30% of the medium-sized UA have existing DH. On the other hand, another studies describes that currently 95% of large UA and 50% of medium-sized UA have DH (Prognos and Hamburg Institut, 2020). This discrepancy can mainly be attributed to the definition of DH, as the other studies also include small heating networks that only cover a few houses, while the DH included in this analysis only consider large-size DH that have been operated for some time.

Based on the baseline scenario in this study, the heat demand in UA is expected to be reduced by around 35% on average, which is in line with various other studies (Lübbers et al., 2022). Most studies (Lübbers et al., 2022; Prognos and Hamburg Institut, 2020) expect DH to cover around 30% of total heat demand among all UAs. Therefore, based on a FEC of around 600 TWh for the buildings sector in 2045, DH would supply around 180 TWh. In comparison, this research assumes a total DH potential of 220 TWh. This can be divided into 135 TWh that will be provided by existing and extended DH and 85 TWh from newly established DH. As the feasibility of establishing new DH is uncertain towards 2045, it can be assumed that still 50% of the possible new DH is established to reach a total heat supply of around 180 TWh. Furthermore, other studies (Paardekooper et al., 2018) even suggest that a DH share of 49% by 2050 would be most beneficial from a socio-economic perspective. Therefore, even more DH in smaller UA below 10,000 inhabitants would have to be established.

While the potential for 4th Gen DH ranges depending on the UA, the share of DH based on the total heat demand is on average around 80% and above 60% in the majority of UA, also including small UA. On the other hand, according to Prognos and Hamburg Institut (2020), the share for large UA is 70%, while for medium-sized and small UA the share of DH compared to the total heat demand is only 35% and 18% respectively. Also Blesl et al. (2023) only expect a moderate extension of DH and suggest that the share of DH in comparison to the total heat demand in large and medium-sized UA could increase form around 25% on average currently to 35%. As the total heat demand is also expected to decrease until 2045 as discussed before, this would mean an average share of around 55% for both large and medium-sized UA assuming a reduction in the heat demand of 35%. This shows that while the share is overall expected to be lower according to literature, especially in small UA, there are different views regarding the share of DH in different types of UA.

Therefore, this research has identified less UA with existing DH compared to literature. On the other hand, this research assumed a higher share of DH compared to the total heat demand in 2045 in general and for the various UAs. Especially regarding small UA, there is a significant difference in the share of DH compared to the total heat demand. This can mainly be attributed to the assumption that all areas with a potential for DH are supplied by DH. Therefore, it should be investigated if the results of the analysis are still true for different connection rates and smaller areas that are connected to the DH.

7.1.2 Potential of renewable and waste heat

Geothermal

According to this research, geothermal energy is not cost-efficient compared to other energy conversion units such as air HPs. Even in cases, when only geothermal heat is available, other units are installed instead. However, most other studies (Bundesverband Erneuerbare Energie (BEE), 2022; Lübbers et al., 2022; Prognos and Hamburg Institut, 2020) see a significant role of geothermal energy in the heat supply mix of DH regarding a transition towards a carbon neutral Germany in 2045. Furthermore, there are large potentials for geothermal energy in Germany and according to a recent study by Bracke and Huenges (2021) at least 100 TWh per year of deep geothermal energy with an installed capacity of 72 GW and 300 TWh with an installed capacity of 72 GW could be provided until 2030 and 2040 respectively.

However, the main obstacle regarding geothermal is the high investment cost for drilling and the large uncertainty related to it. As currently typical plant sizes vary between 5 and 20 MW, this is often not competitive with other types of HPs. Especially in smaller UA, the costs for smaller units is often too high and makes geothermal therefore infeasible. Even though, typical plant sizes are expected to increase in the future, the costs will still be high. (Danish Energy Agency, n.d.) Therefore, further support programs would be needed to subsidize the drilling costs and include insurances for the discovery risk, which could be funded by the government and repaid by small fees from successful projects. (Prognos and Hamburg Institut, 2020)

While there is overall a large potential for geothermal energy, it remains uncertain which role geothermal energy will play in the future, as it will depend to a large extent on the available support mechanisms. Therefore, better data quality is needed to assess the local potentials more accurately, as it is assumed that the role of geothermal energy will depend on local circumstances. Munich for example is planning to invest significantly in geothermal energy, so that 70 to 80% of the DH supply will be covered by geothermal energy. (Schneider, 2022)

Biomass

Another type of heat source that is regarded differently in literature is biomass. While according to this research biomass CHP is only used for the status quo and BEW support scenario in 2020 for existing DH, biogas boilers are used more widely and mainly in order to cover the peak demand, if necessary. However, there is also the case, where the biogas boiler is used to cover the majority of the heat demand for the min cluster in the status quo scenarios 2020. Therefore, the use of biomass depends on the circumstances, while overall biogas is used more than biomass.

In comparison to other studies, a mixed view on biomass is presented. While some studies are assuming an increased use of biomass also for DH (Bundesverband Erneuerbare Energie (BEE), 2022; Papadis et al., 2022), other studies argue that solid and gaseous biomass is limited and should therefore mainly be used in other sectors where it is more urgently needed, such as high-temperature processes in industry (Burkhardt and Blesl, 2023; Institut für Energie- und Umweltforschung (ifeu) et al., 2023).

According to the BEW and the general view of the government, the use of biomass in the heating sector should be limited. Therefore, in the requirements for the BEW, the share of biomass in DH will be limited. However, exceptions still enable the use of biomass for smaller DH based on the length of the DH network. (Bundesamt für Wirtschaft und Ausfuhrkontrolle (BAFA), 2023) While some UA might therefore still consider the use of biomass in the future, especially if the investments are taken rather soon, the role of biomass in the heating supply is expected to decrease overall with time.

Solar thermal

This research has shown that for all min clusters of existing DH, solar thermal is always built while for the max cluster, the major share of DH can be covered by waste heat and therefore no additional solar thermal is required. However, looking at the sensitivity analysis, it can be seen that for all other scenarios solar thermal is built complementary to the HP. In the scenarios for potential DH, the heat demand in the max cluster can usually be covered by waste heat, while in the min cluster there is no potential for solar thermal. Therefore, as concluded, solar thermal plays a significant role for the heat supply in DH areas.

However, according to literature the use of solar thermal is somewhat limited, especially in large UA (Papadis et al., 2022; Prognos and Hamburg Institut, 2020). While the share of solar thermal in small UA could reach up to 25%, the potential is significantly smaller in large and medium-sized areas due to the limited space availability. Furthermore, solar thermal heat is mainly produced during summer and the production overlaps with PV production. Therefore, during these times also rather cheap electricity is available, which could be used by HPs and therefore, there might be a competition between large-scale HPs and solar thermal, especially as large-scale HPs will be needed anyways. This raises the question if it might be more profitable to use the available areas for PV instead in order to supply cheap electricity to the heat pumps.

Overall, the deviations to the results obtain in this research could be explained as the potential analysis does not follow the political outline of municipalities. Therefore, also for larger UAs it is assumed that area from the surrounding municipalities could be used. While this would be possible, it would require more collaboration between the different municipalities and might complicated the implementation. Another aspect that should be considered is that the hourly spot market price for electricity and the hourly weather data are not from the same source and therefore not necessarily matched. Therefore, there might be less competition between solar thermal and cheap electricity prices than to be expected. As also suggested by this research, the main share of the heat supply will still be covered by large-scale HPs. Additionally, solar thermal can contribute to a cheap heat supply and should not be disregarded despite of limited space. It is however recommended to assess if the installation of PV instead of solar thermal would be more feasible.

7.1.3 Reliability of results

As mentioned before, the data availability and quality regarding DH is limited. Therefore, assumptions and other derivations had to be used. However, it was intended to maximize the coherence of data, although this was not always possible and therefore some data and time series might not match. It is however considered that the data used are overall of sufficient quality to come to reliable conclusions.

As this research regards the potential of DH towards 2045, it automatically includes uncertainties regarding future projections. Especially the economic and technological development of the energy conversion units, the development of the commodity prices and the retrofitting rates and thus heat demands is subject to uncertainty. Among others, the EU has presented a proposal for a reform of the electricity market and also Germany has established a platform to discuss the redesign of the electricity market towards climate neutrality in 2045 (Bundesministerium für Wirtschaft und Klimaschutz (BMWK, n.d.; European Commission, 2023). Therefore, it remains uncertain if negative prices in Germany will increase or cease to exist among others. Furthermore, the availability of skilled workers could significantly impact the rate of retrofitting, but also the establishment or extension of DH. If not enough workers are available, this could delay installations and increase costs. However, through municipal heat planning the need for workers can be better calculated and thus reduces the risk of shortage of skilled labour.

Besides, some economical aspects, especially support schemes could not be included due to the scope of the research. It is therefore relevant to address the possible impacts of the operational funding of the BEW and the Kraft-Wärme-Kopplungs-Gesetz while answering the question regarding the role of DH. Moreover, consumers that use electricity only for HPs can access reduced electricity prices. According to the latest monitoring report, the average costs for electricity for HPs was 25 ct/kWh in comparison to 36 ct/kWh for general electricity consumption (Bundesnetzagentur (BNetzA) and Bundeskartellamt (BKartA), 2023). Therefore, both DH and individual heating could achieve lower LCOH through the inclusion of further support mechanisms and funding. However, it is assumed that the impact would be similar for both DH and individual heating and would therefore not impact the conclusion overall. However, the final feasibility of the respective DH in an UA would have to be assessed on an individual basis.

On other hand, the costs for the connection of the RE and waste heat source to the DH are not take into account, as this was beyond the scope of the research. Furthermore, the use of waste heat would need heat exchangers, which are not taken into account. Nevertheless, it can still be assumed that waste heat is the most feasible heat source, as the costs would be lowered compared to HPs. Regarding the impact of the costs of the transmission, this would depend on the local circumstances and can therefore not be answered generally. It can be assumed that most waste heat sources and ambient heat from wastewater treatment plants and rivers as well as solar thermal are in vicinity to the DH system and therefore, do not significantly affect the cost for DH.

Another important aspect is the connection rate of buildings to DH, where this thesis assumes that all buildings are connected to DH. This would represent the optimal case, as the costs for DH can be distributed among as many users as possible, while lower connection rates would increase the DHDCC. This might therefore impact the feasibility of DH in 2045, as the difference in LCOH between individual heating and the min cluster and most sensitivities in UA with existing DH is not so high. However, even if the DHDCC are increased by 20% due to lower connection rates, DH would still be more feasible.

On the other hand, based on the other studies it is also suggested that less area might be connected to DH and that therefore the DH share would lower. This would mean that the DHDCC are expected to decrease marginally, as the outer areas with lower heat demand tend to have higher DHDCC. On the other hand, small energy conversion units might be need and therefore higher specific investment costs. Therefore, it is assumed that a reduction of DH area within an UA has only a marginal impact on the feasibility of DH and would rather improve it. However, it would be worth considering if this could increase the feasibility of potential DH, especially for smaller UA.

The clustering might also have an impact on the results of the analysis, as they are based on statistical analysis instead of clustering algorithms. Therefore, the conclusions drawn for existing and potential DH might not be applicable to all UA. However, in comparison most studies rely on the classification into large, medium-sized and small UA. The clusters formed based on the statistical analysis result in a similar distribution into UA differentiated by size. While this might be a sensible classification for the heat demand, the potentials for RE and waste heat cannot hardly be attributed to UAs based on their size. As the various potentials are taken into account through sensitivities it is therefore assumed that the clustering has no significant impact on the results. However, a more detailed clustering could help for potential DH areas, as the overall feasibility is rather inconclusive.

As no other studies has specifically investigated the potential for DH in comparison to individual heating, there is no reference value to compare the results of the analysis to. Overall, the other studies rather focus on the transition of existing DH and energy system analysis, but do not include LCOH for both RE and DHDCC. The results of other studies (Fraunhofer ISE and Fraunhofer IEE, 2022; Institut für Energie- und Umweltforschung (ifeu) et al., 2023; Lübbers et al., 2022; Papadis et al., 2022; Prognos and Hamburg Institut, 2020) are however overall in line with the analysis of this research and suggest an increase of existing DH with a transition towards RE and waste heat, with an increased importance of waste heat and large scale HPs. It is therefore assumed that the results are considered generally reliable.

7.2 Integration of DH in a smart energy system

As discussed in the problem analysis, significant efforts are needed for the decarbonisation of the society and in order to meet the targets of reaching climate neutrality in 2045. The foundation of the transition will be a 100% RE system that can provide energy without GHG emissions. This energy system will rely to a large extent on wind power and photovoltaic (PV). While these RE sources can provide carbon-free electricity, their production is dependent on the weather and therefore the supply is highly fluctuating. Thus, some capacity reserves in the form of power plants that run with renewable or biobased fuel such as green hydrogen or biogas will be needed besides storages to meet the electricity demand and ensure the stability of the electricity grid. (Lübbers et al., 2022)

Furthermore, according to Connolly and Mathiesen (2014), DH and flexible HPs are the most cost-efficient options in a 100% RE system to provide flexibility in order to integrate fluctuating RE sources. In comparison to electricity storage, the storage of electricity in the form of heat in heat storages is cheaper and more efficient. Therefore, heat storages in DH play an important role to create flexibility on the demand side and also help HPs to operate more independent of the fluctuating electricity prices and the varying heat demand. Another benefit includes the possible use of HPs for balancing power and electric grid services.

The concept of a smart energy system has been defined more concretely by Lund et al. (2017) as an energy system that focuses on the synergies between the various sector and tries to optimize each sector individually and the overall energy system at the same time. For this, DH plays an equally important role, as besides the provision of flexibility to the electricity grid, DH enables the use of waste heat from industry and therefore enables further cascading of energy. This should therefore also be taken into consideration for the establishment of electrolysers and power-to-X facilities.

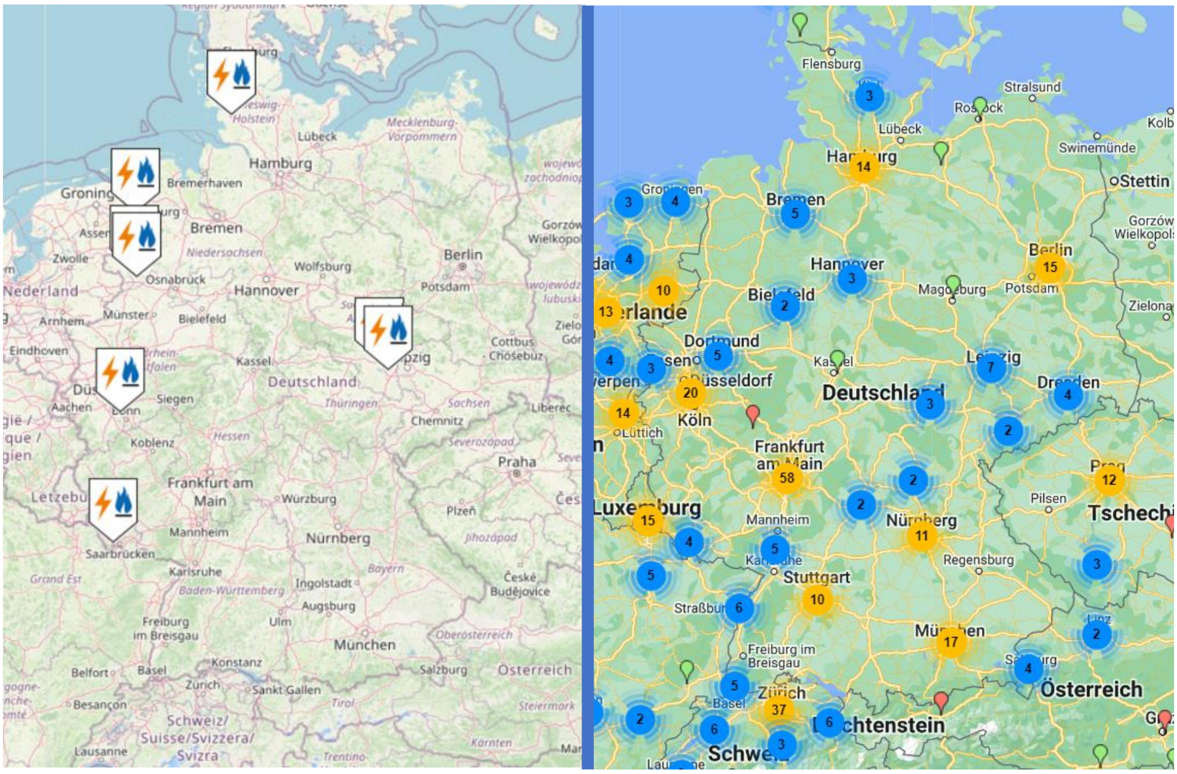


Figure 38: Overview of currently planned power-to-gas facilities above 10 MW (left) and existing data centers (right) in Germany (Data Center Map, n.d.; Deutscher Verein des Gas- und Wasserfaches (DVGW), 2020)

The planned power-to-gas units above 10 MW and the existing data centers in Germany are shown in Figure 38 above. While there are currently only a few planned power-to-gas units, the installed capacity of electrolysers is expected to increase to 4,500 MW by 2030 and therefore provides a significant potential for the use of waste heat. (Ostbayerische Technische Hochschule Regensburg, 2022) On the other hand, there is a large numbers of data centers in Germany which could provide waste heat. The integration of DH should therefore be taken into account for existing units and for the development of future electrolysers and data centers. Furthermore, other waste heat sources, such as supermarkets or metro stations could be investigated. Nevertheless, the possible dependency of DH on waste heat should also be considered. In case the units are not running or if they are closed down, there are not enough heat sources to cover the heat demand of DH. These risks should therefore be considered, while municipal heat planning provides a suitable opportunity to consider these risks and also include future waste heat potentials.

7.3 Acceptance of DH

As DH is considered a natural monopoly, there is the risk of arbitrary prices, which can be set to high levels by DH operators as there is no competition. Therefore, DH need to be regulated accordingly so that the monopoly is not abused. In comparison to other countries the regulation in Germany is rather weak and the prices for DH can vary significantly. (Bürger, 2022) According to a comparison of DH prices in Germany that included 85 DH operators, the prices for DH ranged between around 80 EUR/MWh to around 450 EUR/MWh for 2,000 full load hours (FLH) (Bundesverband der Energie-Abnehmer (VEA), 2023). Therefore, the prices for DH can vary significantly at different locations.

Furthermore, an investigation by WISO magazine (ZDF, 2023) showed cases where DH costumers are facing extreme cost increases and different billing methods put some costumer at disadvantage compared to others. Overall, around one third of DH operators do not have transparent information regarding their prices available online. While the reputation of DH in Germany is overall high, such inconsistency in prices can significantly affect the acceptance and popularity of DH. (Bürger, 2022) However, a high acceptance of DH will be needed in order to achieve high connection rates and thus ensure the feasibility of DH. While it is possible to make the use of DH compulsory in certain areas, it is not a popular measure among politicians and could even further reduce the trust in DH.

Instead, it is therefore important to create transparency regarding DH prices and price increases as well as the quality of DH, such as heat sources and heat losses. Furthermore, stricter regulation could increase the trust in DH, as demanded by various environmental NGOs. It is suggested to implement a national authority that controls DH operators, as is the case with electricity and gas grid operators. Furthermore, a central database for DH should be established where information on prices, heat sources and general supply conditions is available to authorities, municipalities and consumers. (Bürger, 2022; Deutsche Umwelthilfe (DUH) et al., 2023)

Denmark has shown with a DH share of more than 60% that a high acceptance and trust in DH can be achieved through transparency and regulation. In comparison to Germany, Denmark has a very strict regulation and DH operators are not allowed to make profit and have to reduce prices in case of profits. Therefore, most DH operators are local cooperatives or municipal enterprises, which further enhances the trust of consumers in comparison to private companies, which are often profit driven. (Bürger, 2022; ZDF, 2023) As this research has shown, DH becomes feasible with socio-economic discount rates and therefore different ownership models and structures could provide another way to increase the acceptance in DH and reduce costs at the same time.

7.4 Investment horizon and costs

This research has shown that the feasibility of establishing new DH cannot be answered easily and depends on various factors. One of the most important factors is the time of investment, as this can impact the feasibility significantly. However, there are various aspects to take into account. If the investments are made now, there is the possibility of overcapacities, as the heat demand will reduce over time. On the other hand, if the investments are made continuously in order to keep the heat demand more stable, the DHDCC might be higher in the beginning, as fewer people are connected to DH. This could in turn also jeopardize the feasibility of DH. Another aspect that could significantly influence the feasibility of DH, is the installation of individual HPs. If a lot of houses in potential DH areas already installed new renewable individual heating systems due to the requirements of the GEG, this would significantly reduce the connection rate. This in turn would significantly increase the DHDCC, which already contribute the most to the LCOH and thus could make establishing new DH infeasible.

Therefore, municipal heat planning will be an essential instrument for identifying potential DH areas. This would help people that have to exchange their individual heating system to decide if they should install a new HP or connect themselves to DH. In order to ensure the feasibility of DH in the long run, it could be a possibility to make the connection to DH mandatory when the heating system has to be changed. This however would require an increased acceptance and price control of DH. The acceptance for DH can also be increased by involving the citizens as part of the municipal heat planning and thus getting their support for DH or deciding to not install DH because of limited trust. Furthermore, the general infrastructure planning should be integrated with the planning of new DH, as this could significantly reduce the investment costs for DH and thus also influence the feasibility of DH (Burkhardt and Blesl, 2023).

While no studies focus explicitly on the establishment of new DH, Fraunhofer ISE and Fraunhofer IEE (2022) suggest that the time until 2030 will be essential for the transition of the heating sector in general. During this time, the main decisions have to be taken and the extension or the development of new DH has to planned. Therefore, it is suggested to first conduct municipal heat planning including the important stakeholders and then invest into new DH with sufficient support from the society so that high connection rates can be achieved and costs can be reduced through integrated infrastructure planning. While the feasibility of DH might depend significantly on the local circumstances, it is recommended to research the impacts of the time of investment as well as the area covered by DH.

While this research has shown that extending DH is feasible towards 2045, it has mainly focused on the extension and not considered the transformation of the current grid. As most existing DH grids in Germany still operate at temperatures above 100 °C, the supply temperatures would first have to be reduced to around 60 °C, as assumed in this research. This way, the RE and waste heat sources can be better integrated and the grid can operate more efficiently (Burkhardt and Blesl, 2023; Institut für Energie- und Umweltforschung (ifeu) et al., 2023). However, for the transition towards 4th Gen DH a wide range of measures including the division of DH into sub networks, the exchange of heat exchanger stations or the increase of the pump capacity might be needed depending on the local circumstances (Blesl et al., 2023).

According to an analysis by Blesl et al. (2023), the transition of existing DH towards 4th Gen DH will cost around 13 B EUR. Therefore, large UA would have to invest around 130 M EUR on average, while medium-sized UA would need around 12 M EUR on average. In comparison, the costs for the increase of the connection rate and the extension of existing DH would only amount to around 41 M EUR and 6 M EUR on average for large and medium-sized areas respectively. Therefore, the costs for the transition to 4th Gen DH are two to three times higher than the extension of DH. However, the extension of DH assumed by Blesl at el. (2023) is less compared to the assumptions in this research, but still assumes that DH covers around 30% of the total heat demand in 2045. It is assumed that the investments in the transition and extension take place until 2035 in order to balance out the reduction in heat demand due to increased efficiency and retrofitting.

With such investments required both for existing and potential new DH, it raises the question of financing. While support programs are available, investments in DH are very capital intensive and therefore require significant amounts of capital. While a lot of utilities are at least partially owned by municipalities, especially smaller municipalities will have difficulties financing new DH, as they already have tight budgets now. This raises the question of financing and as DH are long term investment with rather long payback periods, they are not so attractive for other investors or would lead to higher interest rates, which in turn reduces the feasibility of DH. (Fraunhofer ISE et al., 2020; Institut für Energie- und Umweltforschung (ifeu) et al., 2023) On the other hand, this also opens the door to new forms of investment and ownership, where cooperatives or citizens get involved into the establishment of DH, following the example of Denmark. Otherwise, the government might be able to provide guarantees for the establishment of DH if it is preferable from a socio-economic perspective.

8 Conclusion

On the way towards climate neutrality in 2045, the buildings sector is facing a transition towards renewable and waste heat. While so far DH has only accounted for around 14% of the heat demand in the buildings sector, research and politics see an important role for DH, especially in densely populated urban areas. In light of the upcoming municipal heat planning and the available support schemes, municipalities and utilities will have to determine the role of DH in this transition. Therefore, the thesis aims to answer the following research question.

Which role can district heating play for German municipalities larger than 10,000 inhabitants in order to supply heat in an economically feasible way and reach climate neutrality in 2045 in light of the new support scheme BEW while considering the different potentials for renewable and waste heat?

This is supported by the following sub-research questions:

1. *How is the heat demand, existence of district heating and the potential for renewable and waste heat distributed among German municipalities larger than 10,000 inhabitants?*
2. *Can municipalities be clustered to determine the potential of district heating towards climate neutrality 2045 while taking the local differences into account?*
3. *Is district heating feasible compared to individual heating from a business economic perspective towards climate neutrality 2045 while considering the BEW support scheme and the local differences?*

Based on the research design, the MLP and Choice Awareness theories form the basis of this thesis. The MLP explains the transition of the buildings sector in general and can be used to determine the current stage of the transition. On the other hand, Choice Awareness provides more specific methods for the implementation of radical technological change, as presented by the transition of the heating sector towards a larger scale use of DH with renewable and waste heat. Due to the scope of this thesis, the application of theories focuses on the scenario design and the conduction of the feasibility study for DH.

This therefore also is the starting point for the methods which is combined with the guidelines for municipal heat planning. The methods therefore consist of an analysis of the heat demand and the potentials for renewable and waste heat. Furthermore, a cluster analysis and an energy system analysis are conducted in order to answer the research question.

While municipalities are the political entities that would establish municipal heat planning and DH, the reference area for this thesis is based on UA, as this allows a more sensible analysis while the results can still be applied to municipalities. Regarding the first sub-research question, it is shown that around 22% out of the 1,016 UA above 10,000 inhabitants have existing DH. However, the UA with existing DH represent around 58% of both the population and heat demand of all UA above 10,000 inhabitants. In general, the majority of large UA have DH, while still around one third of the medium-sized UA have DH. The largest potential for the establishment of new DH therefore lies in small UA. Due to the different approaches and challenges for the transition of existing DH or the establishment of new DH, the further analysis is divided into UA with existing and potential DH.

The heat demand in the UA is distributed unequally, while overall UA with existing DH have a higher heat demand as they consist of larger UA. The median heat demand for 4th Gen DH in UA with existing DH was 419 GWh/a in 2015, while it only amounted to 130 GWh/a in UA with potential DH. Overall, 4th Gen DH can cover around 90% of the total heat demand in both UA with existing and potential DH in 2015. Looking at the future heat demand, the heat demand in the scenario BL2050 is around 35% lower compared to the heat demand in 2015. For the heat demand of 4th Gen, this translates to a heat demand of 215 GWh/a and 66 GWh/a for UA with existing and potential DH respectively. While the DHDCC are overall similar for UA with existing and potential DH, contrary to the heat demand they are increased from 2.0 and 2.2 ct/kWh in 2015 to 5.0 and 5.4 ct/kWh in BL2050 for UA with existing and potential DH respectively.

The potential for renewable and waste heat is also divided unequally among UA and in general a similar picture for UA with existing and potential DH can be drawn. While waste heat and ambient heat from lakes are only available in less than 25% of UA for both existing and potential DH, waste biomass and solar thermal are available in at least 75% of UA and the latter is even available in all UA with existing DH. The available quantities of heat are also varying between the different sources. Overall, large solar thermal potentials exist, but these are mainly available during summer and would therefore require seasonal storage. Otherwise, ambient heat from river and wastewater are the most promising heat sources for most UA with existing and potential DH.

In terms of the second sub-research question, the cluster analysis showed that based on the chosen variables no optimal number of clusters could be determined and that therefore the UA cannot be clustered based on Ward's-linkage algorithm. Therefore, max and min cluster based on statistical criteria are determined instead and the local differences are covered by further sensitivity analyses. The max cluster for UA with existing DH represents a large UA with all available renewable and waste heat potentials, while the min cluster for UA with existing DH represents a medium-sized UA with least renewable and waste heat potentials available. For UA with potential DH, the max and min cluster represent a medium-sized and small UA respectively.

Regarding the third sub-research question, the analysis has shown that DH is feasible for the status quo scenario 2020 and for the BEW support scenario 2020 for both UA with existing and potential DH, as both the max and min cluster have lower LCOH than individual heating. Overall, a lot of similarities can be observed between UA with existing and potential DH, however the main difference is the feasibility in the target scenario 2045. While the LCOH for UA with existing DH range between 6.1 and 13.6 ct/kWh, the LCOH of UA with potential DH range between 9.0 and 17.2 ct/kWh. Therefore, in comparison to the LCOH of 15.1 ct/kWh for individual heating, it can be concluded that DH is feasible in UA with existing DH, while for UA with potential DH it is only feasible if sufficient waste heat is available.

The sensitivity for the target scenario 2045 showed that for UA with existing DH the LCOH for most UA range between 11 and 13 ct/kWh and are therefore on the higher end of the LCOH. This leads to the suggestion that DH is not feasible for most UA with potential DH for the target scenario 2045. On the other hand, through the use of combined infrastructure planning, the LCOH of UA with potential DH could be reduced to 14.1 ct/kWh and would therefore make DH preferable over individual heating. Furthermore, a lower WACC shows that DH in general irrespective of the available potentials and heat demand is feasible from a socio-economic perspective.

The analysis also showed that mainly waste heat is used if available and that otherwise large-scale HPs, preferably from water sources, are used together with solar thermal and heat storage. While the heat storage tank is mainly used in combination with the HPs to make use of the fluctuating electricity prices, the PTES is mainly used as a seasonal storage to make use of the heat produced by solar thermal during summer. In case no potentials are available an air HP is used and even in case biomass or geothermal potentials are available, still an air HP is shown to be more cost-efficient in the target scenario 2045.

For the status quo scenario 2020, the main difference to the target scenario 2045 is the use of the biogas boiler to cover all or almost all of the heat demand of the min cluster in comparison to covering the peak load only. Through the BEW support, it is shown that the use of the biogas boiler is significantly reduced and an air HP is installed instead to cover the majority of the heat demand of the min cluster. Therefore, through the use of the BEW support, the installed energy conversion units are more aligned to the units installed in the target scenario 2045.

Overall, it can therefore be concluded that DH is feasible towards climate neutrality 2045 in UA with existing DH independent of the heat demand, DHDCC and renewable and waste heat potentials, while there might be individual cases where the feasibility cannot be ensured. On the other hand, the feasibility of establishing new DH towards climate neutrality 2045 is only given if sufficient waste heat is available and is otherwise inconclusive and depends on the time of investment or the reduction of DHDCC by combined infrastructure planning.

The comparison with literature has shown that while there are some differences regarding the classification of UA and the projected use of renewable and waste heat sources. However, overall similar conclusions are drawn and the focus is placed on waste heat and large-scale HPs as well as the extension of existing DH. Therefore, it can be assumed that the results of this analysis are reliable, while it should be taken into account that a connection rate of 100% is assumed and the area covered by DH is significantly larger compared to other studies. Furthermore, there are other aspects which could potentially influence the feasibility of DH positively and negative and depend to a large extent on the future developments, the local circumstances and the investment horizon.

Lastly, it is important to also consider other aspects which influence the role of DH towards climate neutrality 2045. This includes the integration of future waste heat sources from electrolysers, the acceptance of DH and price transparency as well as the financial situation of the municipalities and utilities. As DH requires capital intensive investment, this could prevent the establishment or transformation of DH, even if it would be feasible from an economic perspective. Ultimately, municipal heat planning will play an important role to identify potential areas for DH and include the different stakeholders to increase their acceptance and ensure a high connection rate.

It can therefore be concluded that overall DH can play and important role for municipalities larger than 10,000 to supply heat in an economically feasible way and reach climate neutrality in 2045. While extending existing DH is the most feasible heat supply option, the establishment of new DH depends on various aspects and should be further investigated.

9 Recommendations

Based on the scope of the thesis, some limitations to the research conducted in this thesis have been identified. Furthermore, the analysis has shown that the feasibility of establishing new DH on the way to climate neutrality in 2045 is uncertain and requires further analysis. Therefore, the following recommendations for further are formulated.

Most importantly, it is recommended to investigate how the point of investments impacts the feasibility of DH, especially for establishing new DH. Furthermore, this analysis should be elaborated by also incorporating the decreasing heat demand over time which leads to lower capacities of renewable and waste heat sources that are required. Therefore, a feasibility study should be conducted which can identify when it is best to establish new DH for which area and install which energy conversion units.

As there are various parameters that include uncertainties, it is recommended to elaborate the sensitivity analysis and also include aspects such as the connection rate, different rates of retrofitting and commodity prices among others. This would further substantiate the results and lead to a more robust outcome regarding the role of DH.

As this thesis has analysed the feasibility of DH from a business-economic perspective, it is recommended to also include the socio-economic perspective and among others also investigate the impact on employment. This could furthermore be connected to analyse the policies that are currently in place and if the BEW support scheme is well designed. Therefore, further policies and taxation regulations could be proposed to support the most feasible option from a socio-economic perspective.

Additionally, as this thesis has been limited in the cluster analysis, further cluster algorithms and methods to determine the optimal number of clusters should be investigated. This could lead to a better classification of the UA into clusters and would enable municipalities to draw better conclusion regarding the feasibility of DH. On the other hand, there is also the possibility that differences between each municipality are too large, so that no clusters can be formed.

Another recommendation is to analyse the possible competition between solar thermal and PV. If limited space is available, utilities and municipalities have to decide between solar thermal and PV and take into consideration the future development of the electricity prices among others. Furthermore, it is also recommended to investigate and quantify the potential for geothermal heat in municipalities to better estimate the potential and integrate it in municipal heat planning.

While this research has focused on the comparison of DH and individual heating, it is recommended to also include the costs of retrofitting into the calculations and analyse how this impacts the overall systems costs. Hereby, it is recommended to distinguish between the ages of different buildings to also identify which buildings should be renovated first or what effect a shortage of skills workers would have on the transition.

Lastly, it is recommended to also include the hydraulics and different nodes of DH to have a more realistic calculation of the DHDCC and the energy conversion units which are required at different locations. This also includes the incorporation of transmission lines for the connection of renewable and waste heat sources.

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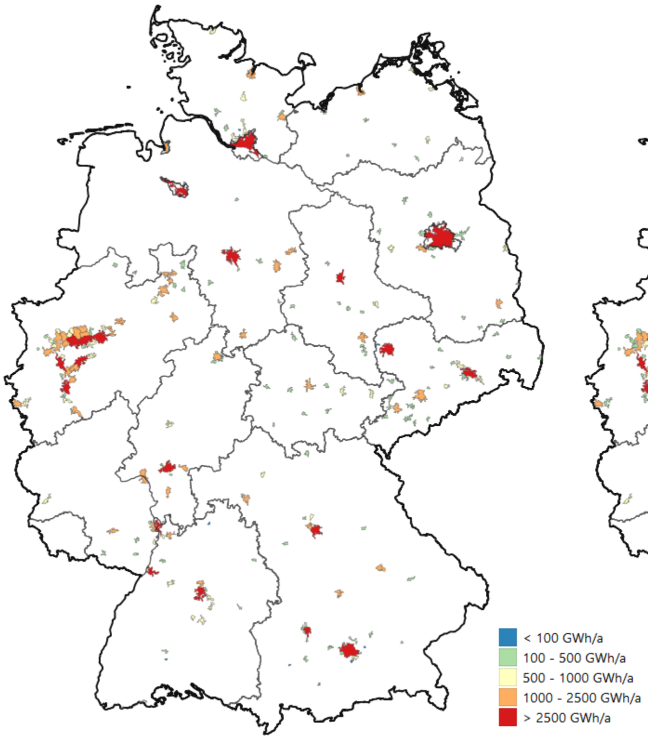
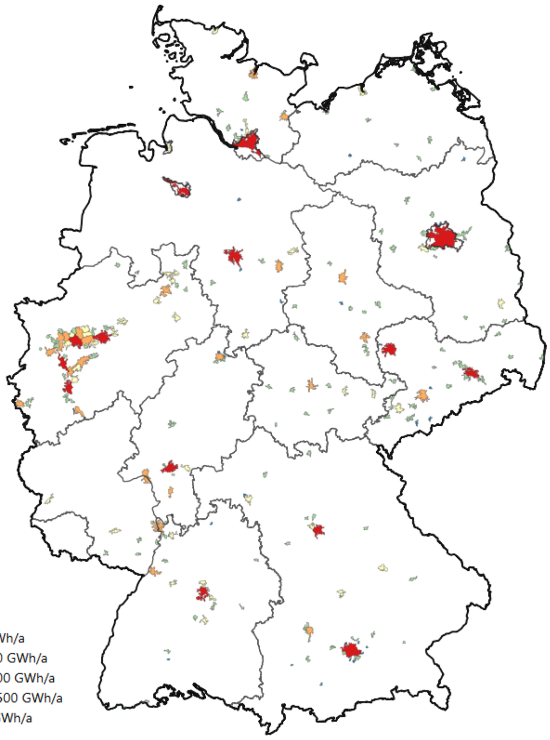
Appendices

Appendix I: Geographical distribution of heat demands in UA with existing DH

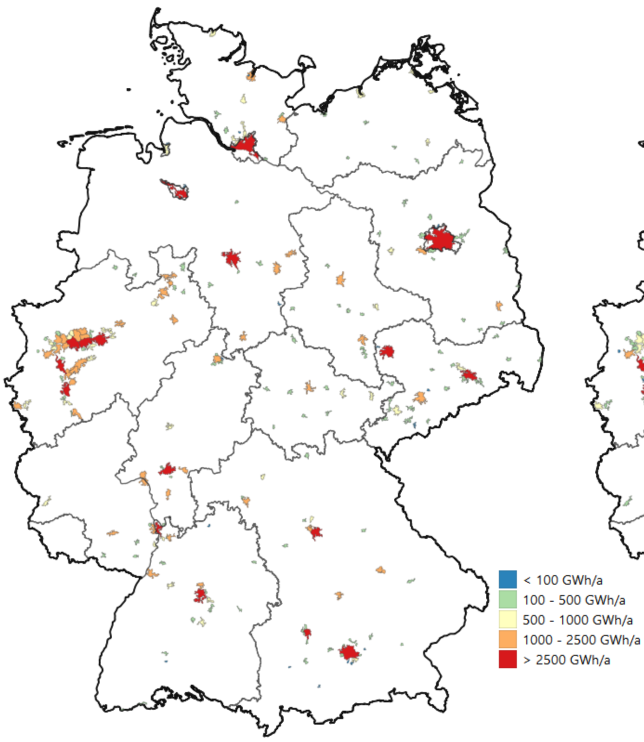
Total HD 2015 in UA with existing DH



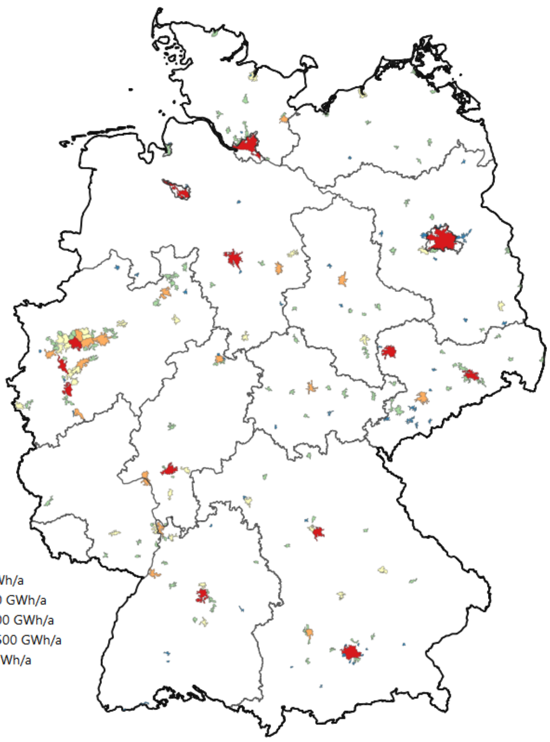
Total HD BL2050 in UA with existing DH



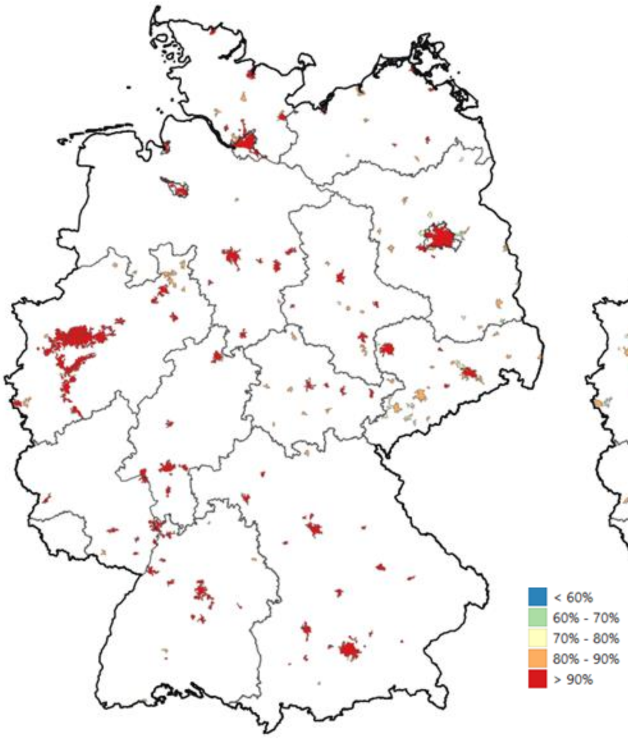
HD 2015 for 4th Gen DH in UA with existing DH



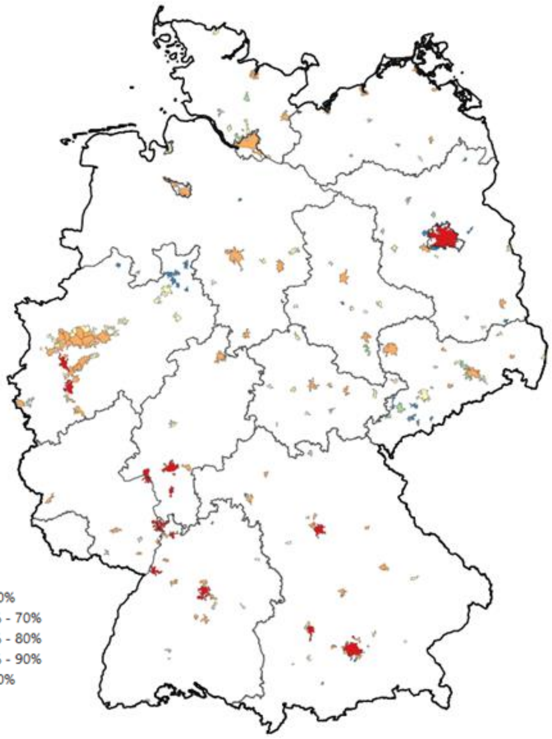
HD BL2050 for 4th Gen DH in UA with existing DH



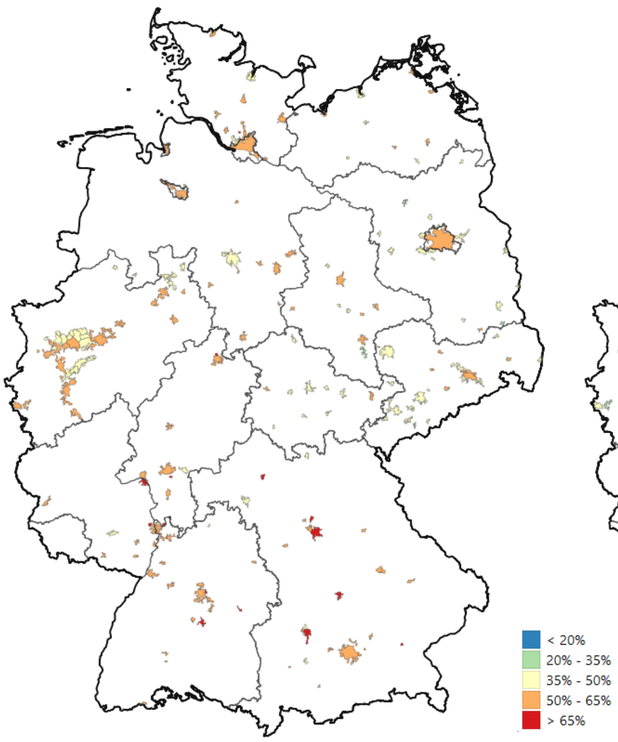
HD share of 4th Gen DH 2015 in UA with existing DH



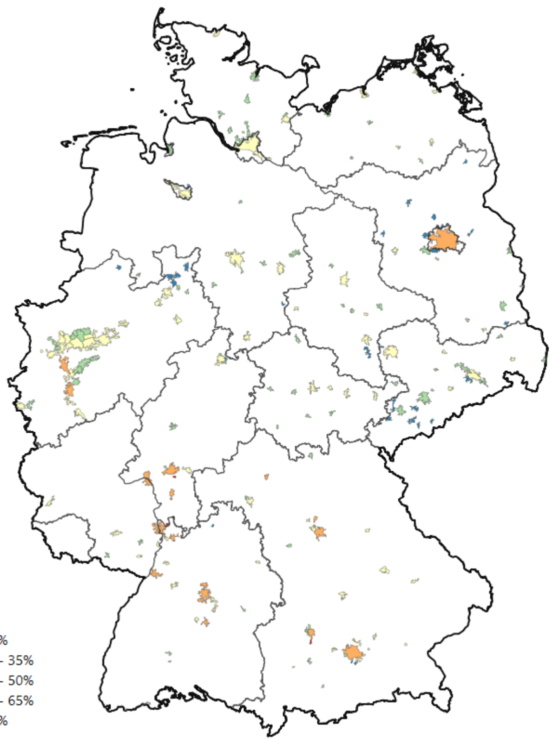
HD share of 4th Gen DH BL2050 in UA with existing DH



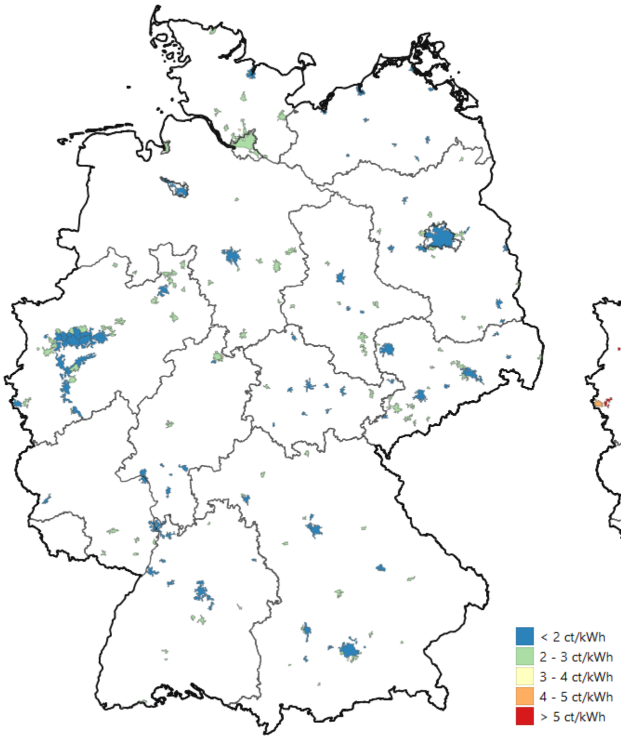
Area share of 4th Gen DH 2015 in UA with existing DH



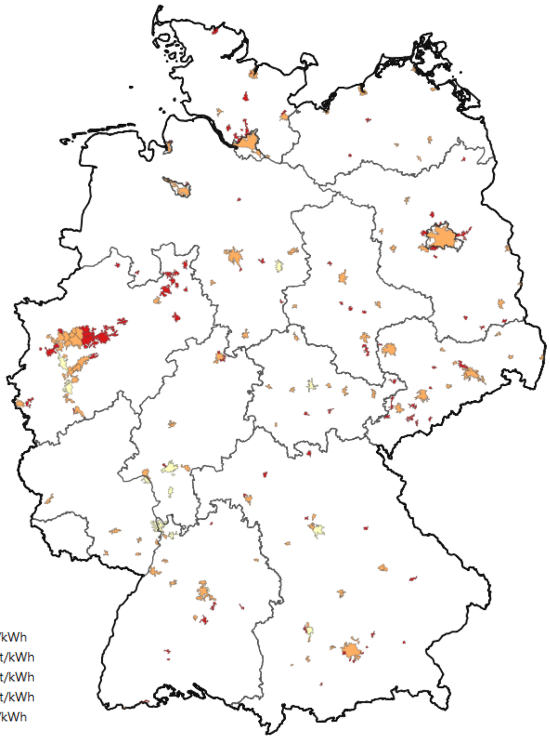
Area share of 4th Gen DH BL2050 in UA with existing DH



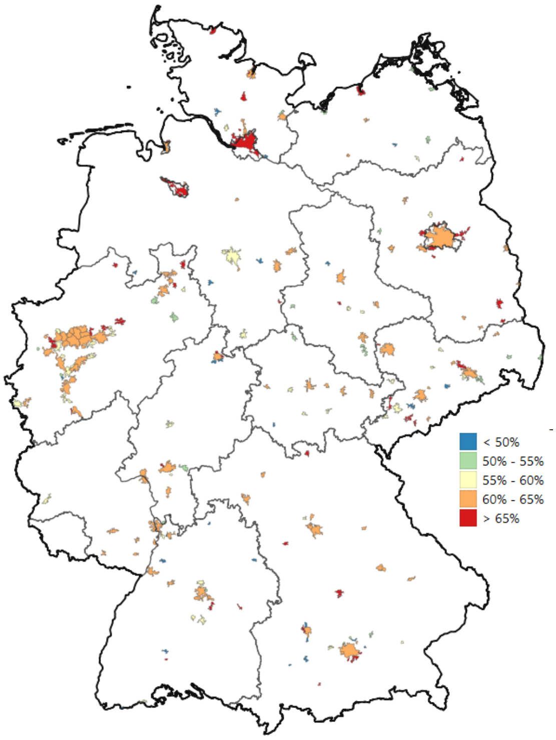
DHDCC 2015 for 4th Gen DH
in UA with existing DH



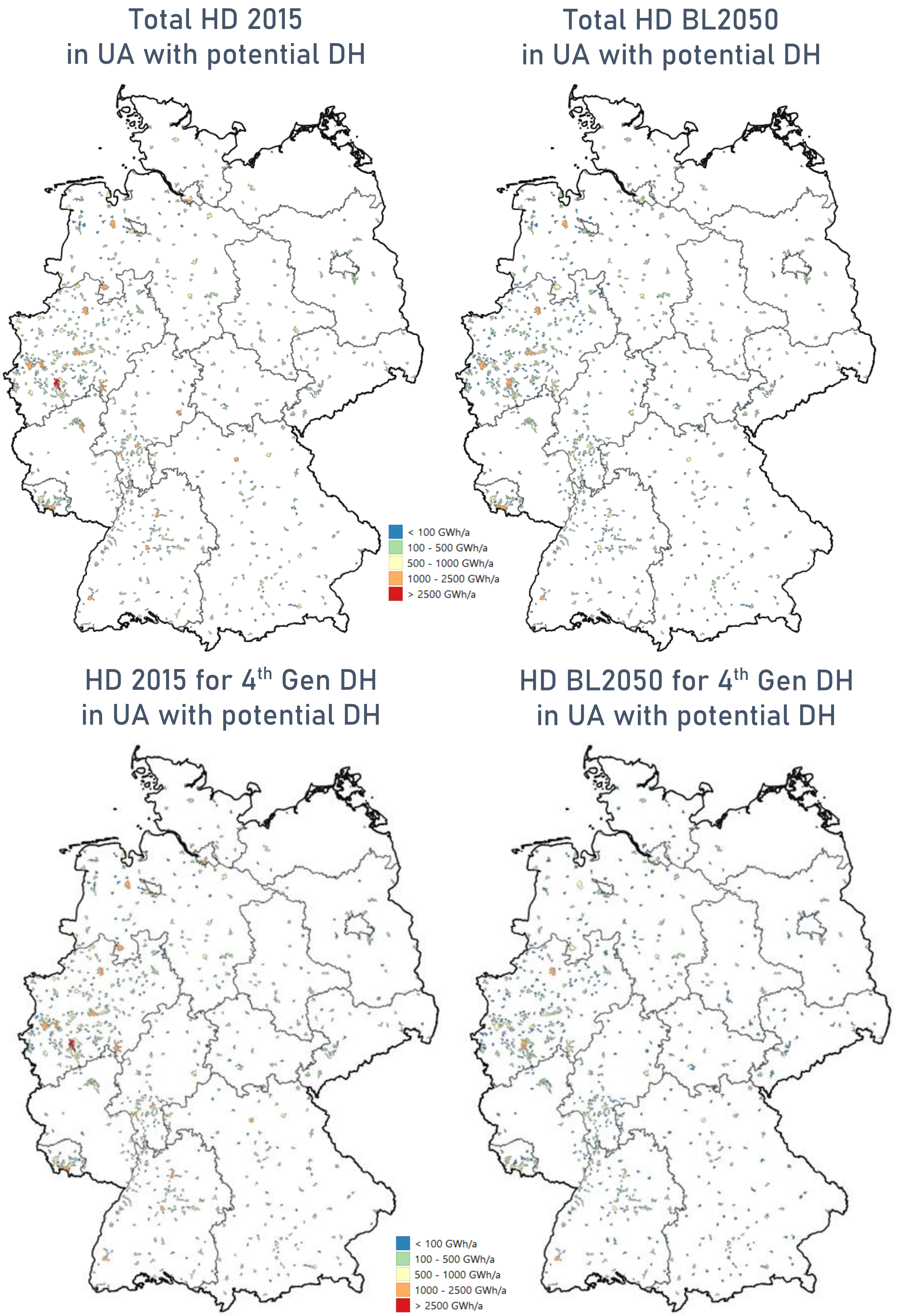
DHDCC BL2050 for 4th Gen DH
in UA with existing DH



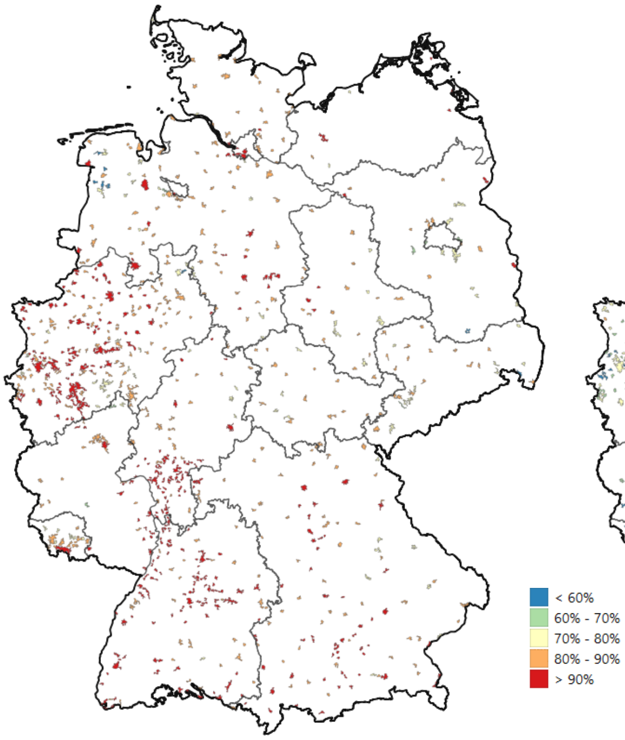
Share of Res HD 2015
in UA with existing DH



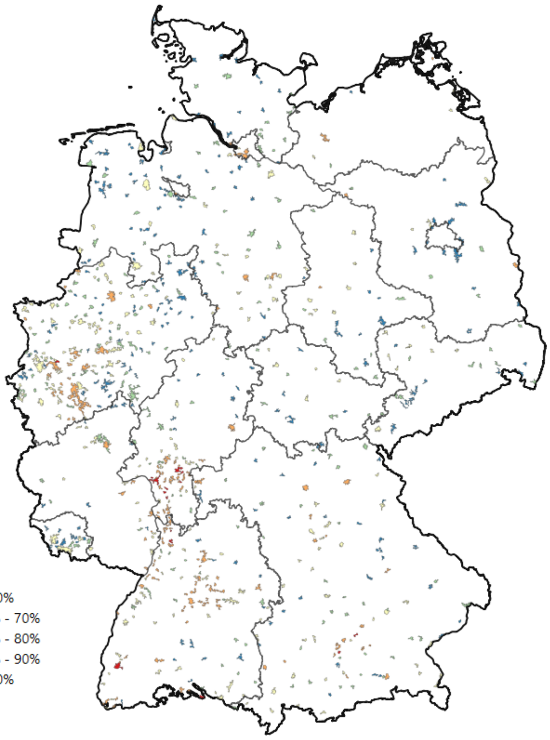
Appendix II: Geographical distribution of heat demands in UA with potential DH



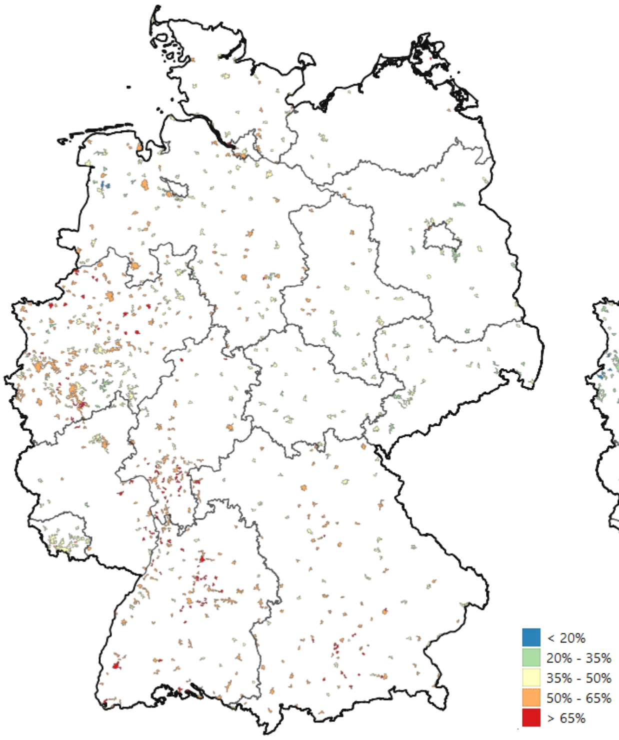
HD share of 4th Gen DH 2015 in UA with potential DH



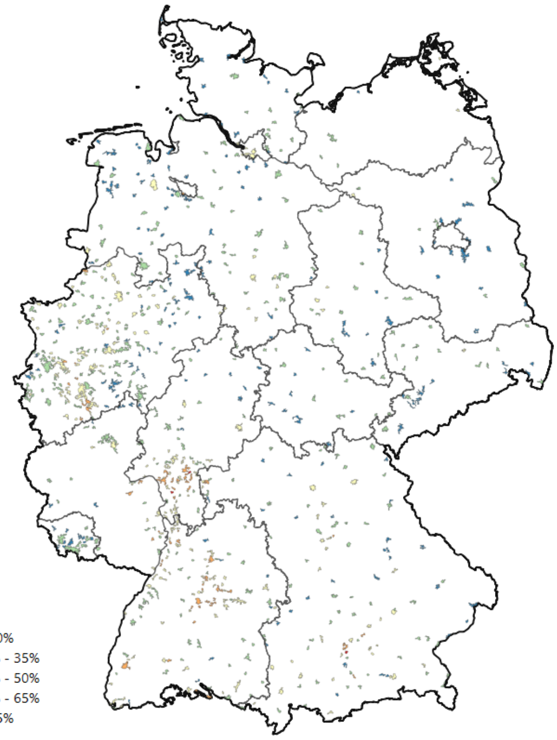
HD share of 4th Gen DH BL2050 in UA with potential DH



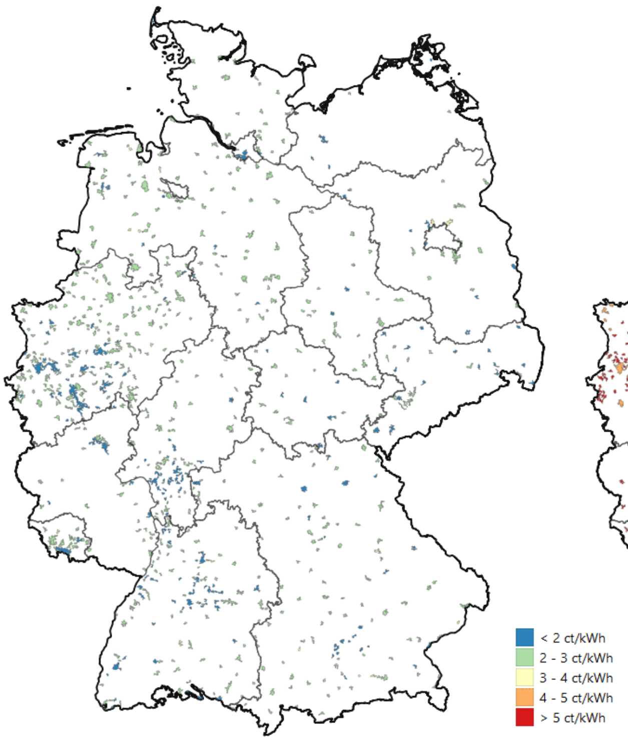
Area share of 4th Gen DH 2015 in UA with potential DH



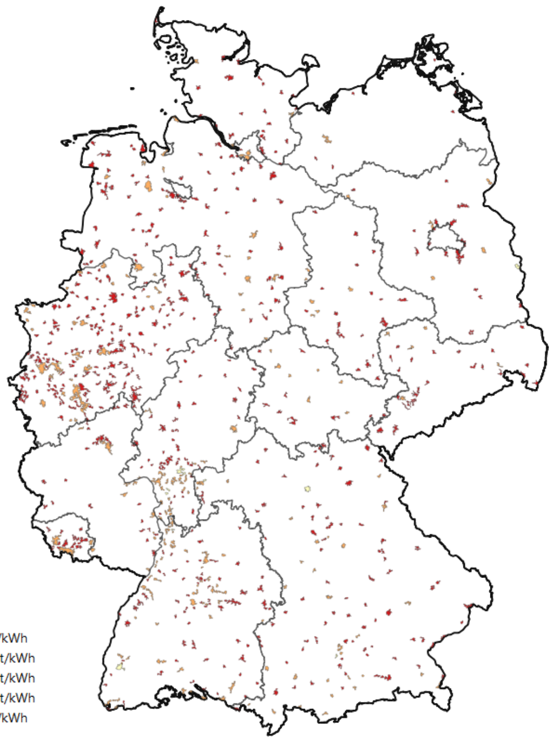
Area share of 4th Gen DH BL2050 in UA with potential DH



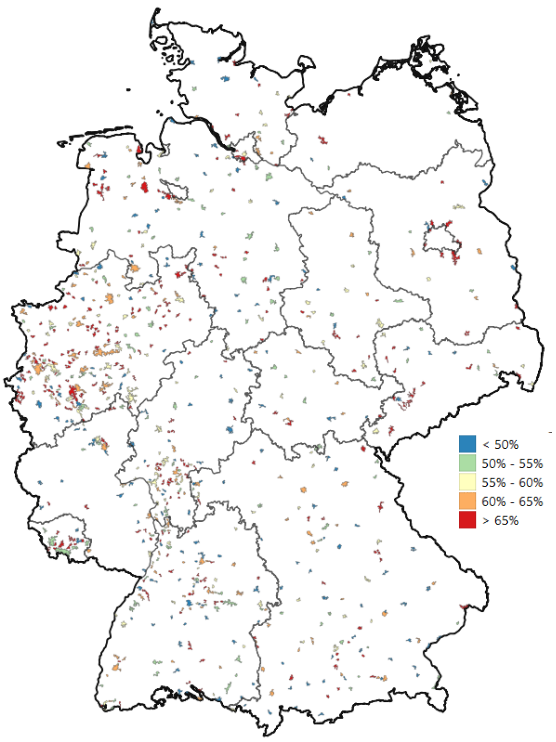
DHDCC 2015 for 4th Gen DH
in UA with potential DH



DHDCC BL2050 for 4th Gen DH
in UA with potential DH

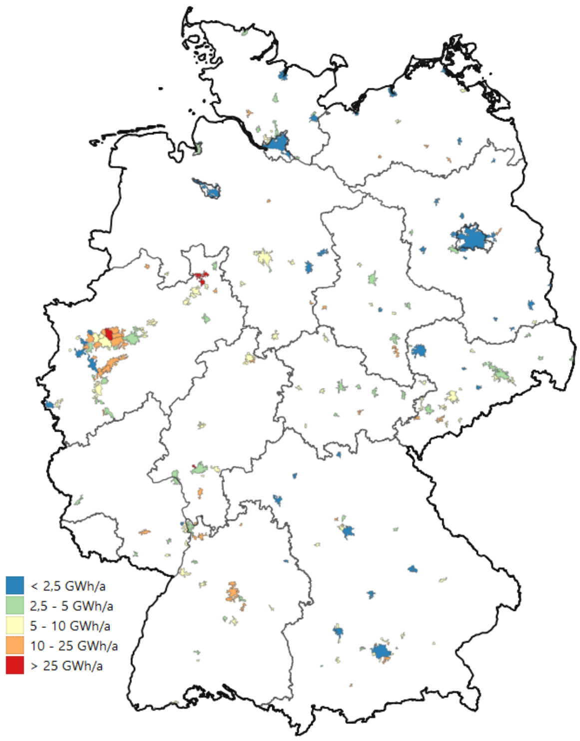


Share of Res HD 2015
in UA with potential DH

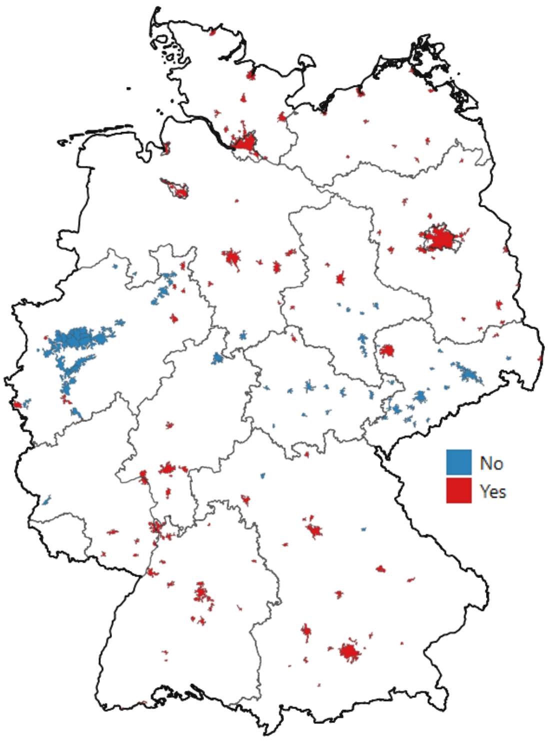


Appendix III: Geographical distribution of renewable and waste heat potentials in UA with existing DH

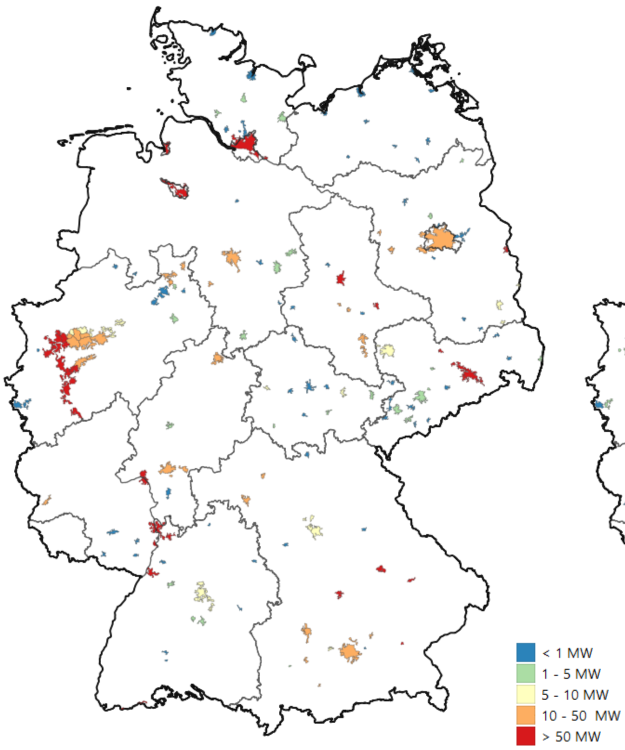
Waste biomass potential
in UA with existing DH



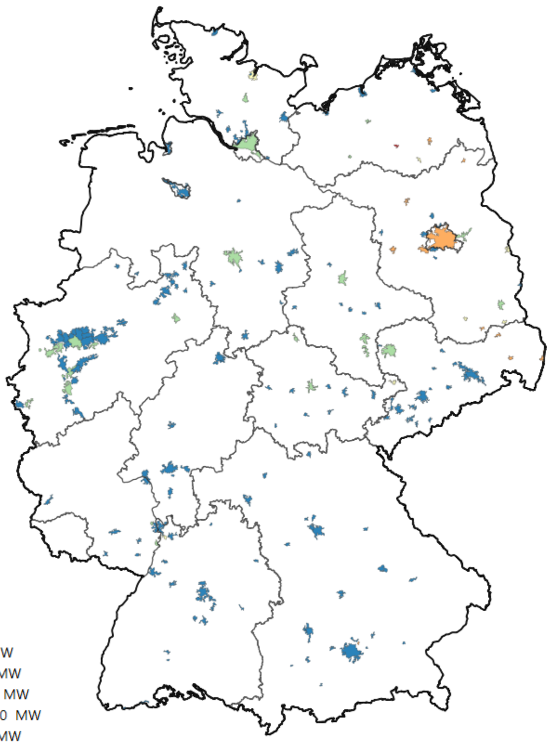
Geothermal potential
in UA with existing DH



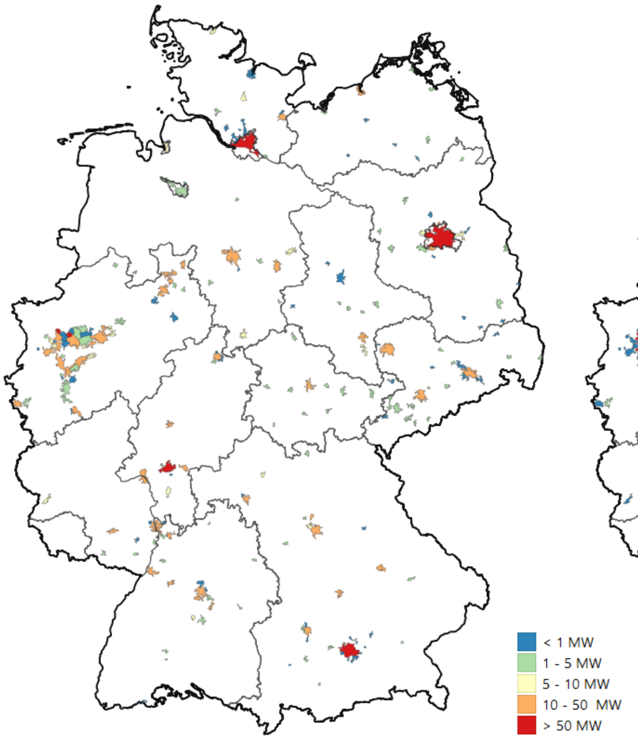
Heat potential from rivers
in UA with existing DH



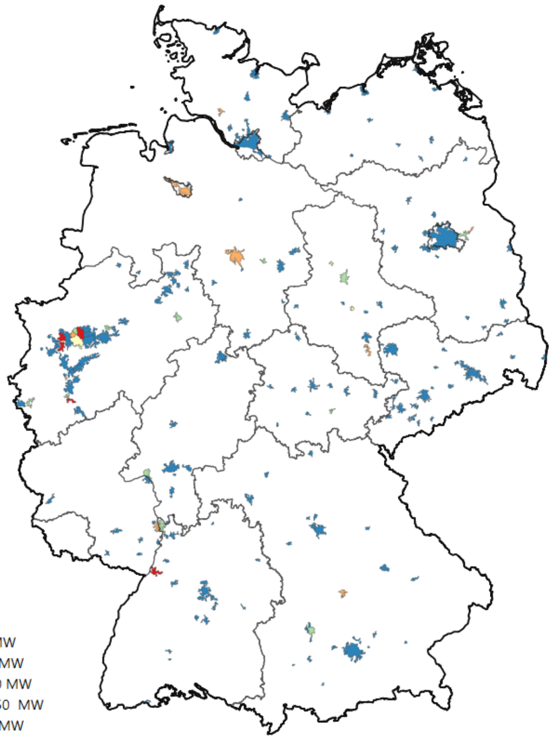
Heat potential from lakes
in UA with existing DH



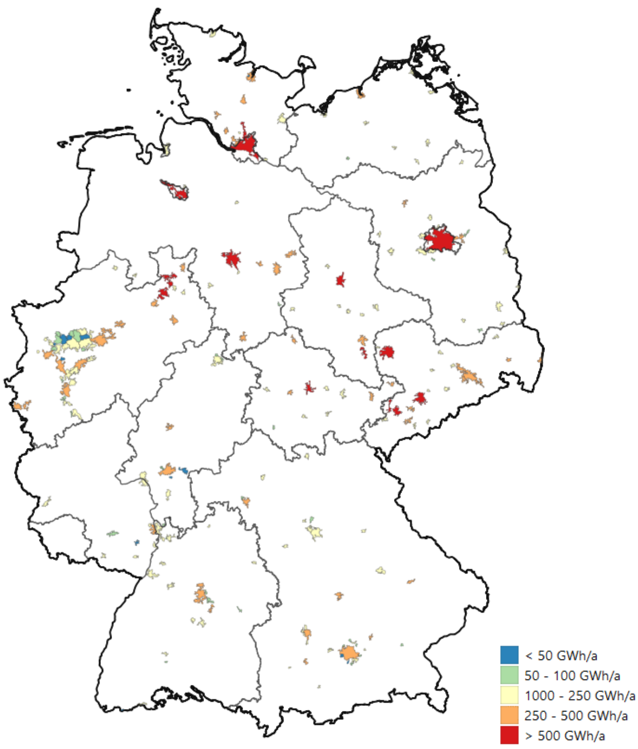
Heat potential from wastewater in UA with existing DH



Waste heat potential in UA with existing DH

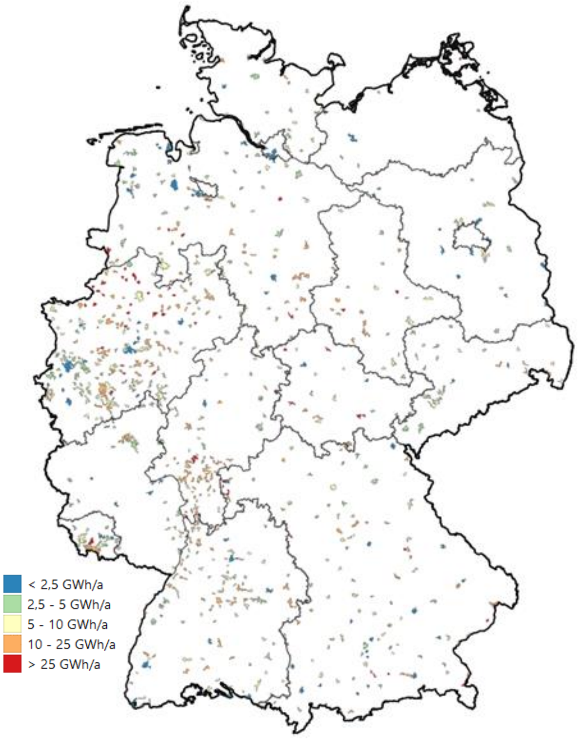


Solar thermal potential in UA with existing DH

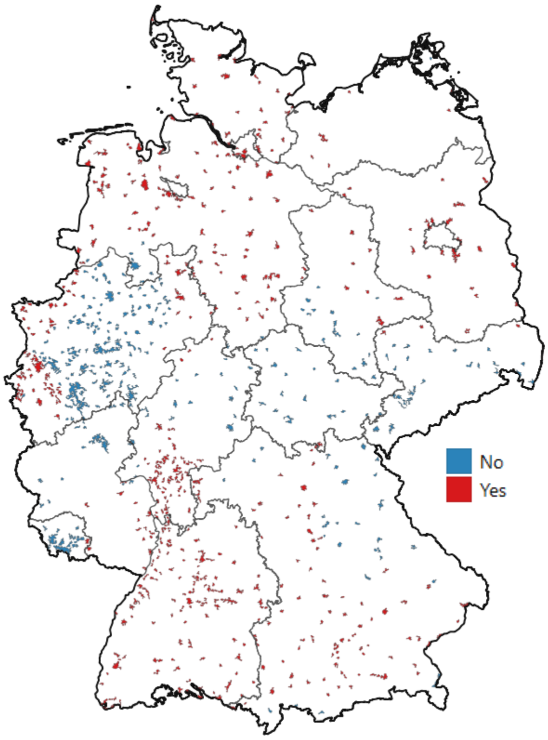


Appendix IV: Geographical distribution of renewable and waste heat potentials in UA with potential DH

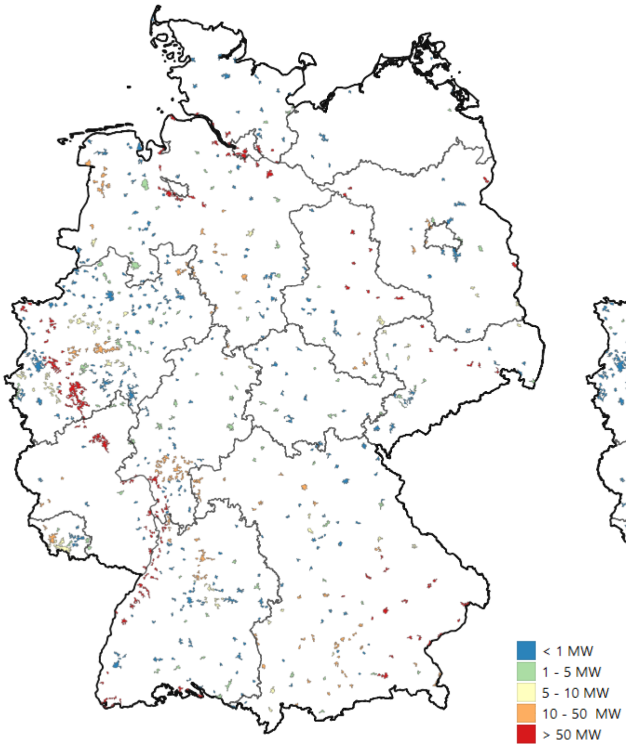
Waste biomass potential
in UA with potential DH



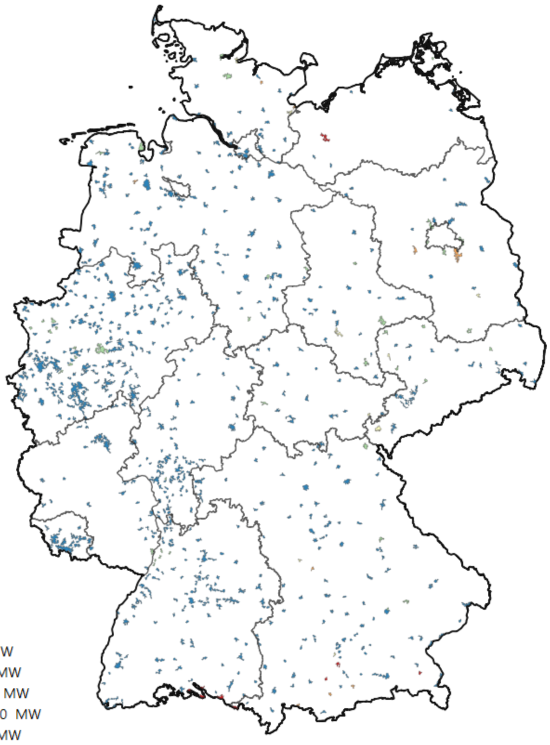
Geothermal potential
in UA with potential DH



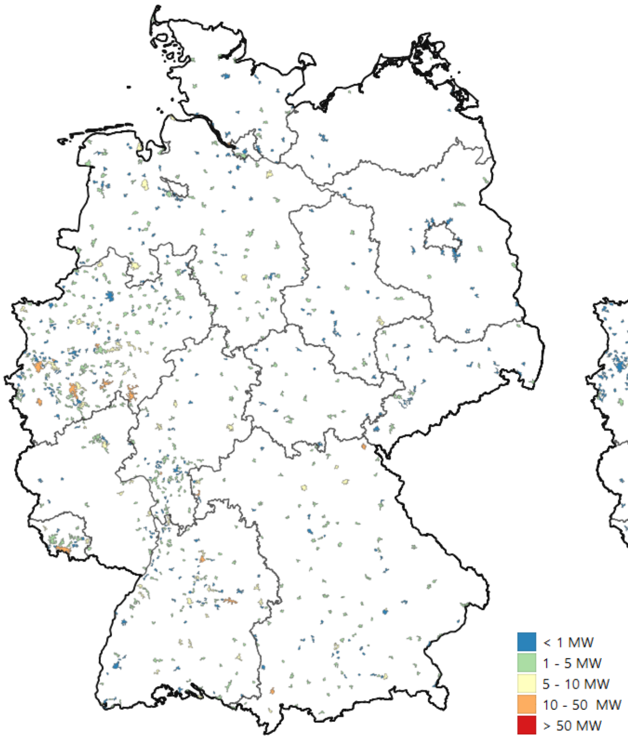
Heat potential from rivers
in UA with potential DH



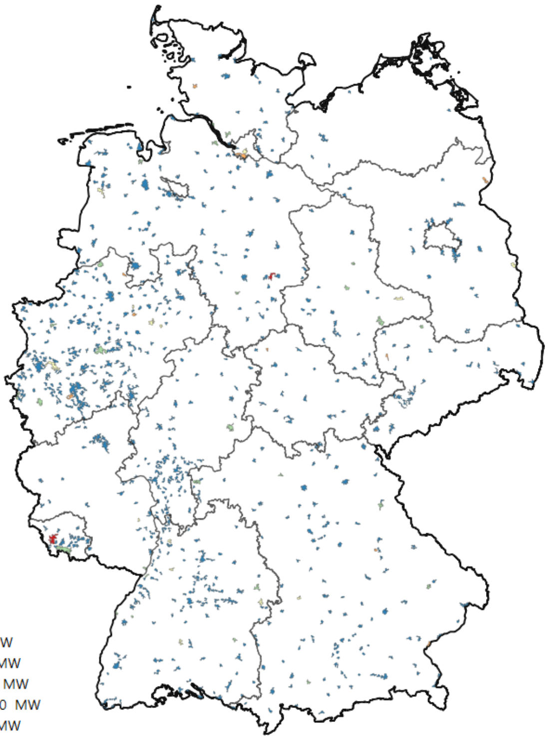
Heat potential from lakes
in UA with potential DH



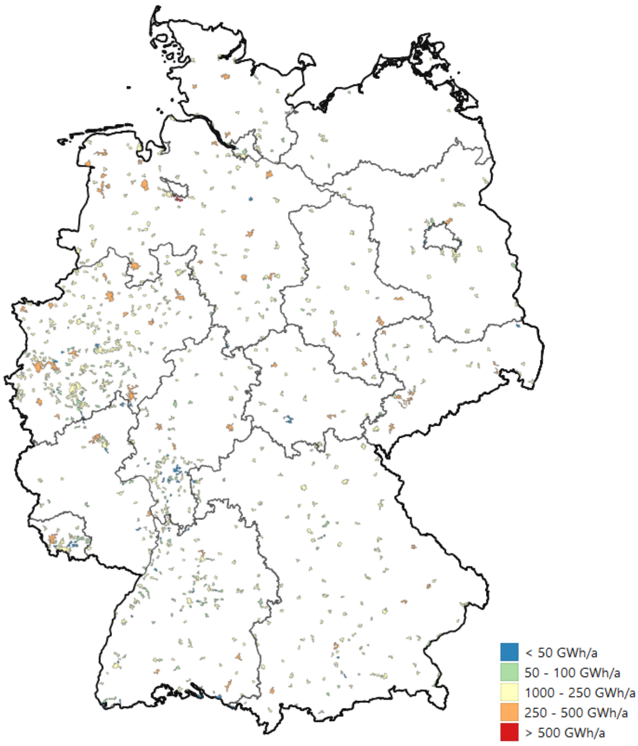
Heat potential from wastewater in UA with potential DH



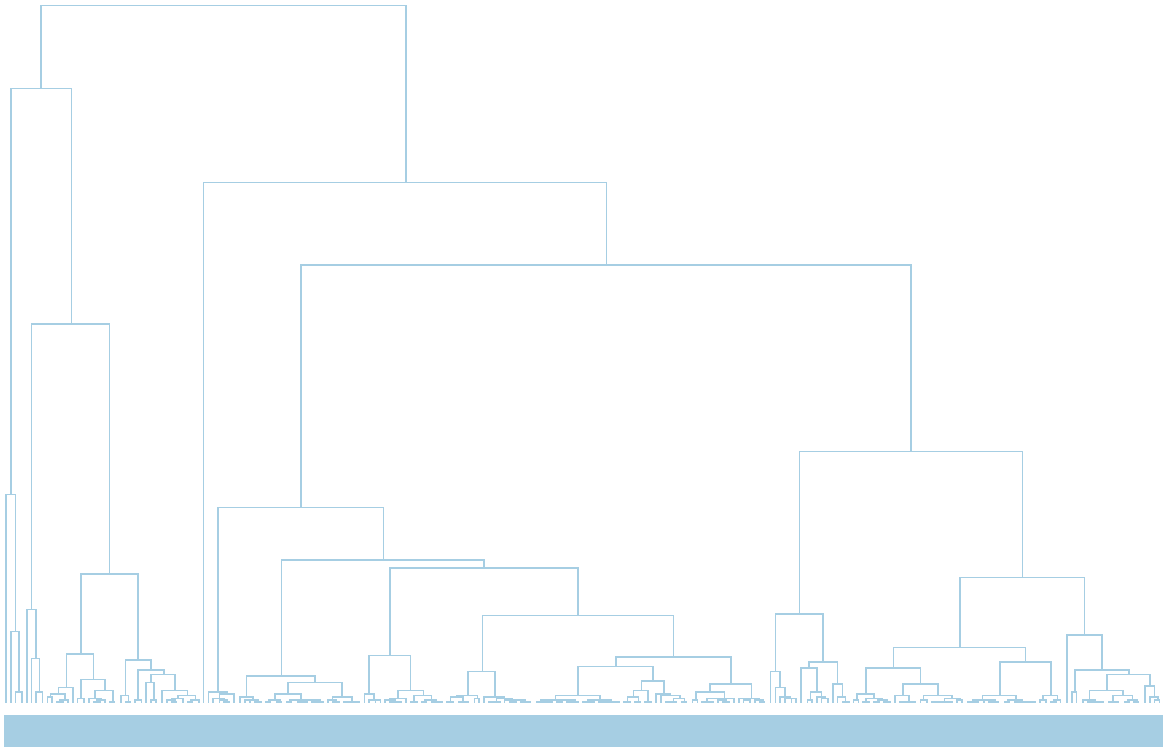
Waste heat potential in UA with potential DH



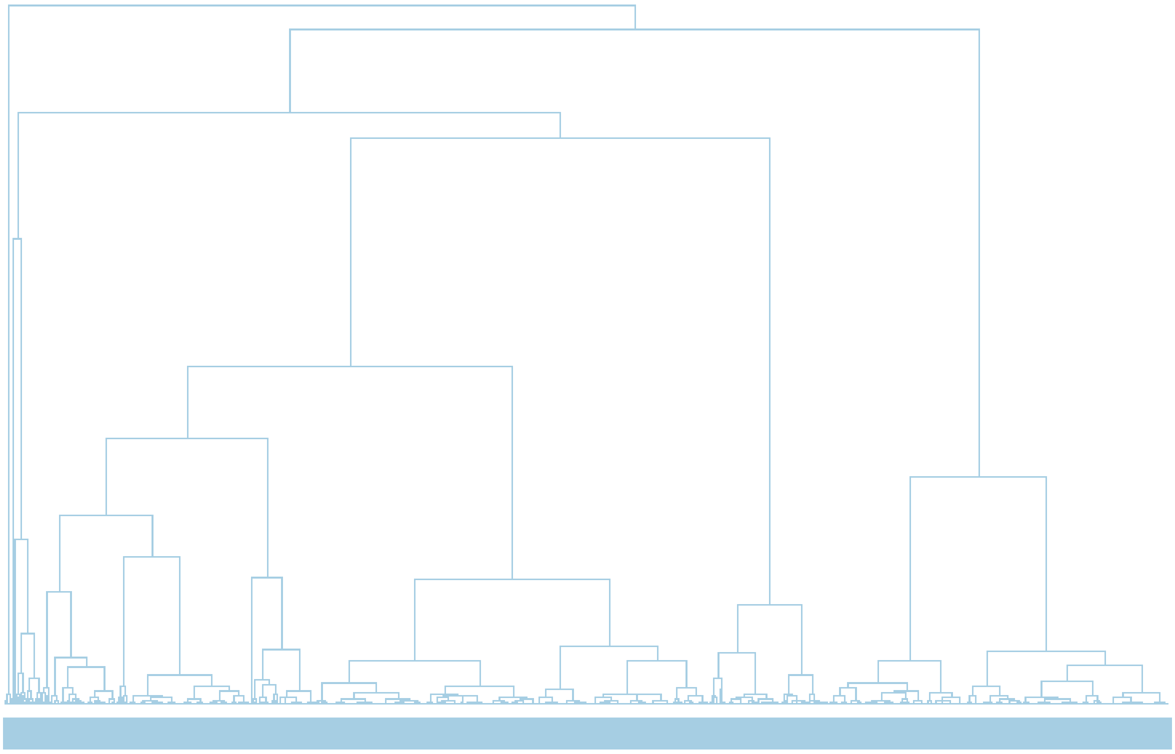
Solar thermal potential in UA with potential DH



Appendix V: Dendrogram of the cluster analysis for UA with existing and potential DH



Dendrogram for UA existing DH according to above mentioned criteria



Dendrogram for UA potential DH according to above mentioned criteria