Brandenburg University of Technology Cottbus-Senftenberg

District Heating in Lusatia

Status Quo and Prospects for Climate Neutrality

Fernwärme in der Lausitz

Status quo und Perspektiven für Klimaneutralität

Thesis

for the degree of

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in

Environmental and Resource Management

submitted by

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Submitted: **29th May 2020**

Statement of Authentication

I hereby declare that I am the sole author of this master thesis and that I have not used any other sources other than those listed in the bibliography and identified as references. I further declare that I have not submitted this thesis at any other institution in order to obtain a degree. The content, either in full or in part, has not been previously submitted for grading at this or any other academic institution.

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Abstract

The master thesis at hand examines the potential of district heating in Lusatia. The thesis follows the approach of first identifying technical and economic potentials in general and then transferring them to the study region. For the quantitative determination of district heating potential in Lusatia, the status quo is determined and a GIS-based analysis is carried out with regard to minimum heat demand densities. The extent to which district heating is suitable for climate-neutral heat supply will be investigated using the potential of renewable and waste heat energy sources. Furthermore, the regional economic effects of developing these potentials are examined. The results show that despite an overall decline in heat demand, there is potential to increase the relative share of district heating in Lusatia. In terms of climate neutrality, district heating in Lusatia offers special opportunities. Solar thermal energy and Power-to-Heat are of particular importance due to the rural character of Lusatia and its status as an energy region. From a regional economic perspective, climate-neutral district heating has a positive effect on value added and employment.

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List of Abbreviations

a ....year
AEE...................................... Agency for Renewable Energies *(Agentur für Erneuerbare Energien)*
AGEB...................Working Group on Energy Balances (Arbeitsgemeinschaft Energiebilanzen)
AGFW ...District Heating Working Group (Der Energieeffizienzverband für Wärme, Kälte und KWK e. V.)
approx. .... approximately
AS.. air source
BGH ....Federal Court of Justice *(Bundesgerichtshof)*
bil. ....billion
BMU ...Federal Ministry for the Environment, Nature Conservation and Nuclear Safety *(Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit)*
BMWi ...Federal Ministry for Economic Affairs and Energy *(Bundesministerium für Wirtschaft und Energie)*
CB...condensation boiler
CHP .... combined heat and power
CO_2.. carbon dioxide
COP... coefficient of performance
DecarbLau ...Mobilizing Endogenous Potentials for Structural Change - Decarbonisation in a Lignite Mining Region (Mobilisierung endogener Entwicklungspotentiale für den Strukturwandel – Dekarbonisierung in einer Braunkohleregion)
DH ....district heating
e.g.. for example
EEG..German Renewable Energies Act *(Erneuerbare-Energien-Gesetz)*
EnEV..Regulation on Energy Saving *(Energieeinsparverordnung)*
Eur ....euro
FNR.................Agency of Renewable Resources (Fachagentur Nachwachsende Rohstoffe e.V.)
G ....giga
GDR ....German Democratic Republic
GHG ....greenhouse gas
GIS ....geographic information system
GS...ground source
GVA ....gross value added
h ....hour
i.e. ....that is
ICT ....information and communications technology
IOER Monitor..Monitor of Settlement and Open Space Development
k ....kilo
KSG...Federal Climate Change Act *(Bundes-Klimaschutzgesetz)*
KWKG.....................................Combined Heat and Power Act *(Kraft-Wärme-Kopplungs-Gesetz)*
LowEx ....low exergy
LTDH.. low temperature district heating
m ....meter
M ....mega
MAP..Market Incentive Programme *(Marktanreizprogramm)*
mil. ....million

MSW .... municipal solid waste
PEF .... primary energy factor
PtG .... Power-to-Gas
PtH .... Power-to-Heat
PtX .... Power-to-X
PV .... photovoltaics
ST .... solar thermal supplement
t .... tonnes
T .... tera
TCS .... trade, commerce and services
W .... Watt
WZ 2008 ...Classification of Economic Activities, issue 2008 *(Klassifikation der Wirtschaftszweige, Ausgabe 2008)*

1 Introduction

This thesis is part of the research project "Mobilizing Endogenous Potentials for Structural Change – Decarbonisation in a Lignite Mining Region (*Mobilisierung endogener Entwicklungspotentiale für den Strukturwandel – Dekarbonisierung in einer Braunkohleregion*, DecarbLau)." Using the example of Lusatia, the project investigates the question of how the coal phase-out can be proactively accompanied in a structurally weak region. This master thesis on district heating systems is embedded in subproject 2b, which focuses on the endogenous development potential in the field of energy system transformation (*Energiewende*) and the related regional economic effects.

In terms of climate protection, the long-term goal of the European Union as well as of German politics is to reach widely greenhouse gas (GHG) neutrality until 2050 (European Commission 2018; BMU 2019a). Today, heating is accountable for about half of Germany's energy related GHG emissions (Kunz and Kirrmann 2016). These two facts emphasise that the energy system transformation must have a focus on heating. On the way to decarbonised energy systems, district heating systems might play an important role (Connolly et al. 2014). Particularly in urban areas, district heating systems have favourable conditions due to high heat demand densities and they allow the integration of renewable and waste heat sources where individual heating systems cannot (Esch et al. 2011; Agora Energiewende 2019). The study region of Lusatia is more of a rural region, nonetheless, district heating networks are relatively widespread. However, most of them work with natural gas or coal and thus, need to be replaced or transformed into fossil-free systems (Richwien et al. 2018). Moreover, Lusatia as a coal mining region is highly affected by the structural change induced by the ongoing coal-phase-out that necessitates alternatives for jobs and value added (Agora Energiewende 2017a). This thesis addresses the question in how far district heating can contribute to a climate-neutral energy system and regional economic development in Lusatia. Therefore, it assesses the general perspective of grid-connected heat supply and examines technical and economic potentials and impediments of utilising heat from renewable sources, waste heat and Power-to-Heat (PtH) in existing and potentially new district heating systems. In addition, it appraises possible regional economic effects of climate-neutral district heating.

In the introduction of this thesis, the motivation for the work and basics on district heating and the study region are explained (Chapter 1). Subsequently, a description of the applied methodology is provided (Chapter 2). Starting point of the actual investigation is a stocktaking of the status quo of district heating in Lusatia (Chapter 3). Potentials and obstacles to the development of district heating are first examined in general terms. Technical and economic aspects of district heating systems are addressed as well as the specifics of different renewable and waste heat energy sources (Chapter 4). This is followed by a region-specific investigation for Lusatia (Chapter 5). The particular potential of grid-based heat supply in the region will be determined quantitatively using a GIS-based analysis. Target year for the analysis is 2038, the year in which the coal phase-out must be completed according to the Federal

Government's draft legislation (BMWi 2020). The assessment of the potential to integrate fossil-free energy sources into district heating as well as the estimation of regional economic effects follow a deductive approach. The previously gathered general insights are transferred to Lusatia, taking into account the regional particularities.

1.1 Transformation of the energy system in the heating sector

The ambitious goal of GHG neutrality until 2050 requires radical changes across all fields: energy economy, buildings, mobility, industry, agriculture, forestry and land-use. German politics have put this topic high on the agenda but efforts to reach the target have to be hugely increased, since business as usual would lead to only halving GHG emissions of 1990 until 2050 (Kunz and Kirrmann 2016). Energy related emissions make up 84 % of all GHG emissions and cutting down non-energy-related emissions is not completely possible (BMWi 2019a; Repenning et al. 2015). These conditions make the decarbonisation of the energy system even more urgent. Within the energy market of the sectors households, trade, commerce and services (TCS) and industry, the field of application with the largest share is heating. The share for space heating of the final energy consumption of these sectors was 36 % in 2018. Water heating accounted for 7 % and process heat for 32 % (Figure 1). Summed up, heating applications accumulated to three quarters of the final energy consumption.

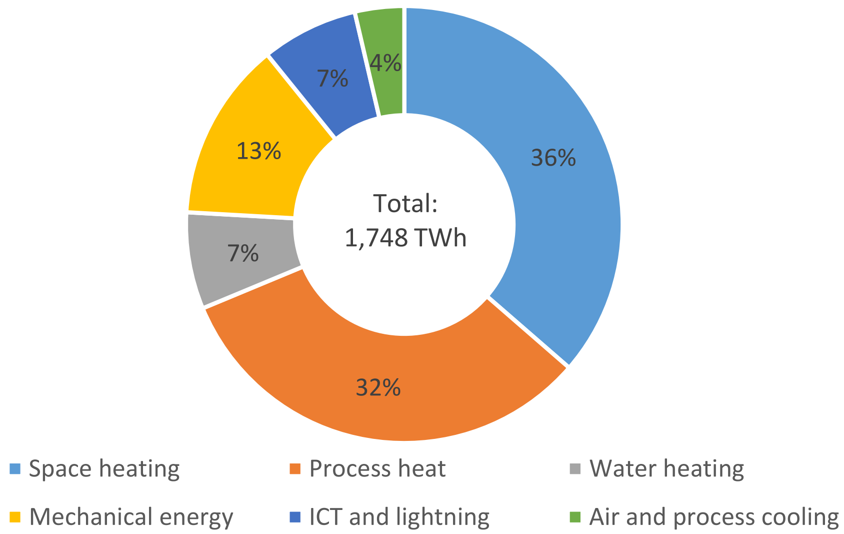

Figure 1 – Shares of the different fields of application of total final energy consumption of the sectors households, TCS and industry in Germany 2018 (BMWi 2019a)

Looking at the goals set for the transformation in the building sector, the official goal of the German government is to reach climate neutrality by 2050. In numbers, the non-renewable primary energy consumption of buildings should be decreased by 80 % compared to 2008 (BMWi and BMU 2010). Since December 2019, the target of a close to carbon-neutral building sector is manifested also in form of a federal law. In the "Federal Climate Change Act (*Bundes-Klimaschutzgesetz*, KSG)", the permissible annual emission budget of the building sector is limited to 70 mil. t of CO_2 equivalents in the year 2030 equating to a reduction of 67 % compared to 1990 and 40 % compared to 2018 (Annex 2 to KSG 2019; BMU 2019a). The law was passed as part of a package which, in addition to various funding schemes, provides for the introduction of a fixed price for CO_2 emissions from heating and fuel (BMU 2019b). The CO_2 pricing will start in 2021 with a price of 25 Eur/t of CO_2 emissions. After that, the price will be increased gradually (Bundesrat 2019). Nevertheless, a recent study concludes that the measures adopted are not sufficient to achieve the climate targets. It comes to the result that the buildings sector will miss the target of limiting its emissions to 70 mil. t of CO_2 in 2030 by about 17 mil. t (Harthan et al. 2020).

In order to actually achieve a drastic reduction of GHG emissions in the building sector, two strategies must be pursued in parallel: the energy demand of buildings has to be decreased and the remaining energy demand has to be covered by renewable energies. So far, however, the energy system transformation is most effective in the electricity sector, particularly due to the expansion of renewable energies (Figure 2). In the period from 1990 to 2018, the share of renewable electricity rose from 3 % to 38 %, while the renewable share in the heating and cooling sector only rose from 2 % to 14 %. In the transport sector the renewable share rose from zero to only 6 %. On the consumption side, heating and cooling is showing a decrease of 23 % contrary to electricity and transport that show a consumption increase by 8 % and 5 %, respectively. For heating and cooling, this is a step in the right direction but further improvement is necessary in order to achieve the goals.

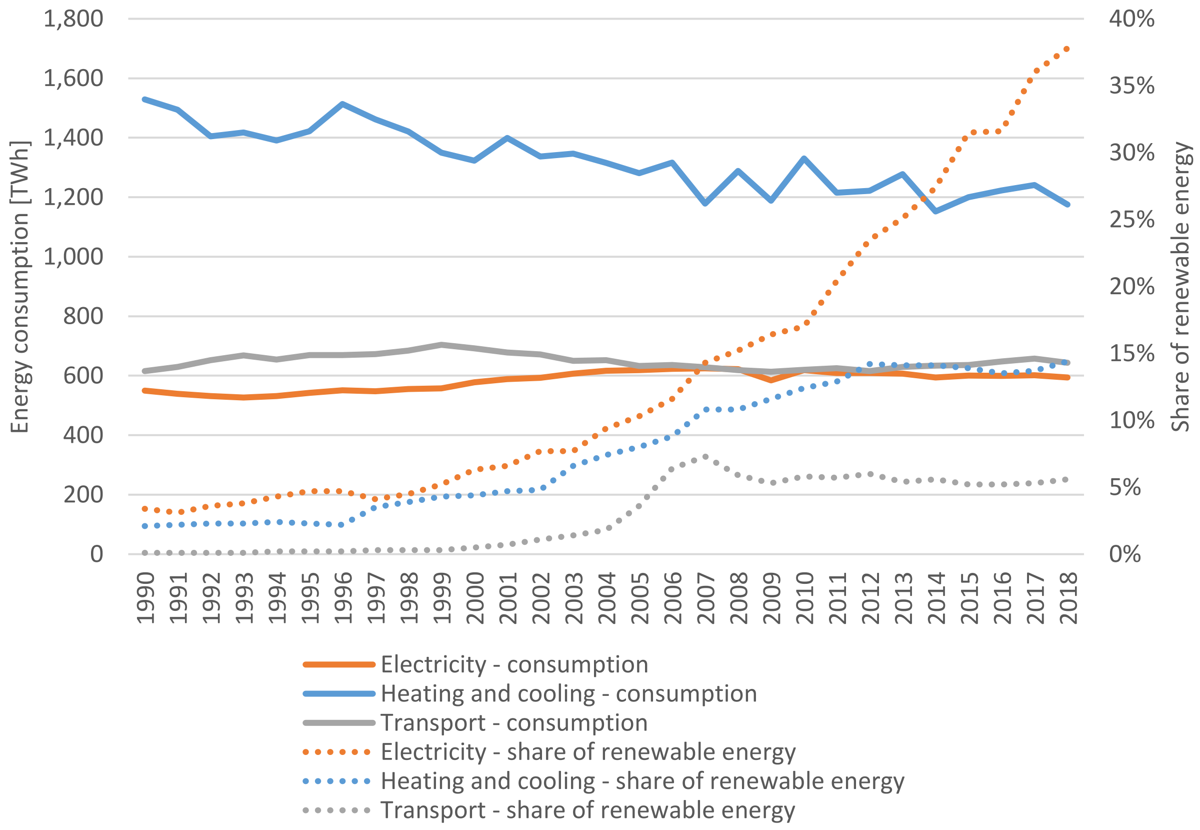

Figure 2 – Development of energy consumption and shares of renewable energy sources in the sectors electricity, heating and cooling and transport from 1990 to 2018 (UBA and AGEE Stat 2019)

To reach carbon neutrality in the field of heating of buildings, Agora Energiewende (2017b) evaluated the possible contribution by savings of final energy consumption due to increased building efficiency between 40 % and 60 % of the final energy consumption in 2018. This presupposes an increase of the energy-saving refurbishment rate from currently 1 % to 2 % in the whole building stock (dena 2019; Agora Energiewende 2017b). The remaining energy demand needs to be covered by individual heating systems with renewable energies and climate-neutral district heating systems. However, the current situation is far away from this scenario. Fossil fuels are still by far the most important energy sources for heating in Germany (Figure 3). In 2018, renewable energies only made up 12 % and the share of district heat was 8 %. Thus, the path making the energy system transformation in the heating sector a success is still long and requires consistent action.

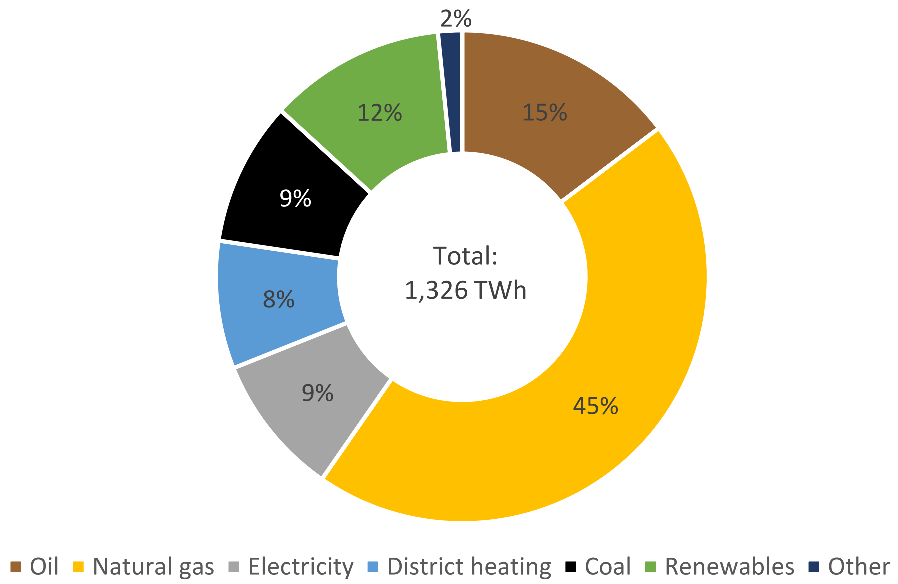

Figure 3 – Shares of fuel sources of total final energy consumption for heating over the sectors of households, TCS and industry in Germany 2018 (BMWi 2019a)

1.2 District heating

District heating systems play an important role in transforming the heating sector. This is mainly because they offer large potentials for the integration of renewable energies, they can act as thermal energy storage and are a tool for sector coupling. In this regard, the German government targets to expand low-carbon district heating and switch existing district heating systems to renewable energy sources (BMU 2019b). In line with this, most scientific scenarios and potential studies give reason to expect that the share of district heating will rise until 2050 and contribute to carbon-neutral heating in Germany (e.g. Gerhardt et al. 2019; Jochum et al. 2017).

1.2.1 Definition

District heating is used for all kinds of stationary heat applications like space heating in buildings, water heating and technical processes that require heat. Heating systems in general differ by the type of fuel used, the place where the heat is generated and the way in which the heat is provided. Thus, a distinct description of the research object is of importance. In particular, the distinction between central district heating networks and decentral individual heating systems needs to be clarified. In literature, authors often use the terms district heating, heat networks and teleheating but also community heating by meaning the same or similar types of heating systems. Also in German literature, the terms *Fernwärme* and *Nahwärme* are often not clearly differentiated. In search for a clear definition, a verdict by the "German Federal Court of Justice (*Bundesgerichtshof,* BGH)" from 1989 provides a definition for *Fernwärme* which is best translated by district heating. In this verdict, conditions for the presence of a district heating system are defined by the property situation and the purpose of heat generation. Firstly, the owner of a building provided with heat is not the owner of the heating system. Secondly, a third party – neither the owner of the building nor the heating customer – is generating and delivering heat as a business. The court did not stipulate a certain distance of the heating systems to the building or the presence of a larger distribution network (BGH 1989). Another definition is provided by the German "Task Force of Federal States for Energy Balances (*Länderarbeitskreis Energiebilanzen*)" and has a focus particulalry on the way of the heat distribution. It defines district heating by heat distributed as steam, condensate or hot water trough pipes and thereby covers both German terms *Nahwärme* and *Fernwärme* (LAK Energiebilanzen 2019). Rezaie and Rosen (2012) use a broader definition and suppose that district heat is delivered through "a system of piping from one or more central sources to industrial, commercial and residential users" (Rezaie and Rosen 2012, 3). This definition encompasses all possible system designs and therefore is used as the basis for this thesis as well. However, one should notice that not all data sources used for this thesis provide definitions. Hence, it could not always be made that data acquisition is based on the same definitions.

1.2.2 System components

A district heating system consists of three fundamental parts. These are following: a heat source or various heat sources, a distribution network and heat sinks (Figure 4). Typically, heat is generated in a central thermal power station used to heat up the water in the piping system. In combined heat and power (CHP) plants, electricity can be produced using an additional generator. With the help of pumps, the hot water is transported through the piping network. The piping lines consist usually of two individual pipes. That one containing hot water coming from the heat source is called "flow". The other pipe with cooled water returning to the central heat station is called "return". The water temperature in the flow is usually between 70 °C and 130 °C and in the return between 50 °C and 70 °C. In many cases, the temperature level of the flow is adjusted depending on the ambient temperature – the colder the outside temperature, the warmer the flow temperature (Konstantin 2018). The heating system of the building supplied is connected with the grid via a substation. In the substation, the hot water is either directly carried into the building system or the heat from the network is transferred to a hydraulically separated building system via a heat exchanger (Arbeitsgemeinschaft QM Fernwärme 2018). If district heating is also used for preparation of domestic hot water, this usually takes place in the substation as well.

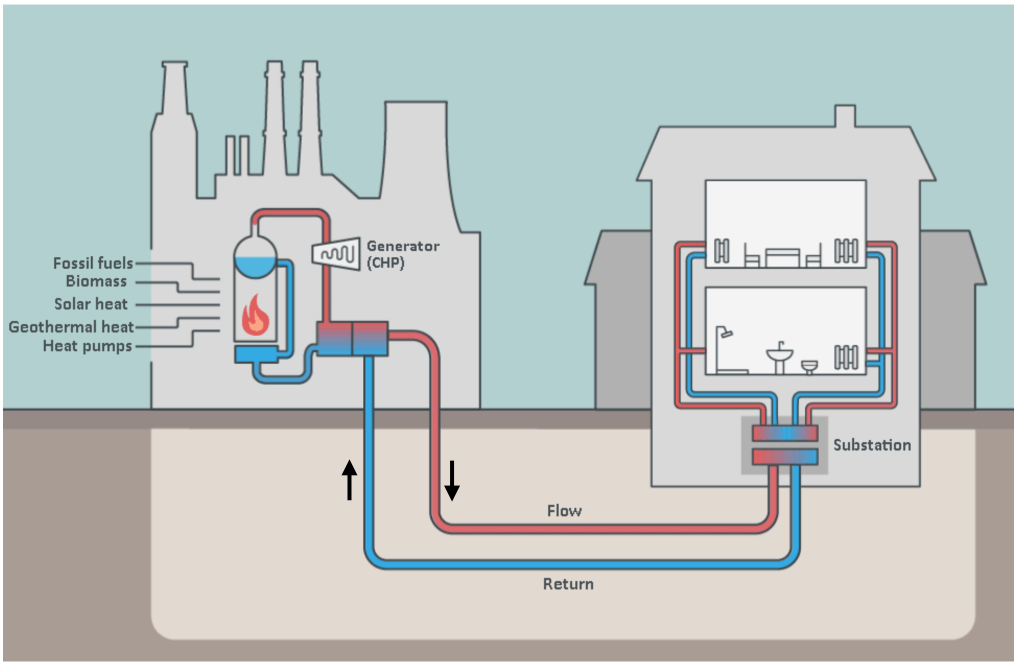

Figure 4 – Schematic diagram of a district heating system (Adapted from Toffetti 2015)

1.2.3 Feed-in structure

A district heating network can have different spatial distributions of heat generating units. In a grid with central feed-in, heat is generated and fed into the grid at only one or two locations. In a multi-central feed-in grid, few thermal power stations generate heat at different locations. In a distributed feed-in grid, many heat sources of different type and size exist at various locations (Paar et al. 2013).

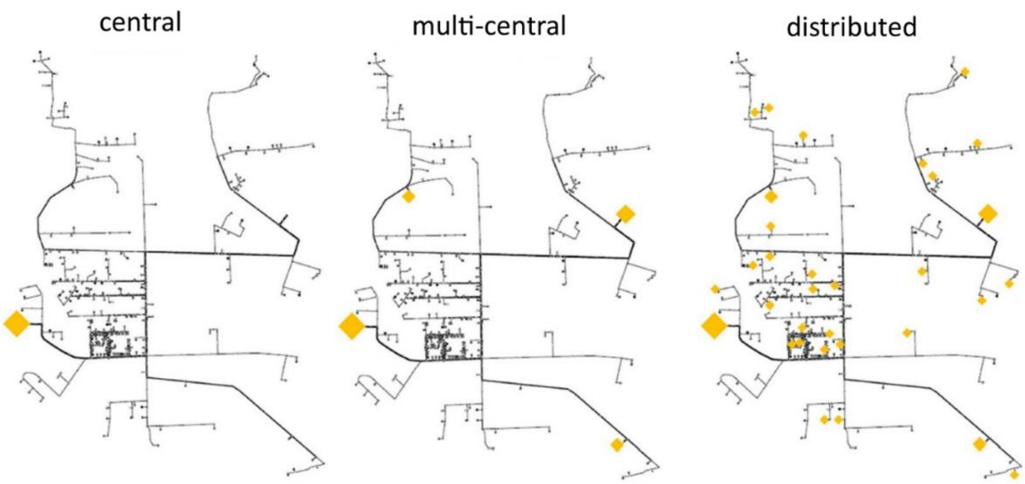

Figure 5 – Types of spatial distributions of heat generating units (Adapted from Paar et al. 2013)

1.2.4 Fuel sources

Among district heating systems, sources of heat differ. A main difference between generation units is whether electricity and heat is cogenerated in a CHP unit or a so-called heat-only generation unit is used. Typically, in larger district heating networks, the two different types of heat generation units are used in combination. CHP units or other generation units with low heat production costs but less flexibility are used to cover the base load. The base load represents 25-30 % of the maximal possible load in the network but makes up 60-70 % of a year's total thermal energy generated. For covering the remaining peak load, heat-only generation units, usually fossil-fuelled boilers are used. In smaller grids with less thermal output, often only a single generation unit, usually a CHP unit, is installed (Paar et al. 2013). Generally, fossil fuels such as oil, natural gas and coal still dominate the spectrum of fuel sources, although their share is declining. From 1998 to 2018, the share of primary fossil fuels for district heat generation in Germany has been reduced from 96 % to 67 %. Primary fuel sources that have gained relevance are renewable resources and waste. Waste includes municipal solid waste (MSW) and industrial waste. Both types of waste have a fossil and a biogenic part. During the period from 1998 and 2018, the share of non-biogenic waste has risen from 0 % to 13 % and the share of renewables from 3 % to 20 % (BMWi 2019a). Looking only at renewable fuel sources, the biogenic part of waste had the highest share with 54 % of renewable fuel sources for district heat in Germany 2017 (Figure 6). It is followed by solid biomass, mainly woody biomass with a share of 35 %. The share of biogas added up to 10 %. Other renewable sources used for district heating are geothermal energy and solar thermal energy. However, until today, these contribute only a very small amount (AGEB 2019a).

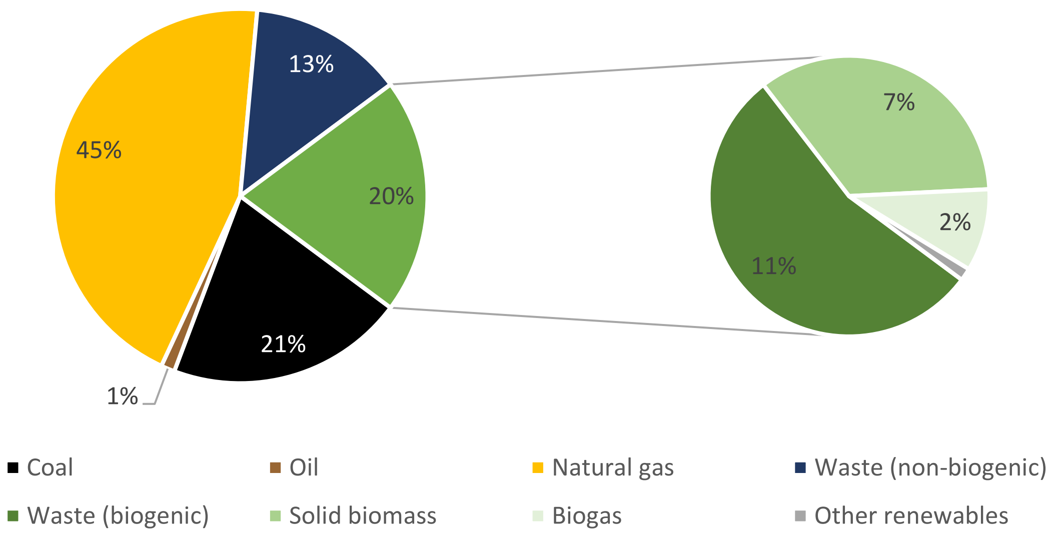

Figure 6 – Shares of fuel sources for district heat generation in Germany 2017 (AGEB 2019b; 2019a)

Two other applicable sources for district heating are waste heat from industry or data centres and PtH, i.e. converting electric energy into heat either via heat pumps or resistive heaters (Pöyry 2018; Bloess et al. 2018). These two sources are not yet listed in the energy balances provided by the German "Working Group on Energy Balances (*Arbeitsgemeinschaft Energiebilanzen*, AGEB)" and as a result, their share is not accounted. However, according to the German "District Heating Working Group (*Der Energieeffizienzverband für Wärme, Kälte und KWK e. V.*, AGFW)" the share of industrial waste heat fed into heat networks was 2 % in 2018 (AGFW 2019a). Data about the share of heat generated via PtH is not available. Yet, in 2017, installed capacity of resistive heaters dedicated to district heat generation was above 600 MW (Christidis et al. 2017).

1.2.5 Primary energy factors

According to the German "Regulation on Energy Saving (*Energieeinsparverordnung,* EnEV)" the primary energy consumption of buildings has to meet certain requirements and has therefore to be determined (EnEV 2007). The primary energy consumption depends on the final energy consumption and the source of heat energy used. The ratio of primary energy consumption and final energy consumption is called primary energy factor (PEF, f_p). PEF are composed of a renewable and a non-renewable part. Only the non-renewable part needs to be applied for assessing the primary energy consumption of a building (Annex 1 to EnEV 2007). Fuel sources used in individual heating systems have fixed PEF. If a building is supplied with district heating, the PEF of the entire district heating network has to be applied. Generally, it can be understood that a district heating system with a low PEF has low CO_2 emissions and high energy efficiency. However, for district heating systems with heat from cogeneration this applies only to a limited extend. According to the guidelines for determining the PEF of a district heating system, heat generated in CHP plants is evaluated differently than heat from heat-only plants (AGFW 2014). It is assumed that electricity originating from CHP plants substitutes electricity from coal power plants. Primary energy saved in this way is subtracted from the primary energy consumption of the cogenerated heat. This approach is called "electricity credit method" and results in advantageous PEF of district heating systems with CHP generation units although fossil fuels are used. This imbalance is subject to discussions on whether this method is appropriate or alternatives would have a better effect to incentivise energy-efficient buildings and climate-friendly heating systems (Schüwer et al. 2015; Schneller et al. 2018; Pehnt et al. 2018).

1.3 Study region of Lusatia

1.3.1 Geographical definition

The region of Lusatia is located in the area along the southern part of the border between Germany and Poland. Subject to this master thesis is only the German part of it (Figure 7). Big neighbouring cities are Berlin in the north and Dresden in the south-west. The exact definition of the study region of the project DecarbLau, and consequently also of this master thesis, is adopted from the final report of the "Comission on Growth, Structural Change and Employment (*Kommission für Wachstum, Strukturwandel und Beschäftigung*)", commonly called "Coal Commission (*Kohlekommission*)" (BMWi 2019b).

Accordingly, the study region comprises six districts (*Kreise*) and one independent city (*kreisfreie Stadt*) in the federal states of Brandenburg and Saxony. These are:

- Brandenburg
  - Disrict of Dahme-Spreewald
  - District of Elbe-Elster
  - District of Oberspreewald-Lausitz
  - District of Spree-Neiße
  - City of Cottbus

- Saxony
    - District of Bautzen
    - District of Görlitz

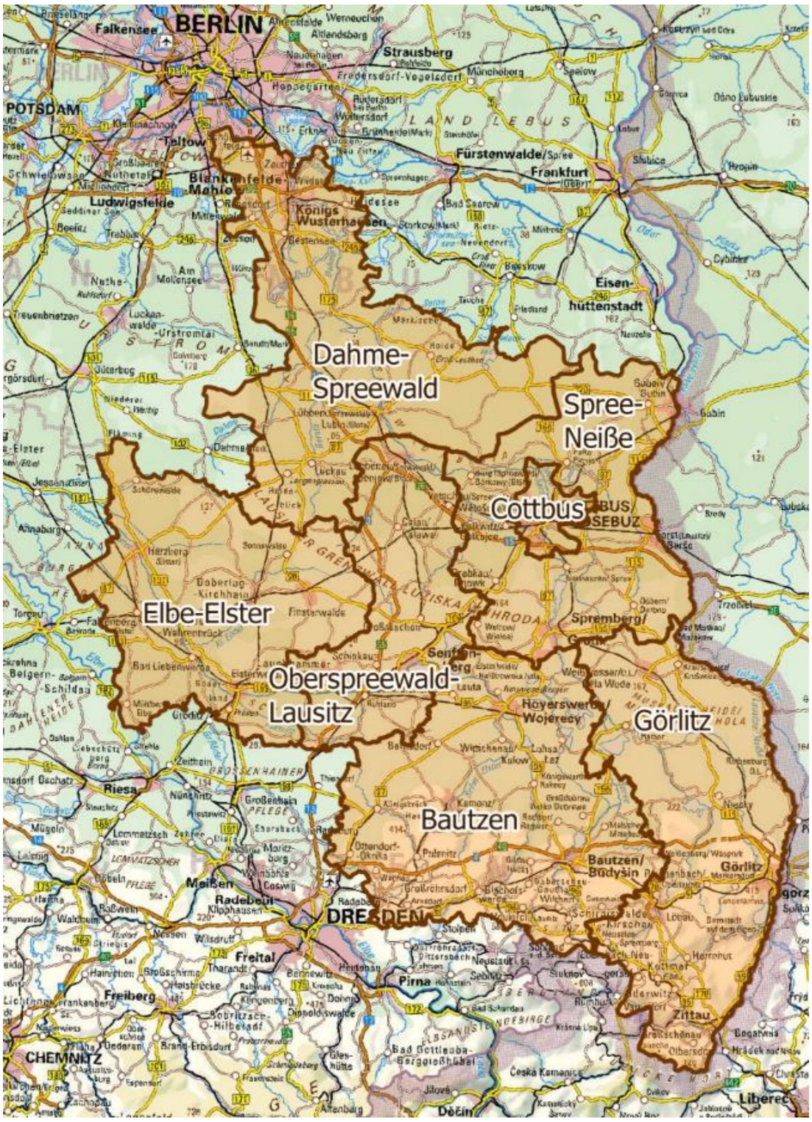

Figure 7 – Overview map of Lusatia, the study region for this thesis (GeoBasis-DE / BKG 2019)

With the exception of four cities acting as regional centres (Cottbus, Görlitz, Bautzen and Hoyerswerda; *Oberzentren*), small towns and rural municipalities (*Gemeinden*) dominate the region of Lusatia. However, the northern part of the district of Dahme-Spreewald can be assigned to the urban area of Berlin (GL B-B 2009).

1.3.2 Demography

In 2018, Lusatia had a population of 1.16 mil. people and its area covers 11,726 km² (AfS Berlin-Brandenburg 2018; StLa Sachsen 2017; Destatis 2019a). Thus, the population density accounts to 99 people/km² which is less than half of Germany's average population density of 232 people/km² (Destatis 2019a). The population in Lusatia has been decreasing over the last decades and will further decrease. From 1998 to 2018, the decline in population added up to approx. 264,000 people or 18.6 % (Figure 8). Until 2038, the population is expected to further decline by another 155,000 people or 13.4 % compared to 2018, coming down to approx. 1.00 mil. people.

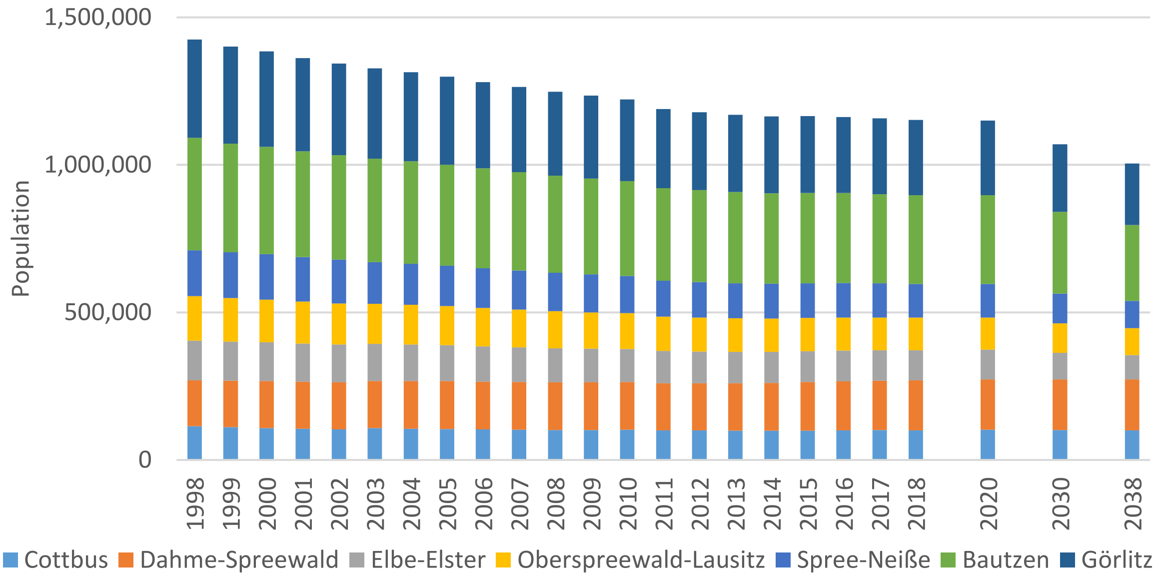

Figure 8 – Population development in the districts of Lusatia from 1998 to 2018 and projections until 2038 (Destatis 2019b; AfS Berlin-Brandenburg 2018; StLa Sachsen 2017 and own projections)

1.3.3 Coal phase-out and structural change

The whole region of Lusatia is described as economically underdeveloped (BMWi 2019b). Its economy has been strongly characterised by lignite-mining and electricity generation in big coal power plants. In 2016, there were still 8,278 jobs directly and an additional 4,967 jobs indirectly relying on the coal industry in Lusatia. The total of 13,245 jobs made up 3.27 % of all jobs in Lusatia being subject to social insurance contributions. The direct and indirect gross value added (GVA) by the coal industry in Lusatia amounted to more than 1.2 bil. Eur or 4.3 % of Lusatia's total GVA in 2016 (RWI 2018).

In the light of Germany's ambitious climate goals, phasing out coal is inevitable (Agora Energiewende 2017a). To this end, the "Coal Commission" was assigned and has proposed to phase out coal in Germany until the year 2038 (BMWi 2019b). Based on this proposal, the Federal Government and the federal states have agreed on a phase-out pathway and are going to pass a corresponding law in the first half year of 2020 (Bundesregierung 2020). Due to the importance of the coal industry for employment and regional value added, this phase-out will highly affect Lusatia. In fact, the phase-out has already begun and its impacts are visible. Block-units of power plants have been decommissioned and the number of jobs in the coal industry is decreasing (Agora Energiewende 2017a). With a progressing phase-out, these impacts will become more and more substantial and increase the demand for a structural change that creates sufficient alternatives. One concept for the development of Lusatia is to further profile the region as an energy region (Rosa-Luxemburg-Stiftung 2019). Inferring from the existing conditions, this idea is promising. Lusatia has existing energy infrastructure, large open space on former mining sites as well as qualified personnel and research institutions in this field (Bornemann et al. 2018). A study from 2018 shows that the potential of the expansion of renewable energies is large and can bring out several hundred or even thousands of jobs and additional value added (Richwien et al. 2018). Particularly, the expansion of wind energy and photovoltaics (PV) offers great opportunities, and also the fields of energy efficiency, mobility, heating and Power-to-X (PtX) have potential for growth.

Various public funding instruments are already available for projects and investments conducive for structural development and more will follow. With an additional law, the Federal Government plans to further support the structural change in all German lignite regions with a total of 40 bil. Eur until the year 2038 (BMWi 2019c). The subsidies will be partially given to the affected federal states directly and partially invested in measures under the authority of the Federal Government. Taken together, Lusatia will receive additional funds in the amount of approx. 17 bil. Eur.

In the context of phasing out coal, district heating is of relevance. During the era of the German Democratic Republic (GDR), many district heating systems were constructed. District heating enabled the use of the domestic resource of lignite and thereby ensured independence from energy imports (Konstantin 2018). Thus, many district heating systems were built and are still fed by coal power plants today. When these power plants are being decommissioned, they cannot feed the district heating systems any longer and consequently, alternatives need to be developed. Either connected consumers switch to individual heating systems or the district heating systems switch to other fuel sources.

2 Methodology

2.1 Inventory

A status quo description of district heating in Lusatia requires comprehensive data about the existing district heating networks. Unfortunately, aggregated data with sufficient spatial resolution is not available and data on individual grids needs to be gathered in extensive research. The difficulty is that grids differ in size, structure, ownership and operators. The stock of grids includes very small grids with only few connected consumers or grids that are operated by contractors. This heterogeneity makes it difficult to obtain data about all existing grids. One useful data source on individual grids is the database of AGFW which includes certificates on the PEF of district heating systems (AGFW 2019b; 2020). Nevertheless, during the research, grids were identified that are not listed by AGFW. For that reason, the research was broadened. In a systematic online search, hints on district heating systems were searched for all municipalities with more than 50 buildings served by district heating according to the Census 2011 (Zensus 2011). Information was found on webpages of municipality administrations and their utility companies and private grid operators, in municipal planning concepts and newspaper articles. No claim is made to completeness for the resulting inventory.

2.2 Model development

Besides reviewing environmental and economic potentials and impediments for district heating and transferring them to the region of Lusatia in a qualitative way, the aim of this thesis is furthermore to provide meaningful figures for a better understanding of the magnitude of eventual potentials. For this purpose, a top-down model is developed based on an analysis of the current heating market in Lusatia and its future projection. This is not as straightforward as it might seem in the first place. Lusatia is spread over 244 municipalities, seven districts and two federal states but does not represent the entire area of the federal states to which it belongs. Many statistics on the energy and housing sectors are published with the federal states as the smallest unit. This makes it difficult to obtain data for a region that is only part of a federal state. Therefore, suitable methods and conversion factors are developed to obtain realistic data.

In Germany, heat that is consumed for space heating and water heating by households and the TCS sector makes up 84 % and 53 % of the sectors' final energy consumption, respectively. The share for the same purposes within the sector of industry only accounts for 6 % while process heat has a share of 67 % (BMWi 2019a). Heat sinks in form of industrial plants are locally concentrated, and their heat demand is often covered partly or entirely by their own heat plants. Required temperature levels of heat for industrial processes differ widely and are often above temperature levels that can be supplied by district heating systems, especially not by those with high shares of renewable heat sources (Frisch et al. 2010; Lund et al. 2014). Consequently, exhaustive data about industrial heat sources and sinks and their potentials for district heating are hard to obtain. Due to these difficulties, the model is limited to heat consumed for space and water heating by households and the TCS sector. According to the guidelines of the project DecarbLau, the year 2018 is chosen as base year for the presented data and the future developments and potentials will be examined until the year 2038.

As first step of the model development, the total final energy consumption for heating and district heating, as part of it, is determined. To that end, data for Brandenburg and Saxony is taken from the official "energy balances". An energy balance provides data about generation and consumption of all energy carriers including district heating. On the side of generation, it provides data on the amount and type of energy used and produced in CHP and heat-only plants. On the side of consumption, it distinguishes between the sectors of industry, TCS and households. Energy balances are published for every federal state and every year, although with a time lag of 18 month or more (SMEKUL 2019). For this thesis, energy balances from 2011 and the latest available ones at the time of writing from 2016 are considered (AfS Berlin-Brandenburg 2014; 2019a; StLa Sachsen 2016; 2019a).

Data from the energy balances do not allow to infer the purpose of the consumed and generated energy, e.g. how much oil is used for space heating in households. This kind of statistics is only available as average values for Germany as a whole (BMWi 2019a). From this data, shares of different applications of different energy sources for each sector can be obtained, e.g. of the total electricity used in the sector of TCS in 2017, 5 % was used for water heating. These shares are in turn applied on the data from the energy balances of the federal states, resulting in very detailed data based on German average and federal state specific data.

Data from energy balances also allow to calculate the shares of fuel used for district heat generation and the share of cogeneration in CHP plants. Thereby, the fuel input in CHP plants is allocated to the generated heat and electricity using the so-called "Finnish Method". The Finnish Method allocates the fuel input by comparing the efficiency of the CHP system with reference efficiency values of systems with individual heat and electricity generation (Mauch et al. 2010). The Finnish method is used for the official energy balances in Germany, too. In the balances for whole Germany, a reference efficiency for heat of 0.8 and 0.4 for electricity is applied (AGEB 2015). Deviating from this, the federal states employ a reference efficiency of 0.9 for heat (LAK Energiebilanzen 2019). For this thesis accordingly, a reference efficiency for heat of 0.8 is used when calculating with data for whole Germany and 0.9 is used when calculating with data for federal states. The energy balances present the figures for the output of district heating in total and one cannot determine the efficiencies for the different fuel types individually. For the allocation of the fuel input, this causes that the value for the CHP efficiency is averaged over all types of fuel sources.

In order to allocate the data on heat energy consumption for Brandenburg and Saxony to the districts of Lusatia, auxiliary data with higher spatial resolution is needed. From this step onwards, only data for the sectors households and TCS are considered further. For the consumption by households, data for allocation is taken from the results of the census that was undertaken in Germany in 2011 (Zensus 2011). It contains detailed results, among others, about population, buildings and apartments on the level of municipalities. Data about buildings and apartments also include the type of heating systems, distinguished between district heating systems and various decentral systems. The census dates back to 2011 and the data has to be projected to the research period from 2018 to 2038. For population, this is done by a linear projection of data from the official population projections for Brandenburg and Saxony (AfS Berlin-Brandenburg 2018; StLa Sachsen 2017). The number of apartments and the total living area is taken from projections available for Brandenburg and Saxony until the year 2018 (AfS Berlin-Brandenburg 2019b; StLa Sachsen 2019b). The allocation of the final energy for space heating is done by weighting on the basis of total living area and for water heating on the basis of population for each district. For regional allocation of the heat consumption by the TCS sector, regional data of GVA is taken into account. Corresponding statistics with a resolution on the level of districts are available until 2016 at the moment of writing (VGRdL 2017). From these statistics the economic sections A, F and G-T according to the "Classification of Economic Activities, issue 2008 (*Klassifikation der Wirtschaftszweige, Ausgabe 2008,* WZ 2008)" are considered to represent the sector of TCS (Destatis 2008). The relevant values are projected until 2038 by assuming a growth rate for the sector of 1 % per year according to the "German Energy Reference Forecast" on behalf of the Federal Ministry for Economic Affairs and Energy (*Bundesministerium für Wirtschaft und Energie*, BMWi) (Schlesinger et al. 2014). The allocation of the final energy for space heating and water heating is then done by weighting on the basis of the GVA for each district. A further allocation of district heating in the year 2018 down to the level of municipalities is done by weighting the total final energy consumption for district heating of each district based on the number of residential buildings equipped with district heating systems in each municipality according to Zensus (2011).

The future development of final heat energy consumption in Lusatia until 2038 is estimated by applying the results of the demographic and economic projection on the energy data from 2018. For this, four key parameters are used, two for the sector of households and two for the sector of TCS. For households, these are the rates of change of final energy demand for space heating and water heating per capita. For the sector of TCS, these are the rates of change of energy productivity for space heating and water heating, i.e. how much energy is needed to create one unit of GVA. Predictions for these rates are taken from the scenarios of the "Energy Reference Forecast *(Energiereferenzprognose)*" (Schlesinger et al. 2014). The Trend Scenario assumes that efforts to protect the climate will be intensified, but in the end only a 65 % reduction in GHG emissions by 2050 compared to 1990 will be achieved. The Goal Scenario sets a fixed reduction of GHG emissions by 80 % and the entire energy system is adjusted according to this goal. The model in this thesis follows these two scenarios and uses according parameters as shown in Table 1.

Table 1 – Rates of change of final energy demand for space heating and water heating in the sectors of households (per capita) and TCS (per Eur GVA) for the Trend and the Goal Scenario (Schlesinger et al. 2014)

		Trend	Goal
Households	Space heating	-1.1	-1.5
[%/person/a]	Water heating	0.1	0.1
TCS	Space heating	-4.3	-4.7
[%/Eur/a]	Water heating	0.0	0.0

Increasing factor on energy consumption for space heating is an increase of living space per person. On the contrary, better thermal insulation of buildings due to restoration or reconstruction in combination with more efficient heating systems and higher ambient temperatures due to global warming lead to decreasing energy consumption for space heating per capita. The effect is much stronger in the sector of TCS because here, cycles of restoration are shorter and old buildings are often completly replaced by new energy-efficient constructions. Decreasing numbers of employees and higher labour productivity comes into effect as well. The small increase in consumption of final energy for water heating, despite increasing efficiency, is due to the fact that more washing machines and dishwashers are being connected to hot water systems (Schlesinger et al. 2014).

Results of the computation are the final energy demands for space and water heating for each district from 2018 to 2038. For evaluating the potential of covering these demands by district heating, a GIS-based analysis is performed using the open-source application "QGIS Desktop 3.10". In the following, performed steps of the analyses are explained. Fundamental idea is that spatial heat demand density has to be higher than a certain threshold in order to allow cost-efficient operation of district heating networks. For adapting this idea, the heat demand density is calculated. In a first step, raster data on population from 2011 with a horizontal resolution of 100 m is taken from the "Monitor of Settlement and Open Space Development (IOER Monitor)" (Leibniz Institute of Ecological Urban and Regional Development 2020). The data for each district is projected until 2038 by applying the average population development and assuming a homogenous development within each district. The estimated heat demand by households for each district in 2038 is then divided by the estimated district's population and multiplied with the projected population raster data leading to a heat demand density map of households. Secondly, the heat demand density of the TCS sector is computed. This is implemented by taking raster data about the percentage of industrial and commercial sites relative to the reference area from the IOER Monitor, also with a spatial resolution of 100 m. By multiplying the data by the cell size of 10,000 m² and summing up the products over each district, a weighted distribution of the heat demand, analogous to the heat demand of households, is obtained. Adding up both heat demand densities, for households and the TCS sector, yields a combined heat demand density map with a grid size of 100 m.

For further analysis of district heating potential, the heat density map is aggregated to a grid size of 500 m, following Jochum et al. (2017). Applying thresholds of minimum heat demand densities on a coarser grid prevents undesired results of identified potentials caused by single blocks of houses or data artefacts. The threshold value for cost-efficient operation of heat networks is set at 15 GWh/km²/a following conservative reference values by Jochum et al. (2017) and Gils (2015). Grid cells with a heat demand density higher than this threshold are considered as potential district heating areas and are applied in turn on the heat demand density map of 100 m grid size. Furthermore, within these identified areas, a dynamic connection rate is employed representing the share of final energy demand for heating delivered via district heating networks. After Jochum et al. (2017), this rate is based on the settlement structure of the area. They assume a high connection rate of 70 % in rural municipalities with low building density, because construction works for grid connection are easier and thus less costly to implement. To carry out the same construction works in urban areas with a high building density, in contrast, works out to be more costly. Consequently, for urban areas a grid connection rate of only 50 % is assumed. Raster data about the percentage of built-up area relative to the reference area as provided by the IOER Monitor is used (Leibniz Institute of Ecological Urban and Regional Development 2020). An assumed inverse proportionality between the density of built-up area and the connection rate in the range of 50 % to 70 % is implemented via the following formula, where x denotes the percentage of built-up area and y denotes the resulting connection rate.

$$y = -\frac{1}{500}x + 0{,}7$$

Result of the previous steps is a map of district heating potential in 2038. However, this map includes areas with very small volumes and also areas with an identified potential which is lower than the actual volume in 2018. To eliminate very small and cost-inefficient grids, a minimum district heating consumption within a municipality is set at 3 GWh/a following Pehnt et al. (2017). Only in grids with more than 100 connected households or an equivalent of about 3 GWh/a, benefits due to economy of scales and technological advance come into effect. This is particularly the case when renewable fuel sources such as solar thermal energy and solid biomass as well as thermal energy storage are integrated into heating systems (Pehnt et al. 2017). In sense of a conservation strategy of existing networks after Jochum et al. (2017), existing grids with a size bigger than the set minimum of 3 GWh/a but a decreasing potential will be retained with their full initial amount of district heating supply. It is supposed that conserving existing district heating networks is more resource-efficient than dismantling and replacing them by individual heating systems and thus is the better choice in the sense of climate protection. Furthermore, it is assumed that decreasing heat demand of individual consumers can be compensated by densification of connected buildings. To implement this, the amount of supplied district heating of each municipality in 2018 is compared to the district heating potential based on the projected heat demand potential in 2038. The respective higher value is chosen for the final district heating potential.

3 Current State of District Heating in the Region of Lusatia

The analysis of future potentials of district heating in Lusatia requires a good database of the current heating market. Unfortunately, comprehensive data in the form of energy balances are only available on the level of federal states and, at the time of writing, only available until 2016. Nevertheless, since Lusatia is part of Brandenburg and Saxony and the heating market is rather inert, the energy balances are well suited to provide an overview of the current state of the heating market in the region compared to the situation in Germany as a whole (Figure 9). The total final energy consumption for heating purposes over the sectors households, TCS and industry from 2011 to 2016 rose in Brandenburg by 1.6 % from 46,814 GWh to 47,572 GWh, in Saxony by 6.7 % from 47,524 GWh to 50,721 GWh and nationwide by 0.5 % from 1.343 mil. GWh to 1.350 mil. GWh. The share of district heating rose in Brandenburg from 10 % to 11 % and fell in Saxony from 16 % to 15 %. The German average was lower in general and fell in the same period from 9 % to 8 %. Similarly, the share of all other fuel sources changed only marginally in all regions considered, indicating that there was no significant change in the heating market over this five-year period.

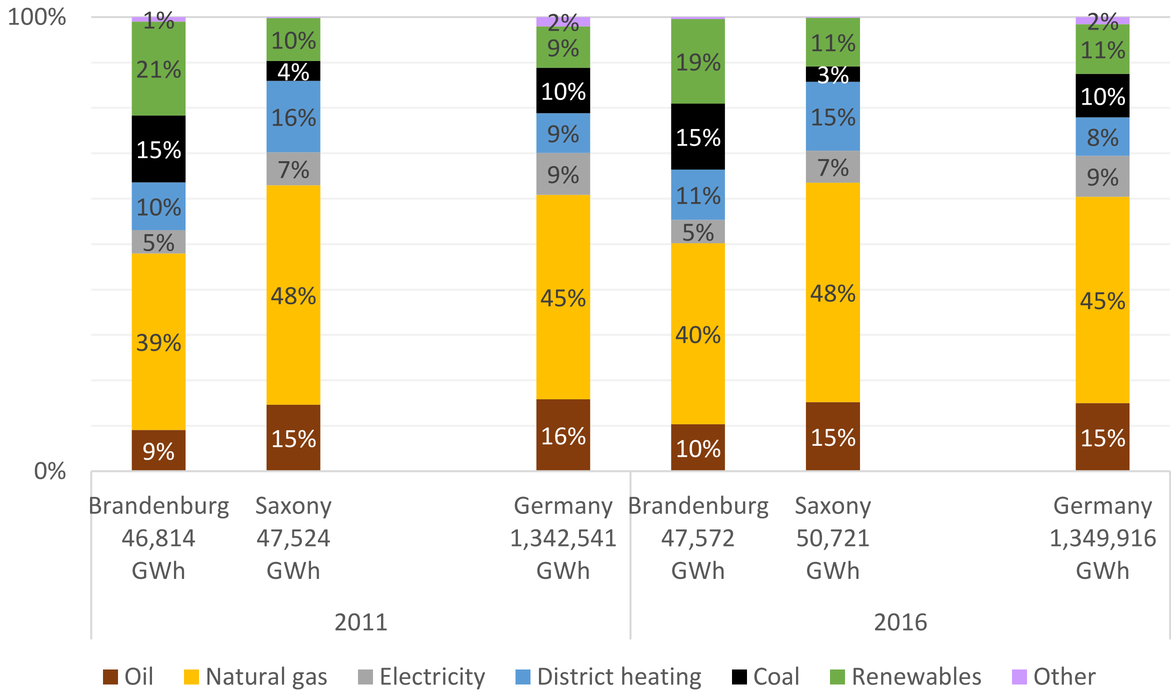

Figure 9 – Shares of fuel sources of total final energy consumption for heating purposes over the sectors households, TCS and industry (own calculations based on data from AfS Berlin-Brandenburg 2014; 2019a; StLa Sachsen 2016; 2019a; BMWi 2019a)

Overall, natural gas was the main energy source for heat; ranging from 39 % in Brandenburg 2011 up to 48 % in Saxony 2011 and 2016. Brandenburg had a remarkable high share of coal directly used for heating with 15 %, while in Saxony it only came up to 3 % in 2016. Moreover, the share of renewable fuel sources in Brandenburg reached 21 % in 2011, more than double of Saxony and Germany. However, while the share of renewables rose in Saxony from 10 % to 11 % and in Germany from 9 % to 11 %, in Brandenburg it went down to 19 %.

According to the annual report 2018 of AGFW (2019a), Brandenburg and Saxony together had 140 district heating grids with a total grid length of 2,436 km, an installed capacity of 4,433 MW and a thermal energy output of 9,642 GWh in 2018 (Table 2). Brandenburg has many small grids. The average grid in Brandenburg has a length of 10 km only and an average yearly thermal energy output of 16 GWh. On the contrary, Saxony has large grids with an average length of 28 km and a yearly thermal energy output of 39 GWh. The German average shows a length of 15 km and a yearly thermal energy output of 19 GWh. The thermal loss in the grids of Brandenburg is, compared to the German average, relatively low.

Table 2 – Overview data on district heating grids in Brandenburg, Saxony and Germany (AGFW 2019a)

	Number of grids	Grid length [km]	Installed capacity [MW]	Peak load [MW]	Thermal energy output 2018 [GWh]	Thermal loss
Brandenburg	80	785	1,564	1,240	3,924	8 %
Saxony	60	1,651	2,869	2,349	5,718	12 %
Germany	1,495	21,735	37,713	28,666	72,414	13 %

In the statistics about the heat energy market in Figure 9, district heating is presented as a fuel source, although it is a secondary energy carrier. District heat itself can be generated by using different types of energy sources like fossil fuels, renewable sources and also other secondary energy carriers like electricity. When examining potentials of district heating for climate-neutral heating, the primary energy source used is of particular importance. Figure 10 shows the shares of the different fuel sources as well as the shares of CHP and heat-only generation for each fuel source. In 2016, Brandenburg and Saxony had an energy input for district heat generation of 7,713 GWh and 7,501 GWh, respectively. In Germany the total energy input for district heat generation was 144,808 GWh. The shares of used energy sources differ significantly between Brandenburg, Saxony and the German average. As in the heating market as a whole, natural gas is also the main energy source for district heating. In Saxony in particular, it is dominant with a share of more than two thirds. The second most import fuel source is coal, ranging between about one quarter in Saxony and one third in Brandenburg. The remaining energy sources are renewables and others. Renewable energy sources refer almost exclusively to biomass and biogas. Among the energy sources designated as other, the fossil part of waste is the only one of quantitative importance. Renewable energy sources account for 15 % in Brandenburg and only 7 % in Saxony, which is low compared to a higher German average of 19 %.

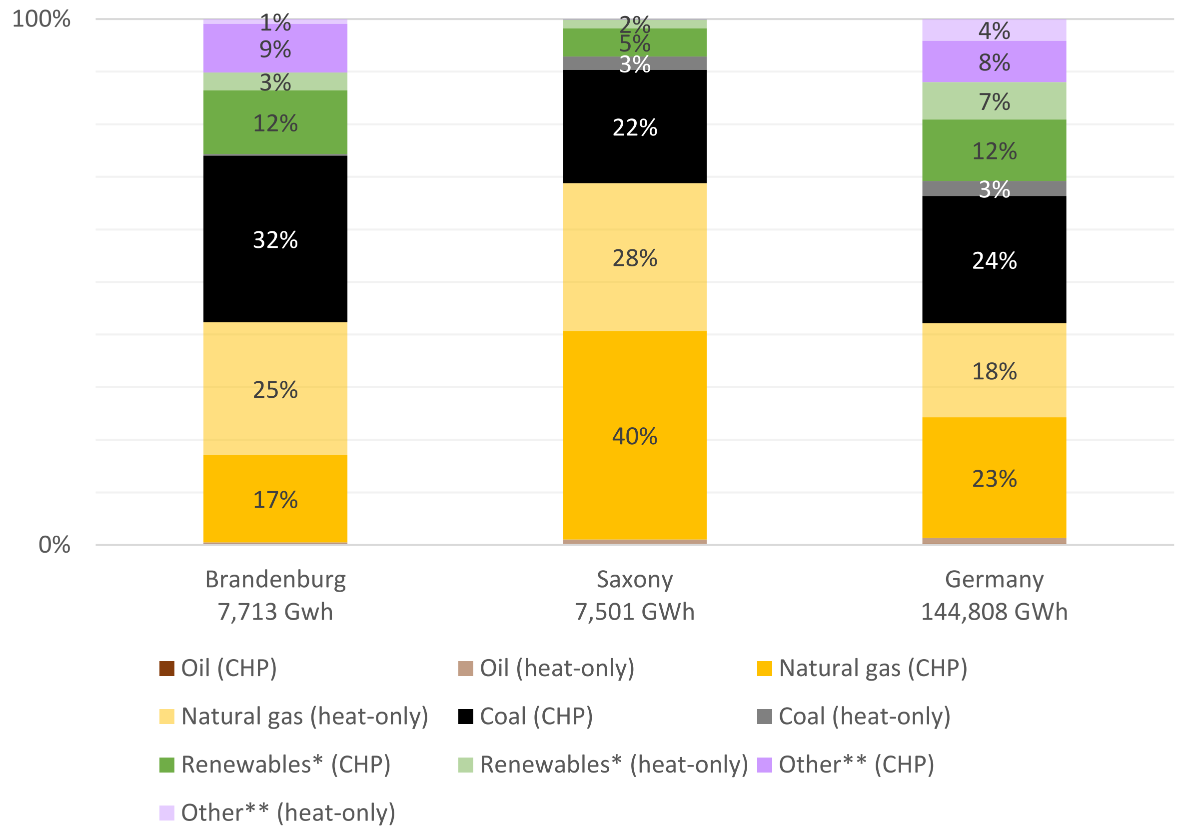

Figure 10 – Shares of fuel sources and cogeneration for district heat generation in Brandenburg, Saxony and Germany 2016. *almost entirely biomass and biogas **almost entirely fossil part of waste (AfS Berlin-Brandenburg 2019a; StLa Sachsen 2019a; AGEB 2018; CHP fuel allocation according to the Finnish Method)

Besides the type of fuel source, it is of interest whether district heat is generated separately in heat-only plants or in cogeneration with electricity in CHP plants. CHP plants benefit from a higher energy efficiency and thus reduce the primary energy consumption. Nevertheless, heat and electricity produced in cogeneration using fossil fuels have, albeit reduced compared to individual production, still existing CO_2 emissions. Only heat from CHP plants with exclusively renewable fuel sources can be considered climate-neutral. Among different fuel sources for district heat generation, coal has the highest share of CHP. In Brandenburg, almost the entire coal based district heat is generated in cogeneration. Also in Saxony and on average in Germany, the CHP share of coal reaches about 90 %. District heating based on renewable fuel sources and other fuel sources have a high share of cogeneration, too. Summarised over all fuel sources the CHP share for district heat generation goes up to 70 % in Brandenburg and 67 % in Saxony and the German average as well.

The previously presented data describe the heating market and district heat generation for the federal states of Brandenburg and Saxony while Lusatia is merely a part of each. The reason for this approach is the lack of data of higher spatial resolution. For this reason, two different approaches are used in the following to describe the current state of district heating in Lusatia. In Section 3.1, an inventory of district heating networks in Lusatia is drawn up based on the available data. However, it should be noted that this inventory may be incomplete. For this reason, in Section 3.2, a model approach is used in parallel to provide a quantitative picture of the district heating market for space heating and hot water preparation of households and the TCS sector in Lusatia.

3.1 Inventory of district heating networks

On the basis of the research carried out, a total of 53 district heating networks in 35 different municipalities were identified, which are operated by 31 different operators. The full list – making no claim to be exhaustive – is set out in Appendix A. The level of detail that is available on the grids varies from only one single parameter like the primary energy factor to comprehensive data about size, heat generation units and operational parameters.

Most of the identified district heating networks are operated by municipal-owned companies. Other networks are operated by private corporations and cooperative entities. The grid size varies from small grids servicing only one building complex, e.g. in Calau, to citywide ranging networks, e.g. in Hoyerswerda. However, it has to be assumed that many existing small grids with single or few connected buildings could not be found during the research and thus, larger networks prevail in the inventory. Largest identified network is the one in Cottbus with a total grid length of 175 km and more than 33,000 connected apartments. In 2012, 57 % of all apartments in Cottbus were provided with district heating (EVC 2019). As in Cottbus, many district heating networks consist of a single grid that covers the entire supply area. In some cases, the district heating network is separated into several local subgrids, e.g. in Radeberg with six independent subgrids. Often, though, the network structure remains unclear due to insufficient information. The structure of heat generation units feeding into the grids differs likewise. Some grids rely on one single thermal power station, e.g. in Guben, where the whole grid with a total length of 19 km is fed by one central station. Other grids employ a more decentralised structure where the heat is produced in different thermal power stations, e.g. in Niesky, where four stations feed heat into the same grid. The range of maximum temperature levels goes from 85 °C to 130 °C of the flow and from 45 °C to 75 °C of the return. The unweighted average of all found temperature levels is 103 °C of the flow and 58 °C of the return. The unweighted average of all identified PEF is 0.60, a comparatively high value. In a study from 2015, the unweighted average PEF for whole Germany was 0.36 (Schüwer et al. 2015). Yet, one has to bear in mind that the inventory-based value for Lusatia is just the result of the identified grids.

Among the different types of installed heat generation units, a combination of one or more CHP plants for the base load, complemented by one or more boilers for peak load hours, is mostly employed. Other system designs with only boilers (e.g. in Lübben) or only CHP units (e.g. in Elsterwerda) occur as well. Main fuel sources for heat generation are the fossil fuels natural gas, oil and lignite. Six district heating networks receive heat from one of the large coal power plants in the region as their main source of heat. The coal power plant Jänschwalde feeds heat into the networks of Cottbus and Peitz; Boxberg/O.L. and Weißwasser receive heat from the coal power plant Boxberg; and heat for Hoyerswerda and Spremberg comes mainly from the coal power plant Schwarze Pumpe. In some district heating networks renewable fuel sources are used, mostly biogas and rarely woody biomass. Where biogas is used, it has to be differentiated between balance based use and direct use. Balance-based use refers to the procedure whereby the amount of gas taken from the grid is fed as biogas into the gas network somewhere else. One example for a district heating system with balance based use of biogas is Lauchhammer (Danpower GmbH 2019). Direct use means that gas from a biogas plant is directly feeding a heat generation unit. The second approach is advantageous for the energy utilisation: when biogas is turned into heat on-site, a part of the heat can be used for the plant itself and the rest can be fed into a district heating system. An example for direct use of biogas is the district heating system in Radeberg (WVR 2020). Additionally in some district heating networks, advanced technologies are applied. The district heating network of Forst is connected to a PtH unit with 550 kW. This system provides ancillary services as negative secondary control power for the electricity grid by using surplus electricity to generate heat that is fed into the district heating grid (WindNODE 2019). Germany's biggest solar thermal district heating plant is located in Senftenberg. With a collector surface area of 8,300 m² it has a maximum capacity of 4.5 MW and produces 4 GWh of heat energy per year, which makes up 4 % of the district heating network's heat demand. During summer, it produces enough heat to cover the full network's heat demand (Ritter XL Solar 2020).

3.2 Model based description

Basic input for the model is data on the number of residential buildings including their type of heating system in each municipality. From a total of 307,264 residential buildings in 2011, 23,106 or 7.5 % had a district heating system. The connection rates range from 0 to above one third. 36 municipalities have no grid-connected residential buildings, 190 municipalities have a rate of less than 5 % and 9 municipalities have a rate of more than 15 %, of which Ostritz is at the top with 35 % (Figure 11).

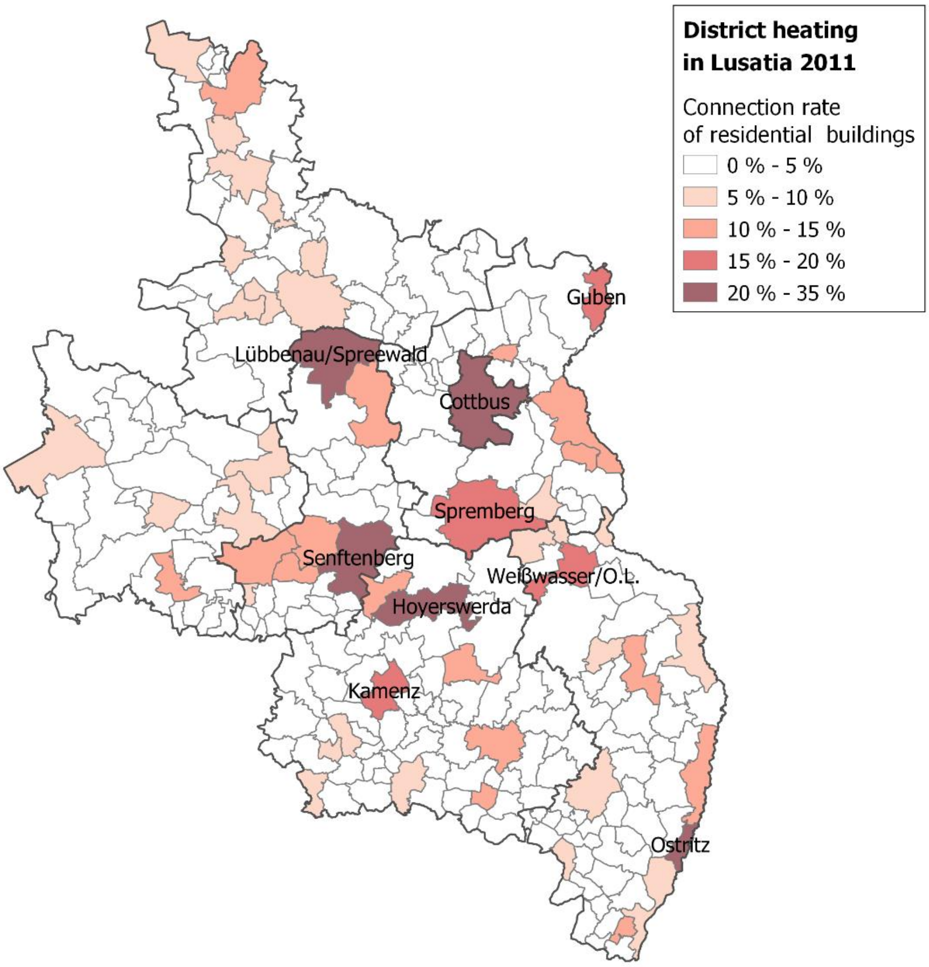

Figure 11 – Rate of buildings connected to district heating grids in the municipalities of Lusatia 2011 (Zensus 2011; GeoBasis-DE / BKG 2019)

Looking on the final energy consumption in Lusatia in the base year 2018, 1,285 GWh of final energy was delivered as district heating to households. This makes up a share of 14.5 % of the sector's heat demand (Figure 12). In the TCS sector, the final energy amount of district heating was 298 GWh or 12.3 % of the heat demand. Summarising both sectors, the share of district heating was 1,583 GWh or 14.0 %. In comparison, the same share for Germany was only 8.7 % (BMWi 2019a). The fact that the energy-related share is almost twice as high as the average connection rate of buildings indicates that larger buildings with several apartments are connected to district heating networks more often than smaller houses.

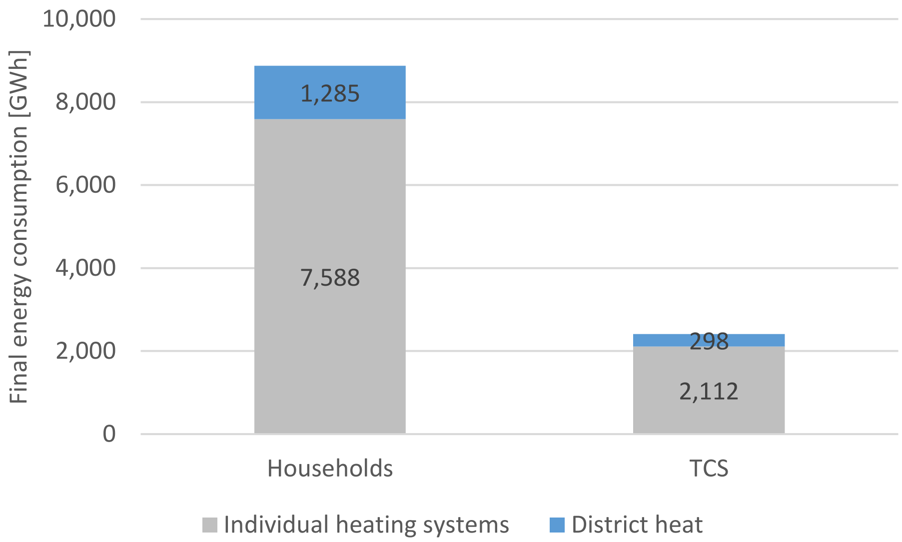

Figure 12 – Final energy consumption for space and water heating with individual heating systems and district heat in the year 2018 (own calculations based on references as provided in Section 2.2)

The map in Figure 13 shows the distribution of district heating in Lusatia based on the inventory and the model data in the year 2018. District heating grids identified by research are marked as single dots and the corresponding name. Model data is visualised by a colour scale that represents the annual final energy consumption for district heating in each municipality. This simplifying approach summarises all district heating networks within one municipality, although they might be separated in individual grids. The results for all municipalities with their corresponding amount of district heating consumption and available additional research based data are listed in Appendix B. 46 municipalities have an amount of district heating of at least 5 GWh of final energy. Most of these are located in the districts Bautzen, Görlitz, Oberspreewald-Lausitz and in Dahme-Spreewald at the border to Berlin. On the contrary, the district Elbe-Elster has only three municipalities with a district heating amount above 5 GWh/a. Cottbus, also the largest city in terms of population in Lusatia, has the highest amount of district heating with 242 GWh/a followed by Hoyerswerda (133 GWh/a) and Görlitz (90 GWh/a). Furthermore, the data reveal that 77 municipalities have small but non-zero amounts of district heating of only 5 GWh/a or below. This fact indicates the presence of very small grids. At the foot of the list, 121 municipalities have a vanishingly small amount or no district heating at all.

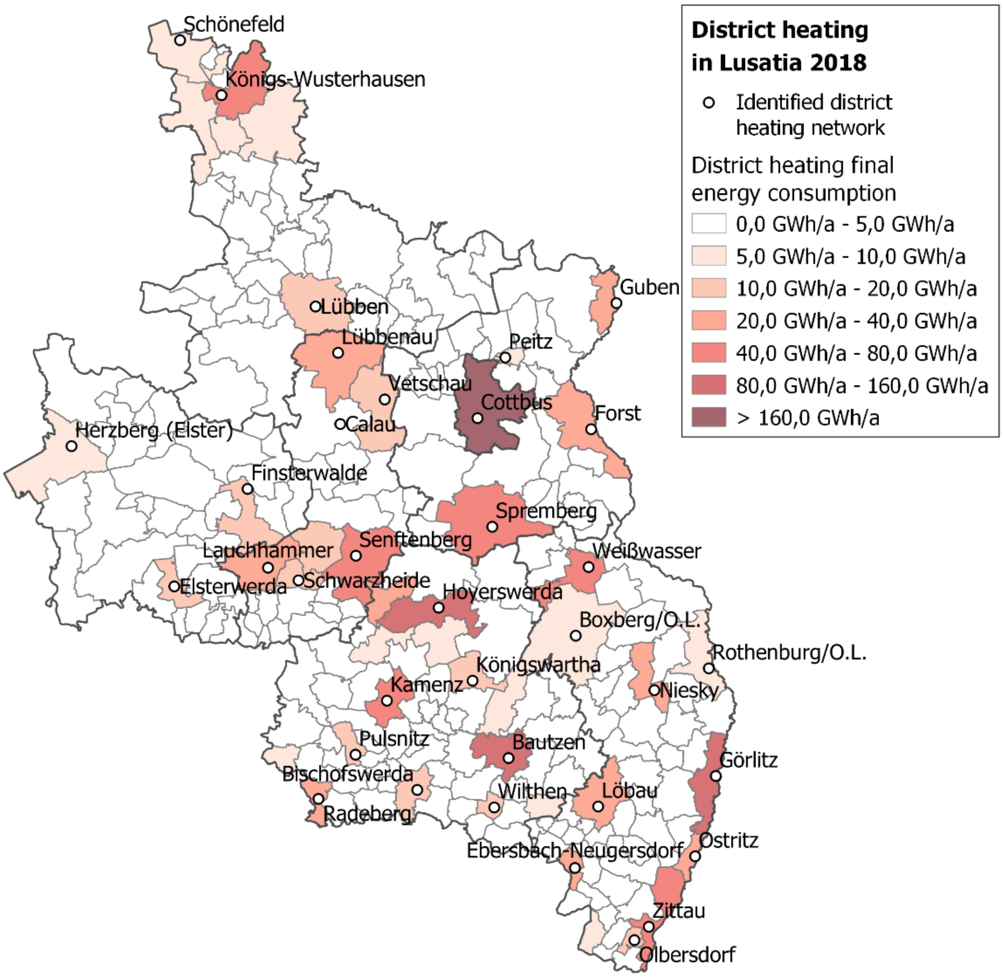

Figure 13 – Overview map of final energy consumption of district heat by the sectors households and TCS in the year 2018 and identified district heating networks from the research based inventory (own calculations based on references as provided in Section 2.2; GeoBasis-DE / BKG 2019)

A comparison between the results of the research and the model shows that the model in total includes more grids and more final energy consumption via district heating. All district heating networks identified by means of research are represented in the model data by district heating amounts of higher than 5 GWh/a. The only exception is Calau, where only one building complex (retirement home) is supplied by district heating (AGFW 2019b). This accounts for only a very small part of the municipality's heat demand and is therefore not visible in the model data. On the other hand, data on small networks, which also fall under the definition of district heating, do not seem to be available by research in public sources of information and are therefore not represented in the inventory. This finding justifies the application of a model for describing the district heating market in Lusatia. A comparison between the orders of magnitudes of the model and the identified grids, where available, shows different levels of congruence. They vary from deviations in both directions up to 94 GWh/a in Guben and close matches with a difference of less than 1 GWh/a in Lübben. Differences where model data show smaller amounts of district heating energy than researched data may be due to the limited scope of the model, which only covers heat used by households and the TCS sector for space and water heating. In some cases, the collected data cover all sectors and applications, as in the case of Guben (Lausitzer Rundschau 2016). Cases where the district heating quantity in the model is higher show the fact that not all existing networks could be identified by the research. Fuel sources of district heating are not included in the model due to insufficient data available. However, bearing in mind the limited scope of the model, it can be taken as a good approximation and it allows further projections.

4 General Potentials for Fossil-Free District Heating

Generally, district heating systems compete with individual heating systems in terms of technical feasibility, economic profitability and their environmental impact. A potential provider of a district heating network will decide for operating such a network if needed technologies are available and it proves to be profitable. Main criterion for or against district heating systems on the consumer side is whether the consumer's heat demand in terms of quantity, availability and temperature level can be covered by a district heating system more cost-efficiently compared to an individual heating system. On the societal and political level, the environmental aspect is coming to the fore and the question arises whether a district heating system or an individual heating system can provide the demanded heat with less environmental impacts, especially climatically harmful emissions. GHG emissions of various heating systems differ widely. Specific emissions for selected heating systems, calculated on the basis of a material and energy flow analysis model, are presented in Figure 14.

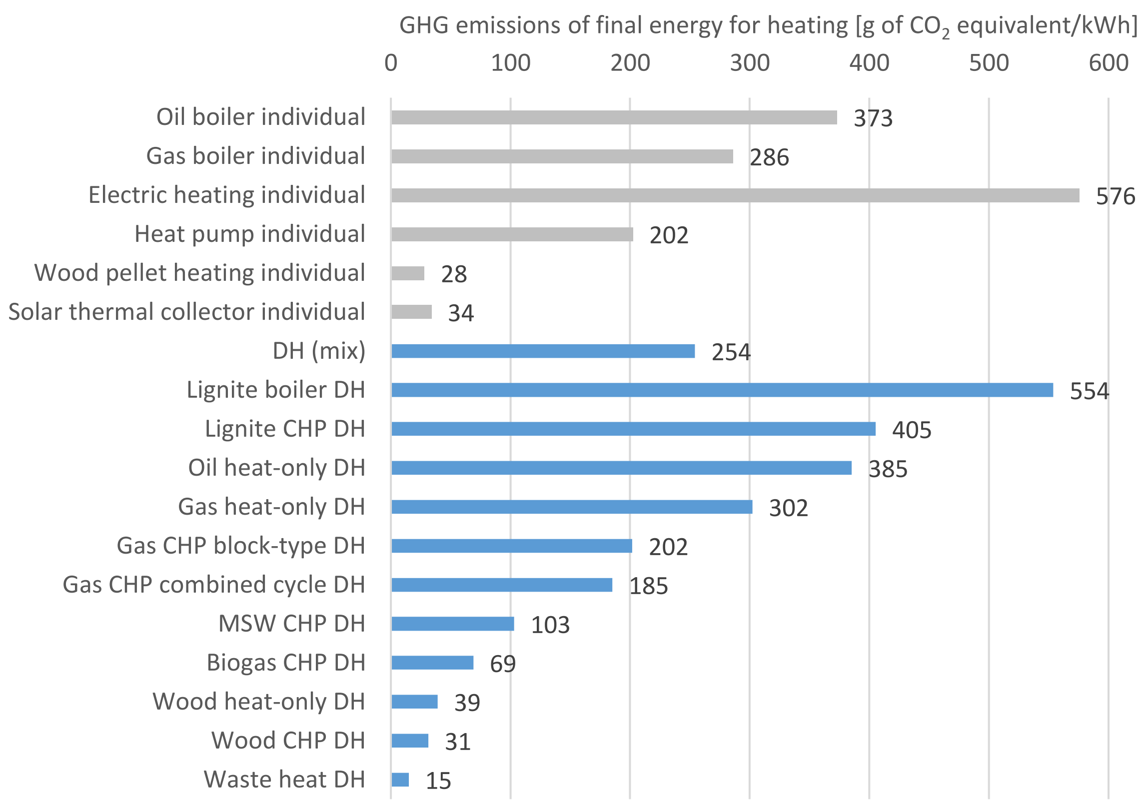

Figure 14 – Specific GHG emissions of selected types of individual and district heating (DH) systems in the reference year 2015 with average mixes of electricity and district heating energy sources (IINAS 2019)

The span of values shows that whether an individual heating systems or a district heating systems is advantageous in terms of climate protection strongly depends on the energy source. An individual heating systems with an oil furnace, for example, emits 47 % more GHG than the average mix of district heating in Germany. On the contrary, a district heating system based on lignite combustion causes at least 40 % more emissions than an individual gas heater.

Generally, it can be concluded that switching to renewable energy sources reduces GHG emissions best, no matter if used in individual or district heating systems.

Consequently, for a sweeping reduction of GHG emissions, fossil-based heating systems must be put out of the market and replaced by fossil-free alternatives. Among individual heating systems, possible options are roof-mounted solar thermal systems, biomass-fired boilers and heat pumps. Among these, heat pumps are the most promising alternative, as recent studies suggest (e.g. Gerhardt et al. 2019; Robinius et al. 2019). Heat pumps allow to use environmental heat from air, water or ground in a very efficient way. However, heat pumps are costly to install and in order to become climate-neutral, they must be powered by electricity from renewable resources (Hoffmann 2012). A current trend in the targeted reduction of the climate footprint of district heating networks is to replace emission intensive fuel sources – mainly coal – by natural gas , e.g. in Cottbus (Stadtwerke Cottbus GmbH 2018). In view of the ambitious goal of climate neutrality, however, in the long term natural gas itself must be largely replaced as a fuel for heat generation (Hirschl 2018). In view of the target of this thesis, assessing the potential of district heating to contribute to climate-neutrality, the analysis focuses on systems with renewable or waste energy sources.

In summary, the potential of climate-neutral district heating must be assessed on two levels: firstly, the potential share of district heating in the total heating market and secondly, the potential share of fossil-free energy sources used for district heat generation.

The future role of district heating has been projected in various energy market simulations. An analysis of projections for heating of buildings shows that the prospective share of district heating is highly depending on the guiding target of GHG emission reduction (Figure 15). Following the current trend of the energy market development up to now and ignoring the climate targets, the market share of district heating will increase until 2030 up to 15.0 %, but decrease to 11.1 % in 2050. The considered GHG emission reduction targets are in line with the climate targets of the German government: a reduction of 80-95 % compared to 1990 until 2050 (BMWi and BMU 2010). In the -80 % Scenario, the range of prospective market shares is the widest and in 2030, the minimum share is even lower than in the Trend Scenario. Nonetheless, in the period between 2018 and 2050, the share is rising at least by 4.7 %. The -95 % Scenario shows the highest shares of district heating with maxima of 15.8 % in 2030 and 23.0 % in 2050. Although these projections are subject to uncertainties, the comparison of the scenarios points out that district heating will play a substantial role in the decarbonisation of heating of buildings.

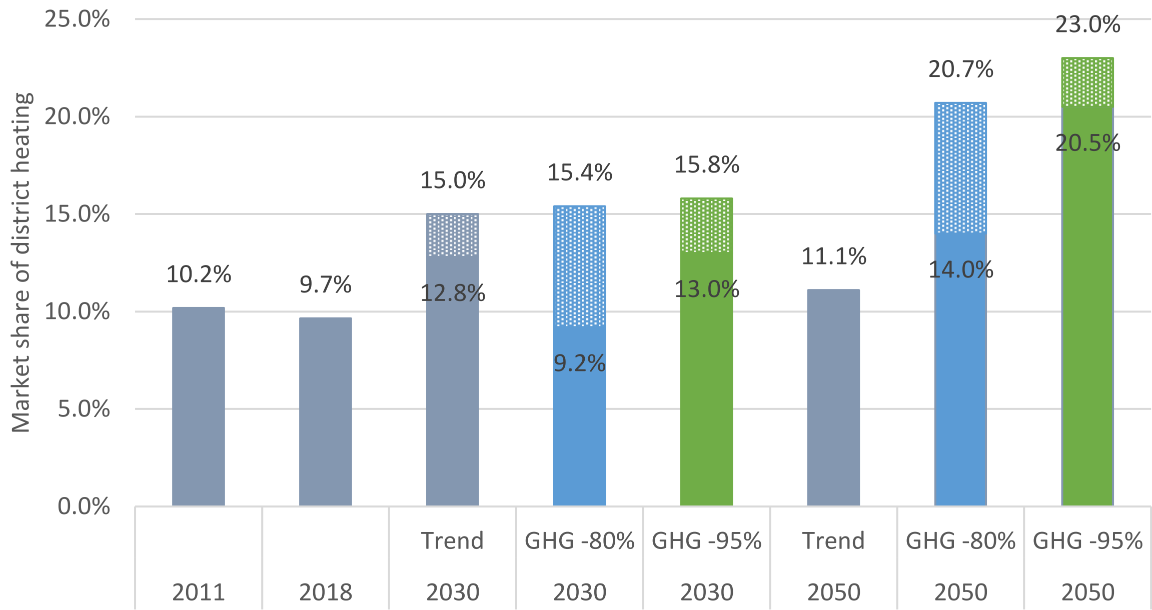

Figure 15 – Records and projections in different climate protection scenarios of the market share of district heating for heating of buildings from 2011 to 2050 (adapted from Agora Energiewende 2017b; update for 2018 from BMWi 2019a)

Possible renewable energy sources that can be used for district heating systems are biomass, biogas, geothermal energy and solar thermal energy. Waste heat from thermal waste treatment, industrial plants and data centres is also considered as climate-neutral. Provided that electricity is generated from renewable resources, PtH appliances in large-scale heat pumps and electric boilers are also options for the generation of fossil-free district heating. The respective potential of application of these technologies in district heating depends on their availability, technical feasibility and cost-efficiency.

In the following sections, general technical and economic potentials and impediments of district heating systems are discussed in detail. Effects on value added and employment of district heating are investigated further in Section 4.3. Specific challenges of transforming existing district heating networks are focussed in Section 4.4. Subsequently, the general potentials of the different climate-neutral energy sources for district heating and thermal energy storage are assessed individually in Section 4.5.

4.1 General technical potentials

The main characteristic of district heating is a spatial and temporal decoupling of heat generation and consumption. This has various advantages compared to individual heating systems. District heating systems allow the integration of large-scale heat generation units. For this reason, they are open for more different types of energy sources and technologies e.g. highly efficient CHP units. The heat demand in district heating networks is generated by many customers. Consequently, it is less fluctuating and thus, increases the efficiency of the heating system (Pehnt et al. 2009). Since changing the energy source of a district heating system affects many households at once, district heating systems offer higher flexibility for the transformation towards carbon neutrality compared to replacing all individual heating systems one by one (Pehnt et al. 2017). In a decarbonised heating market, district heating becomes technologically advantageous even more. For many renewable or waste energy sources, a district heating system is the prerequisite for their utilisation for heating. Especially in very densely populated areas, where space for individual heat pumps or solar thermal heating systems is not sufficient, district heating can be used to transfer heat from areas with sufficient space for generation (Agora Energiewende 2017b; 2019). Moreover, district heating allows sector coupling of the heating sector with the electricity sector, as district heating systems can provide control power and integrate energy storage (Sections 4.5.6 and 4.5.7). Main disadvantages that arise from the characteristics of district heating systems are heat loss from the grid and the fact that once constructed networks are less flexible to adapt to changes in the settlement structure (Bruns et al. 2012).

District heating systems are in a continuous transformation process. The main parameters are temperature and efficiency. Figure 16 illustrates the development over the last 150 years and defines four generations of district heating systems. The current stage of the transformation is moving towards so-called 4th generation district heating systems (Lund et al. 2014). Alternative designations for such district heating systems are heating networks 4.0, low temperature district heating (LTDH) systems or low exergy (LowEx) district heating systems (Pehnt et al. 2017; Schmidt et al. 2017; Felsmann et al. 2010). Maximum temperature thresholds are not standardised and vary widely. A definition with a relatively high maximum temperature threshold is provided by Pehnt et al. (2017, 21):

> *"Heating network systems 4.0 are innovative heating infrastructures based on heating networks with low temperatures (20 to max. 95 °C). The heat supply is based on criteria of climate protection and the perspective of a cost-effective heat supply mainly based on renewable energies and waste heat."*

Decreasing the temperature is crucial for the exploitation of climate-neutral heat generation technologies like solar thermal energy and geothermal energy that can provide limited maximum flow temperatures (Huenges 2014). Lower temperature levels also enable the direct use of low-temperature waste heat such as from data centres (Wahlroos et al. 2017). Energy and exergy efficiency is increased in district heating systems with lower temperatures, as heat loss is reduced and temperature levels of supply and demand are closer together (Li and Svendsen 2012). Moreover, heat pumps used for district heat generation are more efficient when providing lower temperatures (David et al. 2017). The mentioned positive energetic effects become effective particularly if the temperature level of the return is decreased. Whereas a mere reduction of the flow temperature and constant return temperature has no benefit (Bachmann et al. 2018). Accordingly, decreasing the system temperature should start with the return temperature, followed by the flow temperature (Lund et al. 2018).

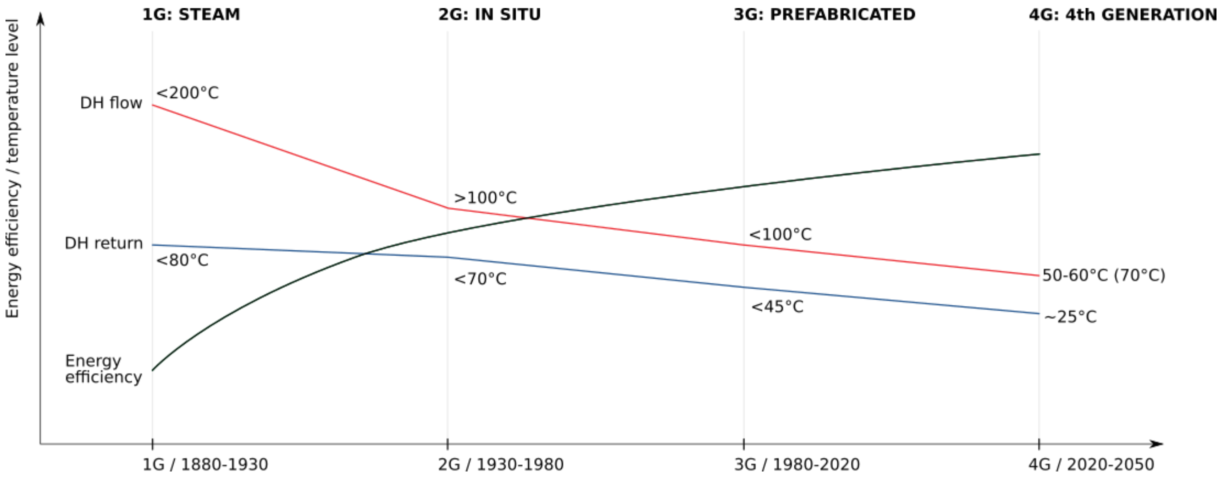

Figure 16 – Development of temperature and energy efficiency of district heating systems from 1st generation to 4th generation (own illustration after Thorsen et al. 2018)

The lower limit of the system temperature is set by the minimum requirements of the connected building systems for space and water heating. In new buildings with good thermal insulation and modern heating systems with large heating surfaces like floor or wall heating systems, flow temperatures close to room temperatures are suitable for comfortable space heating (Ala-Juusela 2004). In existing buildings, with less thermal insulation and small heating elements, the required flow temperature is respectively higher. Conventional heating systems with radiators are designed for flow temperatures between 45 °C in modern buildings and up to 90 °C in old buildings (Bosy 2001). The temperature requirement for water heating is determined by the demand for comfort plus the inhibition of growth of legionella. For comfort reasons, hot domestic water should reach 45 °C (Yang and Svendsen 2017). However, when hot domestic water is circulated or stored inside the building system, as usually the case, the water further needs to be heated up to 60 °C in order to prevent infestation by legionellae (Pehnt et al. 2017). If this is done by a heat exchanger directly connected to the district heating flow, the flow temperature needs to be at 65-70 °C (Paar et al. 2013).

In an existing or prospective district heating supply area, the energy standard of the building stock determines the limit of possible temperature reduction. In order to enable further reduction in temperature, various measures can be carried out on the buildings. For space heating, these include improving of thermal insulation, replacing small radiators by larger heating elements and the installation of advanced heating control systems (Lund et al. 2018). The risk of legionella in the domestic hot water installations can be eliminated by replacing conventional water heating systems with instantaneous heat exchangers. In multi apartment buildings, conventional central water heating systems can be replaced by decentral substations in each flat. This has the additional advantage that heat loss is reduced by up to 30 % (Yang et al. 2016b). Water treatment for inhibition of legionellae by various means of sterilisation are also possible but only recommended as supplementary solution (Yang et al. 2016a). Further decreasing of the flow temperature even beyond the level required for comfort reasons necessitates extra heating of the heat transfer medium inside the supplied building. This approach is called boosting and can be done either by direct electric heaters or heat pumps (Zvingilaite et al. 2012). By this method, very low flow temperatures can be achieved (Heissler et al. 2017). However, boosting shifts the primary energy consumption from the fuel sources of district heating to those of electricity generation. Only with a low carbon electricity mix, this shift can be beneficial in terms of climate protection. Moreover, depending on the overall system design, there might be a limit beyond which further lowering the temperature does not further increase the overall energy efficiency (Elmegaard et al. 2016).

The implementation of low district heating system temperatures is a problem especially in supply areas with a very heterogeneous building stock. In conventional grids, the system temperature must be adapted to the demand of the connected building with the highest temperature requirement. Alternatively, if the system temperature cannot be reduced, low-temperature heat sources can be used in combination with other heat sources that can provide higher temperatures. In this approach, the heat transfer medium from the return flow is preheated by a low-temperature technology and further heated by a suitable high-temperature technology, e.g. a CHP plant (Raab et al. 2005). Thereby, the bandwidth of employed technologies can be broadened and the required capacity of high-temperature energy sources can be reduced. Another technology for more flexibility of the temperature levels of heat sources and sinks is multi-conductor networks. This approach was extensively studied in the project "LowExTra" (Bachmann et al. 2018). Such networks with various temperature levels also facilitate decentralised feed-in and enable consumers to become prosumers, e.g. by in-feeding of heat from a solar thermal roof collector.

High shares of renewable energy in modern district heating networks increase the complexity of the network configuration. For sufficient and reliable heat supply, various renewable resources need to be integrated and are usually not found in one place. This leads to a decentralisation of the feed-in structure. While in networks with central or multi-central feed-in structure, it is relatively straight forward to model the mass and energy flow, it becomes highly complex in networks with a highly spatially distributed feed-in structure. To address this, scientist have developed new modelling methods that allow better understanding and optimisation of the thermodynamic processes in complex district heating systems (Sarbu et al. 2019). One result is that replacing conventional branch structures by a ring structure may be a suitable approach to improve system performance (Laurberg Jensen et al. 2016).

4.2 General economic potentials

General criterion in the economic assessment is profitability, thus also for district heating. For the operator of a district heating network, costs of investment and operation must be refinanced by the sale of heat to connected customers over the operational lifespan of the network. The operator will set the price for the district heating accordingly. Potential customers will compare this price to other available options of individual heating systems and choose, as a rule, the cheapest option.

The costs for district heating are composed of various costs that incur at the various system components and follow the general structure of fixed and variable costs. On the side of generation and distribution, large initial investments are needed to establish the required generation units and distribution grids. Additional fixed costs are those for regular maintenance and personnel. Variable costs include expenditures for fuel, operating supplies and usage-bound maintenance. On the consumer side, fixed costs are a connection fee which is charged once by the grid operator, costs for required on-site installations plus a basic price to be paid regularly. A consumption based fee or working price and maintenance costs form the variable costs. Compared to gas or electricity supply, the share of the basic price is much higher for district heating. It accounts to almost one third of the utilities' total proceeds (Bundeskartellamt 2012). This reflects the fact that district heating producers and grid operators have high fixed costs for investments in required infrastructure.

The heat generation capacity of a district heating network has to be designed for the maximum load of all connected customers. Although this load might be demanded for only few days a year, it must be covered by the network's own generation units. Extra control energy from superregional networks like in the electricity sector is not available. This characteristic of district heating networks challenges the economic efficiency of district heating networks, especially of smaller ones. Even if a system appears to break even, high initial investments are required and amortise only after a long period of time. As a result, potential investors tend to be more reluctant (Bruns et al. 2012). In fact, most present district heating systems in Germany have an integrated utility being heat producer, grid operator and heat supplier at the same time. Since a district heating grid is usually a closed system and buildings are only connected to one grid, the result is a monopolistic situation. In areas with compulsory district heating connection and usage, where customers have no choice between individual and grid connected heating systems, this effect is even stronger (Bundeskartellamt 2012). The integrated network operator benefits from this situation, as the sale of its own heat facilitates the refinancing of the high initial investment costs. On the contrary, third party access to the network for heat distribution opens up the market for small heat producer and introduces competition. However, this approach is only economically feasible in large networks of big cities (Pehnt et al. 2017). Moreover, it increases complexity and does not automatically lead to higher shares of heat from renewable or waste energy (Bürger et al. 2019).

For district heating networks to be economically viable, a certain density of connected customers and corresponding heat demand is required. In this sense, reduced heat demand of buildings due to energy-saving measures is counterproductive for the economic potential of district heating systems (Esch et al. 2011). In fact, the demand for space heating is declining even though the living space per person is rising (Figure 17). According to the Goal Scenario, both the space heating demand per living area and the space heating demand per person are reduced by 36 % and 30 %, respectively, between 2020 and 2040.

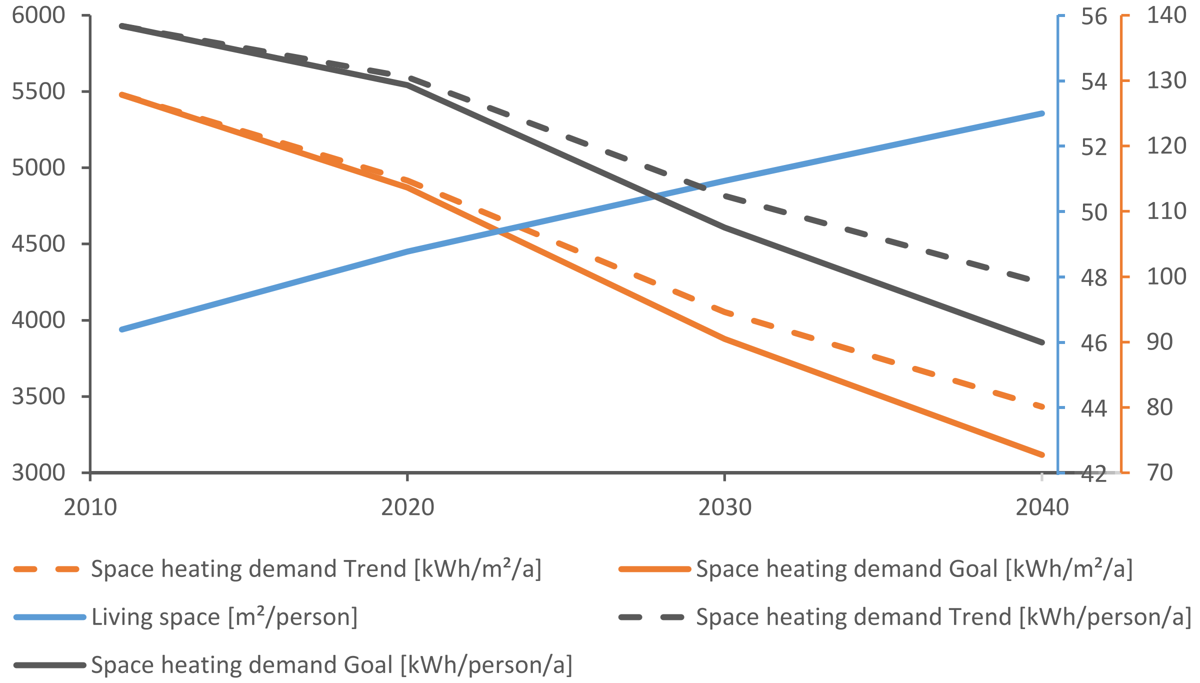

Figure 17 – Trend and Goal Scenario for the relation between space heating demand per unit living area and living space per person in households in Germany from 2011 to 2040 (Schlesinger et al. 2014)

Especially in development areas, where the effort for constructing a heating network is comparatively low, new buildings have greatly reduced space heating demand. This leads to even higher required connection rates in such areas (Bruns et al. 2012). But also in the existing building stock, the declining heat demand must be compensated by densification of connected buildings in order to ensure economic operation (Schubert 2016). Under consideration of declining heat demand densities and the principle of a minimum required heat demand density, Jochum et al. (2017) have assessed the potential of district heating in Germany. They found the biggest potential for new grids in small cities with less than 10,000 inhabitants. In rural municipalities with less than 5,000 inhabitants, the required heat demand density is often not reached and thus, the potential is rather small. Another study from 2011 comes yet to the result, that the construction of district heating systems in rural areas like villages with mainly detached houses is generally not to be recommended due to economic reasons (Wolff and Jagnow 2011). The latter, however, considers conventional mainly fossil-based district heating grids only.

A much noticed study by Pfnür et al. (2016) compares individual and district heating systems regarding energetic, ecological and economic aspects. The authors conclude that in all cases considered, individual heating systems have lower costs compared to district heating. However, on their way to their conclusion, the authors do not pursue the goal of a total decarbonisation of the heating market. Instead, they compare district heating systems with the average values of individual heating systems. In the considered case of partially refurbished single-family houses – typical for rural areas – this average value is based on a share of 87 % fossil-fuelled heating systems. In the view of the emission reduction targets, however, oil and natural gas heating systems must largely disappear, even if they are highly efficient (Gerhardt et al. 2019; Robinius et al. 2019). When focussing on fossil-free heating systems, the picture changes. Figure 18 is solely based on numbers published by Pfnür et al. (2016). It illustrates the difference in annual CO_2 emissions and the difference in the present value after 20 years in the event that an outdated oil or gas boiler is replaced by a new heating system in a partially refurbished single-family house. Options considered for the new heating system are an oil condensation boiler (CB), an oil CB with solar thermal supplement (ST), a gas CB, a gas CB with ST, an air source (AS) heat pump, a ground source (GS) heat pump, a wood pellet boiler and district heating (DH) with renewable based CHP, fossil based CHP and fossil based heat-only generation.

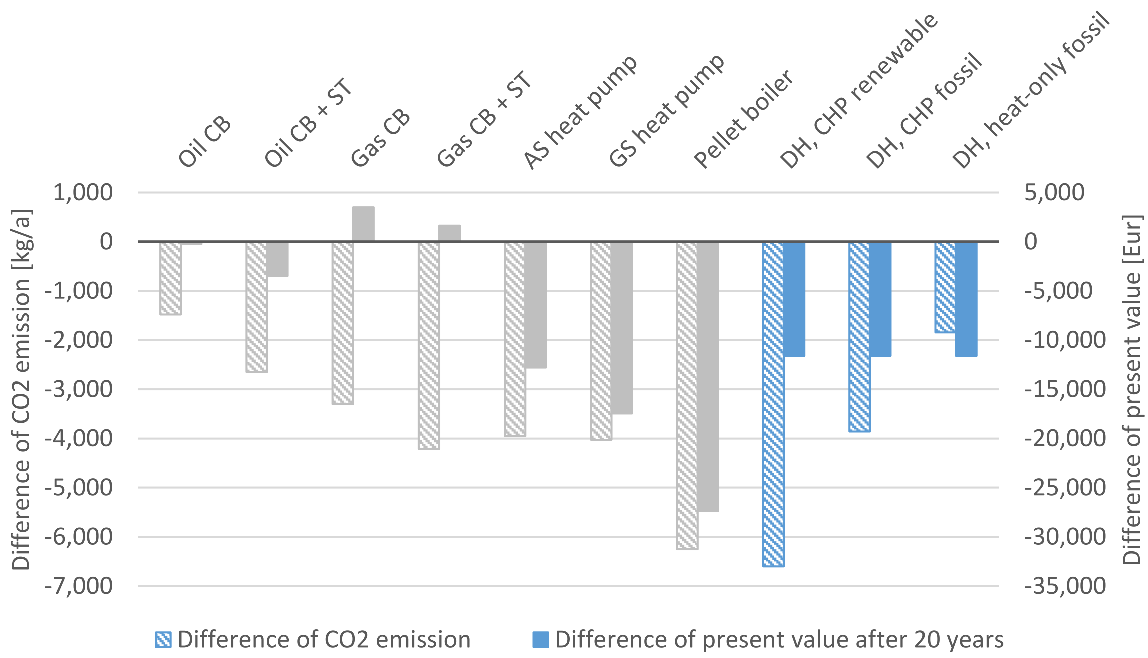

Figure 18 – Differences of CO_2 emissions and present value of a building's heating system after 20 years in the event of replacing an outdated oil or gas boiler by a new heating system in a partly refurbished single-family house (Pfnür et al. 2016)

Substantial savings of CO_2 emission can be achieved with a pellet boiler or a renewable based district heating system. All other options lead to at least 2,000 kg more CO_2 emissions per year. The emission saving potential of a gas condensation boiler with solar thermal supplement is relatively high but presumably outlines the maximum achievable savings with fossil-based systems. CO_2 emission reduction with heat pumps is limited due to the underlying electricity mix in Germany. Their saving potential is yet unexhausted, as with more renewable electricity their CO_2 savings will increase further. Looking at the economic aspect, a replacement of an old gas boiler with a new modern gas fuelled heating system actually saves money compared to maintaining the old system. All other modernisation options lead to higher costs with a pellet boiler, followed by a heat pump, being the most expensive options. The applied costs for a district heating system – the same for all three alternatives of generation technology – are higher than replacing an old oil boiler with a new one. However, among those alternatives based solely on renewable energy and thus have serious climate protection potential, district heating is the cheapest.

Pehnt et al. (2017) also provide a comparison of the costs of different individual heating systems and different types of fossil-free district heating systems (Figure 19). In contrast to Pfnür et al. (2016), the authors take into account that costs for district heating systems may vary considerably depending on the technologies used.

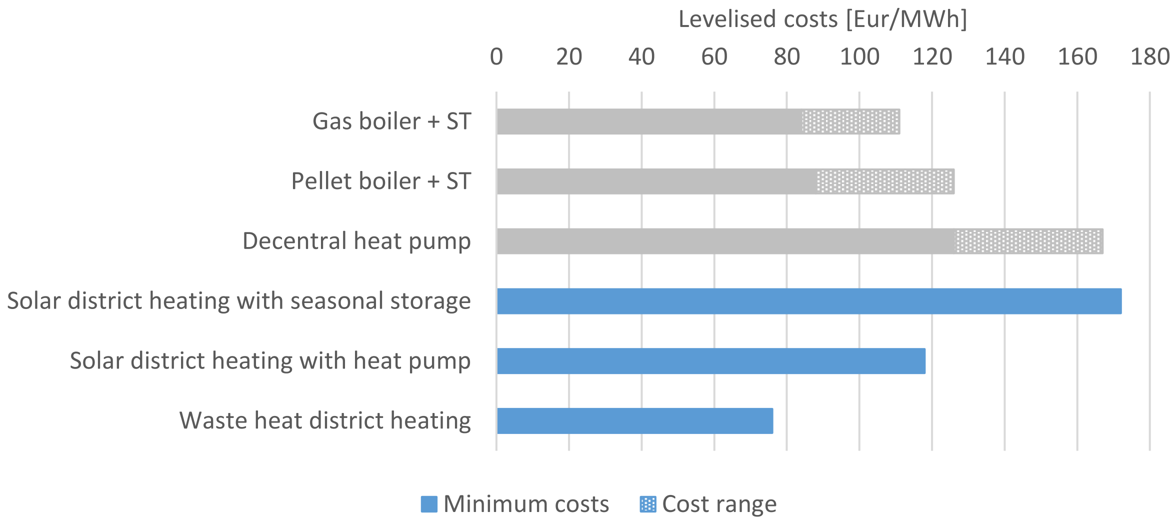

Figure 19 – Levelised costs of different individual and district heating systems (Pehnt et al. 2017)

The combination of a natural gas boiler and solar thermal supplement is often used as a benchmark technology that new technologies have to economically compete with. Its levelised costs range between 84 Eur/MWh and 111 Eur/MWh. Costs for individual heat pumps reach up to 167 Eur/MWh. District heating systems have costs from 76 Eur/MWh for a system with waste heat up to 172 Eur/MWh for a solar thermal system with seasonal storage. This comparative presentation suggests that costs for solar district heating system cannot compete with those of individual gas-fuelled systems. However, solar district heating with heat pump supplement has lower costs than individual heat pumps. Yet, costs for district heating with waste energy are even below all individual benchmark technologies.

Looking ahead, the cost ranking could change due to an expected increase in the price of fossil fuels and the development of cost reduction potentials of fossil-free technologies. Cost reduction potentials include economies of scale, standardisation, improved components and processes, efficiency increase, organisational measures and further innovations (Pehnt et al. 2017). Taking this development into account, IRENA (2017) provides estimates of levelised costs for heating with individual and district heating systems in Germany in the year 2030 (Figure 20).

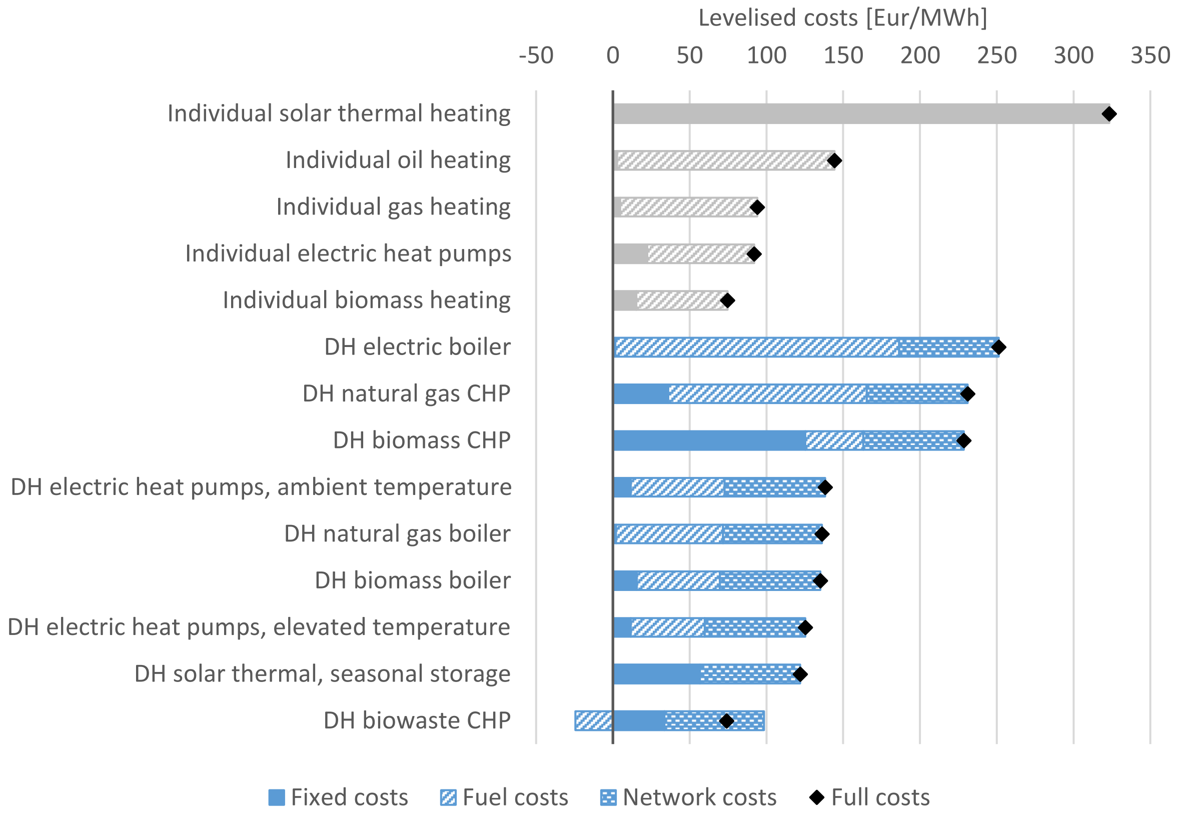

Figure 20 – Levelised costs of individual and district heating technologies in Germany 2030 (IRENA 2017)

The overview coincides with the predicted dominant role of individual heat pumps that are expected to reach the cost level of individual gas-fired heating. The costs of individual biomass heating systems are even lower. Compared to district heating systems, levelised costs of individual heating systems with biomass, heat pumps or gas are lower than those of all district heating systems with the exception of biowaste CHP plants that have assumed negative fuel costs. On the contrary, individual solar thermal heating exceeds all individual and district heating options. Among the district heating technologies, solar district heating in combination with seasonal storage is the second cheapest option. The costs of large-scale electric heat pumps for feeding district heating networks depend on the type of heat source. A large-scale heat pump system using a heat source with an elevated temperature has a better performance and is therefore economically more favourable than a system with a heat source at ambient temperature. District heating systems fuelled with natural gas or biomass are in between the two options of large-scale heat pumps. At the bottom line, however, most types of district heating systems have an economic disadvantage compared to most types of individual systems due to additional network costs.

Taking the entire energy system into account, district heating offers extra economic potential, since it fosters the coupling of the electricity and the heating sector (Schneller et al. 2017). Until now, the cogeneration of electricity and heat in CHP plants is the most important implementation. Parallel to the decarbonisation of heating, electricity will gain importance in the heating sector. In less dense populated and rural areas, the transformation of district heating systems might yet avail the economic potential of district heating. Solar thermal collectors and thermal energy storage need a lot of affordable space, which is rather available in rural areas (Pehnt et al. 2017). Gustafsson et al. (2018) found, that in areas with detached houses, district heating systems that use biomass or waste as fuel have, under certain circumstances, lower overall costs than heat supply by individual heat pumps. Denmark is a showcase example for the fact that it is possible for district heating networks to penetrate rural areas, particularly if they integrate high shares of renewable energy. Although Denmark has a comparatively low population density, 65 % of all Danish citizens were supplied with district heating in 2017. The share of renewable energy for district heat generation was at 60 %, with biomass being the most important renewable energy source (Euroheat & Power 2019). District heating networks in Denmark do not only cover big cities but are also widely spread in rurally structured areas (Sperber and Nast 2014).

The conversion of district heating systems to renewable and waste energy sources and lower system temperatures brings further challenges. If volatile energy sources – primarily solar thermal energy – are used, solutions are needed to cover periods of low energy supply. This can be thermal energy storages or extra fossil based heat generation capacity, both of which lead to higher investment costs (Bruns et al. 2012). Sources of renewable and waste energy sources are often spatially distributed within the area of a district heating network which requires a decentralisation of the feed-in structure. This also leads to slightly higher costs compared to a centralised feed-in structure (Dunkelberg et al. 2018). When lowering the system temperature below the point where boosting is required, additional costs arise from investments in additional equipment like heat pumps or electric heaters and their electricity consumption (see also Section 4.1). Below a certain temperature, these additional costs outweigh the savings of reduced heat loss (Ommen et al. 2016). Multi-conductor networks are a promising solution for flexible adaption of temperature levels to the requirements of heat consumers and generators. However, reference calculations have shown that they incur 30 % higher costs than conventional networks with single flow and return (Dunkelberg et al. 2018).

4.2.1 Funding programmes for district heating in Germany

The comparison of current and future costs between individual benchmark technologies and decarbonised district heating systems shows that grid-based solutions induce higher costs in most cases (Figure 18, Figure 19 and Figure 20). Public funding is therefore needed to exploit the climate protection potential of district heating. Various promotional instruments exist on all administrative levels from the EU, over the level of national and federal states, down to districts and municipalities. Long-established and important instruments on national level are the "Combined Heat and Power Act (*Kraft-Wärme-Kopplungs-Gesetz,* KWKG)" and the "Market Incentive Programme (*Marktanreizprogramm,* MAP)". Under the KWKG, new construction and extension of district heating networks and thermal energy storage are funded without requiring minimum shares of renewable energy (KWKG 2015). The MAP grants redemption loans for renewable heat generation units and district heating networks with required minimum shares of renewable energy (BMWi 2019d). Funds from these two programs are used to a large extent. However, their impact on the expansion of decarbonised district heating networks is evaluated sceptically. They are criticised not to be sufficient in their extent, having too many technical restrictions, being too fragmented by aiming on specific cases and components and aiming mainly on small projects (Schneller et al. 2017; Pehnt et al. 2017). In reply to this critical review, the BMWi has launched the new funding programme "Pilot Projects 4th Generation District Heating (*Modellvorhaben Wärmenetzsysteme 4.0*)" that aims on an integrated promotion of district heating projects with at least 50 % of CO_2-free heat (BMWi 2019e). Besides financial support for the realisation of such projects, the funding starts at the planning stage for carrying out a feasibility analysis. Although the programme is aiming on the realisation of new networks and the transformation of existing grids in the same way, scientists see demand for an extra funding programme exclusively for the transformation of existing grids (Agora Energiewende 2019). Particularly, required measures and installations for the transformation on the customer side have not been covered by any programme yet and need to be addressed by additional funding (Fritz and Pehnt 2019). Another factor that impedes the decarbonisation of district heating systems is the role of the PEF and the method for its determination (Section 1.2.5). Low PEF values are incentivised via the EnEV and allow to obtain favourable loans for the construction or refurbishments of energy-efficient buildings from the state-owned bank KfW. However, the currently applied electricity credit method leads to low PEF values for heat from CHP plants, regardless of whether these are based on fossil fuels or not (Pehnt et al. 2018).

4.3 Effects on value added and employment

Besides economic efficiency by means of lowest costs, effects on value added and employment are of relevance for the economic assessment of district heating. After Hirschl et al. (2015), effects on value added summarise the impact on:

1. Net profit of involved companies
2. Net income of involved employees
3. Taxes paid on profit and income

By considering only those impacts that affect companies, employees and administrative units in a specific geographical region, regional economic impacts are obtained. These are often of particular interest when assessing whether an investment or activity in a region leads to positive effects within the region or value added drains off. Critical factor in this sense is the regional residence of relevant companies. Only if stakeholders are located regionally, profits and income remain in the region.

In the analysis of the regional economic effects of renewable energy systems, corresponding value chains are separated into four stages (Hirschl et al. 2015):

1. Production of generation units and network components
2. Planning and installation
3. System operation and maintenance

4. Profits of system operators

The value adding process of each main component of a district heating system – heat generation units, distribution network and building system – can be broken down to more detailed components and steps. Value adding steps related to heat generation differ with the type of fuel and technology used. For the distribution network and building system, the component structure is mostly uniform.

Assessing the regional availability of the required products and services allows to estimate the regional share of value added. Noteworthy in this context is that almost 80 % of the investment costs for district heating networks account for planning and installation, while costs for pipes and pumps make up less than 20 % (Hirschl et al. 2011). Such specific components are produced by specialised manufactures that often do not reside where a network is constructed. On the contrary, companies for construction works are normally found in the region. Thus, large percentage of the value added by the construction and installation of a district heating system can be realised regionally (Energieagentur Rheinland-Pfalz 2018). The situation is similar for employment. At this, construction and installation have the strongest positive effect, followed by maintenance work, while energy supply companies benefit least (Blesl et al. 2018). Since municipalities often own the district heating network or the operating utility company, they have, besides tax income, extra potential to profit from district heating.

Compared to individual heating systems, district heating appears to have overall more positive effects on value added and employment. Due to a steady demand for operation and maintenance service, district heating systems create long-term plannable employment opportunities. This advantage is particularly pronounced when comparing only fossil-free alternatives of individual and district heating systems (Gröger et al. 2016). However, if the scope is extended, the positive effect of district heating systems is opposed by an expected loss of value added and employment in the sector of building services (Pfnür et al. 2016). Furthermore, district heating networks could displace natural gas networks and thus lead to a loss of revenue for the municipalities. The municipalities receive concession payments from the operator of a natural gas network, which is not the case with district heating networks (Bruns et al. 2012). Nonetheless, district heating creates positive economic effects, which are enhanced particularly on regional level if renewable or waste energy sources are used. Fossil fuels are mostly imported and their value added is lost from the regional economy. On the contrary, renewable fuel sources like biomass, biogas, solar thermal energy, geothermal energy, industrial waste energy and renewable electricity for PtH can be obtained regionally. Exploitation of these energy sources enhances energy autonomy, allows to improve the efficiency of regional material and energy flows and increases the regional value added (Energieagentur Rheinland-Pfalz 2018). Energy-related refurbishment of insulation and heating systems of buildings, which is necessary for the transformation of district heating systems, offers further potential for regional value creation (Weiß et al. 2014).

Based on a sample assessment by Blesl et al. (2018), the efficiency of investments in district heating systems for regional value added, i.e. the ratio of increased value added and invested money, is the highest in small towns with less than 20,000 inhabitants. Actual calculations of the value added and employment effects of individual heating systems and district heating systems in different scenarios show that district heating induces higher value added and employment than individual heating in every case (Dunkelberg et al. 2018). District heating has a particular regional economic advantage due to the initial investments for construction and installation of the system components. The ambitious "70/70 strategy" provides projections of regional effects on value added (Blesl and Eikmeier 2015). The aim of the strategy is for the 70 largest German cities to have a 70 % market share of district heating by 2050. The authors argue that the effect on regional value added of district heating is at least double the corresponding effect of individual systems. Again, the effect becomes more pronounced when renewable fuels, particularly biomass and biogas, are used in district heating systems. Table 3 shows the underlying figures of regional value added for each type of district heat generation technology and the network itself. The authors claim that if the strategy is implemented in the period between 2012 and 2050, regional value added will quadruple and regional employment will increase sixfold.

Table 3 – Effects on regional value added by different district heat generation technologies and the heat distribution network (Blesl and Eikmeier 2015)

	Net profit [Eur/kW]	Net income [Eur/kW]	Business taxes [Eur/kW]	Municipal share of income tax [Eur/kW]	Total value added [Eur/kW]
Solar thermal energy	15.0	30.0	3.0	2.0	**50.0**
Large-scale heat pumps	5.0	16.0	1.0	0.4	**22.4**
Power-to-Heat	1.7	5.3	0.3	0.1	**7.4**
Biogas plant	14.0	81.0	2.0	3.0	**100.0**
Biomass plant	33.0	171.0	3.0	7.0	**214.0**
Natural gas CHP plant	10.7	1.2	0.4	11.8	**24.07**
District heating network	17.7	1.2	0.4	18.9	**38.2**

4.4 Transformation of existing district heating systems

The vast majority of existing district heating networks in Germany are fossil-fuelled, have a centralised feed-in structure and flow temperatures between 90 °C and 140 °C (Pehnt et al. 2017). Consequently, they can be regarded as conventional systems. Following the decarbonisation strategy, they need to be transformed to 4th generation district heating systems. This transformation is about lowering the system temperature, increasing efficiency and integrating climate-neutral energy sources without compromising security of supply (see also Section 4.1). Particularly, lowering the temperature level plays a key role, but also poses the most challenges. Components of the network and connected buildings are laid out for the high temperature level and need to be adapted or replaced. The transformation of existing grids comprises various measures that have to be taken step by step. Paar et al. (2013) list possible steps for decreasing the systems temperature and rank them according to their required effort and their potential effect for temperature reduction. For efficiency reasons, the measures are initially aimed at achieving lower return temperatures in entire subgrids before lowering the flow temperature:

1. Decreasing of the return temperature at large-scale consumers
2. Decreasing of the return temperature at individual customers by adjusting water heating installations
3. Decreasing of the return temperature at individual customers by adjusting space heating installations
4. Decreasing of the return temperature in subgrids, e.g. by flexible supply of the subgrid from the return of the primary grid
5. Decreasing of the flow temperature at individual customers by replacing heating systems and feed them flexibly from the return
6. Decreasing of the flow temperature in subgrids

The amount of transferred heat energy via a district heating network depends on the spread between flow and return temperature. Thus, as long as this spread is not reduced, decreasing the system temperature does not require an increase in the capacity of the network pipes and pumps (Lund et al. 2018). However, this only holds true as long as new heat generation capacities can be integrated at the site of the existing plants to be replaced. If a heat source is to be integrated at a new location, its parameters should be fitted to the width of the pipes as well as the pressure and temperature of the network at that location. The effect on the overall network and the possible need for adjustments of the network hydraulics or control parameter can be very different from case to case and must be examined individually (Paar et al. 2013). Establishing hydraulically separated subgrids around newly developed energy sources can lower the barrier of their integration (Pehnt et al. 2017).

The required measures on the producer side as well as on the customer side are cost-intensive. Such costs represent an obstacle to a complete transformation. An integration of renewable energies for covering base load is usually reasonable. Beyond that, it is an individual optimisation between the reduction of GHG emissions and sustaining economic efficiency of the system (Paar et al. 2013). At this point, additional governmental funding is needed to support increased decarbonisation of existing networks (see also Section 4.2.1).

4.5 Potentials of climate-neutral energy sources for district heating

4.5.1 Biomass and biogas

Biomass and biogas are already commonly used as fuel sources of district heating systems in Germany (Section 1.2.4.). Biomass refers to any kind of biogenic material. In direct use by combustion for district heating, mainly grown wood and its residues are used. In shape of wood chips or pellets, it is used in CHP or heat-only plants, either as the only fuel source or in co-firing with coal (Paar et al. 2013). Biomass from agricultural residues like straw and the fast growing perennial grass Miscanthus are also considered as fuel sources for district heating (Soltero et al. 2018; Parajuli et al. 2015). Biogas is produced by anaerobic digestion of any kind of biomass. It can be also obtained as a by-product from waste water treatment plants and landfills with organic waste. In biogas plants, usually a mixture of manure and different co-substrates is digested. Co-substrates can be residual products like harvest residues or any kind of organic waste but also crops that are cultivated exclusively for energy production (Weiland 2010). As the digestion process itself requires process heat, the biogas produced is normally used in CHP plants on-site of the biogas plant to generate electricity and heat. For off-site use of biogas, it can also be upgraded to biomethane in a treatment process. The produced biomethane can then be fed into the gas network which already exists in many places.

District heating parameters such as temperature and pressure that can be realised with thermal power stations based on biomass or biogas are comparable to their fossil-fuelled counterparts. Thus, they do not require decreasing district heating system temperatures and their technical potential for being used in district heating systems is high (Paar et al. 2013). Usually, biomass or biogas fired CHP plants are located in rural areas, close to their feedstock. For efficient operation they require sinks for the cogenerated heat and consequently facilitate the potential of district heating networks particularly in areas away from conurbations. In combination with a storage for wood or gas, respectively, biomass and biogas plants can be operated very flexibly for covering the base load as well as peak loads.

From the economic point of view, costs of using biomass for district heating are comparable to those of natural gas, which makes biomass a potential alternative fuel source (Paar et al. 2013). Although biogas plants derive their main income from electricity production, additional income is generated when the cogenerated heat can be fed into a district heating network. This results in comparatively low prices for such heat (Herbes and Halbherr 2017). On the contrary, biomethane competes with the price of natural gas as it has same chemical properties and hence same possibilities for distribution and application. Consequently, based on the current price of natural gas, biomethane is economically not efficient without subsidies (Bowe et al. 2018).

Biomass and biogas are highly valuable resources, particularly in the context of the transition of the energy system, and they have various conflicts of use. They are highly flexible fuel sources as they can be stored, transported and used on demand. Due to this flexibility they are a potential substitute for fossil fuels in various applications. Consequently, they should be used primarily in highly efficient processes with limited alternatives to fossil fuels. Within the energy sector, such processes involve high-temperature industrial processes and the operation of CHP plants. For heating, the use of biomass or biogas in district heating CHP plants is much more efficient compared to its use in individual heating systems and accordingly should be prioritised (Gerhardt et al. 2019).

The German "Agency of Renewable Resources (*Fachagentur Nachwachsende Rohstoffe e. V.*, FNR)" claims that only half of the biomass potential has been exploited so far. According to their estimation, especially energy crops and wood from short rotation coppice offer additional potential (FNR 2016). However, biomass production requires a lot of land surface area which limits its sustainable potential for energetic use. Wood is generally a limited resource and the cultivation of energy crops conflicts with the production of food and fodder. Accordingly, in the -95 % climate protection scenario on behalf of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (*Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit*, BMU), the use of cultivated biomass is restricted and only a 10 % increase in production by 2050 compared to 2010 is assumed (Repenning et al. 2015).

4.5.2 Solar thermal energy

In Germany, solar thermal energy is mainly used through decentralised roof collectors as an additional heat source for space heating and hot water preparation. In contrast, the use of solar thermal energy for district heating is not yet widespread. Due to its dependency on the weather, all types of solar heating systems must be combined with other heat generation technologies or thermal energy storage (Stryi-Hipp et al. 2015). In the light of this, district heating systems are an efficient approach for using solar thermal energy. District heating networks offer possibilities for integrating large thermal energy storage and combining different types of heat sources. Nonetheless, a disadvantage of solar thermal heating systems is that heat generation capacity and efficiency is seasonally contrary to heat demand. In winter, sun irradiation is low but heat demand is high. Moreover, with increasing difference between the outside temperature and the temperature of the collector, the collector's efficiency is decreasing. This is why solar district heating systems are usually laid out to cover only the summer heat load or they are combined with large seasonal storage. Accordingly, typical solar thermal fractions of solar district heating systems range between 10 % and 50 % of the system's total heat supply (Pauschinger 2016). If a solar thermal plant is combined with waste heat or a CHP plant that is primarily used to generate electricity, the solar thermal heat should not drive out the other heat that is generated anyway. On the other hand, if the electricity grid is saturated with electricity from PV or wind energy and CHP plants are not in operation, solar thermal heat can drive out heat from fossil-fuelled peak load boilers (Sperber and Nast 2014). Solar thermal collectors are available as flat plate collectors and evacuated tube collectors. Flat plat collectors can heat the heat transfer medium up to 80 °C and evacuated tube collectors can even reach 120 °C. However, the efficiency of solar thermal systems increases with decreasing system temperatures (Paar et al. 2013).

Pioneer in the area of solar district heating is Denmark with an unrivalled installed capacity of 957 MW by the end of 2018 (Weiss and Spörk-Dür 2019). Yet in Germany, the market for solar district heating is growing, too. In 2019, 34 large-scale solar district heating plants with a thermal capacity of 44 MW were in operation and until 2023, the installed capacity is expected to double (Solites 2019). This growth results from cost reductions that have become effective in the last years (Perez-Mora et al. 2018). As solar district heating does not incur fuel costs, investment costs are decisive for its economic efficiency. Specific investment costs are decreasing with increasing plant size and very large solar district heating systems might already be competitive with those based on natural gas (Gerhardt et al. 2019).

Large-scale solar thermal collectors require large, non-shadowed open areas. Consequently, they conflict with any other use of open landscape, as the use for PV plants or agriculture for food, fodder and energy crops. In terms of energy generation, however, solar thermal plants are highly efficient. The area-specific energy yield of large-scale solar thermal plants is 50-times higher than of biomass cultivation (Nitsch et al. 2012). Availability of large open areas is generally better in rural areas than in densely built-up urban areas and thus contrasts with the heat demand density. Whereas in urban areas the free space is quite limited and solar district heating usually requires long connection pipes, in rural areas affordable space is mostly easy to find. Overall, although no detailed GIS-based area potential analysis for Germany has been undertaken so far, it is assumed that space is not a limiting factor for solar thermal energy (Gerhardt et al. 2019; Kunz and Kirrmann 2016). Accordingly, combined with the assumption of competitive prices, the potential of solar district heating is only limited by the district heating demand and the achievable solar thermal fraction (Jochum et al. 2017). Additional potential of solar thermal energy in district heating might arise from a strongly decentralised feed-in structure with grid-connected buildings that act as prosumers. They consume heat from the grid when demanded and feed-in excess heat generated by own roof-mounted solar thermal collectors (Reiterer et al. 2014). In this case, the grid functions as thermal energy storage for the building system.

4.5.3 Deep geothermal energy

Geothermal energy can be divided into two classes. Above the depth of 400 m, the term near-surface geothermal energy is used. Temperatures of near-surface geothermal energy reach up to 25 °C only, which requires additional heating for its utilisation for district heating. This additional heating is mostly provided by heat pumps and is therefore a PtH application discussed in Section 4.5.6. Geothermal energy below 400 m, called deep geothermal energy, is discussed in this section. Deep geothermal energy can be extracted from hydrothermal reservoirs by drilling into a hot aquifer and pumping up the hot water. Where no water is available, geothermal heat can be extracted by the hot dry rock method. However, this approach hasn't been studied exhaustively yet and in the middle term it is expected that hydrothermal energy will be the predominating approach for the utilisation of deep geothermal energy (Bracke 2014). Consequently, the following potential analysis is limited to hydrothermal energy.

The utilisation of deep geothermal energy in Germany has been extended strongly in the last 20 years: from 23 MW_{th} in 1999 up to 346 MW_{th} in 2018 (LIAG 2019). In 2019, 37 deep geothermal systems for heat and electricity production were in operation and another 30 systems were in the planning stage (Bundesverband Geothermie 2019). The potential of deep geothermal energy is determined by its theoretical availability, its technical accessibility, the spatial correlation of accessibility and demand and its economic efficiency. In order to be a suitable energy source for district heating, hydrothermal reservoirs must have a sufficiently high temperature. In this sense, decreasing temperatures in district heating systems allow the direct utilisation also of reservoirs with lower temperatures. Accordingly, potential areas are defined by the existence of hydrothermal reservoirs with temperatures above 40 °C. In Germany, the main areas fulfilling this criterion are the North German Basin, the Upper Rhine Graben and the South German Molasse Basin (Figure 21). These three areas together have a theoretical potential of 420.000 TWh of which approx. 1.4000 TWh per year is technically accessible (Kock and Kaltschmitt 2012). The assessment of the utilisation potential, which is determined by the spatial correlation between technical accessibility and demand, varies between different studies. Agemar et al. (2018) specify the potential to 17 % of the total German heat demand in 2050, with large industrial customers accounting for a large share. Jochum et al. (2017) take only residential buildings into account and conclude that 8-10 % of the heating energy demand could potentially be covered by district heating with deep geothermal energy in 2050. However, considering economic efficiency, they claim that less than half of this potential can be exploited. As the drilling incurs high investment costs, deep geothermal energy is particularly suitable for larger district heating networks (Kayser and Kaltschmitt 1998). In district heating systems, deep geothermal energy is predestined to cover the base load, as it is constantly available. On the other hand, its use to cover peak loads is generally not economical due to the high investment costs (Paar et al. 2013). The actual costs depend on the quantity of heat energy extracted per borehole and range between 25 Eur/MWh and 115 Eur/MWh (Jochum et al. 2017).

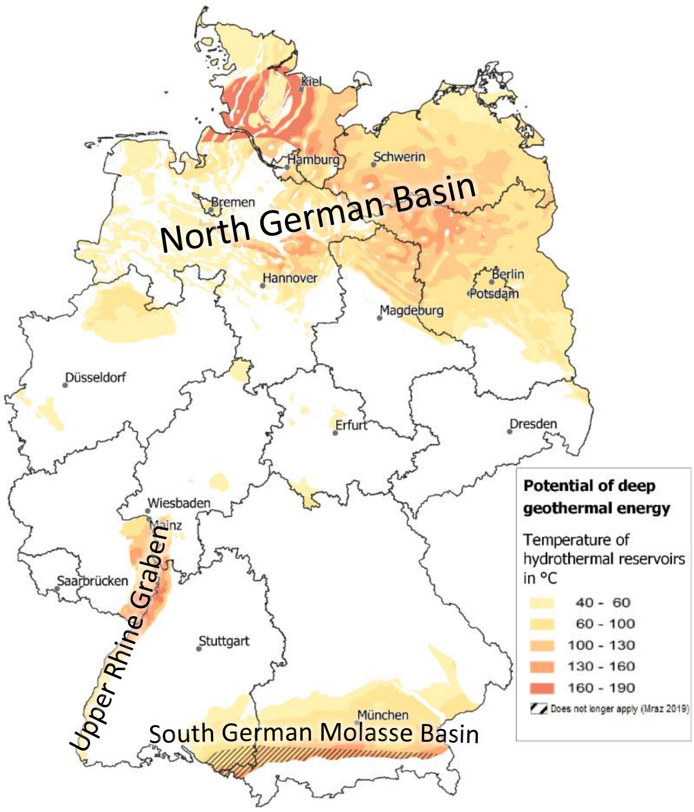

Figure 21 – Regions with potential of deep geothermal energy visualised by the temperature of hydrothermal reservoirs (LIAG 2019; GeoBasis-DE / BKG 2019)

4.5.4 Thermal waste treatment

In waste-to-energy plants, MSW, industrial waste and sewage sludge are incinerated for reducing the volume of waste and recovering chemically bound energy. If the plant is built with CHP technology, generated heat is usually used for district heating. Waste is constantly produced and the 96 waste-to-energy plants in Germany work at full capacity (ITAD 2019). Thus, using the generated heat in district heating systems is mostly suitable for covering the base load. Since the heat is generated anyway, priority should be given to its use. Heat from waste-to-energy plants already accounts for approx. one third of the German district heating and the biogenic part of waste is the most important renewable fuel source (Section 1.2.4). The average fossil share of waste is approx. 64 % (Repenning et al. 2015). Consequently, the incineration of mixed waste inevitably causes emissions of fossil CO_2. However, the waste accrues independently from its energetic utilisation and compared to landfilling, incineration reduces the global warming potential (Istrate et al. 2020). Thus, as long as non-recyclable waste is generated, waste incineration is necessary and allows the recovery of its energy contained. Nonetheless, the quantity of waste incinerated in waste-to-energy plants is expected to decrease due to a higher rate of recycling and direct combustion in industrial processes. According to Repenning et al. (2015), the input of waste for electricity and heat generation will decline by 44-48 % until 2050. Following this assumption, Gerhardt et al. (2019) quantify the potential share of waste incineration for district heat generation to 13.7 TWh in 2050. Depending on the refurbishment rate, this represents a share of 6-11 % of the total district heating potential.

4.5.5 Industrial waste heat

In various industrial processes heat is generated. Examples are industrial furnaces, drying, melting and distillation processes, but also processes in dairies, bakeries, laundries and data centres. In this processes occurrence of excess heat is often unavoidable due to technical reasons. The otherwise lost heat can, for example, be used for district heating. The utilisation of waste heat improves the overall system efficiency. So far, however, waste heat is only used to a very small extent (AGFW 2019a). Although waste heat is not renewable heat in its classical sense it is generated anyway and consequently is considered as climate-neutral, just like heat from thermal waste treatment. However, excess heat should be used for district heating only after exploiting all options for heat loss reduction and internal recycling (Pehnt et al. 2010). Generally, waste heat occurs independently from season, weather and the heat demand in a district heating system. Consequently, it is best suitable for covering the base load of district heating systems (Paar et al. 2013).

In the project “NENIA”, Blömer et al. (2019) have analysed the potential of using industrial waste heat for district heating in Germany. Based on reported data on fuel use and exhaust gas emissions, they found the theoretical potential of waste heat to be 63 TWh. The technical potential is derived from the spatial and temporal correlation of heat supply and demand. Therefore, the availability and location of found waste heat sources were compared to the location of existing district heating systems and areas with potential for new district heating systems. Result of this step is a technical potential of 23-29 TWh in the year 2030, representing 12-15 % of the total potential district heating demand. Slightly more than half of this potential is located in areas that have potential for district heating but not yet existing infrastructure. The potential is concentrated in the industrial Rhine-Ruhr area and apart from that, it is widely spread with hot-spots at larger cities. The actual technical potential depends on the future system temperatures. Lower temperatures in district heating systems allow to incorporate more sources of waste heat and thus increase the potential.

Costs for utilising waste heat accrue due to investments in required heat exchangers, equipment for measurements and control, connection pipelines and planning services (Paar et al. 2013). The individual economic efficiency of a project depends on the distance between heat sources and sinks, specific costs for connection pipes, and the quality of the heat sources, meaning their temperature and availability (Blömer et al. 2019). The respective analysis shows that at reference costs of 80-120 Eur/MWh, large shares of 80-95 % of the technical potential can be exploited economically efficient without subsidies. The resulting total economic potential of using industrial waste heat for district heating in Germany amounts to 10 TWh in existing district heating networks and an additional 9-11 TWh in potentially new district heating networks. This economic potential corresponds to 15 % of the district heating demand in already existing networks and 7-8 % of the additional network potential (Blömer et al. 2019).

4.5.6 Power-to-Heat

Power-to-Heat (PtH) refers to the use of electric energy to generate heat by means of heat pumps or resistive heaters (Bloess et al. 2018). For district heating systems, large-scale PtH units are available. Resistive heaters and heat pumps differ in their cost structure, efficiency, flexibility and in their resulting best suited applications. Resistive heaters have low investment costs and are very flexible to operate. Their energy conversion process achieves an efficiency of up to 99 % (Mollenhauer 2019). Heat pumps are less flexible and have high investment costs. The advantage of heat pumps, however, is that they do not convert electric energy directly into heat. Instead, they extract additional thermal energy from the environment and release it at a higher temperature. Possible heat sources for large-scale heat pumps are sewage water, surface water, industrial waste heat, geothermal water, flue gas, district cooling networks and thermal energy storage (David et al. 2017). By using ambient heat, heat pumps achieve an efficiency of far more than 100 % in relation to the input of electric energy. The value of this efficiency is called coefficient of performance (COP) and depends on the temperature of the cold reservoir and the temperature lift. For example, a large-scale heat pump currently achieves a COP of about 4.8 at a temperature increase from 10 °C to 50 °C (Gerhardt et al. 2019). The COP decreases with increasing temperature lift. In addition, large-scale heat pumps achieve higher COPs than heat pumps of individual heating systems for the same temperature lift. It is also expected that the performance can be improved further in the future. Correspondingly, the use of large-scale heat pumps in district heating systems and decreasing flow temperature increase the efficiency of heating with heat pumps (Gerhardt et al. 2019). Due to their high efficiency and high investment costs, heat pumps are best suited to cover the base load in district heating systems. Whereas, highly flexible resistive heaters with low investment costs are best employed to cover peak loads (Bechem et al. 2015). The environmental performance of PtH depends primarily on the energy source of the electricity used. Since the German electricity mix still includes large shares of fossil fuels, permanent operation of resistive heaters and heat pumps cannot be considered as climate-neutral. This picture changes when PtH is used as an instrument for coupling of the electricity and heat sectors. During times when congestions in the electricity distribution networks occur or the market price of electricity drops below zero, the generation of electricity from renewable energy sources, in particular from wind turbines, is reduced. In 2018, the amount of reduction in generation due to network congestions alone was 5.4 TWh or 2.8 % of the total amount of renewable electricity generated (Bundesnetzagentur and Bundeskartellamt 2020). This otherwise lost electricity can be utilised by PtH units. The surplus heat can replace heat from other preferentially finite resources like coal, natural gas and also biomass and renewable gases (Kunz and Kirrmann 2016). The effect becomes even greater if surplus heat can be stored in thermal energy storage. In addition, PtH systems can also provide operating reserve for control of the electricity network and thereby replace "must-run-capacity" of fossil-fuelled power plants (Agora Energiewende 2014).

In general, the potential of PtH for district heating depends mainly on the cost of electricity. For heat pumps, the availability of sufficient heat sources is also a determining factor. In Germany, the market share of PtH in district heating is still small and centred around resistive heaters. So far, large-scale heat pumps have been installed in small demonstration projects only (Pehnt et al. 2017). High initial investments costs have led to reluctance to use large-scale heat pumps. For resistive heaters, provision of operation reserve is the main field of profitable application (Agora Energiewende 2014). On the contrary, using excess electricity in PtH systems is currently not economically feasible. This is mainly due to taxes and reallocation charges under the "German Renewable Energies Act (*Erneuerbare-Energien-Gesetz,* EEG)" levied on operators of PtH systems regardless if they use self-generated or external electricity (Christidis et al. 2017). The application as a sector coupling instrument requires PtH units with highly flexible loads and low fixed costs and therefore favour the use of resistive heaters. Heat pumps have generally lower variable operation costs and depend less on the price for electricity. Nonetheless, efficient operation of large-scale heat pumps solely with excess electricity is only possible if such excess electricity is available for longer periods of time, which is not the case yet. Accordingly, Brischke et al. (2012) claim to accelerate the expansion of heat pumps not before at least 50 % of the German electricity is generated from renewable energy sources. Provided that burdens by taxes and fees are reduced, the amount of surplus production of electricity determines the PtH potential. For 2023, Agora Energiewende (2014) expects a potential of 2.8 TWh of electricity suitable for PtH due to negative electricity prices. Combined with the amount of electricity generation reduction due to network congestions, the total potential results to 8.2 TWh. However, this potential highly depends on the expansion of the electricity transmission network and generation capacities of renewable energies. An accelerated network expansion will reduce the need for generation reduction due to network congestions. On the other hand, higher shares of renewable generation capacities like wind turbines and PV plants will increase the volatility of the energy system and lead to more and longer periods of times with excess generation. Moreover, with increasing sector coupling, the potential of PtH will be reduced since the use for heat will compete for the excess electricty with other PtX technologies like Power-to-Gas (PtG). If, however, running PtH units becomes economically competitive through further funding, even in times of regular electricity prices, the potential will increase accordingly. Gerhardt et al. (2019) yet assume that using large-scale heat pumps is economical at any time. Therefore, they limit the potential only by the availability of heat sources for heat pumps. As such, they consider near-surface geothermal energy, surface water bodies, sewage water and to a small extend drainage water from coal mining and come to a resulting potential of 57-77 TWh or 33-45 % of the total district heating potential in 2050 (Gerhardt et al. 2019).

4.5.7 Thermal energy storage

Besides the mere replacement of fossil fuels by renewables, the integration of thermal energy storage plays an important role for the transformation of district heating systems. In this regard, thermal energy storage has no end in itself but supports the full exploitation of the potential of different alternative fuel sources and enhances their effect on the overall emission reduction. Basically, in district heating systems, thermal energy storage has two cases of application. At first, thermal energy storage allows the decoupling of demand and supply. Heat demand changes seasonally depending on the outdoor temperature and is also varying during the day with peaks in the morning and the evening (Eller 2015). In district heating systems with thermal energy storage, peak load capacities can be reduced as peak loads can be covered by heat stored during off-peak hours (Gadd and Werner 2015). As discussed in the previous sections, most climate-neutral heat sources cannot be controlled following the varying demand. In fact, heat supply is subject to variations itself or generation units must be operated at full capacity to be economically efficient. Long term balance of supply and demand by a storage system is of particular importance in the case of district heating systems with high solar thermal fractions. These have the highest heat supply in summer, while the heat demand is highest in winter (Carpaneto et al. 2015). The second field of application of thermal energy storages is their use as an instrument in the coupling between the sectors of electricity and heat. As the share of renewable electricity generation increases, the market experiences greater fluctuations in supply, which are reflected in fluctuating prices. This affects district heating systems with CHP and PtH technology. In district heating systems with CHP plants and thermal energy storage, the CHP plants can run during times of low electricity supply and high prices and thereby fill the thermal energy storage. During times of high electricity supply with high shares of wind or solar energy, CHP units can be shut down and the heat demand can be covered from the storage. As CHP plants are usually based on fossil fuel, this also reduces emissions of CO_2. In combination with PtH units, cheap electricity can be used to generate heat and store it for later use (Christidis et al. 2017).

Various types of thermal energy storage exist. They can be differentiated by their temperature level, duration of storage, physical principle of storage and storage medium (Fisch 2005). Mostly used in district heating systems are water based storage systems that store heat as sensible heat either in pressure tanks or at atmospheric pressure. Heat storages with pressurised water can be operated at temperature of 120-130 °C, pressureless systems up to the atmospheric boiling point of water of 100 °C. Whereas pressure tanks offer higher storage density, pressureless storages are less costly and allow for larger storage volumes (Wünsch et al. 2011). Other existing heat storage technologies based on latent heat or thermochemical energy are still in the research stage with high development potential expected (Bechem et al. 2015). Regarding the duration of storage, it can be differentiated between short-term or daily storages and long-term or seasonal storages. Daily storages are usually laid out to store heat for 12-14 h at maximum load of the district heating system. Mostly, they are implemented as water tanks and used to balance daily variations of heat load and generation in combination with CHP units (Stryi-Hipp et al. 2015). Seasonal storages have storage cycles of several months and are primarily used in district heating systems with large solar thermal plants. With large capacities, they allow to reach solar fractions of more than 50 % (Bauer et al. 2010). Types of seasonal thermal energy storages comprise buried or above-ground large tanks, pit thermal energy storages, aquifers and borehole heat exchangers (Olsthoorn et al. 2016). Thermal loss of thermal energy storage systems is lower than 5 % for short-term and about 30 % for long-term storages (Guelpa and Verda 2019).

Short-term thermal energy storage systems in district heating systems with cogeneration are already established on the market. On the other hand, long-term storage systems are impeded by high investment costs in relation to few yearly charging cycles (Stryi-Hipp et al. 2015). Consequently, most thermal energy storages in district heating systems in Germany are installed in systems with CHP plants. By the end of 2019, the total installed storage capacity in such systems was about 580,000 m³ or 25 GWh (Christidis et al. 2017; BAFA 2019). Seasonal thermal energy storage exists only in pilot projects of different funding programmes. As far as known, a total of 16 of such projects have been implemented (Solites 2016). Cost reductions are a prerequisite for further expansion of seasonal thermal energy storage. A possible approach could be upscaling of projects, since specific investment costs decrease with increasing storage volume (Xu et al. 2014). Denmark again is a good example in this context. While in Germany, projects had specific costs of more than 100 Eur/m³, Danish projects have realised larger storage volumes and could achieve costs of only 20-35 Eur/m³. If Germany succeeds in following this example, expansion of long-term storage facilities would also be possible in this country (Pehnt et al. 2017). In addition, the space requirement for large-scale seasonal storage facilities is significant due to the low specific but high total capacity. This is particularly true for shallow pit storages and might favour their realisation rather in rural than in urban areas.

The prospective need for storage capacity is hard to quantify. From the economic point of view, sizing of storage capacity is an optimisation task of increasing investment costs and increasing return due to higher utilisation rates of electricity and heat generating units in the system. Sterner and Stadler (2019) provide detailed findings from the "REMod-D" model by Henning and Pfalzer (2013). This cost optimizing simulation of the entire German energy system aims at an 85 % reduction of CO_2 by 2050 compared to 1990. As a result, the model shows that in district heating systems, thermal energy storage with a total capacity of 641 GWh will be required by 2050. If implemented as water based storage this is equivalent to 25 mil. m^3 of water. With the more ambitious climate target of climate-neutrality, this result will probably be even higher. In any case, the result shows that the expansion potential of thermal energy storage in district heating systems is immense.

4.5.8 Summary

The analysis in the previous sections has shown that, with the exception of thermal waste treatment, all considered energy sources have theoretically high additional potential to be exploited. Nevertheless, the actual potential for each individual district heating system depends on local availability. This can vary greatly between different regions and places, as it is the case with deep geothermal energy or industrial waste heat. Another limiting factor can be a lack of space, as it is the case with solar thermal energy or large thermal energy storage facilities. Biomass and biogas are very suitable to replace fossil fuels but are subject to a conflict of use, plus their supply conflicts with the production of food and fodder. From a climate protection perspective, heat from waste incineration plants is only partially favourable and its supply will decline in the future. PtH is a promising technology for supplying climate-neutral district heat, but depends to a large extent on the expansion of renewable electricity generation. It should be noted that the potentials examined may not locally coincide with the district heating potentials. This can lead to concentrated potential at one location, while elsewhere the potential for heat generation remains below the district heating potential. Regarding their application, different energy sources may displace each other in covering the base load. For example, during times of high solar irradiation, solar thermal energy might drive out heat from a biomass fuelled CHP plant. Thereby the overall system's efficiency is decreased. The use of thermal energy storage can reduce this effect and generally helps to raise the potential of the various energy sources. Overall, the technically accessible potential seems to be sufficient to cover the district heating potential. However, strongest limiting factor for the level of the respective actual potential is the profitability of its exploitation.

In the scenario of 95 % GHG emission reduction compared to 1990, Gerhardt et al. (2019) come to the result that the economic potential of renewable energy sources is sufficient to cover at least 86 % of the district heating potential in 2050. Including solar thermal energy for urban areas via long connection lines, this potential is even increased to 154-156 %. Gerbert et al. (2018) have also analysed the potentials of district heating and its different energy sources. Using a cost-optimizing approach, a district heating mix is composed for different climate protection scenarios (Figure 22). Striking result in the ambitious 95 % GHG Reduction Scenario is that the mix shows a strongly increasing share of PtH until 2050. Also increasing are solar thermal energy, geothermal energy and industrial waste heat. The use of biomass is slightly reduced. Although the share of gas strongly decreases, in 2050 a total of 23 TWh remain and will be totally covered by gas from PtG.

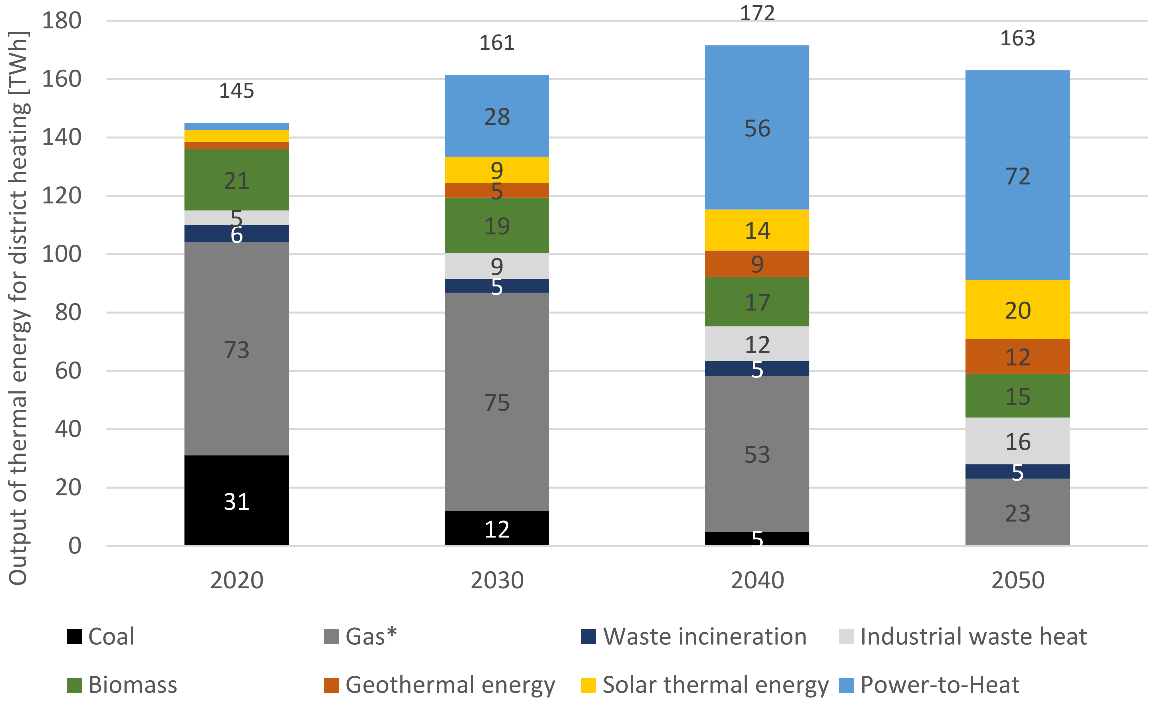

Figure 22 – Development of the German district heating mix in the 95 % GHG Reduction Scenario. *Natural gas is progressively replaced by gas from PtG, up to 100 % in 2050 (Gerbert et al. 2018)

5 Potentials for Climate-Neutral District Heating in the Region of Lusatia until 2038

5.1 Policy strategies

The development in the heating market depends on political strategies that form the framework for action. Public investments in infrastructure and funding programmes highly influence the extent to which climate-neutral district heating will play a future role. Administrative levels relevant for Lusatia in this regard are the federal states of Brandenburg and Saxony, the regional planning groups Lusatia-Spreewald (*Regionale Planungsgemeinschaft Lausitz-Spreewald*) and Upper Lusatia-Lower Silesia (*Regionaler Planungsverband Oberlausitz-Niederschlesien*), the seven districts and 244 municipalities of the study region. Strategies, concepts, programmes or plans exist on all these levels. On the level of the federal states, Brandenburg has passed the "Energy Strategy 2030 (*Energiestrategie 2030)"* in 2012 and Saxony the "Energy and Climate Programme (*Energie- und Klimaprogramm)"* in 2013 (MWE 2012; SMWA and SMUL 2013). The Energy Strategy 2030 of Brandenburg announces the target of covering 39 % of the energy demand for heating by renewables. However, beyond the expansion of PtH it does not specify measures to achieve this goal (MWE 2012). The Energy and Climate Programme of Saxony does not mention any comparable target. It focuses on the expansion of efficient CHP technology but recognises little potential for expanding district heating networks as additional heat sinks. Establishing thermal energy storage, the use of industrial waste heat and local heating networks are mentioned as possible measures (SMWA and SMUL 2013). The final report of the "Coal Commission" does not go into detail in regards to district heating, but calls for the establishment of living labs in the field of "green district heating". As one of the projects to be supported, the development of a long-term thermal energy storage in combination with PtH is proposed for Saxony (BMWi 2019b).

The borders of the two regional planning groups correspond exactly to the borders of the study region; Lusatia-Spreewald on the Brandenburg side and Upper Lusatia-Lower Silesia on the Saxon side. The planning horizon of the "Regional Concept for Energy and Climate Protection (*Regionales Energie- und Klimaschutzkonzept*)" of Upper Lusatia-Lower Silesia from 2012 only extends to the year 2020. During this period, no structural changes of the existing district heating supply are expected. In the planning scenarios, district heating is only used in medium-sized towns, whereas it plays no role in small towns and rural communities. The major share of district heating is generated in CHP plants fired by natural gas. It is not considered appropriate to replace the CHP plants in the medium term (RPV Oberlausitz-Niederschlesien 2012). For the "Regional Energy Concept (*Regionales Energiekonzept)"* of Lusatia-Spreewald from 2013, a detailed analysis of the heating network potentials at the community level was carried out. As a result, 23 municipalities are very well suited for district heating, including Cottbus, Schönefeld, and Guben as the top three. Nonetheless, the analysis focuses on the exploitation of potentials from cogeneration. The integration of renewable energy sources into district heating networks beyond biomass and biogas is not considered (RPG Lausitz-Spreewald 2013).

Most of the municipal energy concepts examined for this thesis find that the grid-based heat supply is coming under pressure due to decreasing population and heat demand. Municipalities plan to increase the connection rate within existing district heating supply areas but often do not consider network expansions to be economically viable, e.g. in Finsterwalde (Stadt Finsterwalde 2013). In some places even the dismantling of heating network infrastructure is considered necessary, e.g. in Lübbenau (Stadt Vetschau et al. 2011).

Almost exclusively heat from CHP plants is considered as a possible energy source. CHP plants are also the preferred option in case of planned investments in new heat generation capacities, e.g. in Forst (Stadt Forst 2010). The energy concept of the LEADER region of West Lusatia describes that heating networks support the integration of renewable energies and energy efficiency. Nevertheless, it demands to give priority to heat from CHP plants with optional biomass use or in combination with large solar thermal plants (Region Westlausitz 2009).

The most comprehensive municipal concept for district heating in Lusatia was presented by the city of Cottbus in 2013 (Stadt Cottbus 2013). The overall objective of the "Municipal Energy Concept *(Kommunales Energiekonzept)*" is to maintain, expand and secure the efficiency of the district heating system which is the largest in Lusatia. In that respect, an increase in the number of connections in the existing coverage area is intended to compensate for the decline in individual heating requirements. Depending on the existing network and generation capacities, new districts with high heat demand densities are also to be developed. For this purpose, a potential analysis of high spatial resolution was carried out. Thereby, two new potential areas were identified that can be developed in an economically efficient manner. On the generation side, central components of the district heating system in Cottbus are a large CHP plant and additionally the coal power plant in Jänschwalde. The energy concept is based on the assumption that the coal power plant Jänschwalde will continue to supply heat long term. In the light of phasing out coal, however, current agreements provide this only until 2032 (rbb 2019). Deviating from the Energy Concept from 2013, it was decided in 2018 to modernise the CHP plant, to integrate thermal energy storage and to convert the fuel from lignite to natural gas (Stadtwerke Cottbus GmbH 2018). Still, district heating in Cottbus will continue to be provided mainly from fossil energy in the long term. Only in areas outside of the main network area, smaller local heating networks which operate on the basis of biomass or geothermal energy are suggested by the concept.

5.2 Potential of grid-based heat supply in Lusatia

Basis of the estimation of the district heating's prospective potential in Lusatia is the future development of the heat demand. As described in Section 2.2 on the model methodology, the projection of energy consumption for space and water heating until 2038 was made for households and the TCS sectors in two different climate protection scenarios – Trend and Goal. In the Trend Scenario the total final energy consumption is reduced by 30 % and in the Goal Scenario by 34 % compared to 2018. Looking at the two sectors separately, the relative decline in heat demand is much more pronounced in the TCS sector (Figure 23).

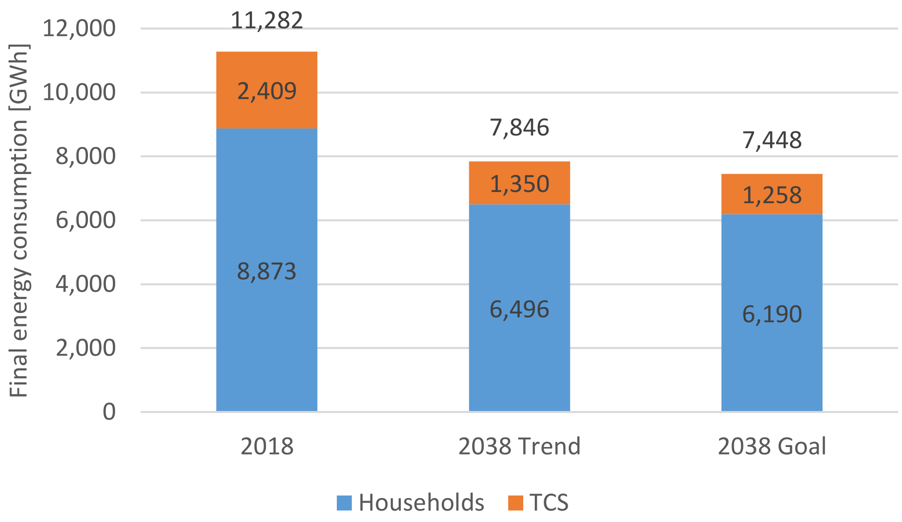

Figure 23 – Final energy consumption for space and water heating by households and the TCS sector in the base year 2018 and for 2038 in the scenarios Trend and Goal (own calculations based on references as provided in Section 2.2)

The summarised result of the GIS-based potential analysis is shown in Figure 24. The resulting potential can be divided in three fractions:

1. District heating to be conserved due to the network conservation strategy although the other potential criteria are not met
2. Potential that is already covered by existing district heating supply
3. Potential for the expansion of district heating

Furthermore, the results include the amount of district heating from networks that are to be dismantled since their existing and potential size is too small.

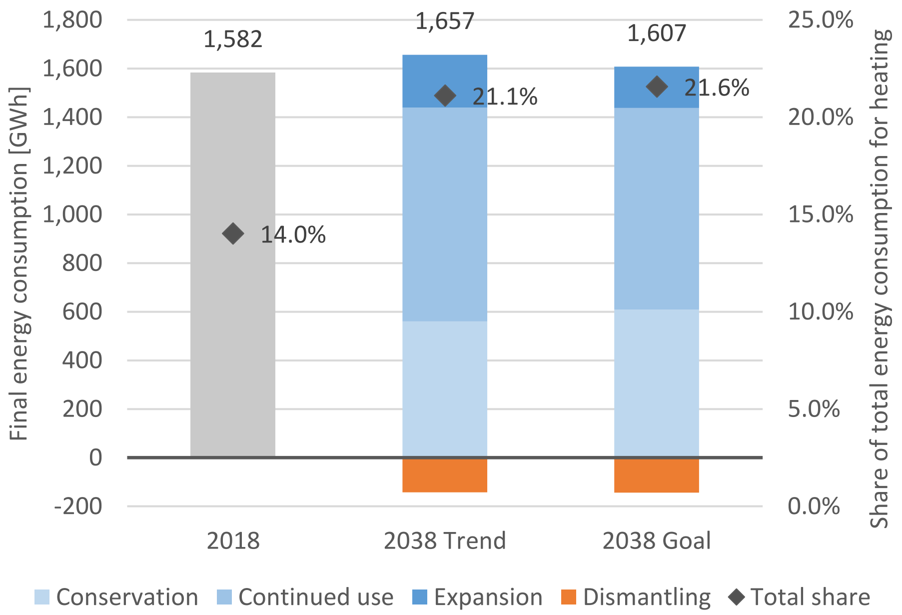

Figure 24 – District heating in 2018 and district heating potential in 2038 in the scenarios Trend and Goal (own calculations based on references as provided in Section 2.2)

In both scenarios for 2038, the potential for total final energy consumption by district heating exceeds the amount of district heating in 2018 only slightly with 1.657 GWh in the Trend Scenario and 1.607 GWh in the Goal Scenario. Since the total final energy consumption for heating will be reduced in 2038, the relative share shows a significant increase up to 21.1 % and 21.6 % in the scenarios Trend and Goal, respectively. The district heating potential in the Trend Scenario is higher, since in this scenario less energy savings are achieved and therefore, the heat demand densities are generally higher than in the Goal Scenario.

Looking at the different fractions, about 34 % of the total district heating in the Trend Scenario and 38 % in the Goal Scenario are continued on the basis of the network conservation strategy. Already existing district heating supply in areas that meet the other potential criteria makes up a share of 53 % of the total potential in the Trend Scenario and 52 % in the Goal Scenario. In the Goal Scenario, more district heating is covered by the conservation strategy because fewer areas meet the potential criteria on density and size. The sum of existing district heating that is further used, either because of the conservation strategy, or because the other potential criteria are fulfilled, is about the same in both scenarios. It amounts to 1.440 GWh. Accordingly, the amounts of district heating lost due to network dismantling are also close to each other in both scenarios at about 144 GWh. The potential for district heating expansion in the Trend Scenario is 217 GWh. This is a sight higher than in the Goal Scenario with 169 GWh.

The spatial distribution of the determined potential over the study area shows, that the potential is concentrated in some municipalities, while most municipalities have very little or no potential (Figure 25). In the Goal Scenario, 51 municipalities have a potential of at least 5 GWh/a, 25 municipalities have a potential of at least 20 GWh/a, but 181 municipalities have no potential at all. In the same scenario, the five municipalities with the largest potential are Cottbus (317 GWh/a), Hoyerswerda (134 GWh/a), Görlitz (91 GWh/a), Bautzen (81 GWh/a) and Senftenberg (51 GWh/a). However, in the case of Hoyerswerda, two thirds of the potential are only due to the conservation of district heating from 2018. Taking only the potential criteria on heat demand density and network size into account, the potential in Hoyerswerda amounts to 44 GW/h only. The highest amount of district heating per capita is found in the municipality of Ostritz with 13 MWh/a. However, this high rate is solely due to network conservation. Other municipalities that have district heating potential only due to the conservation strategy are Wilthen, Radibor and Boxberg/O.L. Among the municipalities that have potential beyond the network conservation, Cottbus has the highest potential per capita with 3 MWh/a. The results of the two scenarios Trend and Goal for all municipalities individually are listed in Appendix B.

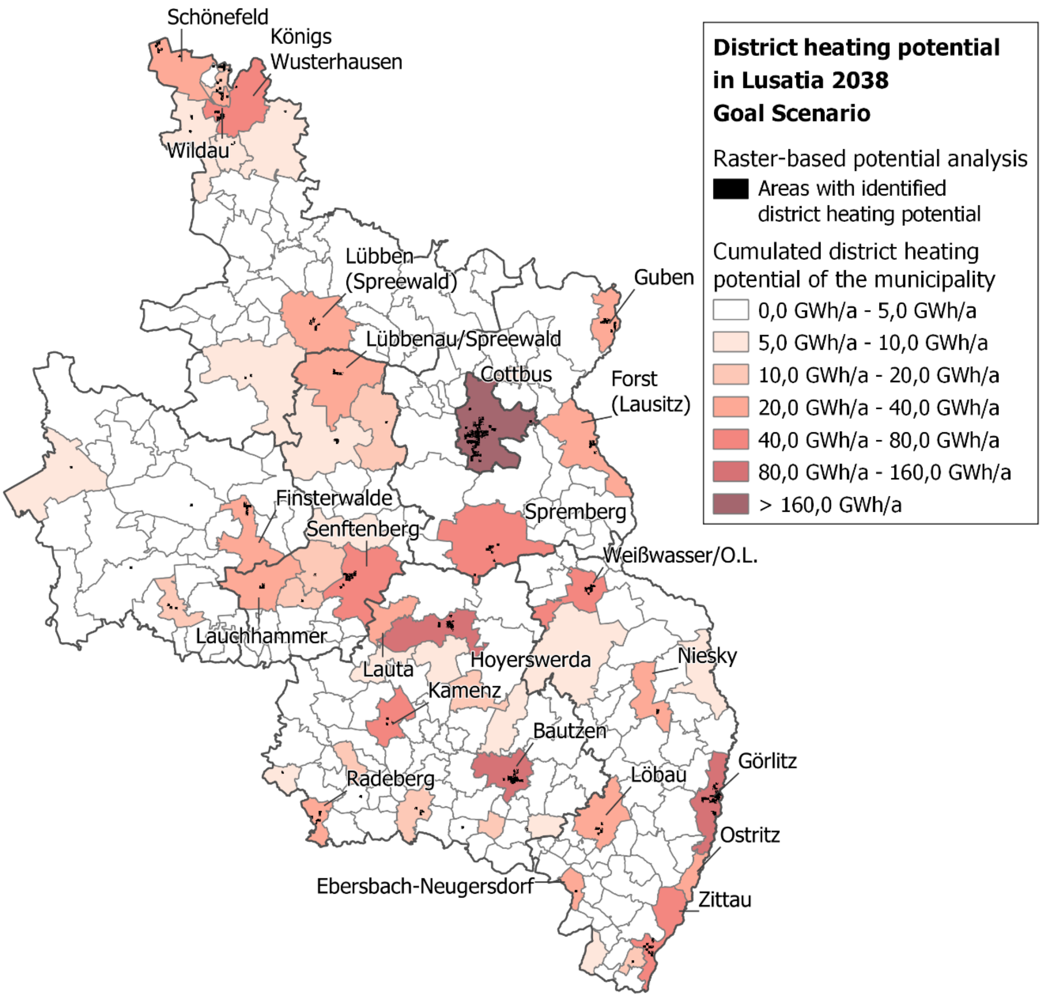

Figure 25 – District heating potential in the municipalities of Lusatia 2038 in the Goal Scenario. Municipalities with a district heating potential greater than 20 GWh/a are labelled (own calculations based on references as provided in Section 2.2; GeoBasis-DE / BKG 2019)

Figure 26 allows an assessment of district heating expansion potential in the Goal Scenario that goes beyond conservation and continuation of existing district heating supply. In addition, it also shows where existing grids are too small and must therefore be dismantled. Only 15 municipalities have potential for an increase in district heating compared to 2018. Of these, Cottbus has the highest expansion potential with 74 GWh/a. Accumulated potential for expansion is also found in the outskirts of Berlin in Schönefeld (21 GWh/a), Wildau (19 GWh/a), Eichwalde (12 GWh/a), Mittenwalde (4 GWh/a) and Königs Wusterhausen (3 GWh/a). In the Saxon districts of Lusatia, Görlitz and Bautzen, no potential for expansion was identified at all. Furthermore, existing district heating networks in 139 municipalities are smaller than the minimum size for efficient operation and should be dismantled. In the remaining 91 municipalities, the potential is unchanged from the 2018 level.

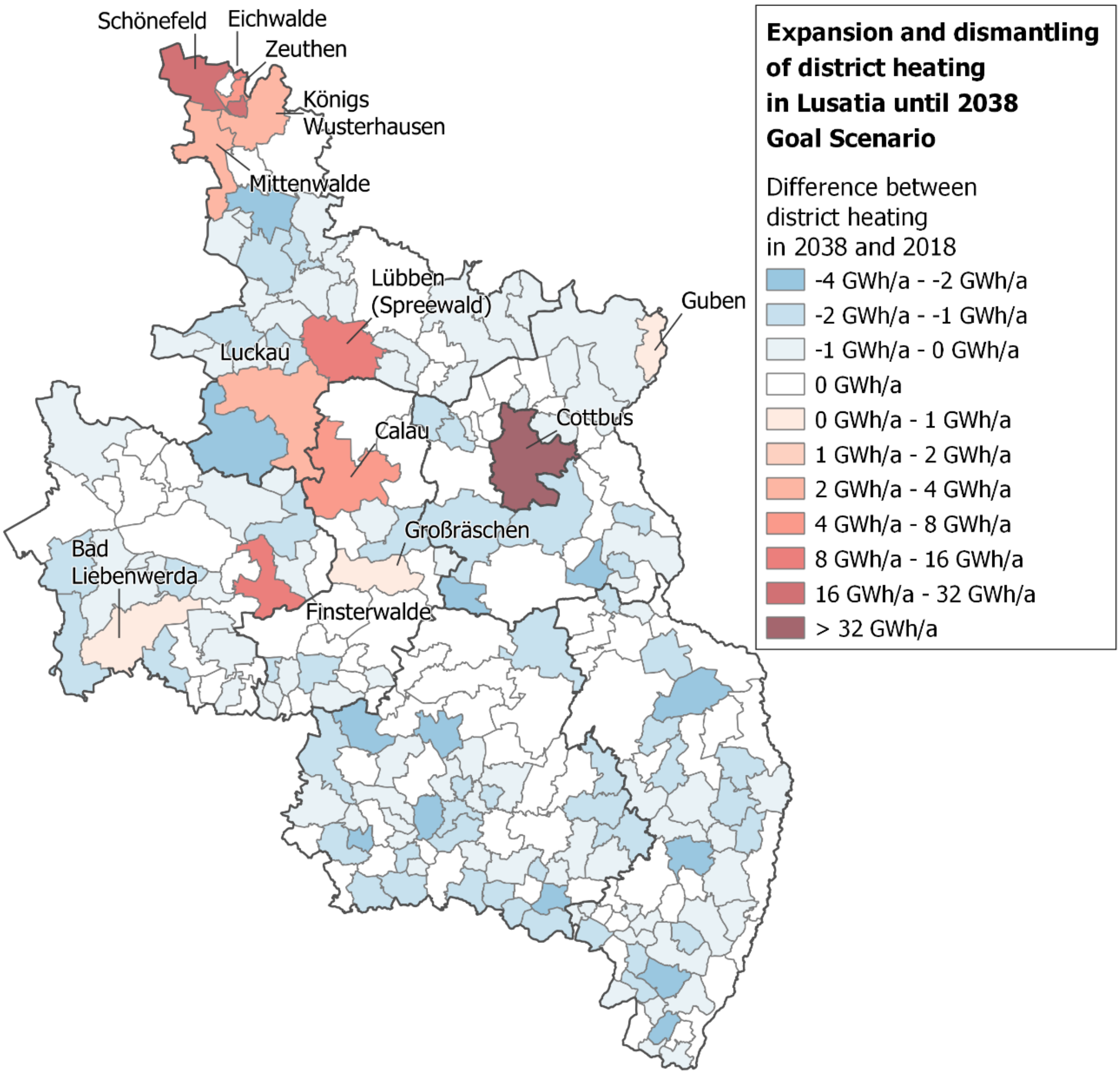

Figure 26 – Potential for expansion and dismantling of district heating in the municipalities of Lusatia in the period of 2018-2038 in the Goal Scenario (own calculations based on references as provided in Section 2.2; GeoBasis-DE / BKG 2019)

To classify the results, the resulting figures can be compared with those from other studies. Projections of the relative district heating share for Germany as a whole, as discussed in Chapter 4, range from 9.2 % to 15.8 % for 2030 and 11.1 % to 23.0 % for 2050. The results for Lusatia 2038 in this thesis are at the upper end of this range. This reflects the fact that Lusatia is a region with a relatively high district heating share already today. On the level of federal states, Bost et. al (2012) assume for Brandenburg that the number of buildings connected to district heating networks will stay constant until 2030 and no new buildings will be connected. In combination with decreasing individual heat demand, this results in a district heating share of only 8.9 % across all sectors in 2030. However, most other studies show an opposite trend. Jochum et al. (2017) also follow a network conservation strategy. They indicate that the potential of new district heating networks alone will account for a relative share of households' heating supply in 2030 of 18.2-24.3 % for Brandenburg and 19.7-24.8 % for Saxony. Until 2050, these shares are decreasing. Nonetheless, in combination with the existing networks to be conserved, the results for the two federal states are significantly higher than those found by this thesis. According to Felsmann et. al (2014), the share of district heating in final energy consumption for heating in households in Saxony will rise to between 20.6 % and 27.8 % by 2050, depending on the scenario chosen. For Brandenburg, Twele et al. (2012) assume that district heating will account for 27.5 % of the energy demand for heating by 2030. It can be summarised that the result for the share of district heating in this thesis is in the range of most reference studies at the level of the federal states. Reference results with an even higher spatial resolution are not available.

5.3 Transformation of district heating towards climate neutrality

The potential analysis in the previous section refers to the potential of district heating in general. It does not take into account to what extent this potential can also be tapped by climate-neutral district heating. As already described in detail in Chapter 4, climate-neutral district heating requires on the one hand a structural transformation of district heating systems and on the other hand that the required energy must come from renewable or waste energy sources. These two aspects are examined in the following two sections specifically for Lusatia. If possible, the generally qualitative results are supported by the presentation of suitable showcase examples from the region.

5.3.1 Structural transformation

Most of the determined district heating potential for the year 2038 is located in areas with already existing network infrastructure. As the inventory in Section 3.1 shows, most of these district heating networks are 2nd or 3rd generation systems. Many have high flow temperatures up to 130 °C and a centralised structure of heat generation. Especially the large systems fed by one of the big coal power plants are laid out for high flow temperatures. However, prerequisite for the integration of various renewable and waste energy sources are low system temperatures and a decentralised feed-in structure. Thus, in order to develop the potential of district heating in a climate-neutral way, the existing networks must be transformed towards 4th generation. Likewise, new systems to be set up must be designed in a suitable way for climate-neutral district heating.

Although very low system temperatures are beneficial for the climate performance of district heating systems in various ways, they require major investments within in the entire system. For this reason, reducing the system temperature involves a trade-off between environmental and economic efficiency. Of those district heating systems in the inventory (Appendix A) with known temperature level, only six networks have a flow temperature below the threshold of 95 °C, which is a criterion for 4th generation district heating systems (Section 4.1). To which extent a temperature reduction is necessary for the integration of available heat sources depends on the local conditions and must be decided individually. After all, in most cases in Lusatia, it can be assumed that considerable temperature reductions are necessary to open up the networks for renewable and waste energy sources. On the consumer side, reducing the system temperature usually requires better thermal insulation of the building and an exchange of the building's heating system. Therefore, the transformation strongly depends on the refurbishment rate within the district heating areas. In 2011, more than 23,000 residential buildings already were connected to a district heating system in Lusatia (Zensus 2011). The decreasing individual heat demand requires densification of connected buildings in existing district heating areas. In addition, there is potential to establish new networks. These two aspects will lead to an increase in the number of connected buildings, even beyond the increase in final energy consumption from district heating. Based on a rough calculation including also non-residential buildings, it can be assumed that the transformation to the full extent of the calculated district heating potential in Lusatia would require the energetic refurbishment of about 40,000 buildings.

The required large investments should be carried out gradually in individual network sections, as described in Section 4.4. A case study for the stepwise transformation of district heating can be found in Cottbus. There, in 2019, the heating system of a newly constructed building was connected to the return flow of the district heating network. The building is equipped with panel heating systems. These enable sufficiently high room temperatures to be achieved even by using the lower temperatures from the return flow of around 60 °C. Via a 3-pipe connection, also the flow can be used for covering peak loads and hot water preparation. The use from the return increases the utilisation rate of the district heating energy and is, at the same time, a step towards a reduction of the flow temperature in the district heating network (DSK 2019).

5.3.2 Integration of fossil-free energy sources

In existing district heating systems in Lusatia, renewable energies are only used in a few cases while most systems are still based on fossil fuels. Likewise, there are only a few examples of sectoral coupling technologies such as PtH and thermal energy storage in the region. For largely climate-neutral district heating, however, the required energy must come from renewable and waste heat sources. These fossil-free energy sources in turn can have limited potential to be integrated into district heating systems as discussed in general in Section 4.5. An exact quantification of the regional potentials of Lusatia is not provided. Instead, in the following, qualitative conclusions are drawn from the findings in Section 4.5 in combination with region-specific studies. In this way, the potential for each energy source individually is discussed below. Three different studies, which analyse the potential of renewable energies at the level of the federal states relevant to Lusatia, are primarily used for this purpose. The studies by Bost et al. (2012) and Twele et al. (2012) provide insights for Brandenburg. For Saxony the study by Felsmann et al. (2014) is used.

Biomass and biogas

Biomass and biogas have so far been the almost exclusively used renewable energy sources for district heating in Lusatia. To what extent the bioenergy potential is already exhausted is treated differently in the literature. For Brandenburg, Twele et al. (2012) assume that the potential for using biomass is already completely depleted. They also assume that the maximum of biogas production has been reached. At the same time, they suggest that the use of waste heat from biogas plants can be expanded by additional district heating networks. This is particularly the case for the rurally dominated region of Lusatia, since biogas plants are usually located outside of urban areas. In contrast to the assumption of an exhausted potential, Bost et al. (2012) assume that the use of bioenergy will increase by over one third until 2030 compared to 2010. However, they suppose that this increase will have an impact mainly on decentralised heat generation. For Saxony, Felsmann et al. (2014) see considerable potential in the production of biomethane. Additionally to decentralised use, biomethane could also be used for district heating in large CHP plants.

The "Potential Atlas Bioenergy *(Potenzialatlas Bioenergie)*" by the German "Agency for Renewable Energies (*Agentur für Erneuerbare Energien,* AEE)" quantifies the potential of different bioenergy sources per federal state (AEE 2013). In addition, it provides maps that show a distribution of potentials among the districts within the federal states. According to this map, bioenergy potentials from agriculture are rather low in the districts of Lusatia. Yet, the use of wood from forestry has additional capacity. In comparison to other federal states where no wood growth remains unused, Brandenburg and Saxony have further potential for utilisation.

Solar thermal energy

Lusatia is generally known as region with a high annual sunshine duration which is also reflected in the long-term average annual solar radiation (Figure 27). This indicator is decisive for the yield obtained by the use of solar energy. At the annual solar radiation, Lusatia does not stand out as much as it does at the sunshine duration. Nonetheless, with values around the German average, the region does have potential to use solar energy from a meteorological point of view.

In the considered regional studies, the potential of using solar thermal energy is limited to the installation of rooftop collectors. For this reason, the results are relatively low. Bost et. al (2012) suggest that solar thermal energy, if used in individual heating systems as well as in district heating systems, can cover just under half of the total heat demand in 2030. Following this suggestion that the availability of land for large solar thermal plants is not a limiting factor, there is a large potential of solar thermal district heating in Lusatia (see also Section 4.5.2). Also from the economic perspective, wide areas which are available at relatively low cost make solar thermal energy a promising climate-neutral energy source for district heating in Lusatia. The plant in Senftenberg is a prime example for the fact that solar district heating is already practicable in the study area (see also Section 3.1). Remaining problem, particularly for mainly rural areas like Lusatia, is the need for long connecting pipes if heat demand is not sufficient in the vicinity of the solar thermal plant.

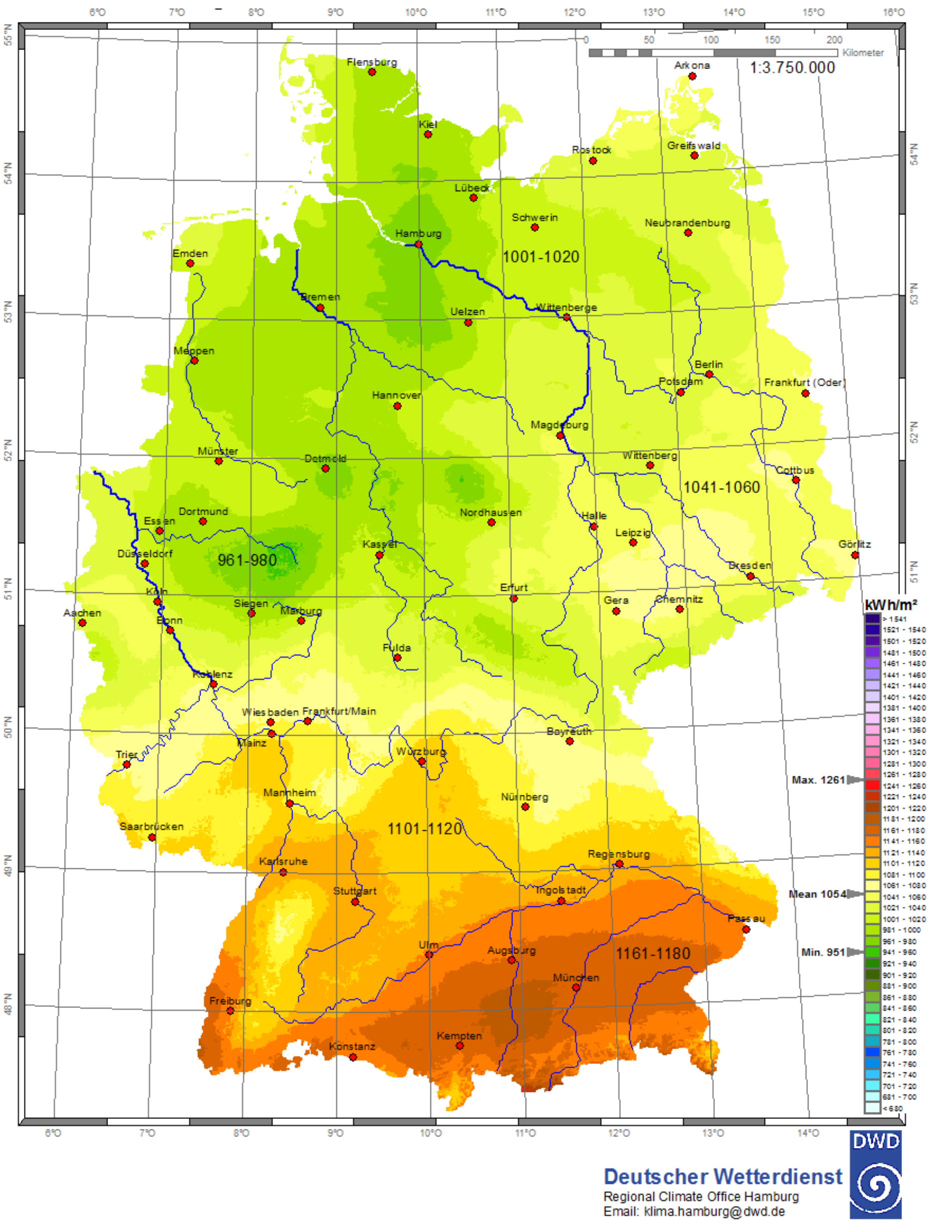

Figure 27 – Average of annual sums of solar global radiation in Germany in the period of 1981-2010 (DWD 2020)

Deep geothermal energy

According to the map in Figure 28, the potential of deep geothermal energy in Lusatia is locally limited to the north-eastern part. Most of the potential areas have hydrothermal reservoirs with temperatures of 40-60 °C. Only in small parts the temperature reaches up to 100 °C. Hence, a spatially and technically limited potential for the use in district heating systems can be assumed, strongly dependent on the reduction of the system temperature in the district heating networks. This situation can be compared to the one in the Ruhr area, a former hard coal mining area with many coal-fired district heating networks still existing (see also Figure 21). For the Ruhr area scientists assume that a large part of the heat from coal in the region can be replaced by geothermal energy in the future (Asendorpf 2019). Nevertheless, it is unclear to what extent this assumption can be transferred to Lusatia.

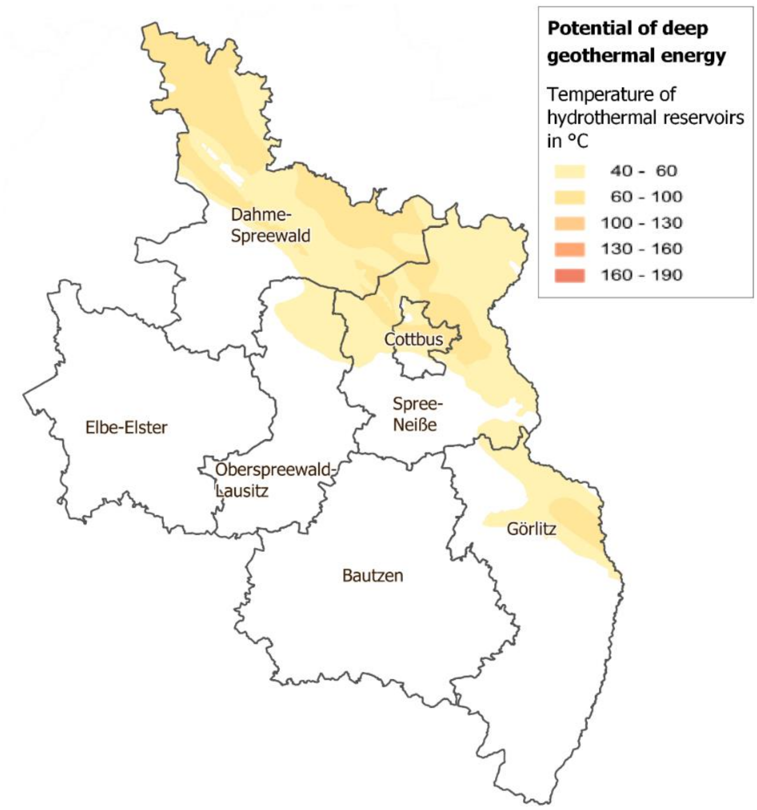

Figure 28 – Potential of deep geothermal energy in Lusatia visualised by the temperature of hydrothermal reservoirs (LIAG 2019; GeoBasis-DE / BKG 2019)

According to Bost et al. (2012), the estimated potential for Brandenburg varies by a factor of ten depending on the source of information. Twele et al. (2012) see great potential and assume that by 2030 all district heating in Brandenburg can be provided using geothermal energy sources. However, the uneven spatial distribution and only rough estimates in the literature do not allow for reliable statements about the potential of geothermal energy for district heating in Lusatia.

Thermal waste treatment

According to the regional energy concepts, almost all waste produced in Lusatia is already being used for material or energy recovery (RPV Oberlausitz-Niederschlesien 2012; RPG Lausitz-Spreewald 2013). Hence, the overall potential of utilisation can be regarded as exhausted. With the same amount of utilizable waste, only the energy yield could be further increased if energetic use were preferred over composting. However, this approach is questionable from a sustainability perspective.

Only in Cottbus, a significant additional amount of municipal solid waste is still available for energy recovery. This potential could be exploited in a new thermal waste treatment plant to be built at the site of the Jänschwalde coal power plant. An application for approval for such a plant with a district heating capacity of up to 100 MW was submitted in February 2020 (LEAG 2020).

Industrial waste heat

Important factor for the potential of using industrial waste heat for district heating is the existence of appropriate heat sources. The map presentation from the final report of the "NENIA" project suggests that there is potential for using industrial waste heat in Lusatia (Blömer et al. 2019). Unfortunately, the Germany-wide presentation does not allow more detailed findings about Lusatia. Other sources which list industrial sites in Lusatia and their suitability as waste heat sources in spatial detail are the "Hotmaps Toolbox" and the "Waste Heat Atlas Saxony (*Abwärmeatlas Sachsen*)" (Hotmaps Consortium 2020; SAENA 2020). The Hotmaps Toolbox contains 14 potential waste heat sources in Lusatia. These include BASF's large chemical industry plant in Schwarzheide and various companies that produce construction materials and glass products. The Waste Heat Atlas Saxony adds three more industrial sites to the list of potential waste heat sources, including a textile company and a detergent manufacturer. Generally, the two Saxon districts of Lusatia are more industrial than those in Brandenburg and therefore the use of industrial waste heat is also more appropriate there. Nonetheless, the use of industrial waste heat must be examined individually for each source of industrial waste heat.

Power-to-Heat

The potential of PtH is essentially dependent on the availability of low-cost renewable electricity. In this regard, surplus electricity production from wind and solar power plants is an important factor. Its available amount depends mainly on the expansion of these generation technologies. At this, the Brandenburg and Saxon parts of Lusatia clearly differ (Figure 29).

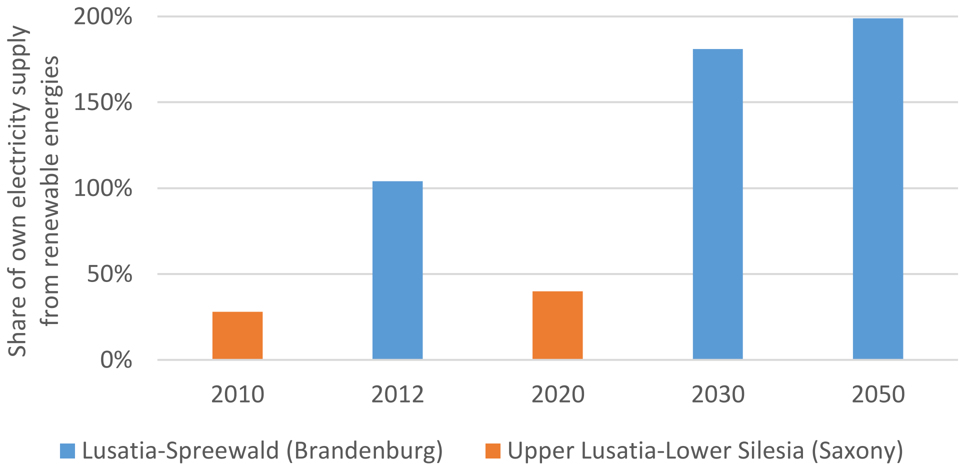

Figure 29 – Ratio of electricity generation from renewable energies and electricity consumption on the Brandenburg and Saxon sides of Lusatia. Actual values from the years 2010 and 2012 as well as projected values for the years 2020, 2030 and 2050 (RPG Lausitz-Spreewald 2013; RPV Oberlausitz-Niederschlesien 2012; Plenz 2016)

On the Brandenburg side, the share of renewable energies of the own electricity consumption in 2012 was already just over 100 % (RPG Lausitz-Spreewald 2013). On the Saxon side, this figure only reached 28 % in 2010 and it was not expected that this share would exceed 40 % by 2020 (RPV Oberlausitz-Niederschlesien 2012). Plenz (2016) analyses the potential of surplus electricity from renewables especially for the planning region Lusatia-Spreewald. This study suggests that the share of self-supply from renewable energies in the region will continue to rise up to 181 % in 2030 and 199 % in 2050, resulting in a PtX potential of up to 2,327 GWh/a and 2,854 GWh/a, respectively.

In order to enable the economic exploitation of this potential, it is necessary to reduce the financial burden of electricity use for PtX applications through fees and taxes. In Cottbus, the use of electricity from wind energy for the operation of a PtH plant with an electrode boiler was investigated in a feasibility study (CEBra 2018). The result is that an economical operation of this plant is only possible if the PtH plant was built directly at the wind farm. If there is a spatial distance between the PtH plant and the wind farm, reallocation charges under the EEG are levied on the operator. This would result in costs exceeding the limit of economic efficiency by far. In the end, the concept was rejected for this reason (Hilscher 2019).

If, in addition to resistive heaters, large heat pumps are used in PtH applications, the availability of ambient heat sources also plays a role. In this context, Lusatia as a lake region offers particular potential. As a result of lignite mining, a total of 36 lakes are being created in former open-cast mines. Of these, 20 are already completely flooded and the others will follow in upcoming years. Covering a total final water surface of almost 150 km², the largest artificial lake landscape in Europe is being created (LMBV 2020). The lake water can serve as a heat source for large-scale heat pumps that can then feed into a district heating network. The implementation of this approach is already being studied in Cottbus. According to the plan of the municipal utility company, 4,000 m³/h of water could be taken from the future lake "Cottbusser Ostsee" and pumped to a heat pump at the site of the cogeneration plant. There, the water would be cooled by two degrees and then returned to the lake. The energy gained can be used to preheat the district heating water before it is heated further by the CHP unit up to the required flow temperature. In this way, 40 % of Cottbus' district heating demand could be covered by the large-scale heat pump (Hilscher 2019).

Thermal energy storage

Up to now, thermal energy storage systems in Lusatia have been used exclusively to allow a more flexible operation of CHP plants. Likewise, a new storage under construction for the district heating network in Cottbus serves this purpose (HKW Cottbus 2018). However, thermal energy storage systems also allow deeper exploitation of the potential of various alternative fuel sources, especially solar thermal and PtH. For this reason, expansion of these energy sources for district heating must be accompanied by expansion of storage facilities. The biggest obstacle in this context so far is the high investment costs for storage solutions (Section 4.5.7). Part of these costs is due to the high land requirements of heat storage facilities. This is especially true for large long-term storages. Compared to areas with a high settlement and population density, it can be an advantage of the rural region of Lusatia that land prices in the countryside are comparably low.

Summary

Although the available data do not allow a quantitative statement to be made about the individual energy sources, it can be concluded that Lusatia does in fact show considerable potential of using renewable and waste energy sources for district heating. In the field of deep geothermal energy and biomass, the available or additionally available potential can be classified as limited or at least uncertain. On the other hand, the region is particularly suitable for the use of solar thermal energy. Large and inexpensively available areas are available for the installation of solar collectors and required thermal energy storage facilities. Available data suggest that industrial sites that can provide significant amounts of waste heat are mainly located in the Saxon part of Lusatia. Nonetheless, the feasibility of using waste heat must be examined site-specifically. The use of PtH is very promising, especially in the Brandenburg part of Lusatia with large electricity surpluses from renewable energies. The use of large-scale heat pumps is particularly favourable, as the region's many lakes can serve as heat sources. In general, however, the increased use of climate-neutral energy sources for district heating might come up against economic limits in most cases and is therefore dependent on political support.

Some examples of existing innovative district heating systems or corresponding plans already exist, e.g. in Forst (PtH unit), Senftenberg (solar thermal plant) and Cottbus (lake water heat pump). An outstanding example that combines different technologies can be found in Guben. A concept for the "Climate Quarter Hegelstraße (*Klimaquartier Hegelstraße*)" was already developed in 2013 (Stadt Guben 2013). In addition to the energy-related refurbishment of the existing buildings, the construction of a new district heating network for the quarter with a total of 38 buildings is planned (Stadt Guben 2019). The planned district heating network will be fed by a large-scale heat pump that draws heat from a seasonal thermal energy storage. This storage is to be designed as an ice storage. Outside the heating season, the water in the tank is heated by ambient heat and additionally by solar collectors. During the heating season, heat is extracted from the tank by the heat pump. This causes the water to freeze, releasing additional latent heat that can be used for district heating. The project is expected to save 1,000 t/a of CO_2 and costs approx. 5.8 mil. Eur. Its implementation is still pending and strongly depends on subsidies (Schauff 2019).

5.4 Regional economic potential

In Section 4.3, it was generally stated that district heating, especially if based on renewable or waste heat sources, generates higher regional value added and employment than heat supply by individual heating systems. The effect was found to be strongest in smaller towns up to 20,000 inhabitants. Of the 51 municipalities of Lusatia for which a district heating potential of above 5 GWh/a was determined in the Goal scenario for 2038, 37 municipalities correspond to this size. Accordingly, increased positive regional economic effects can be expected in Lusatia. As district heating is already widespread in Lusatia today, the number of companies located along the district heating value chain can be considered high. Lusatia has a raised degree of specialisation in the installation, repair and civil engineering sectors that are important for the value added of district heating (Prognos AG 2013). Since, unlike electricity, heat cannot be transported over long distances without major losses, it must be generated by locally based companies. The authors of the Regional Energy Concept for Lusatia-Spreewald assume that this is completely possible for the region (RPG Lausitz-Spreewald 2013). The examined regional potentials of possible energy sources also allow this conclusion to be drawn (Section 5.3.2). In the field of operating district heating networks, municipal utility companies in particular, of which many already operate district heating networks in Lusatia, can create value added regionally. PtH plays a special role in the energy region Lusatia. Electricity production from renewable energies such as wind and solar power, is an important part of the structural change in Lusatia anyhow (Heinbach et al. 2017). Through PtH, their value chain can be extended by further steps on a regional basis and thereby benefit different regional actors. This means that regional renewable electricity production can contribute to secure regional value added and employment even more. Overall, it can be concluded that Lusatia has good prospects of developing the identified additional district heating potential profitably also with regard to regional economic aspects.

6 Conclusion

District heating is an important part of the energy system in Lusatia. Compared to other regions in Germany, it is widespread as it accounts for 14.0 % of the heating energy consumption in households and the TCS sector in 2018. So far, renewable and waste energy sources have played a minor role in district heating in Lusatia. Gas and oil have been the predominant energy sources for district heating. In addition, the region's large coal-fired power plants feed heat into affiliated district heating networks. Even beyond this direct link to the coal industry, district heating plays an important role in Lusatia with regard to the energy system transformation and the structural change caused by the coal phase-out. On the one hand, it offers diverse and promising possibilities to contribute to the transformation towards climate neutrality on a considerable scale. On the other hand, the use of fossil-free district heating also goes along with regional economic potentials that can help compensating the loss of value added and jobs in the region. Especially in these two aspects, climate protection and regional economic development, district heating has a number of advantages over individual heating systems. District heating expands the application possibilities of renewable and waste energy sources and their efficiency in use for heating. Only through district heating networks it is possible to use waste heat, efficient large-scale heat pumps, PtH and also CHP for heat supply. In terms of regional value added and employment, the use of regional fossil-free energy sources in district heating has particular positive effects. Investments in infrastructure mainly benefit regional companies and the value added by the production of renewable heat can usually be realised in the region.

The technical prerequisite for 4th generation district heating systems, which have increased efficiency and integrate various renewable and waste energy sources, is to reduce the grid temperature. This transformation is supported by technological progress in all system components. Generally, suitable climate-neutral energy sources for district heating have sufficient technical potential. However, grid transformation and the development of energy sources often require high investments. From an economic point of view, the most important criterion for the feasibility of district heating is the existence of a sufficiently high heat demand density. This conflicts with the objective to reduce heat demand through efficiency-improving measures at the building insulation and heating systems. Nevertheless, the general view prevails that district heating offers potential for expansion. At present, however, fossil fuels are so inexpensive that individual gas and oil heating systems are still the cheapest option in many cases. This difference in prices impedes the development of the potential of fossil-free district heating. As long as this is the case, affirmative financial support for innovative and climate-friendly district heating networks is necessary. With regard to future developments, it can be assumed that the prices of fossil energy will rise and those of renewable heat generation technologies will decline. Once fossil fuels have been driven out of the market, district heating systems will mainly compete with individual biomass heating systems and heat pumps. However, the use of biomass in individual heating systems has to be viewed critically due to the limited availability. Whether district heating systems or individual heat pumps are more advantageous from an ecological and economical point of view depends on site-specific factors.

In any case, despite the overall positive assessment of the district heating potential, the technical and economic potential of district heating and the availability of climate-neutral energy sources must be assessed individually for each location. With regard to the study region, the predominantly rural character of Lusatia and the demographic development is relevant in this respect. On the one hand, the minimum heat demand density required for economic operation of a district heating system is usually only achieved in more densely populated urban areas, which are rather rare in Lusatia. The expected decline in population will also lead to a stronger reduction in the demand for heat. On the other hand, the large and affordable amount of available space offers the possibility to install space-intensive technologies such as solar thermal plants or long-term thermal energy storage systems at low costs. For the quantitative determination of the district heating potential, a GIS-based scenario analysis was carried out. The result shows that between 2018 and 2038, the heating demand of households and the TCS sector in Lusatia will decrease by 30-34 %. Nevertheless, the determined district heating potential of households and the sector TCS in 2038 is higher compared to the district heating consumption in 2018. The potential district heating share amounts to 21.1-21.6 %; more than 7 % higher than in 2018. However, the absolute district heating potential is only slightly above the level of 2018. The conservation and continued use of existing district heating networks account for the largest part of the identified potential. The connection rate within these networks must therefore be considerably increased in order to achieve the corresponding quantities of district heating. Moreover, most existing networks have high system temperatures and are predominantly based on fossil energy sources. Thus, they are currently not yet at the standard required for climate-neutral district heating. The transformation of the existing networks is of central importance in exploiting the potential of district heating. Required measures are extensive and range from refurbishment measures at the connected buildings and their heating systems to the construction of new heat generation plants. As this involves high investment costs, the transformation should be carried out gradually over time and by establishing sub-networks, so that the costs are incurred in stages. There are various technical possibilities for this. In addition to the dominant role of continuing already existing district heating, there is also the potential to further expand district heating in individual cases. At this, Cottbus and the surrounding area of Berlin as conurbations with correspondingly high heat demand densities have the greatest potential. On the contrary, there is no further potential for expansion in the Saxon part of Lusatia.

As a highly efficient technology, CHP is employed extensively in Lusatia. According to political strategies, CHP is intended to remain the most important heat generation technology in the future. CHP plants are primarily fuelled with natural gas and therefore counterproductive for achieving a climate-neutral heat supply. Moreover, large investments in CHP plants often lead to a lock-in effect. Instead of replacing them with climate-neutral technologies, CHP plants must be operated continuously in the long term for economic reasons. However, Lusatia offers great potential for integrating renewable and waste heat energy sources into district heating. Solar thermal energy in particular is promising due to the availability of land and sufficient solar radiation. Generally, the use of industrial waste heat and PtH for district heating is also well possible in Lusatia from a technical point of view. Moreover, it is clear that district heating based on fossil-free energy sources offers great advantages from a regional economic perspective. In this context, PtH is particularly interesting for the energy region Lusatia. In the conversion of regionally generated renewable electricity into usable heat, a district heating system serves as a kind of catalyst, which allows the regional value added to be expanded.

In summary, this thesis finds that district heating has considerable potential to contribute to a climate-neutral heat supply and regional economic development in Lusatia. This is, however, a general assessment and questions remain open in detail. The GIS-based analysis of the district heating potential was carried out only on the level of municipalities due to the coarse resolution of available data. This means that neither several individual networks within a municipality nor cross-municipality networks could be considered. Furthermore, the availability and accessibility of possible energy sources for district heating should be more in the focus of future assessments of the district heating potential. It must be examined in detail for each individual location whether the use of a potentially available energy source is suitable and economically feasible for district heating. To this end, uniformly structured municipal heat supply plans should be drawn up for the entire region.

References

AEE (2013). "Potenzialatlas. Bioenergie in den Bundesländern." German Agency for Renewable Energies (Agentur für Erneuerbare Energien). URL: https://mediathek.fnr.de/media/downloadable/files/samples/a/e/aee_potenzialatlas_090114_2013_fnr.pdf.

AfS Berlin-Brandenburg (2014). "Energie- und CO2-Bilanz im Land Brandenburg 2011." Amt für Statistik Berlin-Brandenburg. URL: https://www.destatis.de/GPStatistik/servlets/MCRFileNodeServlet/BBHeft_derivate_00004461/SB_E04-04-00_2011j01_BBa.pdf.

AfS Berlin-Brandenburg (2018). "Statistischer Bericht. Tabellenteil der Bevölkerungsvorausberechnung für das Land Brandenburg 2017 bis 2030." Amt für Statistik Berlin-Brandenburg. URL: https://www.statistik-berlin-brandenburg.de/publikationen/stat_berichte/2018/SB_A01-08-00_2018u00_BB.xlsx.

AfS Berlin-Brandenburg (2019a). "Energie- und CO2-Bilanz im Land Brandenburg 2016." Amt für Statistik Berlin-Brandenburg. URL: https://www.statistik-berlin-brandenburg.de/publikationen/stat_berichte/2019/SB_E04-04-00_2016j01_BB.pdf.

AfS Berlin-Brandenburg (2019b). "Fortschreibung des Wohngebäude- und Wohnungsbestandes im Land Brandenburg am 31. Dezember 2018." Amt für Statistik Berlin-Brandenburg, 38. URL: https://www.statistik-berlin-brandenburg.de/publikationen/Stat_Berichte/2019/SB_F01-01-00_2018j01_BB.pdf.

AGEB (2015). "Vorwort zu den Energiebilanzen für die Bundesrepublik Deutschland." Working Group on Energy Balances (Arbeitsgemeinschaft Energiebilanzen). 2015. Webpage: https://www.ag-energiebilanzen.de/files/vorwort.pdf (accessed: 2020-1-22).

AGEB (2018). "Energiebilanz der Bundesrepublik Deutschland 2016." Working Group on Energy Balances (Arbeitsgemeinschaft Energiebilanzen). URL: https://ag-energiebilanzen.de/index.php?article_id=29&fileName=bilanz16d.xls.

AGEB (2019a). "Satellitenbilanz Erneuerbare Energieträger zur Energiebilanz der Bundesrepublik Deutschland Jahr 2017." Working Group on Energy Balances (Arbeitsgemeinschaft Energiebilanzen). URL: https://ag-energiebilanzen.de/index.php?article_id=29&fileName=sat17.xlsx.

AGEB (2019b). "Energiebilanz der Bundesrepublik Deutschland 2017." Working Group on Energy Balances (Arbeitsgemeinschaft Energiebilanzen). URL: https://ag-energiebilanzen.de/index.php?article_id=29&fileName=bilanz17d.xlsx.

Agemar, T., E. Suchi and I. Moeck (2018). "Die Rolle der tiefen Geothermie bei der Wärmewende. Wie Deutschland 60 % erneuerbare Wärme bis 2050 schaffen könnte." Leibniz Institute for Applied Geophysics. URL: https://www.leibniz-liag.de/fileadmin/user_upload/s4/downloads/positionspapier_waermewende.pdf.

AGFW (2014). "Arbeitsblatt AGFW FW 309 Teil 1. Energetische Bewertung von Fernwärme - Bestimmung der spezifischen Primärenergiefaktoren für Fernwärmeversorgungssysteme." Der Energieeffizienzverband für Wärme, Kälte und KWK e.V. URL: https://www.agfw.de/index.php?eID=tx_securedownloads&p=150&u=0&g=0&t=1589036552&hash=0f52a3d6544daecb971c205d63313af3e1fb4473&file=fileadmin/user_upload/Technik_u_Normung/Erzeugung/Energetische_Bewertung/EnEV_und_Fernwaerme/FW_309_1_Arbeitsblatt_und_Geschaeftsordnung.pdf.

AGFW (2019a). “AGFW - Hauptbericht 2018.” Der Energieeffizienzverband für Wärme, Kälte und KWK e.V. URL: https://www.agfw.de/index.php?eID=tx_securedownloads&p=436&u=0&g=0&t=1589360063&hash=7e0f557ee1fd33ef1dfc86e455c31cf05cd69f11&file=fileadmin/user_upload/Zahlen_und_Statistiken/Version_1_HB2018.pdf.

AGFW (2019b). “Liste der fp-Bescheinigungen nach FW 309-1 nach Städten sortiert.” Der Energieeffizienzverband für Wärme, Kälte und KWK e.V., 24. URL: https://www.agfw.de/index.php?eID=tx_securedownloads&p=150&u=0&g=0&t=1589293356&hash=d33a659aee38d869317165275ea3060f80a051e5&file=fileadmin/user_upload/Technik_u_Normung/Erzeugung/Energetische_Bewertung/Liste_der_fP-Bescheinigungen_nach_FW_309-1.pdf.

AGFW (2020). “District Energy Systems Datenbank (DESI).” Der Energieeffizienzverband für Wärme, Kälte und KWK e.V. 2020. Webpage: https://www.district-energy-systems.info/ (accessed: 2020-5-11).

Agora Energiewende (2014). “Power-to-Heat zur Integration von ansonsten abgeregelten Strom aus Erneuerbaren Energien. Handlungsvorschläge basierend auf einer Analyse von Potenzialen und energiewirtschaftlichen Effekten.” Fraunhofer IWES. URL: https://www.agora-energiewende.de/fileadmin2/Projekte/2013/power-to-heat/Agora_PtH_Langfassung_WEB.pdf.

Agora Energiewende (2017a). “Eine Zukunft für die Lausitz - Elemente eines Strukturwandelkonzepts für das Lausitzer Braunkohlerevier.” URL: https://www.agora-energiewende.de/fileadmin2/Projekte/2017/Strukturwandel_Lausitz/Agora_Impulse_Strukturwandel-Lausitz_WEB.pdf.

Agora Energiewende (2017b). “Wärmewende 2030.” Fraunhofer IWES/IBP. URL: https://www.agora-energiewende.de/fileadmin2/Projekte/2016/Sektoruebergreifende_EW/Waermewende-2030_WEB.pdf.

Agora Energiewende (2019). “Wie werden Wärmenetze grün? Dokumentation zur Diskussionsveranstaltung am 21. Mai 2019 auf den Berliner Energietagen 2019.” URL: https://www.agora-energiewende.de/fileadmin2/Projekte/2019/Waermenetze/155_Waermenetze_WEB.pdf.

Ala-Juusela, M., ed. (2004). *Heating and cooling with focus on increased energy efficiency and improved comfort: Guidebook to IEA ECBCS Annex 37 low exergy systems for heating and cooling of buildings*. Espoo: VTT. URL: https://www.vttresearch.com/sites/default/files/pdf/tiedotteet/2004/T2256.pdf.

Arbeitsgemeinschaft QM Fernwärme (2018). *Planungshandbuch Fernwärme*. Version 1.2. Swiss Federal Office of Energy. URL: http://www.verenum.ch/Dokumente/PLH-FW_V1.2.pdf.

Asendorpf, D. (2019). “Fernwärme: Mollig warm ohne Kohle.” *DIE ZEIT*, 2019, 52 edition. URL: https://www.zeit.de/2019/52/fernwaerme-kohlekraftwerke-kohleausstieg-ruhrgebiet/komplettansicht.

Bachmann, M., A. Schneller, S. Gilani and M. Kriegel (2018). “LowExTra. Niedrig-Exergie-Trassen zum Speichern und Verteilen von Wärme.” Herrmann-Rietschel-Institut, TU Berlin. URL: https://doi.org/10.2314/GBV:1040512348.

BAFA (2019). "Zulassung von Wärme- und Kältespeichern nach dem Kraft-Wärme-Kopplungsgesetz (KWKG)." Last update: 2019-12-31. Federal Office for Economic Affairs and Export Control (Bundesamt für Wirtschaft und Ausfuhrkontrolle). URL: https://www.bafa.de/SharedDocs/Downloads/DE/Energie/kwk_waerme_kaeltespeicher_statistik_2009_2018.pdf;jsessionid=A267E1B8D8113DCB9C7035F0ADB8369E.1_cid378?__blob=publicationFile&v=16.

Bauer, D., R. Marx, J. Nußbicker-Lux, F. Ochs, W. Heidemann and H. Müller-Steinhagen (2010). "German central solar heating plants with seasonal heat storage." *Solar Energy* 84 (4): 612–23. DOI: 10.1016/j.solener.2009.05.013.

Bechem, H., M. Blesl, M. Brunner, J. Conrad, T. Falke, C. Felsmann, M. Geipel, N. Gerhardt, W. Glaunsinger, J. Hilpert, et al. (2015). "Potenziale für Strom im Wärmemarkt bis 2050. Wärmeversorgung in flexiblen Energieversorgungssystemen mit hohen Anteilen an erneuerbaren Energien." Energietechnische Gesellschaft (ETG) and Verband der Elektrotechnik Elektronik Informationstechnik e.V. URL: http://www.energiedialog2050.de/BASE/DOWNLOADS/VDE_ST_ETG_Warmemarkt_RZ-web.pdf.

BGH (1989). *Verdict (Urteil). 1989-10-25, VIII ZR 229/88*. Federal Court of Justice. URL: https://research.wolterskluwer-online.de/document/089e2fbe-3026-4580-b794-acdce7b93ba6.

Blesl, M. and B. Eikmeier (2015). "Die 70/70 Strategie. Konzept und Ergebnisse." AGFW | Der Energieeffizienzverband für Wärme, Kälte und KWK e.V. URL: https://www.agfw.de/index.php?eID=tx_securedownloads&p=631&u=0&g=0&t=1589467478&hash=bec01d77a46f79c315fe2e9e8df4c0ce2a8bad3f&file=fileadmin/user_upload/Startseite/Studie_70_70_Endversion_01.pdf.

Blesl, M., M. Koziol, M.C. Ludwig, H. Rapp, B. Tenberg, S. Vautz and S. Wolf (2018). "40/40-Strategie. Unser Konzept für die Wärmewende." AGFW | Der Energieeffizienzverband für Wärme, Kälte und KWK e.V. URL: https://www.agfw.de/index.php?eID=tx_securedownloads&p=631&u=0&g=0&t=1589467478&hash=7899f240c9da9a02370422cffb6bad1377948bd7&file=fileadmin/user_upload/Startseite/180705_Studie_40_40_final_web.pdf.

Bloess, A., W.-P. Schill and A. Zerrahn (2018). "Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials." *Applied Energy* 212 (February): 1611–26. DOI: 10.1016/j.apenergy.2017.12.073.

Blömer, S., C. Götz, M. Pehnt, D. Hering, S. Ochse, S. Hespeler, S. Richter, P. Thomassen, G. Grytsch, C. Zopff, et al. (2019). "EnEff:Wärme - netzgebundene Nutzung industrieller Abwärme (NENIA). Kombinierte räumlich-zeitliche Modellierung von Wärmebedarf und Abwärmeangebot in Deutschland." ifeu - Institut für Energie- und Umweltforschung Heidelberg, GEF Ingenier AG, indevo GmbH and geomer GmbH. URL: https://www.ifeu.de/wp-content/uploads/Schlussbericht_EnEffW%C3%A4rme-NENIA.pdf.

BMU (2019a). "Klimaschutz in Zahlen - Fakten, Trends und Impulse deutscher Klimapolitik." Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. URL: https://www.bmu.de/fileadmin/Daten_BMU/Pools/Broschueren/klimaschutz_zahlen_2019_broschuere_bf.pdf.

BMU (2019b). "Klimaschutzprogramm 2030 der Bundesregierung zur Umsetzung des Klimaschutzplans 2050." Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. URL:

https://www.bundesregierung.de/resource/blob/975226/1679914/e01d6bd855f09bf05cf7498e06d0a3ff/2019-10-09-klima-massnahmen-data.pdf?download=1.

BMWi (2019a). "Zahlen und Fakten. Energiedaten. Nationale und Internationale Entwicklung." Federal Ministry for Economic Affairs and Energy. URL: https://www.bmwi.de/Redaktion/DE/Binaer/Energiedaten/energiedaten-gesamt-xls.xlsx?__blob=publicationFile&v=121.

BMWi (2019b). "Kommission Wachstum, Strukturwandel und Beschäftigung - Abschlussbericht." Federal Ministry for Economic Affairs and Energy. URL: https://www.bmwi.de/Redaktion/DE/Downloads/A/abschlussbericht-kommission-wachstum-strukturwandel-und-beschaeftigung.pdf?__blob=publicationFile.

BMWi (2019c). "Entwurf eines Strukturstärkungsgesetzes Kohleregionen." Federal Ministry for Economic Affairs and Energy. URL: https://www.bmwi.de/Redaktion/DE/Downloads/E/entwurf-eines-strukturstaerkungsgesetzes-kohleregionen.pdf?__blob=publicationFile&v=12.

BMWi (2019d). "Richtlinien zur Förderung von Maßnahmen zur Nutzung erneuerbarer Energien im Wärmemarkt." Federal Ministry for Economic Affairs and Energy. URL: https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/richtlinien-erneuerbare-energien-dez-2019.pdf?__blob=publicationFile&v=4.

BMWi (2019e). "Förderbekanntmachung zu den Modellvorhaben Wärmenetzssyteme 4.0." Federal Ministry for Economic Affairs and Energy. URL: https://www.bundesanzeiger.de/ebanzwww/contentloader?state.action=genericsearch_loadpublicationpdf&session.sessionid=6fd954737853c37efbc18a6ca91137bc&fts_search_list.destHistoryId=79355&fts_search_list.selected=b7101c47d9e9c4a5&state.filename=BAnz%20AT%2024.12.2019%20B1.

BMWi (2020). "Entwurf eines Gesetzes zur Reduzierung und zur Beendigung der Kohleverstromung und zur Änderung weiterer Gesetze (Kohleausstiegsgesetz)." Federal Ministry for Economic Affairs and Energy. URL: https://www.bmwi.de/Redaktion/DE/Downloads/G/gesetzentwurf-kohleausstiegsgesetz.pdf?__blob=publicationFile&v=8.

BMWi and BMU (2010). "Energiekonzept 2010." Federal Ministry for Economic Affairs and Energy and Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. URL: https://www.bmwi.de/Redaktion/DE/Downloads/E/energiekonzept-2010.html.

Bornemann, H., O. Arndt, L. Schulte, A. Ulmer and M. Harders (2018). "Zukünftige Handlungsfelder zur Förderung von Maßnahmen zur Strukturanpassung in Braunkohleregionen." Prognos AG. URL: https://www.bmwi.de/Redaktion/DE/Publikationen/Wirtschaft/endbericht-prognos-zukuenftige-handlungsfelder-foerderung-von-massnahmen-zur-strukturanpassung-in-braunkohleregionen.pdf?__blob=publicationFile&v=16.

Bost, M., T. Böther, B. Hirschl, S. Kreuz, A. Neumann and J. Weiß (2012). "Erneuerbare Energien Potenziale in Brandenburg 2030." Institut für ökologische Wirtschaftsforschung. URL: https://www.ioew.de/uploads/tx_ukioewdb/Bericht_EE-Potenziale_und_Wertschoepfung.pdf.

Bosy, B. (2001). "Heizflächen-Kühlflächen." 2001. Webpage: http://www.bosy-online.de/Heizflaechen.htm (accessed: 2020-2-21).

Bowe, S., C. Kühnel, T. Reinholz and C. Sutor (2018). "dena-Analyse: Biomethan in der Wärmewende." Deutsche Energie-Agentur GmbH (dena). URL:

https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9282_dena-Anlayse_Biomethan_in_der_Waermewende.pdf.

Bracke, R. (2014). "Petrothermale Nutzung und Stimulationsoptionen." In: *Handbuch Tiefe Geothermie*, edited by Mathias Bauer, Willi Freeden, Hans Jacobi, and Thomas Neu, 245–73. Berlin, Heidelberg: Springer. DOI: 10.1007/978-3-642-54511-5_6.

Brischke, L.-A., M. Pehnt, P. Mellwig and F. Herbert (2012). "Nutzung von Strom aus erneuerbaren Energien in Wärmeanwendungen." ifeu - Institut für Energie- und Umweltforschung Heidelberg. URL: https://www.ifeu.de/wp-content/uploads/EE-Strom_Waerme_Strategiepapier.pdf.

Bruns, E., M. Futterlieb, D. Ohlhorst and B. Wenzel (2012). "Erneuerbare Energien in Wärmenetzen – eine realistische Perspektive?" *Zeitschrift für Energiewirtschaft* 36 (3): 159–72. DOI: 10.1007/s12398-012-0087-z.

Bundeskartellamt (2012). "Sektoruntersuchung Fernwärme." URL: http://www.bundeskartellamt.de/SharedDocs/Publikation/DE/Sektoruntersuchungen/Sektoruntersuchung%20Fernwaerme%20-%20Abschlussbericht.pdf?__blob=publicationFile&v=3.

Bundesnetzagentur and Bundeskartellamt (2020). "Monitoringbericht 2019." Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen. URL: https://www.bundesnetzagentur.de/SharedDocs/Mediathek/Berichte/2019/Monitoringbericht_Energie2019.pdf?__blob=publicationFile&v=6.

Bundesrat (2019). "Vermittlungsausschuss erzielt Kompromiss zum Klimapaket." 2019. Webpage: https://www.bundesrat.de/SharedDocs/pm/2019/015.html (accessed: 2020-4-28).

Bundesregierung (2020). "Bund-/Länder-Einigung zum Kohleausstieg." Federal Government. 2020. Webpage: https://www.bundesregierung.de/breg-de/suche/bund-laender-einigung-zum-kohleausstieg-1712774 (accessed: 2020-1-21).

Bundesverband Geothermie (2019). "Tiefe Geothermie-Projekte in Deutschland 2019." URL: https://www.geothermie.de/fileadmin/user_upload/Bibliothek/Downloads/Poster_TG-Projekte_in_Deutschland_2019.pdf.

Bürger, V., J. Steinbach, L. Kranzl and A. Müller (2019). "Third party access to district heating systems - Challenges for the practical implementation." *Energy Policy* 132 (September): 881–92. DOI: 10.1016/j.enpol.2019.06.050.

Carpaneto, E., P. Lazzeroni and M. Repetto (2015). "Optimal integration of solar energy in a district heating network." *Renewable Energy* 75 (March): 714–21. DOI: 10.1016/j.renene.2014.10.055.

CEBra (2018). "Kurzstudie Windwärme." Centrum für Energietechnologie Brandenburg e.V.

Christidis, A., E. Mollenhauer, G. Tsatsaronis, G.K. Schuchardt, S. Holler, D. Böttger and T.C. Brückner (2017). "EnEff:Wärme - Einsatz von Wärmespeichern und Power-to-Heat-Anlagen in der Fernwärmeerzeugung." *AGFW Forschung und Entwicklung*, no. 44. DOI: 10.2314/GBV:1023701839.

Connolly, D., H. Lund, B.V. Mathiesen, S. Werner, B. Möller, U. Persson, T. Boermans, D. Trier, P.A. Østergaard and S. Nielsen (2014). "Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system." *Energy Policy* 65 (February): 475–89. DOI: 10.1016/j.enpol.2013.10.035.

Danpower GmbH (2019). “Lauchhammer Biomethan-Blockheizkraftwerk.” 2019. Webpage: https://www.danpower.de/de/kompetenz-und-service/standorte/lauchhammer_biomethan_blockheizkraftwerk (accessed: 2020-5-12).

David, A., B.V. Mathiesen, H. Averfalk, S. Werner and H. Lund (2017). “Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems.” *Energies* 10 (4): 578. DOI: 10.3390/en10040578.

dena (2019). “dena-Gebäudereport Kompakt 2019. Statistiken und Analysen zur Energieeffizienz im Gebäudebestand.” Deutsche Energie-Agentur GmbH. URL: https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2019/dena-GEBAEUDEREPORT_KOMPAKT_2019.pdf.

Destatis (2008). “WZ 2008 - Classification of Economic Activities, issue 2008.” Federal Statistical Office. URL: https://www.klassifikationsserver.de/klassService/jsp/common/url.jsf?variant=wz2008&lang=EN.

Destatis (2019a). “Daten aus dem Gemeindeverzeichnis Kreisfreie Städte und Landkreise nach Fläche, Bevölkerung und Bevölkerungsdichte. Gebietsstand: 31.12.2018.” Federal Statistical Office. URL: https://www.destatis.de/DE/Themen/Laender-Regionen/Regionales/Gemeindeverzeichnis/Administrativ/04-kreise.html.

Destatis (2019b). “GENESIS - Ergebnis 12411-0015. Fortschreibung des Bevölkerungsstandes, Kreise, Stichtag.” Federal Statistical Office. URL: https://www-genesis.destatis.de/genesis/online.

DSK (2019). “Exergetische Optimierung der Fernwärme.” Deutsche Stadt- und Grundstücksentwicklungsgesellschaft mbH & Co. KG. 2019. Webpage: https://energetische-stadtsanierung-cottbus.de/2019/07/29/exergetische-optimierung-der-fernwaerme/ (accessed: 2020-4-23).

Dunkelberg, E., S. Gährs, J. Weiß and S. Salecki (2018). “Wirtschaftlichkeit von Mehrleiter-Wärmenetzen. Ökonomische Bewertung von Mehrleiter-Wärmenetzen zur Nutzung von Niedertemperaturwärme.” Institut für ökologische Wirtschaftsforschung. URL: https://www.ioew.de/fileadmin/user_upload/BILDER_und_Downloaddateien/Publikationen/2018/IOEW-SR_215_Wirtschaftlichkeit_Mehrleiter-W%C3%A4rmenetze.pdf.

DWD (2020). “Global Radiation in Germany. Average of annual sums, period: 1981-2010.” Deutscher Wetterdienst. 2020. Webpage: https://www.dwd.de/EN/ourservices/solarenergy/maps_globalradiation_average.html (accessed: 2020-4-21).

Eller, D. (2015). “Wärmenachfrage in Deutschland.” In: *Integration erneuerbarer Energien mit Power-to-Heat in Deutschland*, 75–107. Wiesbaden: Springer Fachmedien. DOI: 10.1007/978-3-658-10561-7_5.

Elmegaard, B., T.S. Ommen, M. Markussen and J. Iversen (2016). “Integration of space heating and hot water supply in low temperature district heating.” *Energy and Buildings* 124 (July): 255–64. DOI: 10.1016/j.enbuild.2015.09.003.

Energieagentur Rheinland-Pfalz (2018). “Regionale Wertschöpfung mit der Energiewende - Erfahrungen aus der Praxis für die Praxis.” URL: https://www.energieagentur.rlp.de/fileadmin/user_upload/Praxisleitfaeden/201806_Leitfaden_Regionale_Wertschoepfung_Energiewende_4.pdf.

EnEV (2007). *Regulation on Energy Saving (Energieeinsparverordnung - Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden)*. URL: https://www.gesetze-im-internet.de/enev_2007/BJNR151900007.html.

Esch, T., H. Taubenböck, C. Geiß, C. Schillings, M. Nast, A. Metz, W. Heldens and M. Keil (2011). “Potenzialanalyse zum Aufbau von Wärmenetzen unter Auswertung siedlungsstruktureller Merkmale.” Deutsches Zentrum für Luft- und Raumfahrt e.V. URL: https://elib.dlr.de/76816/1/Waermenetzpotenzial_DLR_Endbericht_final.pdf.

Euroheat & Power (2019). “District Energy in Denmark.” 2019. Webpage: https://www.euroheat.org/knowledge-hub/district-energy-denmark/ (accessed: 2020-2-4).

European Commission (2018). “A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy.” COM/2018/773. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0773.

EVC (2019). “Netzstrukturdaten.” Elektroenergieversorgung Cottbus GmbH. 2019. Webpage: https://www.energienetze-cottbus.de/de/Netze/Waermenetz/ (accessed: 2019-12-12).

Felsmann, C., A. Dittmann, W. Richter, K. Rühling, S. Gnüchtel, T. Sander, M. Rhein, A. Wirths, S. Robbi, D. Haas, et al. (2010). “LowEx Fernwärme. Multilevel District Heating. Zusammenfassung.” Technische Universität Dresden. URL: https://doi.org/10.2314/GBV:659401061.

Felsmann, C., E. Eckstädt and K. Rühling (2014). “Wärmeversorgung für Sachsen aus erneuerbaren Energien.” Technische Universität Dresden. URL: https://www.gruene-fraktion-sachsen.de/fileadmin/user_upload/Studien/Waermeversorgung_Sachsen_Studie_EE2050_2014-11.pdf.

Fisch, N., ed. (2005). *Wärmespeicher*. 4 erweiterte und völlig überarbeitete Auflage. BINE - Informationspaket. Köln: TÜV-Verlag.

FNR (2016). “Einheimische Bioenergie kann 2050 bis zu 26 Prozent unseres Primärenergiebedarfs decken.” German Agency of Renewable Resources (Fachagentur Nachwachsende Rohstoffe e.V.). 2016. Webpage: https://www.fnr.de/presse/pressemitteilungen/archiv/archiv-nachricht/tx_news/einheimische-bioenergie-kann-2050-bis-zu-26-prozent-unseres-primaerenergiebedarfs-decken/?tx_news_pi1%5Bcontroller%5D=News&tx_news_pi1%5Baction%5D=detail&cHash=dc6c05792349d23226e72e8b715dab3b (accessed: 2020-2-26).

Frisch, S., M. Pehnt, P. Otter and M. Nast (2010). “Prozesswärme im Marktanreizprogramm.” ifeu - Institut für Energie- und Umweltforschung Heidelberg and Deutsches Zentrum für Luft- und Raumfahrt. URL: https://elib.dlr.de/82173/1/Prozessw%C3%A4rme_im_MAP.pdf.

Fritz, S. and M. Pehnt (2019). “Der Kohleausstieg und die Auswirkungen auf die betroffenen Wärmenetze.” ifeu - Institut für Energie- und Umweltforschung Heidelberg. URL: https://www.ifeu.de/wp-content/uploads/190820_Kohleausstieg_und_Fernwaerme_Bericht_v06.pdf.

Gadd, H. and S. Werner (2015). “Thermal energy storage systems for district heating and cooling.” In: *Advances in Thermal Energy Storage Systems*, 467–78. Cambridge, Waltham, Kidlington: Elsevier. DOI: 10.1533/9781782420965.4.467.

GeoBasis-DE / BKG (2019). “Open Data.” Federal Agency for Cartography and Geodesy. URL: https://gdz.bkg.bund.de/index.php/default/open-data.html.

Gerbert, P., P. Herhold, J. Burchardt, S. Schönberger, F. Rechenmacher, A. Kirchner, A. Kemmler and M. Wünsch (2018). “Klimapfade für Deutschland.” Boston Consulting

Group GmbH and Prognos AG. URL: https://image-src.bcg.com/Images/Klimapfade-fuer-Deutschland_tcm108-181356.pdf.

Gerhardt, N., I. Ganal, M. Jentsch, J. Rodriguez, K. Stroh and E.K. Buchmann (2019). "Entwicklung der Gebäudewärme und Rückkopplung mit dem Energiesystem in -95 % THG-Klimazielszenarien." Fraunhofer IEE. URL: https://www.iee.fraunhofer.de/content/dam/iee/energiesystemtechnik/de/Dokumente/Veroeffentlichungen/2019/2019_Feb_Bericht_Fraunhofer_IEE_-_Transformation_Waerme_2030_2050.pdf.

Gils, H.C. (2015). "Balancing of Intermittent Renewable Power Generation by Demand Response and Thermal Energy Storage." University of Suttgart. URL: https://elib.uni-stuttgart.de/bitstream/11682/6905/1/Gils_Dissertation_online.pdf.

GL B-B (2009). "Landesentwicklungsplan Berlin-Brandenburg." Gemeinsame Landesplanungsabteilung der Länder Berlin und Brandenburg. URL: https://gl.berlin-brandenburg.de/landesplanung/mdb-bb-gl-landesentwicklungsplanung-lep_bb_broschuere.pdf.

Gröger, M., T. Weinsziehr and T. Bruckner (2016). "Regionale Wertschöpfungseffekte von Wärmeversorgungssystemen." presented at the 14.Symposium Energieinnovation, Graz. URL: https://www.tugraz.at/fileadmin/user_upload/Events/Eninnov2016/files/pr/Stream_F/Session_F6/PR_Groeger1.pdf.

Guelpa, E. and V. Verda (2019). "Thermal energy storage in district heating and cooling systems: A review." *Applied Energy* 252 (October): 113474. DOI: 10.1016/j.apenergy.2019.113474.

Gustafsson, M.S., J. Myhren and E. Dotzauer (2018). "Life Cycle Cost of Heat Supply to Areas with Detached Houses—A Comparison of District Heating and Heat Pumps from an Energy System Perspective." *Energies* 11 (12): 3266. DOI: 10.3390/en11123266.

Harthan, R.O., J. Repenning, R. Blanck, H. Böttcher, V. Bürger, L. Emele, W.K. Görz, K. Henneberg, W. Jörß, S. Ludig, et al. (2020). "Treibhausgasminderungswirkung des Klimaschutzprogramms 2030 (Kurzbericht)." Öko-Institut e.V. URL: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-03-05_climate-change_12-2020_treibhausgasminderungswirkungen-klimaschutzprogramm-2030.docx_.pdf.

Heinbach, K., J. Rupp and B. Hirschl (2017). "Studie_GPE-IOeW_Jobs_BK_u._EE_final.pdf." Institut für ökologische Wirtschaftsforschung. URL: https://www.greenpeace-energy.de/fileadmin/docs/publikationen/Studien/Studie_GPE-IOeW_Jobs_BK_u._EE_final.pdf.

Heissler, K.M., J. Metz, W. Lang, T. Auer and I. Nemeth (2017). "Potenziale von Niedrigtemperaturnetzen zur Steigerung des Anteils erneuerbarer Energien in Quartieren." Technische Universität München. DOI: 10.14459/2017md1403265.

Henning, H.-M. and A. Pfalzer (2013). "Energiesystem Deutschland 2050." Fraunhofer ISE. URL: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Fraunhofer-ISE_Energiesystem-Deutschland-2050.pdf.

Herbes, C. and V. Halbherr (2017). "Stärkere Wärmenutzung in Biogasanlagen kann sich lohnen." *Biogas Journal*, no. 1: 68–71. URL: https://www.biogas.org/edcom/webfvb.nsf/id/DE-Waermenutzung-von-

Biogasanlagen-in-Deutschland/$file/Biogas%20Journal%201-2017_W%C3%A4rmestudie.pdf.
Hilscher, A. (2019). "Cottbus im Strukturwandel: Heizen mit Ostseewasser." *Lausitzer Rundschau Online*, 2019. URL: https://www.lr-online.de/lausitz/cottbus/cottbus-im-strukturwandel-heizen-mit-ostseewasser-38274216.html.
Hirschl, B. (2018). "The Urban Energy Transition: Pathways to Climate Neutrality in Our Cities." In: *Urban Energy Transition*, 245–54. Elsevier. DOI: 10.1016/B978-0-08-102074-6.00027-9.
Hirschl, B., K. Heinbach, A. Prahl, S. Salecki, A. Schröder, A. Aretz and J. Weiß (2015). "Wertschöpfung durch erneuerbare Energien. Ermittlung der Effekte auf Länder- und Bundesebene." Institut für ökologische Wirtschaftsforschung. URL: https://www.ioew.de/fileadmin/user_upload/BILDER_und_Downloaddateien/Publikationen/Schriftenreihen/IOEW_SR_210_Wertsch%C3%B6pfung_durch_erneuerbare_Energien_auf_Landes-_und_Bundesebene.pdf.
Hirschl, B., S. Salecki, T. Böther and K. Heinbach (2011). "Wertschöpfungseffekte durch Erneuerbare Energien in Baden-Württemberg." Institut für ökologische Wirtschaftsforschung. URL: https://www.ioew.de/fileadmin/_migrated/tx_ukioewdb/IOEW_Wertschoepfung_Erneuerbare_Baden-Wuerttemberg_02.pdf.
HKW Cottbus (2018). "Heizkraftwerk Cottbus: Modernisierung zum Gasbetrieb." Heizkraftwerksgesellschaft Cottbus mbH. 2018. Webpage: https://heizkraftwerk-cottbus.de/heizkraftwerk-morgen/ (accessed: 2020-4-23).
Hoffmann, R. (2012). *Heizen mit der Wärmepumpe*. Haar: Franzis Verlag. URL: http://d-nb.info/1023345587.
Hotmaps Consortium (2020). "Toolbox." 2020. Webpage: https://www.hotmaps.eu/map (accessed: 2020-5-18).
Huenges, E. (2014). "Regenerative Wärmequellen für Wärmenetze." In: *FVEE Themen*, 96–101. URL: https://www.fvee.de/fileadmin/publikationen/Themenhefte/th2014/th2014_07_03.pdf.
IINAS (2019). *GEMIS 5.0. Globales Emissions-Modell integrierter Systeme*. Internationales Institut für Nachhaltigkeitsanalysen und -strategien GmbH. URL: http://iinas.org/gemis-de.html.
IRENA (2017). "Renewable Energy in District Heating and Cooling: A sector roadmap for REmap." International Renewable Energy Agency, 112. URL: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Mar/IRENA_REmap_DHC_Report_2017.pdf.
Istrate, I.-R., D. Iribarren, J.-L. Gálvez-Martos and J. Dufour (2020). "Review of life-cycle environmental consequences of waste-to-energy solutions on the municipal solid waste management system." *Resources, Conservation and Recycling* 157 (June): 104778. DOI: 10.1016/j.resconrec.2020.104778.
ITAD (2019). "Jahresbericht 2018." Interessengemeinschaft der Thermischen Abfallbehandlungsanlagen in Deutschland e.V. URL: https://www.itad.de/ueber-uns/mehr/jahresbericht/itad-jahresbericht-2018.pdf.
Jochum, P., J. Lempik, S. Böttcher, D. Stelter, T. Krenz, P. Mellwig, M. Pehnt, A. v Oehsen, S. Blömer and H. Hertle (2017). "Anlagenpotenzial. Ableitung eines Korridors für den Ausbau der erneuerbaren Wärme im Gebäudebereich." Beuth Hochschule für Technik Berlin and ifeu - Institut für Energie- und Umweltforschung Heidelberg GmbH. URL:

https://www.ifeu.de/wp-content/uploads/BeuthHS_ifeu_Anlagenpotenzial_Endbericht_2017.pdf.

Kayser, M. and M. Kaltschmitt (1998). "Potentiale hydrothermaler Erdwärme in Deutschland." Universität Stuttgart. URL: http://bib.gfz-potsdam.de/pub/str9809/9809-2.pdf.

Kock, N. and M. Kaltschmitt (2012). "Geothermisch erschließbare Niedertemperaturwärmesenken in Deutschland – Identifikation und Quantifizierung." *Zeitschrift für Energiewirtschaft* 36 (3): 191–203. DOI: 10.1007/s12398-012-0079-z.

Konstantin, P. (2018). *Praxisbuch der Fernwärmeversorgung*. Berlin, Heidelberg: Springer. DOI: 10.1007/978-3-662-55911-6.

KSG (2019). *Federal Climate Change Act (Bundes-Klimaschutzgesetz)*. URL: https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Gesetze/ksg_final_en_bf.pdf.

Kunz, C. and S. Kirrmann (2016). "Die Neue Wärmewelt - Szenario für eine 100% erneuerbare Wärmeversorgung in Deutschland." Agentur für Erneuerbaren Energien e.V. URL: https://www.unendlich-viel-energie.de/media/file/551.AEE_Neue_Waermewelt_Online.pdf.

KWKG (2015). *Gesetz für die Erhaltung, die Modernisierung und den Ausbau der Kraft-Wärme-Kopplung (Kraft-Wärme-Kopplungsgesetz)*. URL: https://www.gesetze-im-internet.de/kwkg_2016/KWKG.pdf.

LAK Energiebilanzen (2019). "Glossar." Task Force of Federal States for Energy Balances. 2019. Webpage: https://www.lak-energiebilanzen.de/glossar-2/#_Fernwaerme (accessed: 2019-11-20).

Laurberg Jensen, L., D. Trier, M. Brennenstuhl, M. Cozzini and B. Gómez-Uribarri Serrano (2016). "Flexynets. D3.1 - Analysis of Network Layouts in Selected Urban Contexts." PlanEnergi, ZAFH, EURAC and ACCIONA. URL: http://www.flexynets.eu/Download?id=file:33652100&s=-6552244369753625473.

Lausitzer Rundschau (2016). "Heiße Luft für Gubener Haushalte," 2016. URL: https://www.lr-online.de/lausitz/guben/heisse-luft-fuer-gubener-haushalte-35082088.html.

LEAG (2020). "Genehmigungsantrag für EVA Jänschwalde eingereicht." Lausitz Energie Bergbau AG. 2020. Webpage: https://www.leag.de/de/news/details/genehmigungsantrag-fuer-eva-jaenschwalde-eingereicht/ (accessed: 2020-4-21).

Leibniz Institute of Ecological Urban and Regional Development (2020). *Monitor of Settlement and Open Space Development (IOER Monitor)*. URL: https://www.ioer-monitor.de/.

Li, H. and S. Svendsen (2012). "Energy and exergy analysis of low temperature district heating network." *Energy* 45 (1): 237–46. DOI: 10.1016/j.energy.2012.03.056.

LIAG (2019). *Geothermal Information System*. Leibniz Institute for Applied Geophysics. URL: https://www.geotis.de/.

LMBV (2020). "Flutungsstand von Bergbaufolgeseen." Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH. 2020. Webpage: https://www.lmbv.de/index.php/Flutungsstand.html (accessed: 2020-4-22).

Lund, H., P.A. Østergaard, M. Chang, S. Werner, S. Svendsen, P. Sorknæs, J.E. Thorsen, F. Hvelplund, B.O.G. Mortensen, B.V. Mathiesen, et al. (2018). "The status of 4th generation district heating: Research and results." *Energy* 164 (December): 147–59. DOI: 10.1016/j.energy.2018.08.206.

Lund, H., S. Werner, R. Wiltshire, S. Svendsen, J.E. Thorsen, F. Hvelplund and B.V. Mathiesen (2014). "4th Generation District Heating (4GDH)." *Energy* 68 (April): 1–11. DOI: 10.1016/j.energy.2014.02.089.

Mauch, W., R. Corradini, K. Wiesemeyer and M. Schwentzek (2010). "Allokationsmethoden für spezifische CO2-Emissionen von Strom und Wärme aus KWK-Anlagen." *Energiewirtschaftliche Tagesfragen* 55 (9): 12–14. URL: https://www.ffe.de/download/wissen/334_Allokationsmethoden_CO2/ET_Allokationsmethoden_CO2.pdf.

Mollenhauer, E. (2019). "Power-to-Heat-Anlagen in der Fernwärmeversorgung." Technische Universität Berlin. DOI: 10.14279/DEPOSITONCE-8950.

MWE (2012). "Energiestrategie 2030 des Landes Brandenburg." Ministerium für Wirtschaft und Europaangelegenheiten des Landes Brandenburg. URL: https://mwae.brandenburg.de/media/bb1.a.3814.de/Energiestrategie2030_2012.pdf.

Nitsch, J., T. Pregger, T. Naegler, D. Heide, D.L. de Tena, F. Trieb, Y. Scholz, K. Nienhaus, N. Gerhardt, M. Sterner, et al. (2012). "Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global." Deutsches Zentrum für Luft- und Raumfahrt e.V., Fraunhofer IWES and Ingenieurbüro für neue Energien. URL: https://www.dlr.de/dlr/Portaldata/1/Resources/bilder/portal/portal_2012_1/leitstudie2011_bf.pdf.

Olsthoorn, D., F. Haghighat and P.A. Mirzaei (2016). "Integration of storage and renewable energy into district heating systems: A review of modelling and optimization." *Solar Energy* 136 (October): 49–64. DOI: 10.1016/j.solener.2016.06.054.

Ommen, T., W.B. Markussen and B. Elmegaard (2016). "Lowering district heating temperatures – Impact to system performance in current and future Danish energy scenarios." *Energy* 94 (January): 273–91. DOI: 10.1016/j.energy.2015.10.063.

Paar, A., F. Herbert, M. Pehnt, S. Ochse, S. Richter, S. Maier, M. Kley, H. Huther, J. Kühne and I. Weidlich (2013). "Transformationsstrategien von fossiler zentraler Fernwärmeversorgung zu Netzen mit höheren Anteilen erneuerbarer Energien." ifeu - Institut für Energie- und Umweltforschung Heidelberg, GEF Ingenieur AG, AGFW - Der Energieeffizienzverband für Wärme, Kälte und KWK e.V. URL: https://www.ifeu.de/wp-content/uploads/Endbericht_Transformationsstrategien_FW_IFEU_GEF_AGFW.pdf.

Parajuli, R., K. Sperling and T. Dalgaard (2015). "Environmental performance of Miscanthus as a fuel alternative for district heat production." *Biomass and Bioenergy* 72 (January): 104–16. DOI: 10.1016/j.biombioe.2014.11.011.

Pauschinger, T. (2016). "Solar thermal energy for district heating." In: *Advanced District Heating and Cooling (DHC) Systems*, 99–120. Elsevier. DOI: 10.1016/B978-1-78242-374-4.00005-7.

Pehnt, M., M. Arens, E. Jochem and F. Idrissova (2010). "Die Nutzung industrieller Abwärme – technisch-wirtschaftliche Potenziale und energiepolitische Umsetzung." ifeu - Institut für Energie- und Umweltforschung Heidelberg, Fraunhofer ISE and IREES GmbH. URL: https://www.ifeu.de/wp-content/uploads/Nutzung_industrieller_Abwaerme.pdf.

Pehnt, M., P. Mellwig, S. Blömer, H. Hertle, M. Nast, A. v Oehsen, J. Lempik, N. Langreder, N. Thamling, A. Hermelink, et al. (2018). "Untersuchung zu Primärenergiefaktoren." ifeu - Institut für Energie- und Umweltforschung Heidelberg, Prognos AG, Ecofys and dena

- Deutsche Energie-Agentur GmbH. URL: https://www.gih.de/wp-content/uploads/2019/05/Untersuchung-zu-Prim%C3%A4renergiefaktoren.pdf.

Pehnt, M., M. Nast, C. Götz, S. Blömer, A. Barckhausen, D. Schröder, R. Miljes, C. Pottbäcker, H. Breier, C. Nabe, et al. (2017). "Wärmenetzsysteme 4.0." ifeu - Institut für Energie- und Umweltforschung Heidelberg, adelphi consult GmbH, PricewaterhouseCoopers GmbH, Ecofys Germany GmbH and Agentur für Erneuerbare Energien e.V. URL: https://www.ifeu.de/wp-content/uploads/W%C3%A4rmenetze-4.0-Endbericht-final.pdf.

Pehnt, M., A. Paar, P. Otter, F. Merten, T. Hanke, W. Irrek, D. Schüwer, N. Supersberger and C. Zeiss (2009). "Energiebalance - Optimale Systemlösungen für erneuerbare Energien und Energieeffizienz." ifeu - Institut für Energie- und Umweltforschung Heidelberg and Wuppertal-Institut für Klima, Umwelt, Energie. URL: https://www.ifeu.de/wp-content/uploads/Energiebalance-Endbericht.pdf.

Perez-Mora, N., F. Bava, M. Andersen, C. Bales, G. Lennermo, C. Nielsen, S. Furbo and V. Martínez-Moll (2018). "Solar district heating and cooling: A review." *International Journal of Energy Research* 42 (4): 1419–41. DOI: 10.1002/er.3888.

Pfnür, A., B. Winiewska, B. Mailach and B. Oschatz (2016). "Dezentrale vs. zentrale Wärmeversorgung im deutschen Wärmemarkt - Vergleichende Studie aus energetischer und ökonomischer Sicht." ITG Institut für Technische Gebäudeausrüstung Dresden Forschung und Anwendung GmbH and Technische Universität Darmstadt. URL: https://www.bdh-koeln.de/fileadmin/user_upload/pressemitteilungen_pdf/studie_dezentrale_vs_zentrale_waermeversorgung.pdf.

Plenz, M. (2016). "Potenzialanalyse Überschussstrom für Power-to-Heat und Power-to-Gas." Gebäude-Energiewende Arbeitspapier 5. URL: https://www.gebaeude-energiewende.de/data/gebEner/user_upload/Bilder/Dateien/GEW_Arbeitspapier_5__Nutzung_%C3%9Cberschussstrom_Plenz.pdf.

Pöyry (2018). "Third-party access to district heating networks." Pöyry Management Consulting Oy, 65. URL: https://energia.fi/files/2634/Third-Party_Access_to_District_Heating_Networks_FINAL_REPORT_20180509.pdf.

Prognos AG (2013). "Kompetenzfeldanalyse im Zukunftsdialog Energieregion Lausitz." URL: https://wirtschaftsregion-lausitz.de/visioncontent/mediendatenbank/kompetenzfeldanalyse_lang_prognos.pdf.

Raab, S., D. Mangold and H. Müller-Steinhagen (2005). "Validation of a computer model for solar assisted district heating systems with seasonal hot water heat store." *Solar Energy* 79 (5): 531–43. DOI: 10.1016/j.solener.2004.10.014.

rbb (2019). "Vereinbarung mit Leag: Cottbus bekommt bis 2032 Fernwärme aus Jänschwalde." Rundfunk Berlin-Brandenburg. 2019. Webpage: https://www.rbb24.de/studiocottbus/wirtschaft/2019/10/jaenschwalde-fernwaerme-cottbus.html (accessed: 2020-5-15).

Region Westlausitz (2009). "Energiekonzept für die Region Westlausitz." Westlausitz-Regionale.Wirtschaft.Leben e.V. Dresdner ÖKOTHERM GmbH. URL: https://www.region-westlausitz.de/files/downloads/projekte/energie/Energiekonzept_Bericht_Endversion_Onlineversion.pdf.

Reiterer, D., D. Wöss, C. Halmdienst and K. Lichtenegger (2014). "Bidirektionale Einbindung von Gebäuden mit Wärme- erzeugern in Wärmenetze (BiNe)." AEE NÖ-Wien, BOKU

Wien - Institut für Verfahrens- und Energietechnik, Pink GmbH and Bioenergy 2020+ GmbH. URL: https://nachhaltigwirtschaften.at/resources/hdz_pdf/berichte/endbericht_1518_bine.pdf?m=1469659820&.

Repenning, J., L. Emele, R. Blanck, H. Böttcher, G. Dehoust, H. Förster, B. Greiner, R. Harthan, K. Henneberg, H. Hermann, et al. (2015). "Klimaschutzszenario 2050. 2. Endbericht." Öko-Institut e.V. and Fraunhofer ISI. URL: https://www.oeko.de/oekodoc/2451/2015-608-de.pdf.

Rezaie, B. and M.A. Rosen (2012). "District heating and cooling: Review of technology and potential enhancements." *Applied Energy* 93 (May): 2–10. DOI: 10.1016/j.apenergy.2011.04.020.

Richwien, M., B. Baums, K. Rehfeldt, J. Simmering, K.-H. Remmers, F. Krömke, M. Wünsch, E.-M. Klotz, H. Dambeck, S. Kreidelmeyer, et al. (2018). "Erneuerbare Energien-Vorhaben in den Tagebauregionen." IFOK Gmbh, Deutsche WindGuard GmbH, Solarpraxis Engineering GmbH, Prognos AG, Institut für ökologische Wirtschaftsforschung GmbH and Becker Büttner Held PartGmbB. URL: https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/Berichte/erneuerbare-energien-vorhaben-in-den-tagebauregionen.pdf;jsessionid=715C823A870239DE7AE72C7B8201B414?__blob=publicationFile&v=4.

Ritter XL Solar (2020). "Stadtwerke Senftenberg. Solarwärme für städtisches Fernwärmenetz." Ritter Energie- und Umwelt-technik GmbH & Co. KG. 2020. Webpage: https://www.ritter-xl-solar.de/anwendungen/waermenetze/stadtwerke-senftenberg/ (accessed: 2020-5-12).

Robinius, M., P. Markewitz, P. Lopion, F. Kullmann, P.-M. Heuser, K. Syranidis, S. Cerniauskas, M. Reuß, S. Ryberg, L. Kotzur, et al. (2019). "Wege für die Energiewende. Kosteneffiziente und klimagerechte Transformationsstrategien für das deutsche Energiesystem bis zum Jahr 2050 (Kurzfassung)." Forschungszentrum Jülich GmbH. URL: https://www.fz-juelich.de/iek/iek-3/DE/_Documents/Downloads/transformationStrategies2050_studySummary_2019-10-31.pdf.pdf?__blob=publicationFile.

Rosa-Luxemburg-Stiftung (2019). "Nach der Kohle. Alternativen für einen Strukturwandel in der Lausitz." URL: https://www.rosalux.de/fileadmin/rls_uploads/pdfs/Studien/Studien_4-19_Nach_der_Kohle.pdf.

RPG Lausitz-Spreewald (2013). "Regionales Energiekonzept Lausitz-Spreewald." Regionale Planungsgemeinschaft Lausitz-Spreewald. Faktor-i3 GmbH. URL: https://region-lausitz-spreewald.de/visioncontent/mediendatenbank/endbericht.pdf.

RPV Oberlausitz-Niederschlesien (2012). "Regionales Energie- und Klimaschutzkonzept für die Planungsregion Oberlausitz-Niederschlesien." Regionaler Planungsverband Oberlausitz-Niederschlesien. Leipziger Institut für Energie GmbH. URL: http://www.tgz-bautzen.de/fileadmin/media/pdf/Energieagentur/Publikationen/20121212-Endbericht.pdf.

RWI (2018). "Erarbeitung aktueller vergleichender Strukturdaten für die deutschen Braunkohleregionen." Leibniz-Institut für Wirtschaftsforschung. URL:

https://www.bmwi.de/Redaktion/DE/Publikationen/Wirtschaft/endbericht-rwi-erarbeitung-aktueller-vergleichender-strukturdaten-deutsche-braunkohleregionen.pdf?__blob=publicationFile&v=10.

SAENA (2020). “Energieportal Sachsen: Abwärmequellen.” Sächsische Energieagentur - SAENA GmbH. 2020. Webpage: http://www.energieportal-sachsen.de/# (accessed: 2020-5-18).

Sarbu, I., M. Mirza and E. Crasmareanu (2019). “A review of modelling and optimisation techniques for district heating systems.” *International Journal of Energy Research*, May, er.4600. DOI: 10.1002/er.4600.

Schauff, D. (2019). “Hegelstraße: Gubens künftiges Super-Quartier.” *Lausitzer Rundschau Online*, 2019. URL: https://www.lr-online.de/lausitz/guben/hegelstrasse-gubens-kuenftiges-super-quartier-38259210.html.

Schlesinger, M., P. Hofer, A. Kemmler, A. Kirchner, S. Koziel, A. Ley, A. Piégsa, F. Seefeldt, S. Straßburg, K. Weinert, et al. (2014). “Entwicklung der Energiemärkte - Energiereferenzprognose.” Prognos AG, EWI - Energiewirtschaftliches Institut an der Universität zu Köln and GWS - Gesellschaft für wirtschaftliche Strukturforschung. URL: https://www.bmwi.de/Redaktion/DE/Publikationen/Studien/entwicklung-der-energiemaerkte-energiereferenzprognose-endbericht.pdf?__blob=publicationFile&v=7.

Schmidt, D., A. Kallert, M. Blesl, S. Svendsen, H. Li, N. Nord and K. Sipilä (2017). “Low Temperature District Heating for Future Energy Systems.” *Energy Procedia* 116 (June): 26–38. DOI: 10.1016/j.egypro.2017.05.052.

Schneller, A., L. Frank and W. Kahlenborn (2018). “Wärmenetze 4.0 im Kontext der Wärmewende. Politische Handlungsempfehlungen für eine Dekarbonisierung der leitungsgebundenen Wärmeversorgung.” adelphi consult GmbH. URL: https://www.adelphi.de/de/system/files/mediathek/bilder/W%C3%A4rmenetze%204.0%20im%20Kontext%20der%20W%C3%A4rmewende%20-%20adelphi_0.pdf.

Schneller, A., L. Frank and K. Töpfer (2017). “Wärmenetze 4.0 im Kontext der Wärmewende. Analyse der Regelungs- und Förderlandschaft innovativer Wärmenetzsysteme.” adelphi consult GmbH. URL: https://www.adelphi.de/de/system/files/mediathek/bilder/W%C3%A4rmenetze%204.0%20im%20Kontext%20der%20W%C3%A4rmewende%20-%20adelphi.pdf.

Schubert, S. (2016). “Ausbau von Wärmenetzen vs. energetische Sanierung? – Umgang mit konkurrierenden Strategien zur Umsetzung der „Wärmewende“ auf kommunaler Ebene.” *Raumforschung und Raumordnung* 74 (3): 259–71. DOI: 10.1007/s13147-016-0393-8.

Schüwer, D., T. Hanke and H.-J. Luhmann (2015). “Konsistenz und Aussagefähigkeit der Primärenergie-Faktoren für Endenergieträger im Rahmen der EnEV.” Wuppertal Institut für Klima, Umwelt und Energie GmbH. URL: https://epub.wupperinst.org/frontdoor/deliver/index/docId/6267/file/6267_PEF_EnEV.pdf.

SMEKUL (2019). “Zahlen und Fakten - Energie.” Sächsisches Staatsministerium für Energie, Klimaschutz, Umwelt und Landwirtschaft. 2019. Webpage: https://www.energie.sachsen.de/3790.html (accessed: 2019-11-25).

SMWA and SMUL (2013). “Energie- und Klimaprogramm Sachsen 2012.” Sächsisches Staatsministerium für Wirtschaft, Arbeit und Verkehr and Sächsisches

Staatsministerium für Umwelt und Landwirtschaft. URL: https://www.klima.sachsen.de/download/EKP2012.pdf.

Solites (2016). "Projekte in Deutschland." Steinbeis Forschungsinstitut für solare und zukunftsfähige thermische Energiesysteme. 2016. Webpage: http://www.saisonalspeicher.de/Projekte/ProjekteinDeutschland/tabid/91/Default.aspx (accessed: 2020-3-26).

Solites (2019). "Infoblatt Solare Wärmenetze Nr. 2. Solare Wärmenetze - Markstatus 2018 für Deutschland und Europa." Steinbeis Forschungsinstitut für solare und zukunftsfähige thermische Energiesysteme. URL: https://www.solar-district-heating.eu/wp-content/uploads/2019/05/Infoblatt_Solnet_Nr2.pdf.

Soltero, V., R. Chacartegui, C. Ortiz, J. Lizana and G. Quirosa (2018). "Biomass District Heating Systems Based on Agriculture Residues." *Applied Sciences* 8 (4): 476. DOI: 10.3390/app8040476.

Sperber, E. and M. Nast (2014). "Nahwärmenetze als zentrale Komponente für die zukünftige Energieversorgung." presented at the Kooperationsforum "Zentrale Wärmeversorgung in Kommunen," Ingolstadt. URL: https://elib.dlr.de/89660/.

Stadt Cottbus (2013). "Kommunales Energiekonzept der Stadt Cottbus." DSK Deutsche Stadt- und Grundstücksentwicklungsgesellschaft mbH & Co. KG and Brandenburgische Technische Universität Cottbus. URL: https://www.cottbus.de/.files/storage/file/003970be-d37a-4e7c-938d-ce65353f2169/Energiekonzept_CB_Endbericht_30-09-2013.pdf.

Stadt Finsterwalde (2013). "Energetische Stadtsanierung in der Innenstadt Finsterwalde." complan Kommunalberatung GmbH. URL: https://www.finsterwalde.de/images/bauen_und_wohnen/2013-12-10%20Energet_Quartierskonzept%20Finsterwalde.pdf.

Stadt Forst (2010). "Energie- und Klimakonzept Forst (Lausitz). Klimaneutrale Stadt Forst bis 2030." Nymoen Strategieberatung GmbH & Co. KG. URL: https://www.forst-lausitz.de/sixcms/media.php/674/Energie-_und_Klimakonzept_Forst.pdf.

Stadt Guben (2013). "Integriertes, energetisches Quartierskonzept Klimaquartier Hegelstraße." DSK Deutsche Stadt- und Grundstücksentwicklungsgesellschaft mbH & Co. KG and seecon Ingenieure GmbH. URL: https://guben.de/downloads/2013-11-22_KQ_Guben.pdf.

Stadt Guben (2019). "Stadtumbaustrategie Guben - Fortschreibung 2017." Brandenburgische Beratungsgesellschaft für Stadterneuerung und Modernisierung mbH. URL: https://www.guben.de/downloads/2019-07-29_Stadtumbau-Guben.pdf.

Stadt Vetschau, Stadt Lübbenau, Stadt Calau and Amt Burg (2011). "Regionales Energiekonzept Spreewalddreieck." Brandenburgische Beratungsgesellschaft für Stadterneuerung und Modernisierung mbH. URL: https://stadt.vetschau.de/cms/upload/dokumente/2018/Stadtentwicklung/Energiekonzept/Endbericht_-_Reg._Energiekonzept_Spreewalddreieck.pdf.

Stadtwerke Cottbus GmbH (2018). "Stadtwerke investieren in die Zukunft." 2018. Webpage: https://www.stadtwerke-cottbus.de/de/privatkunden/themen/unternehmen/presse/aktuell/artikel-stadtwerke-investieren-in-die-zukunft.html (accessed: 2020-1-28).

Sterner, M. and I. Stadler, eds. (2019). *Handbook of Energy Storage: Demand, Technologies, Integration*. Berlin, Heidelberg: Springer. DOI: 10.1007/978-3-662-55504-0.

StLa Sachsen (2016). “Energiebilanz 2011. Freistaat Sachsen.” Statistisches Landesamt des Freistaates Sachsen. URL: https://www.energie.sachsen.de/download/Bilanz_2011_in_Energieeinheiten_Revision2016_neu.pdf.

StLa Sachsen (2017). “6. Regionalisierte Bevölkerungsvorausberechnung für den Freistaat Sachsen bis 2030.” Statistisches Landesamt des Freistaates Sachsen. URL: https://www.statistik.sachsen.de/download/300_Voe-Faltblatt/SH_6_RBV_2017_SN.pdf.

StLa Sachsen (2019a). “Energiebilanz 2016. Freistaat Sachsen.” Statistisches Landesamt des Freistaates Sachsen. URL: https://www.energie.sachsen.de/download/2016_Bilanz_endg_in_Energieeinheiten.pdf.

StLa Sachsen (2019b). “GENESIS - Ergebnis 31231-002Z. Fortschreibung des Wohngebäudebestandes und Wohnungsbestandes.” Statistisches Landesamt des Freistaates Sachsen. URL: https://www.statistik.sachsen.de/genonline/online.

Stryi-Hipp, G., F. Baur, F. Borggrefe, N. Gerhardt, A. Hauer, J. Horst, E. Huenges, O. Kastner, V. Lenz, N. Martin, et al. (2015). “Erneuerbare Energien im Wärmesektor - Aufgaben, Empfehlungen und Perspektiven.” ForschungsVerbund Erneuerbare Energien. URL: https://www.fvee.de/fileadmin/publikationen/Politische_Papiere_FVEE/15.EEWaerme/15_FVEE-Positionspapier_EE-Waerme.pdf.

Thorsen, J.E., H. Lund and B.V. Mathiesen (2018). “Progression of District Heating - 1st to 4th generation.” Aalborg University. URL: https://vbn.aau.dk/en/publications/progression-of-district-heating-1st-to-4th-generation-3.

Toffetti, L. (2015). “District heating.” CC BY-SA 4.0. DensityDesign Research Lab. URL: https://commons.wikimedia.org/wiki/File:District_heating.gif.

Twele, J., B. Müller and C. Möller (2012). “Szenarioberechnung einer Strom- und Wärmeversorgung der Region Brandenburg-Berlin auf Basis erneuerbarer Energien.” Reiner Lemoine Institut gGmbH. URL: https://reiner-lemoine-institut.de/wp-content/uploads/2015/12/M%C3%B6ller-M%C3%BCller-Twele-2012-Szenarioberechnung-einer-Strom-und-W%C3%A4rmeversorgung-der-Region-Brandenburg-Berlin-auf-Basis-Erneuerbar.pdf.

UBA and AGEE Stat (2019). “Time series for the development of renewable energy sources in Germany.” Federal Environmental Agency and Working Group on Renewable Energy-Statistics. URL: https://www.erneuerbare-energien.de/EE/Navigation/DE/Service/Erneuerbare_Energien_in_Zahlen/Zeitreihen/zeitreihen.html.

VGRdL (2017). “Bruttoinlandsprodukt, Bruttowertschöpfung in den kreisfreien Städten und Landkreisen der Bundesrepublik Deutschland 1992 und 1994 bis 2016 Reihe 2, Kreisergebnisse Band 1.” Arbeitskreis Volkswirtschaftliche Gesamtrechnungen der Länder. URL: https://www.statistikportal.de/de/veroeffentlichungen/bruttoinlandsprodukt-bruttowertschoepfung-0.

Wahlroos, M., M. Pärssinen, J. Manner and S. Syri (2017). “Utilizing data center waste heat in district heating – Impacts on energy efficiency and prospects for low-temperature district heating networks.” *Energy* 140 (December): 1228–38. DOI: 10.1016/j.energy.2017.08.078.

Weiland, P. (2010). "Biogas production: current state and perspectives." *Applied Microbiology and Biotechnology* 85 (4): 849–60. DOI: 10.1007/s00253-009-2246-7.

Weiß, J., A. Prahl, A. Neumann, A. Schröder, K. Bettgenhäuser, A. Hermelink, A. John and B. v. Manteuffel (2014). "Kommunale Wertschöpfungseffekte durch energetische Gebäudesanierung (KoWeG)." Institut für ökologische Wirtschaftsforschung and Ecofys Germany GmbH. URL: https://www.klimaschutz.de/sites/default/files/Endbericht_KoWeG_final%20f%C3%BCr%20ver%C3%B6ffentlichung%20mit%20logo.pdf.

Weiss, W. and M. Spörk-Dür (2019). "Solar Heat Worldwide. Global Market Development and Trends in 2018. Detailed Market Figures 2017." AEE - Institute for Sustainable Technolgies. URL: https://www.iea-shc.org/Data/Sites/1/publications/Solar-Heat-Worldwide-2019.pdf.

WindNODE (2019). "Stadtwerke Forst GmbH." 50Hertz Transmission GmbH. 2019. Webpage: https://www.windnode.de/partner/assoziierte-partner/stadtwerke-forst-gmbh/ (accessed: 2019-12-13).

Wolff, D. and K. Jagnow (2011). "Überlegungen zu Einsatzgrenzen und zur Gestaltung einer zukünftigen Fern- und Nahwärmeversorgung." URL: https://www.zukunftsheizen.de/fileadmin/user_upload/3_Technik/3.6_Projekte_und_Studien/3.6.3_Nah-_und_Fernwaermenetze/Studie_Untersuchung_Nah-_und_Fernwaermenetze_IWO.pdf.

Wünsch, M., N. Thamling, F. Peter and F. Seefeldt (2011). "Beitrag von Wärmespeichern zur Integration erneuerbarer Energien." Prognos AG. URL: https://www.prognos.com/uploads/tx_atwpubdb/111219_Prognos_Studie_AGFW_Waermespeicher_Integration_Erneuerbare_Energien_01.pdf.

WVR (2020). "Standorte." Wärmeversorgung Radeberg GmbH. 2020. Webpage: https://wvr-radeberg.com/standorte/ (accessed: 2020-5-12).

Xu, J., R.Z. Wang and Y. Li (2014). "A review of available technologies for seasonal thermal energy storage." *Solar Energy* 103 (May): 610–38. DOI: 10.1016/j.solener.2013.06.006.

Yang, X., H. Li and S. Svendsen (2016a). "Alternative solutions for inhibiting Legionella in domestic hot water systems based on low-temperature district heating." *Building Services Engineering Research and Technology* 37 (4): 468–78. DOI: 10.1177/0143624415613945.

Yang, X., H. Li and S. Svendsen (2016b). "Decentralized substations for low-temperature district heating with no Legionella risk, and low return temperatures." *Energy* 110 (September): 65–74. DOI: 10.1016/j.energy.2015.12.073.

Yang, X. and S. Svendsen (2017). "Achieving low return temperature for domestic hot water preparation by ultra-low-temperature district heating." *Energy Procedia* 116 (June): 426–37. DOI: 10.1016/j.egypro.2017.05.090.

Zensus (2011). "Census database of the Census 2011." Federal Statistical Offices. URL: https://ergebnisse.zensus2011.de/#.

Zvingilaite, E., T. Ommen, B. Elmegaard and M.L. Franck (2012). "Low Temperature District Heating Consumer Unit with Micro Heat Pump for Domestic Hot Water Preparation." In: *Proceedings of the 13th International Symposium on District Heating and Cooling*, 136–43. District Energy Development Center. URL: http://www.fvu-center.dk/sites/default/files/publication.pdf.

Appendix A – Inventory of District Heating Networks in Lusatia

Municipality	Operator	Service area / connected buildings	Grid length	Maximum temperature level of flow / return	Thermal energy output (year)	Number of thermal power stations	Installed thermal capacity (type if known)	Primary energy factor
Bautzen	Energie- und Wasserwerke Bautzen GmbH (1)	Gesundbrunnen, residential area north-east (Kantstraße), town centre, Allende neighborhood, authority centre (1)	33 km (2)	100 °C / 55 °C (3)	77,067 MWh (2018) (2)	3	3.9 MW (natural gas CHP) + 3.4 MW (boiler) + 7 MW + 2 x 9 MW (4)	0.42 (4)
Bischofswerda	Techem Energy Contracting GmbH (5)	Bischofswerda south / 1195 housing units, 4 commercial units, 1 retirement home (6)	(?)	(?)	10,898 MWh (2014) (7)	1	538 kW (biogas CHP) (7)+ (?) MW (natural gas boilers) (8)	0.56 (9)
Boxberg/O.L.	envia Therm GmbH (10)	(?)	6.5 km (10) + (?)	(?)	(?)	2	2,9 MW (10) + 125 MW (coal power plant Boxberg) (11)	(?)
Calau	Techem Energy Contracting GmbH (12)	1 retirement home (9)	(?)	(?)	(?)	(?)	(?)	0.62 (9)
Cottbus	Stadtwerke Cottbus GmbH (13)	Town centre, north-northwest, Südeck / 33,342 apartments (14)	Primary grid: 48 km Secondary grid: 127 km (14)	120 °C (15) / 60 °C (16)	(?)	2	90 MW (lignite CHP) + 30 MW (gas / oil boilers) (17) + 233 MW (coal power plant Jänschwalde) (18)	0.59 (19)

Municipality	Operator	Service area / connected buildings	Grid length	Maximum temperature level of flow / return	Thermal energy output (year)	Number of thermal power stations	Installed thermal capacity (type if known)	Primary energy factor
Ebersbach-Neugersdorf	Stadtwerke Oberland GmbH [20]	1500 units [20]	(?)	(?)	(?)	1	(?) MW (lignite / gas / oil CHP) [20]	(?)
Elsterwerda	Stadtwerk Elsterwerda GmbH [21]	(?)	(?)	(?)	(?)	1	12 MW (biomass CHP) [21]	0
Finsterwalde	Stadtwerke Finsterwalde GmbH [22]	3 subgrids: South: Residential area south, town centre (market area); West: school and sports centre Tuchmacherstraße; East: residential area Schacksdorfer Straße [22] / 161 properties in total [23]	(?)	South: 125 °C / 75 °C West: 110 °C / 70 °C [24]	31,221 MWh (2014) [25]	(?)	(?) MW (biogas CHP) + (?) [26]	(?)
Forst	Stadtwerke Forst GmbH [27]	3400 apartments [27]	10 km [28]	(?)	(?)	3	(?) MW (natural gas CHP) + (?) MW (biogas CHP) + (?) MW (gas boiler) [29] + 550 kW (PtH) [30]	(?)
Görlitz	Stadtwerke Görlitz AG [31]	Town of Görlitz, 1 main grid and 2 local grids [32]	(?)	100 °C / 60 °C [33]	(?)	main grid: 4 local grids: 1 each	13.7 MW (CHP) + 400 kW (pellet boiler) + 2.7 MW (natural gas boiler) [34]	(?)

Municipality	Operator	Service area / connected buildings	Grid length	Maximum temperature level of flow / return	Thermal energy output (year)	Number of thermal power stations	Installed thermal capacity (type if known)	Primary energy factor
Guben	Energieversorgung Guben GmbH (35)	(?)	19 km (35)	Primary grid: 130 °C / 73 °C Secondary grid: 95 °C / 65 °C (35)	123,000 MWh (2015) (36)	1	57 MW (natural gas CHP) (37)	(?)
Herzberg (Elster)	envia Therm GmbH (10)	(?)	4.5 km (10)	(?)	(?)	(?)	5.2 MW (natural gas boilers + biogas CHP) (10)	0.405 (10)
Hoyerswerda	Versorgungsbetriebe Hoyerswerda GmbH (38)	New town, old town (39) / 500 connected houses (40)	Primary grid: 19 km Secondary grid: 69 km (40)	110 °C / 65 °C (41)	(?)	2	120 MW (coal power plant Schwarze Pumpe) (42) + 19,8 MW (40)	0.7 (43)
Kamenz	ewag Kamenz (44)	Town of Kamenz (45)	(?)	(?)	(?)	(?)	(?)	0.5 (19)
Königs Wusterhausen	WKW Wärmeversorgungsgesellschaft Königs Wusterhausen mbH (9)	6,000 households (46)	(?)	(?)	(?)	(?)	(?)	0.36 (9)
Königswartha	ENSO Energie Sachsen Ost AG (47)	42 substations (48)	4 km (48)	(?)	(?)	1	371 kW (gas boiler, CHP) (48)	(?)
Lauchhammer	EKT Energie und Kommunal-Technologie GmbH (19)	439 buildings (49)	24 km (49)	(?)		1	5.5 MW (lignite boiler) + 9.8 MW (gas/oil boiler) (49) + 1.2 MW (bio methane CHP) (50)	0.63 (19)

Municipality	Operator	Service area / connected buildings	Grid length	Maximum temperature level of flow / return	Thermal energy output (year)	Number of thermal power stations	Installed thermal capacity (type if known)	Primary energy factor
Löbau	Stadtwerke Löbau GmbH [51]	5 subgrids: North-East, East, Centre, South I, South II [51]	(?)	North-East: 100 °C / 50 °C East: 100 °C / 50 °C Centre: 85 °C / 50 °C South I: 85 °C / 50 °C South II: 100 °C / 50 °C [52]	(?)	(?)	(?)	(?)
Lübben	Stadt- und Überlandwerke GmbH Lübben (North, Centre) [53]; K & S – Dr. Krantz Sozialbau und Betreuung SE & Co. KG (Grid IV, Grid V) [19]	4 subgrids: North, Centre, Grid IV, Grid V [19,53]	North, centre: 3,3 km [53] IV, V: (?)	North, Centre: 105 °C / 65 °C [54] IV, V: (?)	North, Centre: 10,967 MWh (2011) [53] IV, V: (?)	North, Centre: 1 each IV, V: (?)	North: 9.3 MW (gas/oil boiler) centre: 4.3 MW (gas/oil boiler) [54] IV, V: (?)	North, Centre: 1.3 [53] IV: 0.7 V: 0.75 [19]
Lübbenau	Stadt-und Überlandwerke GmbH Luckau- Lübbenau [12]	(?)	(?)	(?)	(?)	1	2.3 MW (gas CHP)+ 39 MW (gas boiler) [55]	0.62 [9]
Niesky	Stadtwerke Niesky GmbH [56]	1,800 customers [56]	12.2 km [56]	90 °C / 50 °C [57]	(?)	4	13 MW (wood chips CHP + (?)) [56]	0
Olbersdorf	Wärmeversorgungsgesellschaft Olbersdorf mbH [58]	1,400 apartments, 3 day care centres, 1 school, 1 shopping-mall, 1 commercial centre, town hall [59]	2 km + 4,85 km under construction [60]	(?)	(?)	1	(?) MW (gas / biogas CHP) [58,59]	0.69 [9]
Ostritz	Technische Werke Ostritz GmbH [61]	300 customers [62]	16 km [62]	(?)		1	4 MW (wood chips boiler) + (?) MW (boiler) [63]	0.44 [9]

Municipality	Operator	Service area / connected buildings	Grid length	Maximum temperature level of flow / return	Thermal energy output (year)	Number of thermal power stations	Installed thermal capacity (type if known)	Primary energy factor
Peitz	envia Therm GmbH [10]	(?)	7 km [10]	(?)	(?)	2	4,5 MW [10] + 233 MW (coal power plant Jänschwalde) [18]	(?)
Pulsnitz	ewag Kamenz [45]	Town of Pulsnitz / 1300 people in 1000 apartments [45,64]	(?)	(?)	(?)	(?)	(?)	(?)
Radeberg	WVR Wärmeversorgung GmbH Radeberg [65]	6 subgrids: Waldstraße (1) / 18 properties, 665 apartments; Schillerstraße (2) / 158 properties, 1,535 apartments; Röderstraße-Pestalozzistraße (3) / 4 properties, 189 apartments; community centre (5)/ 3 properties, 8 apartments; town hall (6) / 5 properties; secondary school (7) / 2 properties [65,66]	(?)	100 °C / 45 °C [67]	(?)	1 per subgrid	1: 2.4 MW (gas/oil CHP) 2: 8.4 MW (gas/oil/biogas CHP) 3: 1.3 MW (gas boiler) 5: 238 kW (gas boiler) 6: 208 kW (gas boiler) 7: 320 kW (biogas CHP) [66]	1: 0.74 2: 0.22 3: 1.30 5: 1.30 6: 1.30 7: 0.0 [66]
Rothenburg/O.L.	Stadtwerke Rothenburg/O.L. [68]	Südstraße, Friedensstraße, Uhsmannsdorfer Straße [68]	9.5 km [68]	(?)	(?)	(?)	(?)	(?)

Municipality	Operator	Service area / connected buildings	Grid length	Maximum temperature level of flow / return	Thermal energy output (year)	Number of thermal power stations	Installed thermal capacity (type if known)	Primary energy factor
Schönefeld	e.distherm Wärmedienstleistungen GmbH (19)	Schönefeld centre west (19)	(?)	95 °C / 55 °C (69)	(?)	(?)	(?)	0.26 (19)
Schwarzheide	URBANA Energiedienste GmbH (9) (GETEC WÄRME & EFFIZIENZ GmbH Nord) (70)	Schipkauer Straße (9)	(?)	(?)	(?)	(?)	(?)	0.7 (9)
Senftenberg	Stadtwerke Senftenberg GmbH (71)	Town of Senftenberg and Brieske (71)	33 km (71)	95 °C / 60 °C (72)	100,000 MWh (2017) (73)	3	4.5 MW (solar thermal) (73) + 25 MW (lignite CHP with co-incineration of biomass) + 44 MW (gas/oil boiler) (74)	0.69 (9)
Spremberg	Stadtwerke Spremberg (Lausitz) GmbH (75)	Town of Spremberg / 200 buildings (75)	26 km (75)	120 °C / 60 °C (75)	(?)	1	18.5 MW (coal power plant Schwarze Pumpe) (75)	0.7 (75)
Vetschau	envia Therm GmbH (12)	(?)	7.5 km (10)	(?)	(?)	(?)	10.4 MW (biomethane CHP, oil/lignite boiler) (10)	0.64 (10)
Weißwasser	Stadtwerke Weißwasser GmbH (76)	Town of Weißwasser / 7,000 households and 180 public facilities (77)	Primary grid: 16 km Secondary grid: 36 km (77)	(?)	(?)	3	40 MW (coal power plant Boxberg) + 3 MW (gas CHP) + 25 MW (natural gas boiler) (77)	(?)

Municipality	Operator	Service area / connected buildings	Grid length	Maximum temperature level of flow / return	Thermal energy output (year)	Number of thermal power stations	Installed thermal capacity (type if known)	Primary energy factor
Wilthen	Wilthener Wohnungsbaugesellschaft mbH (78)	Karl-Marx-Straße / August-Bebel-Straße (79)	(?)	(?)	(?)	(?)	(?)	(?)
Zittau	Stadtwerke Zittau GmbH (80)	4 subgrids: Friedensstraße (1), Chopinstraße (2), Lessingschule (3), Roseggerstraße (4) (81) / 618 connected meters (82)	23 km (82)	(?)	48,000 MWh (2018) (82)	(?)	(?) MW (natural gas, biomethane) (80)	1: 0.49 2: 0.51 3: 0.19 4: 0.13 (81)

(?) Information not available

(1) Energie- und Wasserwerke Bautzen GmbH (2020). "Fernwärmeausbau." 2020. Webpage: https://www.ewbautzen.de/privatkunden/waerme/fernwaerme/fernwaermeausbau (accessed: 2020-5-19).

(2) Energie- und Wasserwerke Bautzen GmbH (2020). "Daten und Fakten." 2020. Webpage: https://www.ewbautzen.de/die-ewb/daten-und-fakten/ (accessed: 2020-5-19).

(3) Energie- und Wasserwerke Bautzen GmbH (2016). "Technische Anschlussbedingungen Heizwasser (TAB-HW 2016) für Hausanschlüsse an das Fernwärmenetz der Energie- und Wasserwerke Bautzen GmbH." URL: https://www.ewbautzen.de/fileadmin/media/dokumente/ewb-waerme-technische-anschlussbedingungen-heizwasser.pdf.

(4) Energie- und Wasserwerke Bautzen GmbH (n.d.). "Energiezentrum Bautzen." URL: https://www.ewbautzen.de/fileadmin/media/dokumente/ewb-faltblatt-waerme-energiezentrum-bautzen.pdf.

(5) Region Westlausitz (2009). "Energiekonzept für die Region Westlausitz." Westlausitz-Regionale.Wirtschaft.Leben e.V. Dresdner ÖKOTHERM GmbH. URL: https://www.region-westlausitz.de/files/downloads/projekte/energie/Energiekonzept_Bericht_Endversion_Onlineversion.pdf.

(6) Wendler, A. (2014). "Praxis aus der Region. Nahwärmeversorgung mit BHKW in Bischofswerda und Großdrebnitz." presented at the Branchentreff. URL: https://newsroom.techem.de/fileadmin/de/pdf/branchentreff.techem.de/02_Vortraege/141021_Dresden/Branchentreff_Dresden_Wendler_211014.pdf.

(7) Otto, R. (2015). "Umbruch im Strom- und Wärmemarkt. Wohnungswirtschaftlicher Beitrag zum Umweltschutz." presented at the 1. Chemnitzer Energietag. URL: https://www.vi-strategie.com/fileadmin/user_upload/download/Chemnitz_Praesentation_10_09_2015_V5_SM.PDF.

(8) Techem Energy Contracting GmbH (2015). "Wohnungswirtschaft und Bau (WuB) Bischofswerda. Wärmeservice mit Blockheizkraftwerk." URL: https://www.techem.de/fileadmin/de/Downloads/Techem/Referenzen/Referenz-Waermeservice-WuB-Bischofswerda-20180416.pdf.

(9) AGFW (2019). “Liste der fp-Bescheinigungen nach FW 309-1 nach Städten sortiert.” Der Energieeffizienzverband für Wärme, Kälte und KWK e.V., 24. URL: https://www.agfw.de/index.php?eID=tx_securedownloads&p=150&u=0&g=0&t=1589293356&hash=d33a659aee38d869317165275ea3060f80a051e5&file=fileadmin/user_upload/Technik_u_Normung/Erzeugung/Energetische_Bewertung/Liste_der_fP-Bescheinigungen_nach_FW_309-1.pdf.
(10) envia THERM GmbH (2019). “Fernwärme. Unsere Erzeugungsanlagen für Fernwärme im Überblick.” 2019. Webpage: https://www.envia-therm.de/w%C3%A4rmeversorgung/fernw%C3%A4rme (accessed: 2020-5-19).
(11) LEAG (2020). “Braunkohlekraftwerk Boxberg.” Lausitz Energie Bergbau AG. 2020. Webpage: https://www.leag.de/de/geschaeftsfelder/kraftwerke/kraftwerk-boxberg/ (accessed: 2020-5-19).
(12) Stadt Vetschau, Stadt Lübbenau, Stadt Calau and Amt Burg (2011). “Regionales Energiekonzept Spreewalddreieck.” Brandenburgische Beratungsgesellschaft für Stadterneuerung und Modernisierung mbH. URL: https://stadt.vetschau.de/cms/upload/dokumente/2018/Stadtentwicklung/Energiekonzept/Endbericht_-_Reg._Energiekonzept_Spreewalddreieck.pdf.
(13) Stadt Cottbus (2013). “Kommunales Energiekonzept der Stadt Cottbus.” DSK Deutsche Stadt- und Grundstücksentwicklungsgesellschaft mbH & Co. KG and Brandenburgische Technische Universität Cottbus. URL: https://www.cottbus.de/.files/storage/file/003970be-d37a-4e7c-938d-ce65353f2169/Energiekonzept_CB_Endbericht_30-09-2013.pdf.
(14) EVC (2019). “Netzstrukturdaten.” Elektroenergieversorgung Cottbus GmbH. 2019. Webpage: https://www.energienetze-cottbus.de/de/Netze/Waermenetz/ (accessed: 2019-12-12).
(15) Stadtwerke Cottbus GmbH (2020). “Fernwärme - FAQ.” 2020. Webpage: https://www.stadtwerke-cottbus.de/de/privatkunden/themen/produkt-center/waerme/artikel-fernwaerme-oft-gestellte-fragen.html (accessed: 2020-5-19).
(16) DSK (2019). “Exergetische Optimierung der Fernwärme.” Deutsche Stadt- und Grundstücksentwicklungsgesellschaft mbH & Co. KG. 2019. Webpage: https://energetische-stadtsanierung-cottbus.de/2019/07/29/exergetische-optimierung-der-fernwaerme/ (accessed: 2020-4-23).
(17) HKW Cottbus (2018). “Heizkraftwerk heute.” Heizkraftwerksgesellschaft Cottbus mbH. 2018. Webpage: https://heizkraftwerk-cottbus.de/heizkraftwerk-heute/ (accessed: 2020-5-19).
(18) LEAG (2020). “Kraftwerk Jänschwalde.” Lausitz Energie Bergbau AG. 2020. Webpage: https://www.leag.de/de/geschaeftsfelder/kraftwerke/kraftwerk-jaenschwalde/ (accessed: 2020-5-19).
(19) AGFW (2020). “District Energy Systems Datenbank (DESI).” Der Energieeffizienzverband für Wärme, Kälte und KWK e.V. 2020. Webpage: https://www.district-energy-systems.info/ (accessed: 2020-5-11).
(20) Stadtwerke Oberland GmbH (n.d.). “Wärmeversorgung.” Webpage: https://swoberland.de/Waermeversorgung (accessed: 2020-5-19).
(21) Consulting Engineers Oskar von Miller GmbH (n.d.). “Biomasse-Heizkraftwerk Elsterwerda: Erstellung des Basiskonzeptes, Projektsteuerung und Bauüberwachung.” Webpage: http://www.ech-ovm.de/ref_u_elsterwerda.htm (accessed: 2020-5-19).
(22) Stadtwerke Finsterwalde GmbH (n.d.). “Produkte / Preise.” Webpage: https://www.stadtwerke-finsterwalde.de/cms/Waerme/ (accessed: 2020-5-19).
(23) Lausitzer Rundschau (2008). “Stadtwerke wollen Ton angeben.” URL: https://www.lr-online.de/lausitz/finsterwalde/stadtwerke-wollen-ton-angeben-36237898.html.

(24) Stadtwerke Finsterwalde GmbH (2012). “Technische Anschlussbedingungen für Fernwärme der Stadtwerke Finsterwalde GmbH (gemäß § 17 AVB FernwärmeV) TAB Fernwärme – Stand 12/2012.” URL: https://www.stadtwerke-finsterwalde.de/cms/Service/Dokumente/Verordnungen_und_Allgemeine_Teegelungen/Verordnungen_und_Allgemeine_Teegelungen/TAB-Fernwaerme.pdf.
(25) Stadtwerke Finsterwalde GmbH (n.d.). “Unternehmen.” Webpage: https://www.stadtwerke-finsterwalde.de/cms/Unternehmen/ (accessed: 2020-5-19).
(26) Stadtwerke Finsterwalde GmbH (2018). “Aus Gülle und Mais wird umweltfreundliches Biogas. Partnerschaftliche Zusammenarbeit zwischen PROWIB und den Stadtwerken.” *StadtWerke Zeitung*, 2018, 04 edition. URL: https://www.stadtwerke-finsterwalde.de/cms/Unternehmen/SWF_Zeitung/SWF_Zeitung/Dezember2018.pdf.
(27) Stadtwerke Forst GmbH (n.d.). “Fernwärme ganz nah.” Webpage: https://www.stadtwerke-forst.de/waerme (accessed: 2020-5-19).
(28) Stadtwerke Forst GmbH (2014). “Blicke hinter die Kulissen der Fernwärmeversorgung.” 2014. Webpage: https://www.stadtwerke-forst.de/unternehmen/aktuelles/2014/blicke-hinter-die-kulissen-der-fernwaermeversorgung (accessed: 2020-5-19).
(29) Stadtwerke Forst GmbH (n.d.). “Geschichte mit Zukunft.” Webpage: https://www.stadtwerke-forst.de/unternehmen/geschichte (accessed: 2020-5-19).
(30) WindNODE (2019). “Stadtwerke Forst GmbH.” 50Hertz Transmission GmbH. 2019. Webpage: https://www.windnode.de/partner/assoziierte-partner/stadtwerke-forst-gmbh/ (accessed: 2019-12-13).
(31) Stadtwerke Görlitz AG (2020). “Fernwärme.” 01/23/2020. Webpage: https://www.stadtwerke-goerlitz.de/privatkunden/produkte/fernwaerme/ (accessed: 2020-5-19).
(32) Stadtwerke Görlitz AG (2017). “Versorgungsgebiet.” 04/05/2017. Webpage: https://www.stadtwerke-goerlitz.de/privatkunden/unternehmen/ueber-uns/versorgungsgebiet/ (accessed: 2020-5-19).
(33) Stadtwerke Görlitz AG (2014). “Technische Anschlussbedingungen - TAB - für die Versorgung aus den Fernwärmenetzen folgender Versorgungsgebiete der Stadtwerke Görlitz AG - SWG -: Königshufen, Weinhübel, Rauschwalde, Goethestraße.” 2014. Webpage: https://www.stadtwerke-goerlitz.de/fileadmin/user_upload/Technische_Anschlussbedingungen_01.pdf (accessed: 2020-5-19).
(34) Stadtwerke Görlitz AG (2020). “Anlagen.” 01/31/2020. Webpage: https://www.stadtwerke-goerlitz.de/privatkunden/unternehmen/ueber-uns/anlagen/ (accessed: 2020-5-19).
(35) Energieversorgung Guben GmbH (2016). “Fernwärmenetz.” 2016. Webpage: https://www.ev-guben.de/netzbetreiber/fernwaermenetz/18-fernwaermenetz.html (accessed: 2020-5-19).
(36) Lausitzer Rundschau (2016). “Heiße Luft für Gubener Haushalte,” 2016. URL: https://www.lr-online.de/lausitz/guben/heisse-luft-fuer-gubener-haushalte-35082088.html.
(37) envia THERM GmbH and Energieversorgung Guben GmbH (2011). “Pressemitteilung: Energieversorgung Guben und envia THERM verlängern Wärmeliefervertrag.” URL: https://www.enviam.de/irj/go/km/docs/z_ep_em_unt_documents/unternehmensportal/Presse/1_Pressemitteilungen/1.1_Archiv%20&%20Suche/2011/07-2011/PM_enviaTHERM_Guben_110715.pdf.
(38) Versorgungsbetriebe Hoyerswerda GmbH (2013). “Fernwärme in Hoyerswerda.” 2013. Webpage: https://www.vbh-hoy.de/Fernwaerme-3 (accessed: 2020-5-19).

(39) Versorgungsbetriebe Hoyerswerda GmbH (2013). “Fernwärmeversorgung im Stadtgebiet Hoyerswerda.” 2013. Webpage: https://www.vbh-hoy.de/Fernwaermeversorgung-im-Stadtgebiet-Hoyerswerda-2 (accessed: 2020-5-19).
(40) Versorgungsbetriebe Hoyerswerda GmbH (2009). “Fernwärmeversorgung auf einen Blick - der Weg der Wärme, ….” URL: https://www.vbh-hoy.de/Files/rte/file/2009_Fernwaerme.pdf.
(41) Versorgungsbetriebe Hoyerswerda GmbH (2014). “Technische Anschlussbedingungen der Versorgungsbetriebe Hoyerswerda GmbH für den Anschluss an Heizwassernetze.” 2014. Webpage: https://www.vbh-hoy.de/Files/rte/file/TAB_Fernwaerme_07_2014(1).pdf (accessed: 2020-5-19).
(42) LEAG (2020). “Kraftwerk Schwarze Pumpe.” Lausitz Energie Bergbau AG. 2020. Webpage: https://www.leag.de/de/geschaeftsfelder/kraftwerke/kraftwerk-schwarze-pumpe/ (accessed: 2020-5-19).
(43) Versorgungsbetriebe Hoyerswerda GmbH (2013). “Primärenergiefaktor.” 2013. Webpage: https://www.vbh-hoy.de/Primaerenergiefaktor (accessed: 2020-5-19).
(44) ewag kamenz (n.d.). “Wärmeversorgung ewag kamenz: Wärmespeicher, Wärmepumpen, Heizversorgung, Fernwärme.” Energie und Wasserversorgung AG. Webpage: https://ewagkamenz.de/waerme (accessed: 2020-5-19).
(45) ewag kamenz (n.d.). “Versorgungsgebiet | Wärme.” Energie und Wasserversorgung AG. Webpage: https://ewagkamenz.de/waerme-news/waermeversorgung/versorgungsgebiet (accessed: 2020-5-19).
(46) KaWe-Kurier (2018). “Fernwärme liegt schon an.” 2018. Webpage: https://kw-kurier.de/fernwaerme-liegt-schon-an/ (accessed: 2020-5-19).
(47) Fiedler, K. (2015). “Enso will Fernwärme-Netz in Königswartha ausbauen.” Sächsische Zeitung. 2015. Webpage: https://www.saechsische.de/plus/enso-will-fernwaerme-netzin-koenigswartha-ausbauen-3027272.html (accessed: 2020-5-19).
(48) Hache, S. (2014). “ENSO erzeugt neben Wärme bald auch Strom in Königswartha.” Wochenkurier. 2014. Webpage: https://www.wochenkurier.info/sachsen/bautzen/artikel/enso-erzeugt-neben-waerme-bald-auch-strom-in-koenigswartha-20367/ (accessed: 2020-5-19).
(49) Danpower GmbH (2020). “Lauchhammer Heizkraftwerk.” 2020. Webpage: https://www.danpower.de/de/kompetenz-und-service/standorte/lauchhammer_heizkraftwerk (accessed: 2020-5-19).
(50) Danpower GmbH (2019). “Lauchhammer Biomethan-Blockheizkraftwerk.” 2019. Webpage: https://www.danpower.de/de/kompetenz-und-service/standorte/lauchhammer_biomethan_blockheizkraftwerk (accessed: 2020-5-12).
(51) Stadtwerke Löbau GmbH (n.d.). “Oberlausitz Wärme.” Webpage: https://www.sw-l.de/index.php/strom/oberlausitz-waerme (accessed: 2020-5-19).
(52) Stadtwerke Löbau GmbH (n.d.). “TAB-Fernwärme. Anhang A.” URL: https://www.sw-l.de/index.php/component/jdownloads/send/54-hausanschluss/76-anhang-a-zur-tab-heizwasser.
(53) Stadt Lübben (2013). “Kommunales Klimaschutzkonzept Lübben.” seecon Ingenieure GmbH. URL: http://www.luebben-rathaus.de/de/rathaus/stadtentwicklung/klimaschutzkonzept/documents/2483_KSK%20Luebben_Endbericht%2020140110.pdf.
(54) Stadt- und Überlandwerke GmbH Lübben (n.d.). “Wärme. Versorgungsgebiete.” Webpage: https://www.stadtwerke-luebben.de/Produkte/Waerme/Versorgungsgebiete (accessed: 2020-5-19).
(55) Mühlstein, J. (2004). “Gesetzestreu.” *Energie & Management*, 04/2004. URL: https://www.bhkw-infozentrum.de/beispiele/bhkw_des-_monats_04_2004.pdf.
(56) Stadtwerke Niesky GmbH (2015). “Wärme.” 2015. Webpage: https://www.stadtwerke-niesky.de/Waerme.html (accessed: 2020-5-19).

(57) Stadtwerke Niesky GmbH (2016). “Technische Anschlussbedingungen für Fernwärmeanschlüsse (TAB-Heizwasser) der Stadtwerke Niesky GmbH.” URL: https://www.stadtwerke-niesky.de/filelist/download/20181004_Technische_Anschlussbedingungen_fuer_Fernwaermeanschluesse_SWN.pdf.
(58) WVO Wärmeversorgung Olbersdorf mbH (2012). “Energieträgermix der WVO.” Text. 2012. Webpage: https://www.wvo-olbersdorf.de/energie-umwelt/energietraegermix-der-wvo/ (accessed: 2020-5-19).
(59) Gemeindeverwaltung Olbersdorf (2016). “Gemeindeblatt Olbersdorf vom 28.09.2016.” URL: http://www.olbersdorf.de/pdf/gemeindeblatt/Amtsblatt_September_16.pdf.
(60) Sefrin, M. (2018). “Mehr Fernwärme für Olbersdorf.” Sächsische Zeitung. 2018. Webpage: https://www.saechsische.de/mehr-fernwaerme-fuer-olbersdorf-3923283.html (accessed: 2020-5-19).
(61) Technische Werke Ostritz GmbH (2013). “Fernwärme.” 2013. Webpage: http://www.gesellschaften-ostritz.de/de/TWO/Fernw%C3%A4rme (accessed: 2020-5-19).
(62) Technische Werke Ostritz GmbH (2013). “Fernwärmenetz.” 2013. Webpage: http://www.gesellschaften-ostritz.de/de/TWO/Fernw%C3%A4rmenetz (accessed: 2020-5-19).
(63) Technische Werke Ostritz GmbH (2013). “Technische Anlagen.” 2013. Webpage: http://www.gesellschaften-ostritz.de/de/TWO/Technische+Anlagen (accessed: 2020-5-19).
(64) Sächsische Zeitung (2017). “Nächster Abschnitt für Fernwärme.” 2017. Webpage: https://www.saechsische.de/naechster-abschnitt-fuer-fernwaerme-3713688.html (accessed: 2020-5-19).
(65) WVR Wärmeversorgung GmbH Radeberg (n.d.). “Über uns.” Webpage: https://wvr-radeberg.com/ueber-uns/ (accessed: 2020-5-19).
(66) WVR Wärmeversorgung GmbH Radeberg (n.d.). “Standorte.” Webpage: https://wvr-radeberg.com/standorte/ (accessed: 2020-5-19).
(67) WVR Wärmeversorgung GmbH Radeberg (2019). “Technische Anschlussbedingungen für den Anschluss an das Fernwärmenetz der WVR Wärmeversorgung GmbH Radeberg.” URL: https://wvr-radeberg.com/wp-content/uploads/Technische-Anschlussbedingungen-WVR.pdf.
(68) Stadtwerke Rothenburg (n.d.). “Fernwärme.” Webpage: https://www.sw-rothenburg.de/de.php?hauptmenue=FW (accessed: 2020-5-19).
(69) e.distherm Wärmedienstleistungen GmbH (2018). “Technische Anschlussbedingungen Heizwasser (TAB).” URL: https://www.edistherm.de/content/dam/revu-global/e-distherm/5_Unternehmen/2018-01-01_tab_heizwasseredistherm.pdf.
(70) G+E GETEC Holding GmbH (2020). “URBANA wird GETEC.” 2020. Webpage: https://www.urbana.de/ (accessed: 2020-5-19).
(71) Stadtwerke Senftenberg GmbH (n.d.). “Netzgebiet - Das Fernwärmenetz der Stadtwerke Senftenberg GmbH.” Webpage: https://www.stadtwerke-senftenberg.de/de/fernwaerme/kunden/netzgebiet.html# (accessed: 2020-5-19).
(72) Stadtwerke Senftenberg GmbH (2017). “Technische Anschlussbedingungen (TAB) der Fernwärmeversorgung in Senftenberg.” 2017. Webpage: https://www.stadtwerke-senftenberg.de/ancedis/content/documents/2017/TAB%20Fernw%C3%A4rme%20Stand%201.%20Juni%202017.pdf (accessed: 2020-5-19).
(73) Ritter XL Solar (2020). “Stadtwerke Senftenberg. Solarwärme für städtisches Fernwärmenetz.” Ritter Energie- und Umwelt-technik GmbH & Co. KG. 2020. Webpage: https://www.ritter-xl-solar.de/anwendungen/waermenetze/stadtwerke-senftenberg/ (accessed: 2020-5-12).
(74) Stadt Senftenberg (2013). “Kommunales Energiekonzept Senftenberg.” Thüringer Institut für Nachhaltigkeit und Klimaschutz GmbH, Institut für Neue Industriekultur GmbH and Institut für Energieoptimierte Standorte c/ o BTU Cottbus-Senftenberg. URL:

https://www.senftenberg.de/PDF/Endbericht_Kommunales_Energiekonzept_Senftenberg.PDF?ObjSvrID=2055&ObjID=2388&ObjLa=1&Ext=PDF&WTR=1&_ts=1390566706.
(75) Städtische Werke Spremberg (Lausitz) GmbH (n.d.). "Netzbeschreibung." Webpage: https://swspremberg.de/netze/netzbetrieb-fernwaerme/netzbeschreibung/detail/22 (accessed: 2020-5-19).
(76) Stadtverwaltung Weißwasser/O.L. (2014). "Energie- und Klimaschutzkonzept Große Kreisstadt Weißwasser/O.L." KEM Kommunalentwicklung Mitteldeutschland GmbH, seecon Ingenieure GmbH and INM Institut für Nachhaltigkeitsanalytik und -management. URL: https://www.weisswasser.de/sites/default/files/news/energie-und-klimaschutzkonzept-weisswasser_122014.pdf.
(77) Stadtwerke Weißwasser GmbH (2020). "Bereich Fernwärme." 2020. Webpage: https://www.stadtwerke-weisswasser.de/privatkunden/unternehmen/ueber-uns/anlagen/bereich-fernwaerme/ (accessed: 2020-5-19).
(78) Stadtverwaltung Wilthen (n.d.). "Wohnen in Wilthen." Webpage: https://www.wilthen.de/buergerservice/wohnen.html (accessed: 2020-5-19).
(79) Stadt Wilthen (2013). "Fernwärmesatzung der Stadt Wilthen." URL: https://www.wilthen.de/files/wilthen/Seiten/Buergerservice/Satzungen%20Formulare/Fernw%C3%A4rmesatzung.pdf.
(80) Stadtwerke Zittau GmbH (n.d.). "Produktübersicht Heißwasser Haushalt." Webpage: https://stadtwerke-zittau.de/swzittau/content/privatkunden/waerme/fernwaerme_-_heisswasser_ (accessed: 2020-5-19).
(81) Stadtwerke Zittau GmbH (n.d.). "Zertifikate. Primärenergiefaktor." Webpage: https://stadtwerke-zittau.de/swzittau/content/privatkunden/waerme/zertifikate (accessed: 2020-5-19).
(82) Stadtwerke Zittau GmbH (n.d.). "Daten und Fakten." Webpage: https://stadtwerke-zittau.de/swzittau/content/ueber_uns/unternehmen/daten_fakten (accessed: 2020-5-19).

Appendix B – District Heating Consumption per Municipality

Municipality	District heating final energy consumption [GWh/a] Model (2018)	Research (year)	Trend Scenario (2038)	Goal Scenario (2038)
Cottbus	242		332	316
Hoyerswerda	133		133	133
Görlitz	90		91	90
Bautzen	81	77 (2018)	81	81
Senftenberg	50	100 (2017)	50	50
Kamenz	49		49	49
Spremberg	46		46	46
Königs Wusterhausen	43		55	46
Zittau	43	48 (2018)	43	43
Weißwasser/O.L.	43		43	43
Lübbenau/Spreewald	36		36	36
Radeberg	32		32	32
Niesky	31		31	31
Ebersbach-Neugersdorf	30		30	30
Guben	29	123 (2015)	31	29
Löbau	29		29	29
Lauchhammer	26		26	26
Lauta	25		25	25
Ostritz	25		25	25
Forst (Lausitz)	23		23	23
Bischofswerda	20	11 (2014)	20	20
Pulsnitz	16		16	16
Vetschau/Spreewald	15		15	15
Wilthen	15		15	15
Schipkau	14		14	14
Finsterwalde	13	31 (2014)	25	24
Schwarzheide	12		12	12
Lübben (Spreewald)	11	11 (2011)	28	23
Olbersdorf	11		11	11
Königswartha	10		10	10
Elsterwerda	10		10	10
Ottendorf-Okrilla	9		9	9
Herzberg (Elster)	9		9	9
Bestensee	8		8	8
Rothenburg/O.L.	8		8	8

Municipality	District heating final energy consumption [GWh/a] Model (2018)	Research (year)	Trend Scenario (2038)	Goal Scenario (2038)
Schönefeld	8		30	29
Großschönau	7		7	7
Bernsdorf	7		7	7
Peitz	7		7	7
Wittichenau	6		6	6
Zeuthen	6		11	11
Cunewalde	6		6	6
Heidesee	5		5	5
Mittenwalde	5		9	8
Boxberg/O.L.	5		5	5
Radibor	5		5	5
Großräschen	4		7	5
Doberlug-Kirchhain	4		4	4
Schulzendorf	4		4	4
Bad Muskau	4		4	4
Elsterheide	4		4	4
Krauschwitz	4		4	4
Luckau	4		10	7
Lohsa	4		4	4
Schleife	4		4	4
Großröhrsdorf	3		3	3
Kolkwitz	3		3	3
Calau	3		7	7
Großdubrau	3		3	3
Märkische Heide	3		3	3
Oderwitz	2		0	0
Reichenbach/O.L.	2		0	0
Rietschen	2		0	0
Oßling	2		0	0
Bertsdorf-Hörnitz	2		0	0
Bad Liebenwerda	2		3	3
Heideblick	2		0	0
Schwepnitz	2		0	0
Groß Köris	2		0	0
Felixsee	2		0	0
Wildau	2		22	21

Municipality	District heating final energy consumption [GWh/a] Model (2018)	Research (year)	Trend Scenario (2038)	Goal Scenario (2038)
Schirgiswalde-Kirschau	2		0	0
Welzow	2		0	0
Elstra	2		0	0
Lichtenberg	2		0	0
Sohland a.d. Spree	1		0	0
Arnsdorf	1		0	0
Malschwitz	1		0	0
Schmölln-Putzkau	1		0	0
Bretnig-Hauswalde	1		0	0
Golßen	1		0	0
Massen-Niederlausitz	1		0	0
Groß Düben	1		0	0
Groß Schacksdorf-Simmersdorf	1		0	0
Kreba-Neudorf	1		0	0
Falkenberg/Elster	1		4	0
Eichwalde	1		15	13
Leutersdorf	1		0	0
Ruhland	1		0	0
Neusalza-Spremberg	1		0	0
Großharthau	1		0	0
Burkau	1		0	0
Kodersdorf	1		0	0
Halbe	1		0	0
Horka	1		0	0
Schönborn	1		0	0
Drebkau	1		0	0
Neuhausen/Spree	1		0	0
Eibau	1		0	0
Königsbrück	1		0	0
Burg (Spreewald)	1		0	0
Mühlberg/Elbe	1		0	0
Döbern	1		0	0
Weißenberg	1		0	0
Altdöbern	1		0	0
Schöpstal	1		0	0
Panschwitz-Kuckau	1		0	0

Municipality	District heating final energy consumption [GWh/a] Model (2018)	Research (year)	Trend Scenario (2038)	Goal Scenario (2038)
Berthelsdorf	1		0	0
Quitzdorf am See	1		0	0
Räckelwitz	1		0	0
Neukirch/Lausitz	1		0	0
Wachau	1		0	0
Röderland	1		0	0
Steinigtwolmsdorf	1		0	0
Obergurig	1		0	0
Spreetal	1		0	0
Werben	1		0	0
Guttau	1		0	0
Weißkeißel	1		0	0
Bersteland	1		0	0
Puschwitz	1		0	0
Tettau	1		0	0
Märkisch Buchholz	1		0	0
Herrnhut	0		0	0
Schenkendöbern	0		0	0
Mittelherwigsdorf	0		0	0
Sonnewalde	0		0	0
Schönewalde	0		0	0
Großpostwitz/O.L.	0		0	0
Hochkirch	0		0	0
Hohenleipisch	0		0	0
Obercunnersdorf	0		0	0
Neißeaue	0		0	0
Neiße-Malxetal	0		0	0
Gablenz	0		0	0
Ralbitz-Rosenthal	0		0	0
Niedercunnersdorf	0		0	0
Großschweidnitz	0		0	0
Nebelschütz	0		0	0
Hohenbocka	0		0	0
Crostwitz	0		0	0
Rietzneuendorf-Staakow	0		0	0
Uebigau-Wahrenbrück	0		0	0

Municipality	District heating final energy consumption [GWh/a]			
	Model (2018)	Research (year)	Trend Scenario (2038)	Goal Scenario (2038)
Haselbachtal	0		0	0
Seifhennersdorf	0		0	0
Bernstadt a.d. Eigen	0		0	0
Plessa	0		0	0
Demitz-Thumitz	0		0	0
Oppach	0		0	0
Kubschütz	0		0	0
Waldhufen	0		0	0
Ohorn	0		0	0
Schönteichen	0		0	0
Hohendubrau	0		0	0
Laußnitz	0		0	0
Teupitz	0		0	0
Steina	0		0	0
Schwielochsee	0		0	0
Rückersdorf	0		0	0
Schönau-Berzdorf a.d. Eigen	0		0	0
Oybin	0		0	0
Lieberose	0		0	0
Neupetershain	0		0	0
Crinitz	0		0	0
Beiersdorf	0		0	0
Großkmehlen	0		0	0
Schönwald	0		0	0
Lichterfeld-Schacksdorf	0		0	0
Tröbitz	0		0	0
Frauendorf	0		0	0
Tauer	0		0	0
Kasel-Golzig	0		0	0
Krausnick-Groß Wasserburg	0		0	0
Schlepzig	0		0	0
Doberschau-Gaußig	0		0	0
Markersdorf	0		0	0
Neschwitz	0		0	0
Vierkirchen	0		0	0
Jänschwalde	0		0	0

Municipality	District heating final energy consumption [GWh/a] Model (2018)	Research (year)	Trend Scenario (2038)	Goal Scenario (2038)
Jonsdorf	0		0	0
Hainewalde	0		0	0
Hirschfeld	0		0	0
Tschernitz	0		0	0
Königshain	0		0	0
Teichland	0		0	0
Neu Zauche	0		0	0
Großnaundorf	0		0	0
Frankenthal	0		0	0
Unterspreewald	0		0	0
Luckaitztal	0		0	0
Hermsdorf	0		0	0
Byhleguhre-Byhlen	0		0	0
Lindenau	0		0	0
Schwerin	0		0	0
Drahnsdorf	0		0	0
Jamlitz	0		0	0
Drehnow	0		0	0
Steinreich	0		0	0
Guhrow	0		0	0
Alt Zauche-Wußwerk	0		0	0
Schilda	0		0	0
Münchehofe	0		0	0
Göda	0		0	0
Schlieben	0		0	0
Ortrand	0		0	0
Lawalde	0		0	0
Rosenbach	0		0	0
Neukirch	0		0	0
Sallgast	0		0	0
Wiesengrund	0		0	0
Gröden	0		0	0
Rammenau	0		0	0
Hähnichen	0		0	0
Sohland a. Rotstein	0		0	0
Schönbach	0		0	0

Municipality	District heating final energy consumption [GWh/a]			
	Model (2018)	Research (year)	Trend Scenario (2038)	Goal Scenario (2038)
Turnow-Preilack	0		0	0
Großthiemig	0		0	0
Mücka	0		0	0
Dürrhennersdorf	0		0	0
Gorden-Staupitz	0		0	0
Dissen-Striesow	0		0	0
Trebendorf	0		0	0
Straupitz	0		0	0
Wiednitz	0		0	0
Kremitzaue	0		0	0
Merzdorf	0		0	0
Schmogrow-Fehrow	0		0	0
Drachhausen	0		0	0
Lebusa	0		0	0
Briesen	0		0	0
Schwarzbach	0		0	0
Kroppen	0		0	0
Hohenbucko	0		0	0
Fichtwald	0		0	0
Heinersbrück	0		0	0
Bronkow	0		0	0
Hornow-Wadelsdorf	0		0	0
Guteborn	0		0	0
Grünewald	0		0	0
Neu-Seeland	0		0	0
Heideland	0		0	0
Schraden	0		0	0
Spreewaldheide	0		0	0
Jämlitz-Klein Düben	0		0	0