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Electricity, Heat, and Gas Sector Data for Modeling the German System

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Data Documentation

Electricity, Heat, and Gas Sector Data for Modeling the German System

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langfristige Planung und kurzfristige Optimierung des **Elektrizitätssystems in Deutschland** im europäischen Kontext

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1 Introduction

This data documentation describes a data set of the German electricity, heat, and natural gas sectors compiled within the research project 'LKD-EU' (Long-term planning and short-term optimization of the German electricity system within the European framework: Further development of methods and models to analyze the electricity system including the heat and gas sector). The project is a joined effort by the German Institute for Economic Research (DIW Berlin), the Workgroup for Infrastructure Policy (WIP) at Technische Universität Berlin (TUB), the Chair of Energy Economics (EE2) at Technische Universität Dresden (TUD), and the House of Energy Markets & Finance at University of Duisburg-Essen. The project was funded by the German Federal Ministry for Economic Affairs and Energy through the grant 'LKD-EU', FKZ 03ET4028A.

The objective of this paper is to document a reference data set representing the status quo of the German energy sector. We also update and extend parts of the previous DIW Data Documentation 75 (Egerer et al. 2014). While the focus is on the electricity sector, the heat and natural gas sectors are covered as well. With this reference data set, we aim to increase the transparency of energy infrastructure data in Germany. On the one hand, this documentation presents sources of original data and information used for the data set. On the other hand, it elaborates on the methodologies which have been applied to derive the data from respective sources in order to make it useful for modeling purposes and to promote a discussion about the underlying assumptions. Furthermore, we briefly discuss the underlying regulations with regard to data transparency in the energy sector. Where not otherwise stated, the data included in this report is given with reference to the year 2015 for Germany.

This document is structured as follows: Section 2 describes data of the German electricity sector and explains the methods for deriving this data. Section 3 discusses the data preparation for German heating networks. Section 4 covers the natural gas system in Germany. While Sections 2 to 4 focus on Germany, interactions on a European level are considered in a stylized way. Finally, Section 5 introduces some research questions to be answered with the help of the presented data set and discusses a range of limitations.

The data set described in the following chapters can be downloaded from the Zenodo repository under the DOI https://doi.org/10.5281/zenodo.1044463.

2 Electricity data

In general, electricity can be produced in renewable or conventional generation units. The generation of electricity is required to serve loads from different sectors, such as the residential sector, industry, or trade and commerce. With the increasing electrification of the heating and mobility sectors – referred to as sector coupling – the level and time-profile of electric load will change in the future. As the locations of electricity generation and load typically do not coincide, electricity transmission networks are required to spatially match generation and load.

The electricity sector in Germany was characterized by conventional generation, that is, nuclear, hard coal, lignite, natural gas and others for decades, but faced a steep increase of renewable generation, particularly wind and solar PV, since the year 2000. Wind and solar PV generators accounted for around 20% of German gross electricity consumption in 2016 and have to be expanded much further in order to achieve the German government's renewable energy targets.[9] Because of the general characteristics of variable wind and solar renewable generators, this development poses specific challenges, for example flexibility requirements, to the electricity sector. Moreover, the development of decentralized renewable generators induces significant shifts of spatial generation patterns, with consequences for the transmission network. Thus, the congestion management cost of the transmission network recently increased substantially due to more frequent limitations of transmission capacities. Exemplarily, congestion management costs amounted to 58 mEUR in 2010 (BNetzA and BKartA 2012) and increased to 727 mEUR in 2015 (BNetzA and BKartA 2016).

[9] By 2050, at least 80% of German gross electricity consumption have to be covered by renewable energy sources according to § 1 of the Renewable Energy Sources Act (EEG). Furthermore, a target corridor of 40-45% and 55-60% has been defined for the years 2025 and 2035, respectively.

To investigate these and other issues of the current and future electricity system, techno-economic models are often applied to gain insights on different levels of technical detail. These models usually aim to provide a realistic representation of the current German electricity system, which requires data for a range of input parameters from multiple sources. Moreover, the transparency of such data as well as the applied methodologies of data refinement are of importance and attracted increasing interest during the last years. Therefore, we describe not only the electricity sector data of our reference data set in the following (overview of sources in Section 2.1), but also the methodologies which we are applying to approximate missing information. Beside generation (Section 2.3) and load (Section 2.4), particular attention is given to the electricity transmission network (Section 2.2). Additionally, we aim to include additional data required for a basic electricity system model (such as imports and exports in Section 2.5).

2.1 Data sources

Obligations for data publication by German transmission system operators are defined within § 17 of the Electricity Grid Access Ordinance of 2005 (*Stromnetzzugangsverordnung*, StromNZV). The data has to be published at least on a website and includes hourly vertical load, annual peak load and quarter-hourly load measurement, network losses, quarter-hourly balance of the control area and minute reserve actually activated, quarter-hourly exchange flow aggregated for each cross-border exchange point with an outlook on capacity allocation, outages, and planned revisions of the network which are relevant to the market, quantities and prices of lost energy, and data on projected and actual wind feed-in. Moreover, concerns about security of supply led to a monitoring of power plant capacities on plant (and block) level by the federal network agency BNetzA.

As this data documentation aims for highest levels of transparency and traceability, we only use open data sources. The sources include a limited number of publications by different institutions, organizations, associations, exchanges, and companies which are publicly available (Table 1). We do not consider commercial data sets (e.g. on power plants), information only available under non-disclosure agreements (e.g. on network data), and references for individual infrastructure objects.

Table 1: Data sources of German electricity sector data

Institution	Type of data
ENTSO-E (European Network of Transmission System Operators for Electricity)	- Time series on: • Load data (hourly) • Physical cross-border flows (Baltic cable)
50Hertz, Amprion, TenneT, Trans-netBW (German TSOs)	- Transmission network map - Static network data sets - Generation capacities in the renewable sup-port scheme (until August 2014) - Time series on: • Renewable generation (15min) • Cross-border flows (15min)
BNetzA (German regulator)	- Generation capacities in the renewable sup-port scheme (since August 2014) - Generation capacities (with address) • Conventional power plants (block level) • Renewables >10 MW, (<10MW as aggre-gated values)
EEX (Energy exchange)	- Market price data: • Emission allowances for carbon • Day-ahead market prices for electricity
Statistik der Kohlenwirtschaft e.V. (Association)	- Fuel price data: • Natural gas • Hard coal • Fuel oil
AG Energiebilanzen e.V. (Working group)	- Load statistics - Generation statistics
BDEW (Association)	- Standard load profiles
Eurostat	- Regional information on: • Population (NUTS3 level)

Institution	Type of data
DESTATIS (Statistics departments of the federation and the federal states)	- Regional information on: • Sectoral gross value added (NUTS3 level)
NASA MERRA-2	- Regional wind speed (hourly)
Open Power System Data project	- Geographical information on power plants - Regional wind speed (hourly) - Consolidated data on: • TSO's renewable generation • ENTSO-E's load data
Open Street Map	- Geographic information on: • Transformer stations • Transmission lines

Beside the listed original data sources, we make use of data sets provided by the Open Power System Data project[10]. The project consolidates historic electricity data from various data sources, adds additional information, for example geographical information on conventional and renewable capacities, and provides final data sets for European countries through an open-source data platform. Specifically, we derive consolidated data sets on:

- TSO's renewable generation (hourly),
- ENTSO-E's load data (hourly),
- BNetzA's power plant list,
- TSO's and BNetzA's renewable plant register,
- NASA's MERRA-2 regional wind speeds.

Moreover, the availability of open-source processing scripts by the Open Power System Data platform allows for an easy adaption of data sets to (our) specific requirements. We make use of this functionality to derive regional wind speed data for the year 2015.

[10] https://open-power-system-data.org/

2.2 High-voltage transmission networks

During the last years, various developments lead to an increasing interest in publicly available data sets on German and European transmission networks. On the one hand, the availability of open-source geographical data sets, for example Open Street Map, attracted academic research. For instance, the SciGrid-project[11] extracts and processes technical and geographical network information from Open Street Map to provide an open-source data set on the German and European transmission network (Matke, Medjroubi, and Kleinhans 2016). On the other hand, the introduction of flow-based market coupling in the central western European region requires a more detailed understanding of physical network realities in the industry. Therefore, German and other European TSOs nowadays publish static network data sets with technical and topological information of transmission lines in their control zone (50Hertz 2017; Amprion 2017; TenneT TSO 2017a; TransnetBW 2017). A non-exhaustive list of available electricity network data sets can be found in openmod Initiative (2017).

The transmission network covers the voltage levels of 220 and 380 kV and enables a spatial matching of generation sources and load sinks in Germany as well as (on an aggregated basis) across European countries. This data set focuses solely on the German electricity network. Interactions with other European countries are based on exogenously defined imports and exports for the year 2015.

We base our network data set on the geographical information provided by Open Street Map and extend it by additional information in particular on the network topology, that is the start and end substations of individual lines or circuits. Whereas Open Street Map provides sufficiently precise spatial information, it has limited information on the network topology. Contrarily, TSOs' static network models include detailed technical and topological information, but do not include spatial information. Therefore, we base our initial network data set on the 2012 version described in Egerer et al. (2014) and update it to 2015 using TSOs' static network information, Open Street Map, as well as information on finished network extension projects.

[11] http://scigrid.de/

A detailed description of the initial network data set and underlying data sources can be found in Egerer et al. (2014).

We include the following realized network expansion projects which are laid down in two German laws, that is the Power Grid Expansion Act (*Energieleitungsausbaugesetz*, EnLAG) and the Federal Requirement Plan Act (*Bundesbedarfsplangesetz*, BBPlG). Herein, individual network expansion projects are listed and described. They are based on a regular mid-term assessment of network capacity needs (so called grid development plan, in German *Netzentwicklungsplan*) by German TSOs and the federal network agency BNetzA. Moreover, the federal network agency reports the progress of these projects (BNetzA 2017c) which we use to identify realized projects. Additionally, we account for two projects by 50Hertz which are realized outside the aforementioned regulations. Table 2 lists realized projects included in our network data set.

Table 2: List of network expansion projects considered in the data set

Project	Realized part of the project	Description	Capacity per circuit
EnLAG 3	Vierraden – Krajnik (PL)	Replacement of an existing 220 kV line through a 380 kV line	1,700 MVA
EnLAG 4	Lauchstädt – Vieselbach – Altenfeld – Redwitz	New-built 380 kV transmission line	2,300 MVA
EnLAG 10	Redwitz – Würgau – Oberhaid – Eltmann – Grafenrheinfeld	Replacement of an existing 220 kV line through a 380 kV line	2,100 MVA
EnLAG 15	Sechtem – Weißenthurm	New-built 380 kV transmission line	1,700 MVA
EnLAG 17	Gütersloh - Bechterdissen	Replacement of an existing 220 kV line through a 380 kV line	1,700 MVA

Project	Realized part of the project	Description	Capacity per circuit
EnLAG 18	Point Gaste - Westerkappeln	Replacement of an existing 220 kV line through a 380 kV line	1,700 MVA
EnLAG 20	Dauersberg – Hünfelden	Replacement of an existing 220 kV line through a 380 kV line	1,700 MVA
EnLAG 23	Neckarwestheim – Mühlhausen	Upgrade of existing 220 kV line to 380 kV	1,700 MVA
BBPlG 26	Bärwalde – Schmölln	Upgrade of an existing 380 kV line	2,300 MVA
BBPlG 27	Förderstedt	Connection of substation Förderstedt to 380 kV line 'Wolmirstedt-Ragow' and deconstruction of 220 kV lines	1,700 MVA
50Hertz	Remptendorf – Redwitz	Upgrade of an existing 380 kV line	2,300 MVA
50Hertz	Ragow – Thyrow – Wustermark	Upgrade of existing 220 kV line to 380 kV	1,700 MVA

Moreover, the projects EnLAG 1 and 5 as well as BBPlG 8 and 9 were partly realized, but not fully operational or in test operation in 2015. Therefore, these projects are not included in the reference data set.

The final data set of the German transmission network consists of 724 transmission lines and 981 circuits. The transmission lines connect 450 network nodes, that is substations and auxiliary nodes, of which 427 are located in Germany and 22 are located in neighboring countries. Figure 1 gives a graphical illustration of the German transmission network.

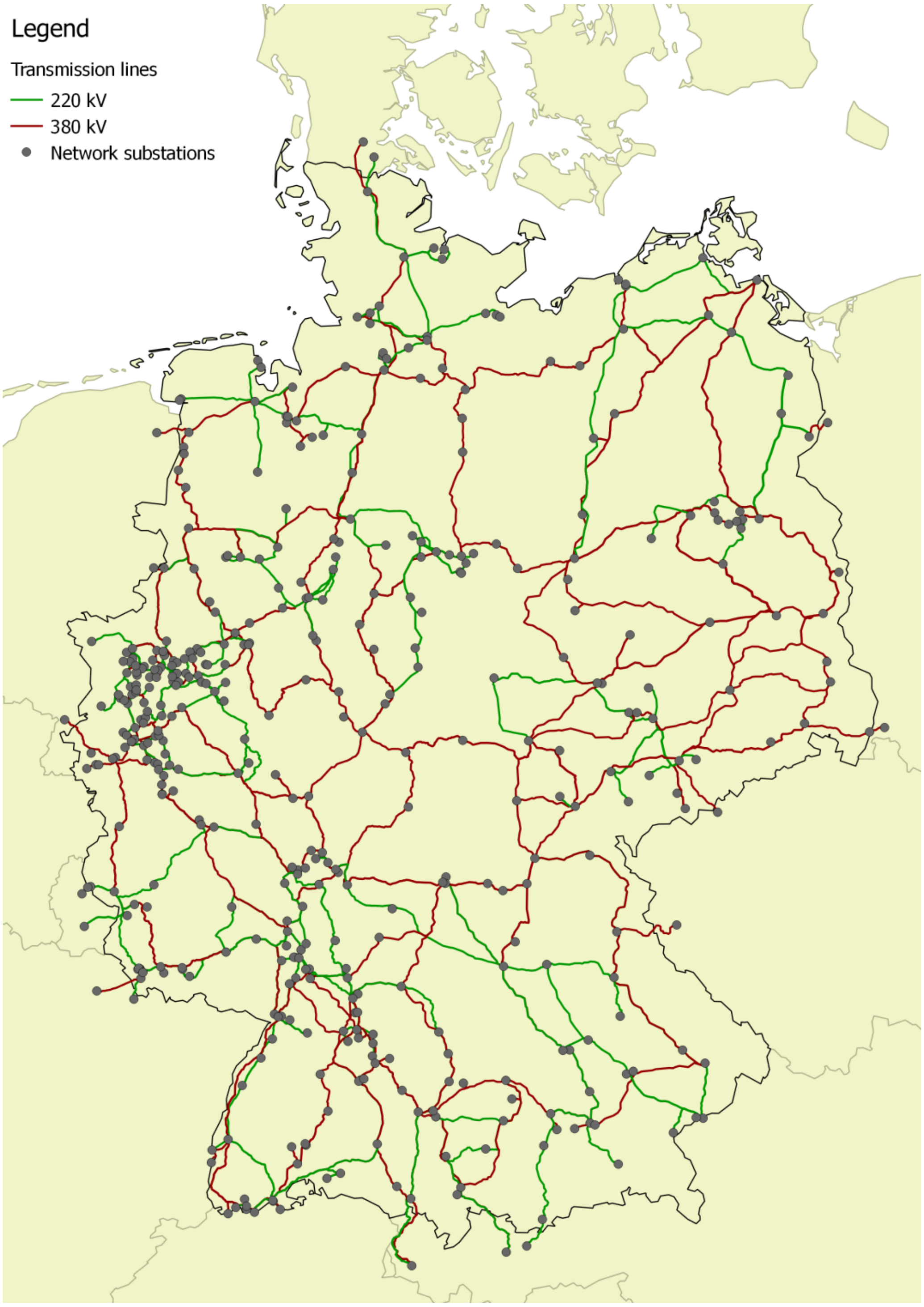


Figure 1: The transmission network of Germany

Source: own illustration

Based on georeferenced transmission lines and substations, we determine the network topology, i.e. start and end substations, as well as the length of individual lines. The network data comprises a circuit length of 37,152 km, which is slightly higher than the reported 36,001 km in 2015 (BNetzA and BKartA 2016, 26).[12] The length of individual transmission lines is important to determine technical characteristics, that is, resistance and reactance, using specific values per circuit from literature (Table 3). Similarly, we use standard assumptions on the thermal transmission limit per circuit, which defines the maximum transfer limit of individual lines. However, new-built transmission lines use advanced conductor materials, allowing for higher maximum currents. Based on detailed network information by the German TSOs, we set the maximum thermal capacity for the new-built 380 kV projects listed in Table 2 to 2,100 or 2,300 MVA. As the data is intended to be used in linear power flow models which omit reactive power flows and do not explicitly account for N-1, we reduce the thermal transmission capacity by 20% as an approximation for these limitations (Leuthold, Weigt, and Hirschhausen 2012).

Table 3: Technical characteristics of transmission lines

Voltage [kV]	Specific resistance [Ohm/km]	Specific reactance [Ohm/km]	Thermal transmission limit [MVA]
220	0.059	0.32	490
380	0.03	0.26	1,700

Source: Fischer and Kießling (1989)

[12] The difference in the length can be explained by the following reasons: (i) we already include the new transmission lines between Remptendorf (50Hertz) and Redwitz (TenneT TSO), which is fully in operation since 2017; (ii) the length of cross-border lines can be accounted differently in the statistics and our network data as these lines are owned by two TSOs; and (iii) approximations of routes can result in differences in length.

Generally, the transmission network covers only Germany as an isolated system. Thus, we limit all physical flows to the German transmission network and abstract from direct interactions with respect to physical flows with neighboring countries. To reflect at least the physical exchanges with these countries, physical exchanges at cross-border lines with neighboring European countries can be used as exogenous model parameters based on historical time series as described in Section 2.5.

2.3 Generation capacity

The general data availability of national generation capacities has improved with the power plant lists provided by the German federal network agency (BNetzA) and the federal environmental protection agency (*Umweltbundesamt*, UBA), as well as the publication of the renewable installation register:

i) The German federal network agency provides a list with block-specific information on generation infrastructure connected to the German transmission network (BNetzA 2017b). The main motivations for this list have been improved transparency in the German network development plan and security of supply considerations after the second German nuclear phase-out decision following the partial meltdowns in the nuclear reactors of Fukushima.

ii) A comparable list of generation units above 100 MW is compiled by the federal environmental protection agency (UBA 2017). The power plant list is comparable to the previous one, but provides additional information, such as detailed generation technologies and maximum heat output for CHP units.

iii) The German TSOs (until August 2014; 50Hertz et al., 2017) and the federal network agency BNetzA (since August 2014; BNetzA, 2017) collect data for all renewable installations which are covered by the German renewable support scheme under the Renewable Energy Sources Act (*Erneuerbare-Energien-Gesetz*, EEG).

In the following, we distinguish between conventional generation capacities, listed in the power plant list (BNetzA 2017b), and renewable capacities which are part of the installation register (50Hertz et al. 2017; BNetzA 2017a).

2.3.1 Conventional generation capacity

The conventional generation capacities comprise power units that are dispatchable at specified direct (or indirect) variable generation costs. Thus, they are considered separately in the data set with specific information on the respective main fuel, technology, electrical capacity, electrical efficiency, and location in the German transmission network. Additionally, the energy storage capacity of pumped-hydro plants is included. We further identify power plants which jointly produce heat and electricity, so called combined heat and power (CHP) plants, and detail the technology, maximum heat output, the specific electricity reduction factor, as well as the heating network the unit is connected to (see Section 3 for detailed information).

We base our data set on an extended power plant list (Open Power System Data 2016a), initially provided by the federal network agency (BNetzA 2017b). Beside general information on power units, the extended list provides further information on the generation technology as well as additional geographical information. The latter information is used to specify the location of individual units in the 220/380 kV transmission networks. Moreover, we adopt the efficiency assumptions provided by Open Power System Data (2016), which rely on Egerer et al. (2014) and describe a linear relationship between generation fuel or technology and commissioning year.

The extended power plant list provides most recent information on generation capacities. However, as we are interested in the power plant list for 2015, we only include operating plants which are commissioned prior to 2015.[13] We further verify the status of recently decommissioned power plants (be it permanently or temporarily) with respect to the year 2015.

Table 4 compares our plant list with reported statistics on conventional generation capacity in BNetzA and BKartA (2016) for 2014 and 2015. We are close to reported capacities, but differences can be observed for all fuels. Most importantly, natural gas capacities are lower by roughly 4.9 GW_{el} in our plant list. One reason is that we neglect natural gas capacities (ca. 2.3-2.7 GW_{el} depending on the status of the power plant list) that are listed in the power plant list

[13] Decommissionings of large capacities during the year 2015 may be accounted for in model applications on a case-by-case-basis.

by the federal network agency BNetzA as an aggregated capacity. This is also true for other fuels, although to a lower extent. It should be noted that the reported statistics in BNetzA and BKartA (2016) for natural gas capacities are already higher than the operating capacity in the official BNetzA power plant list. A 2014 version of the power plant list reports an operating natural gas capacity of 23.6 GW_{el} and additionally 4.8 GW_{el} gas-fired capacity which is labelled as temporary shut-down, reserve capacity, or as special cases. Thus, even if the data set is not able to fully replicate reported capacity numbers, they are in a reasonable range.

The spatial distribution of installed conventional generation capacities differentiated by main fuel is depicted in Figure 2. To structure the initial power plant list for model applications, we define the following main fuels: nuclear (uranium), lignite, hard coal, natural gas, oil (heavy and light), waste, hydro, biomass, and other fuels. The generation technologies are differentiated between steam turbine, gas turbine, combined cycle, combustion engine, and pumped storage. Each power plant in the list is assigned a main fuel and a corresponding technology. It is important to note that renewable energy sources and run-of-river hydro are considered on an aggregated nodal basis as described in Section 2.3.2 and are therefore not part of the detailed power plant list. Finally, we complement the power plant list by CHP information which are detailed in Section 3.

Table 4: Comparison of installed conventional generation capacities

Fuel	Capacity 2014 (BNetzA and BKartA 2016)	Capacity 2015 (BNetzA and BKartA 2016)	Reference data set
Nuclear	12,068 MW_{el}	10,800 MW_{el}	12,075 MW_{el}[14]
Lignite	21,068 MW_{el}	20,901 MW_{el}	20,901 MW_{el}
Hard coal	26,205 MW_{el}	28,661 MW_{el}	28,571 MW_{el}[15]
Natural gas	28,978 MW_{el}	28,466 MW_{el}	23,625 MW_{el}
Oil[16]	4,236 MW_{el}	4,190 MW_{el}	3,675 MW_{el}
Waste	869 MW_{el}	880 MW_{el}	1,631 MW_{el}
Other fuels	3,379 MW_{el}	3,346 MW_{el}	2,466 MW_{el}
Pumped storage	9,245 MW_{el}	9,440 MW_{el}	8,789 MW_{el}
Total	**106,048 MW_{el}**	**106,684 MW_{el}**	**101,732 MW_{el}**

[14] The nuclear power plant Grafenrheinfeld (1,275 MW_{el}) was shut down on 27th June 2015 and we manually account for this within our data set.

[15] We manually account for the commissioning of the coal plant Wilhelmshafen (731 MW_{el}) as well as the decommissioning of the coal-fired plant Veltheim (303 MW_{el}) during the year 2015.

[16] In the following chapters, oil is differentiated in light and heavy oil since fuel prices and carbon emission factors differ. We assume the oil power plants in Leuna (BNA0596), Köln Godorf (BNA0547), Schwedt (BNA0894a-e), and Heide (BNA1526) to be fueled with heavy oil as they belong to refineries. The remaining oil-fired power plants are assumed to be fueled with light oil.

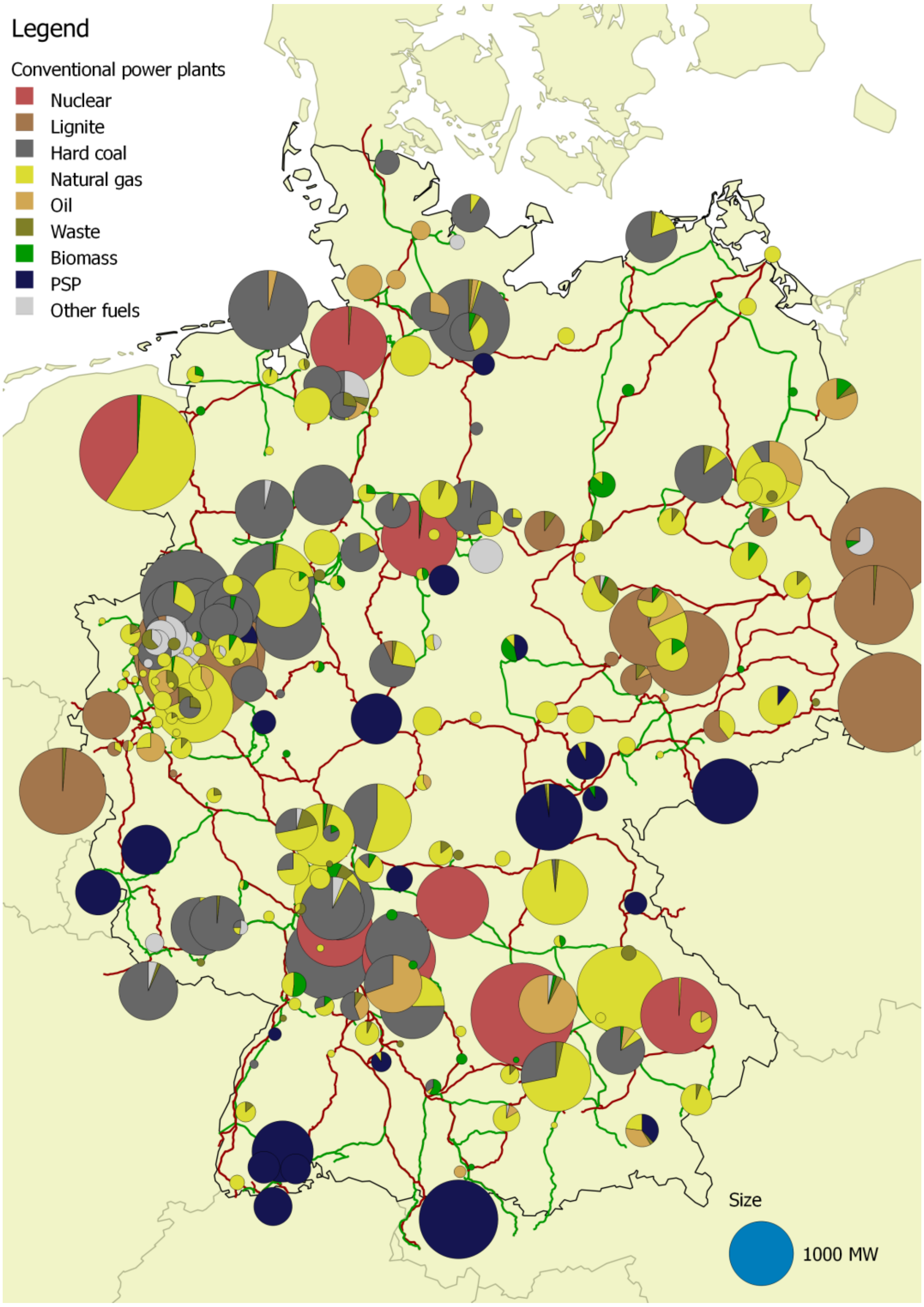


Figure 2: Spatial distribution of conventional generation capacities

Source: own illustration

2.3.2 Renewable generation capacity

The majority of renewable generation capacities are part of the renewable support scheme and therefore listed in the renewable installation register (50Hertz et al. 2017; BNetzA 2017a). Consequently, we use this register to extract information on generation technology, capacity, and geographical location. However, the shift of the register's responsibility to the German federal network agency lead to a break in the reporting with the risk of inconsistent information. Additionally, geographical information, that is postal address of installations, are classified as private information and published with a lower level of detail.

As mentioned previously, the Open Power System Data project addresses these issues and provides a consolidated data set of renewable installations from the two sources as well as approximated geographical information of individual installations (Open Power System Data 2017a). Moreover, the data set has been checked for consistency, and suspicious data entries are marked. We use this publicly available data set to identify the renewable installations operating by the end of 2015. Moreover, we omit suspicious or inconsistent data entries which are marked in the data set.

We further process the data set to determine nodal generation capacities for wind onshore, solar PV, biomass, run-of-river hydro, and geothermal. Figure 3 depicts the general process. As the original data set provides approximated geographical coordinates, we can assign the installation capacity to the closest network node in the transmission network. We then aggregate individual capacities to derive aggregated nodal capacities per renewable technology. Moreover, we use statistics on regional capacities at the level of federal states from BNetzA (2017c) to scale the renewable capacities to reported EEG statistics. For run-of-river hydro plants, we complement the capacities in the support scheme by the renewable installation register with capacities outside the support scheme which are provided by the federal network agency (BNetzA 2017b) and consolidated in Open Power System Data (2016a). Thus, all run-of-river hydro plants, even if they are listed in a power plant list, are incorporated on an aggregated nodal level.

1. Capacities per ZIP code	2. Allocate ZIP areas to nodes	3. Table: Capacity per node
Allocate the renewable capacities per technology by ZIP code.	Allocate ZIP code areas to closest 220/380 kV network node.	Aggregation of ZIP code capacities per node and technology.

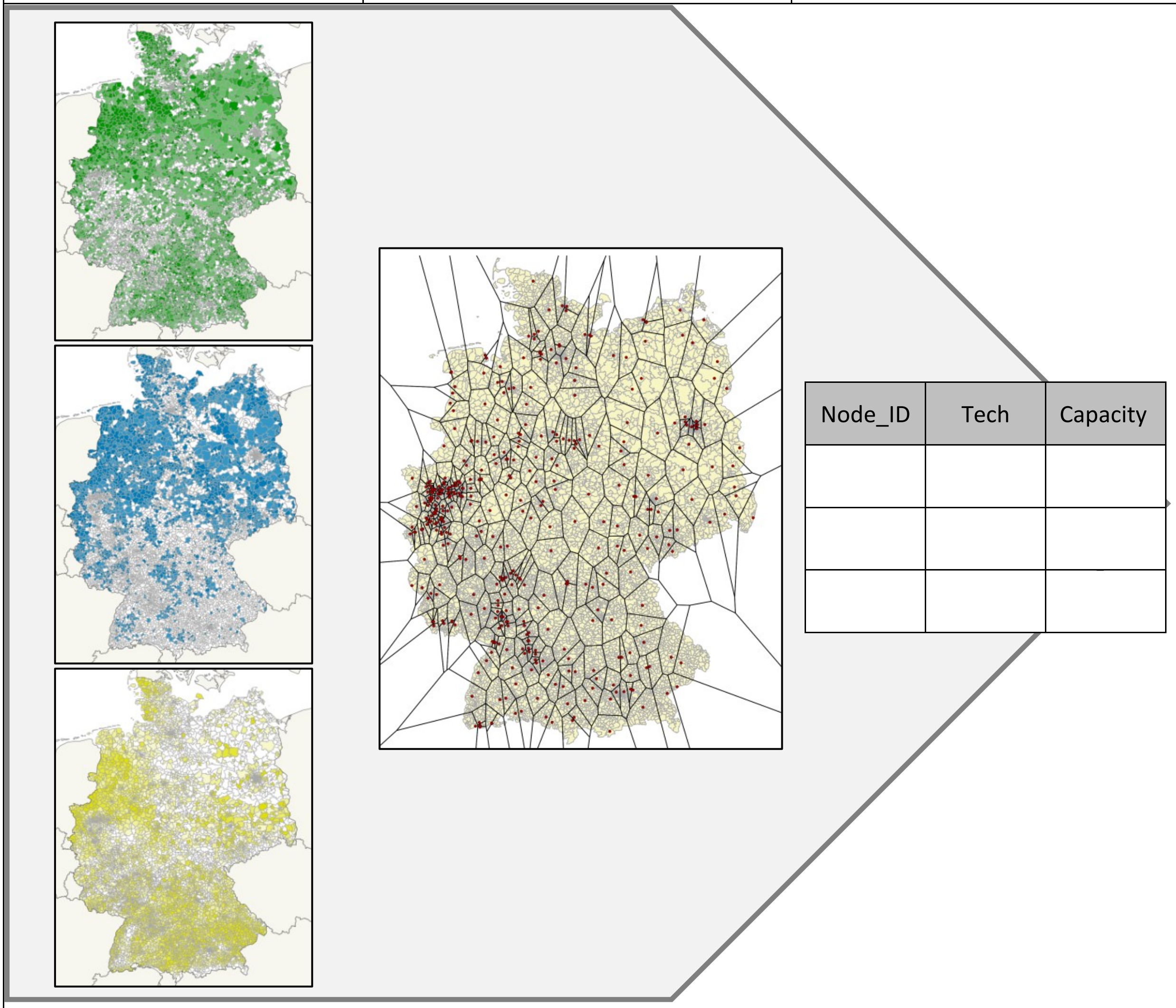


Figure 3: Data processing for renewable capacities in the renewable installation register

Source: Egerer et al. (2014)

Finally, offshore wind farms and their capacities are identified manually (Stiftung Offshore Windenergie 2017) including their connection to the transmission network. Considered offshore wind farms are listed in Table 5.

Table 5: List of offshore wind farms connected to the German transmission grid

Offshore wind farm	Capacity	Commission-ing year	Region	Network node
Alpha Ventus	60 MW_{el}	2010	North sea	Hagermarsch
EnBW Windpark Baltic 1	48 MW_{el}	2011	Baltic sea	Bentwisch
Bard Offshore 1	400 MW_{el}	2013	North sea	Diele
Riffgat	108 MW_{el}	2014	North sea	Emden/Borßum
Meerwind Süd/Ost	288 MW_{el}	2014	North sea	Dörpen/West
Trianel Windpark Borkum	200 MW_{el}	2015	North sea	Büttel
Global Tech 1	400 MW_{el}	2015	North sea	Diele
Nordsee Ost	295 MW_{el}	2015	North sea	Büttel
Dan Tysk	288 MW_{el}	2015	North sea	Büttel
Borkum Riffgrund 1	312 MW_{el}	2015	North sea	Dörpen/West
Butendiek	288 MW_{el}	2015	North sea	Büttel
Amrumbank West	288 MW_{el}	2015	North sea	Büttel
EnBW Windpark Baltic 2	288 MW_{el}	2015	Baltic sea	Bentwisch
Total	**3,263 MW_{el}**			

Using the approach described above, we derive renewable generation capacities for other renewables as depicted in Table 6. As we scale the regional capacities from the renewable installation register with the statistical data from the federal network agency, we are able to replicate the installed capacities on a national level. Differences are observable for run-of-river hydro as we also include hydro capacities outside the national renewable support scheme (EEG) in the amount of 2 GW_{el}. Additionally, the wind offshore capacity is slightly lower than statistically reported.

Table 6: Comparison of renewable generation capacities

Renewable technology	Capacity 2015 (BNetzA 2017c)	Data set
Run-of-river hydro	1,550 MW_{el}	3,700 MW_{el}
Wind onshore	41,242 MW_{el}	41,242 MW_{el}
Wind offshore	3,428 MW_{el}	3,263 MW_{el}
Solar PV	39,332 MW_{el}	39,332 MW_{el}
Biomass	6,900 MW_{el}	6,900 MW_{el}
Geothermal	33 MW_{el}	33 MW_{el}
Total	**92,485 MW_{el}**	**94,312 MW_{el}**

The distribution of renewable generation capacities to network nodes in the 220/380 kV transmission grid is depicted in Figure 4. The diagram shows the share of renewable technologies and size reflects the total installed renewable capacity. As we assign wind offshore capacities to their connection node in the (onshore) transmission grid rather than their exact location in the North or Baltic Sea, they are included at specific nodes. Finally, the figure indicates the regional distribution of individual renewable technologies: wind in the northern and eastern part; solar in the southern part, but also significant in remaining regions; hydro in southern parts of Germany.

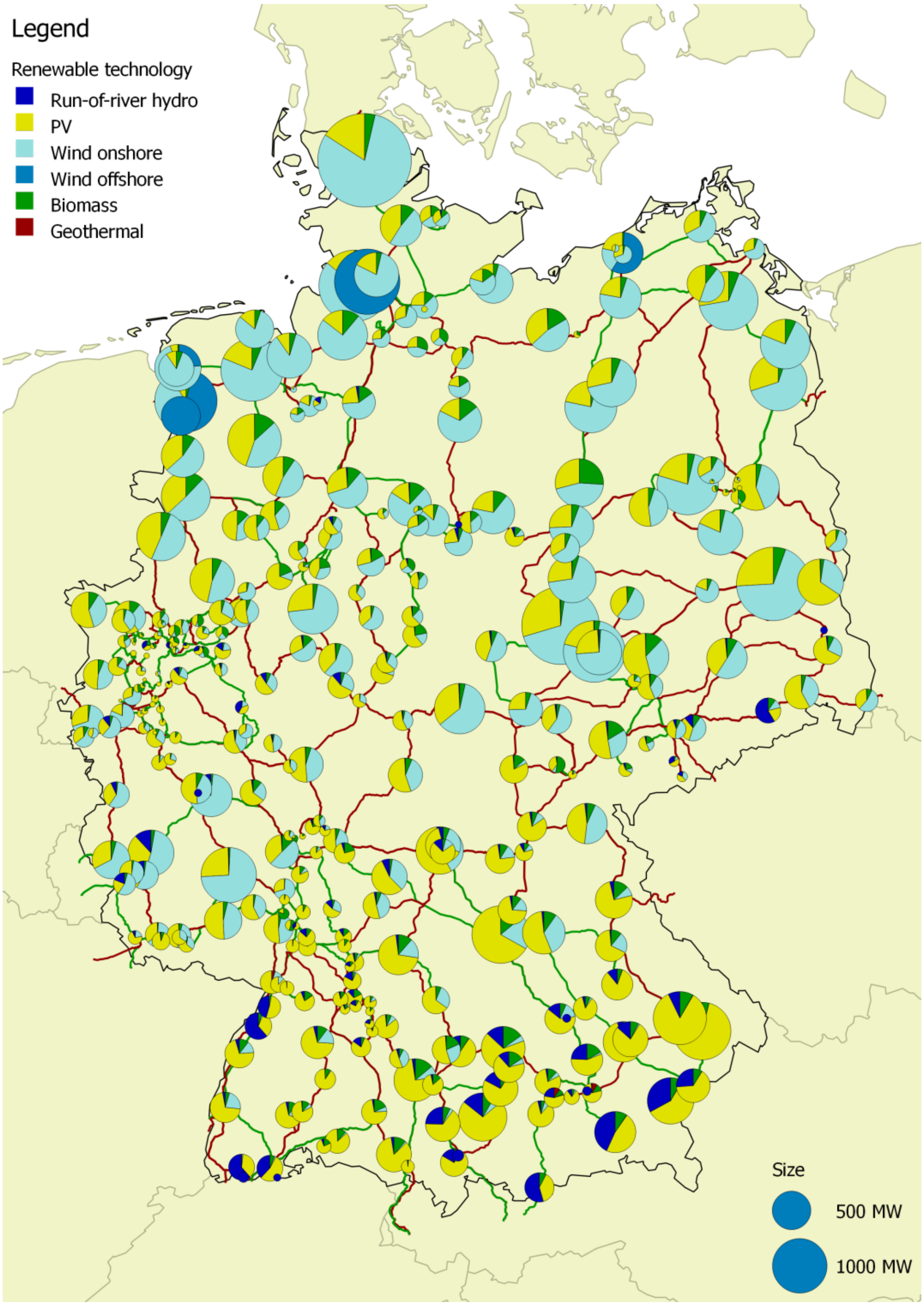


Figure 4: Spatial distribution of renewable capacities

Source: own illustration

2.3.3 Generation cost

Variable costs of electricity generation are calculated for each power plant block based on several parameters (Table 7):

- resource price of the respective fuel (annual average and monthly price data);
- allowance price for carbon emissions (annual average and daily price data);
- efficiency value specific to the power plant block (Egerer et al. 2014);
- carbon intensity of the fuel.

Table 7: Annual fuel cost data for 2015 and carbon intensity

	Fuel costs		Carbon factor	
	[EUR/t SKE]	[EUR/MWh_{th}]	[t CO_2/MWh_{th}]	[EUR/MWh_{th}]
Uranium	-	3.00****	-	
Lignite	-	3.10 ***	0.399**	3.03
Hard coal	68.00*	8.35	0.337**	2.56
Natural gas	185.00*	22.73	0.201**	1.53
Fuel oil (light)	373.00*	45.82	0.266**	2.02
Fuel oil (heavy)	180.00*		0.293**	2.22
Emission allowances	7.59 EUR/t CO_2			

Source: * Statistik der Kohlenwirtschaft e. V. (2017), ** UBA (2016), *** BNetzA (2016), **** Estimate

Fuel costs are derived from the resource price (incl. 28.12 EUR/t SKE[17] tax for fuel oil) divided by the efficiency value. For each carbon-based fuel we consider a carbon factor. The emission costs on net generation are calculated using the carbon factor divided by the efficiency value

[17] Coal equivalent

of the specific power plant block and are factored in with the emission allowance price. O&M costs could be considered but are often neglected in electricity market models because of the difficulty to distinguish between fixed and variable components. For power plants fired by hard coal, fuel transportation costs are approximated depending on the plant's location (aggregated by DENA zone). The transportation costs are measured in EUR/t SKE and the values used in the fuel cost calculations are illustrated in Figure 5.

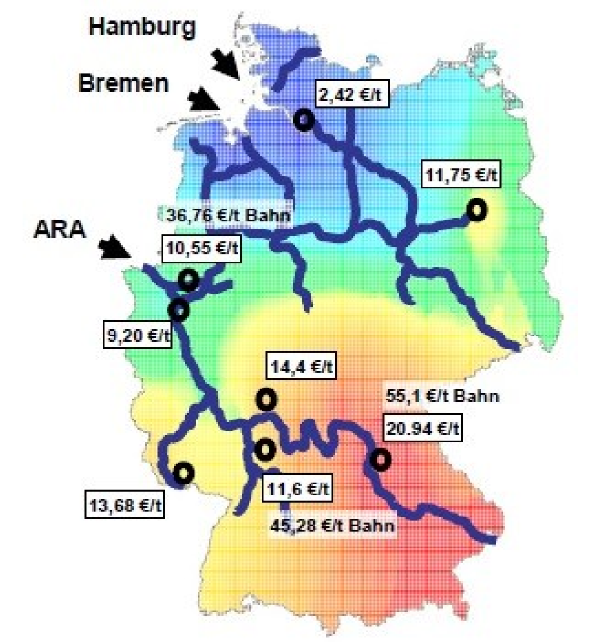
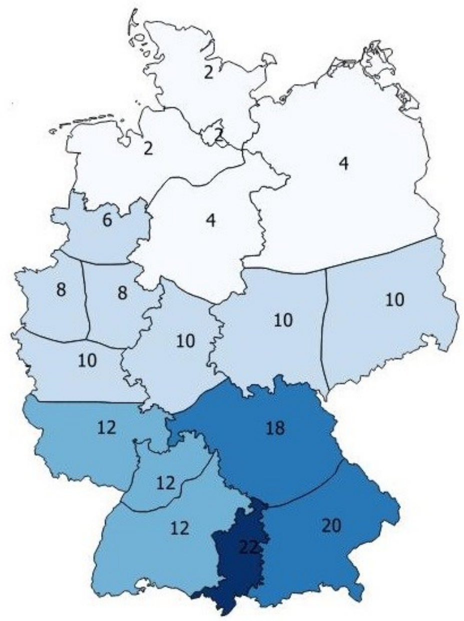
<table>
<tr><th>Study</th><th>Assumption on DENA zones [EUR/t SKE]</th></tr>
<tr><td>
</td><td>
</td></tr>
</table>

Figure 5: Spatial shipping costs for hard coal

Source: Frontier Economics and Consentec (2008)

The resulting merit order is illustrated in Figure 6. It includes all generation capacity of renewables and waste with the assumption of zero marginal costs.

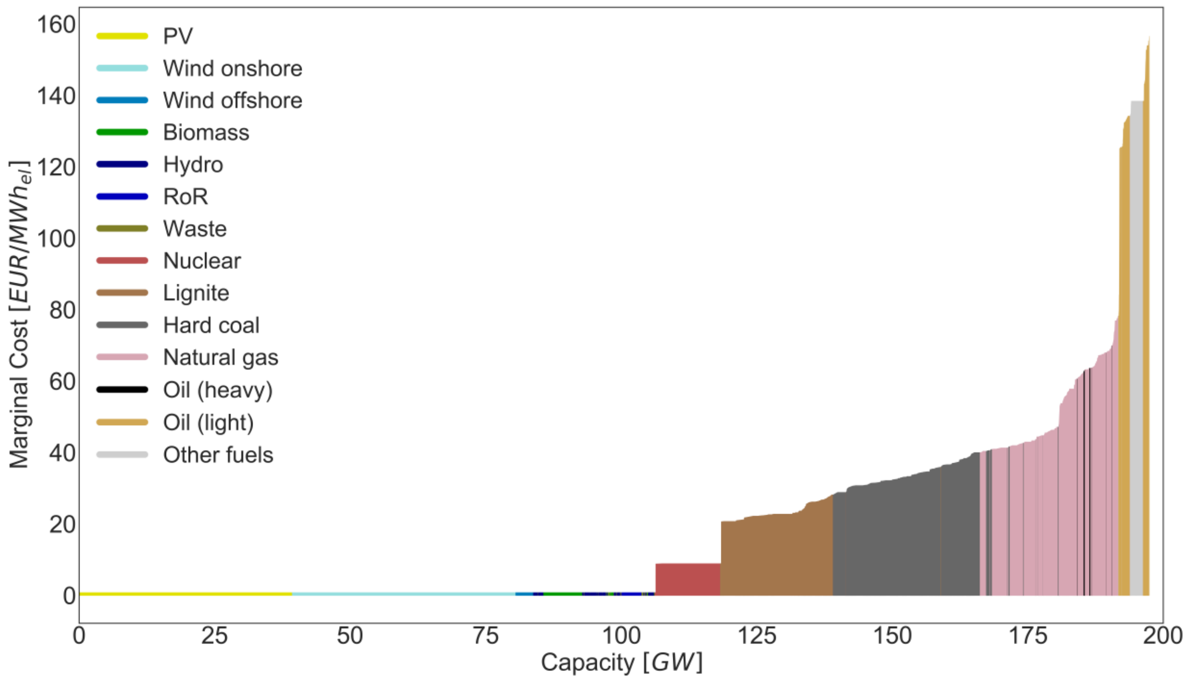


Figure 6: Merit order for the German electricity market with all capacities in 2015

Source: own illustration

Monthly fuel price data is available for hard coal, natural gas, and fuel oil. Figure 7 illustrates the significant price changes in 2015. The highest monthly prices differed by about 16% for hard coal, 31% for natural gas, and 57% for light fuel oil compared to the lowest monthly price. The yearly price assumptions for uranium (3.00 EUR/MWh_{th}) and lignite (3.10 EUR/MWh_{th}) are assumed to be constant throughout the year, as no publically available data exists. Daily data is used for the allowance price of carbon emissions (Figure 8).

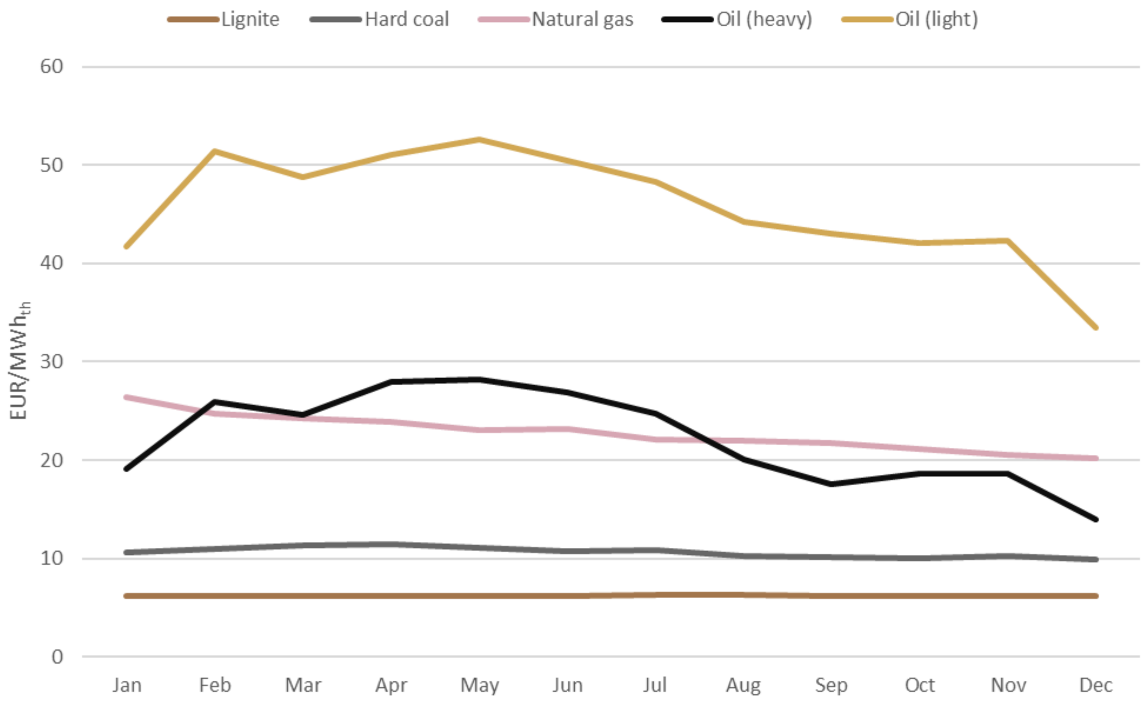


Figure 7: Monthly hard coal, natural gas, and fuel oil prices in 2015

Source: Statistik der Kohlenwirtschaft e. V. (2017), own illustration

Figure 8: Daily price of European Emission Allowances (EEA) in 2015

Source:EEX (2015), own illustration

2.3.4 Availability of generation capacity

Generation units face (un-)scheduled temporary shutdowns or generation capacity reductions. Reasons of such capacity reductions are, for instance, scheduled maintenances or revisions of generation units, or unplanned non-availabilities due to outages. While unplanned non-availabilities are stochastic, planned non-availabilities can be determined, for example, by economic considerations, i.e. drawing on the pattern of market prices. Due to lower load and market prices in summer periods, availability factors are assumed to be lower in these periods. Temporary non-availabilities of units are reflected in the data set by average availability factors and are differentiated by fuel. The same factors are used for all generation units with identical fuels.

Fuel-specific availability factors are derived in two steps. For generation technologies with rather low variable generation costs, that is nuclear, lignite, biomass, and run-of-river hydro, ENTSO-E generation statistics (ENTSO-E 2017b) are used to determine monthly generation profiles. Moreover, the total annual generation is derived from net generation statistics for 2015 (BDEW 2017) to align the ENTSO-E generation profiles with historical reported values. The adjusted monthly production is finally corrected by the installed capacity to yield hourly availability factors between zero and one. The underlying assumption inherent to this approach is that available generation capacities of these technologies are fully utilized. This assumption might be questionable for individual generation technologies in the context of actual and especially with increasing renewable generation as their utilization is increasingly affected. Consequently, the derived availability factors are specific to the year 2015 and do not reflect estimations on expected availabilities of these technologies.

For geothermal, waste, and other generation technologies, we apply constant availability factors throughout the year. Figure 9 depicts availability factors for selected dispatchable conventional and renewable generation technologies. For remaining technologies, that is hard coal, natural gas and oil, generic availability factors need to be applied as their dispatch strongly depends on hourly market situations. These factors could be based on statistical information on planned and unplanned non-availabilities, for instance to reflect maintenance or revision periods during summer months. Moreover, the availability factors can be considered as a parameter for model calibration due to its generic character.

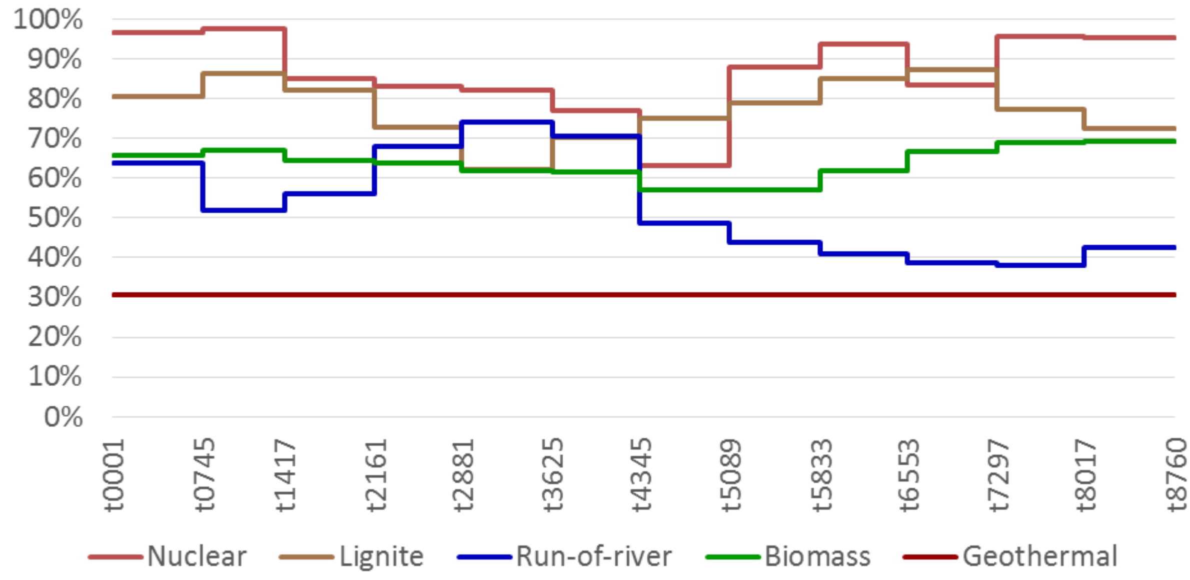


Figure 9: Availability factors for selected conventional and renewable technologies

Source: ENTSO-E (2017a), own illustration

In the case of variable and non-dispatchable renewable energy sources, that is wind and solar PV, availability factors reflect the respective hourly generation and are derived from historical feed-in time series from German TSOs (Open Power System Data 2016b). For solar, we account for individual control zones of German TSOs to reflect regional differences of PV electricity generation. Additionally, TenneT TSO provides a further regionalization of PV electricity generation in its control zone to individual Bundesländer (TenneT TSO 2017b). The historical regional time series are then corrected by the installed solar PV capacity in the respective region to derive hourly availability factors. The spatial distribution of annual full load hours for solar PV is depicted Figure 10. Full load hours are generally higher in southern Germany because of higher solar radiation. Due to the underlying methodology building on TSO control zones, full load hours are identical in larger regions, for example in the control zone of 50Hertz in eastern Germany.

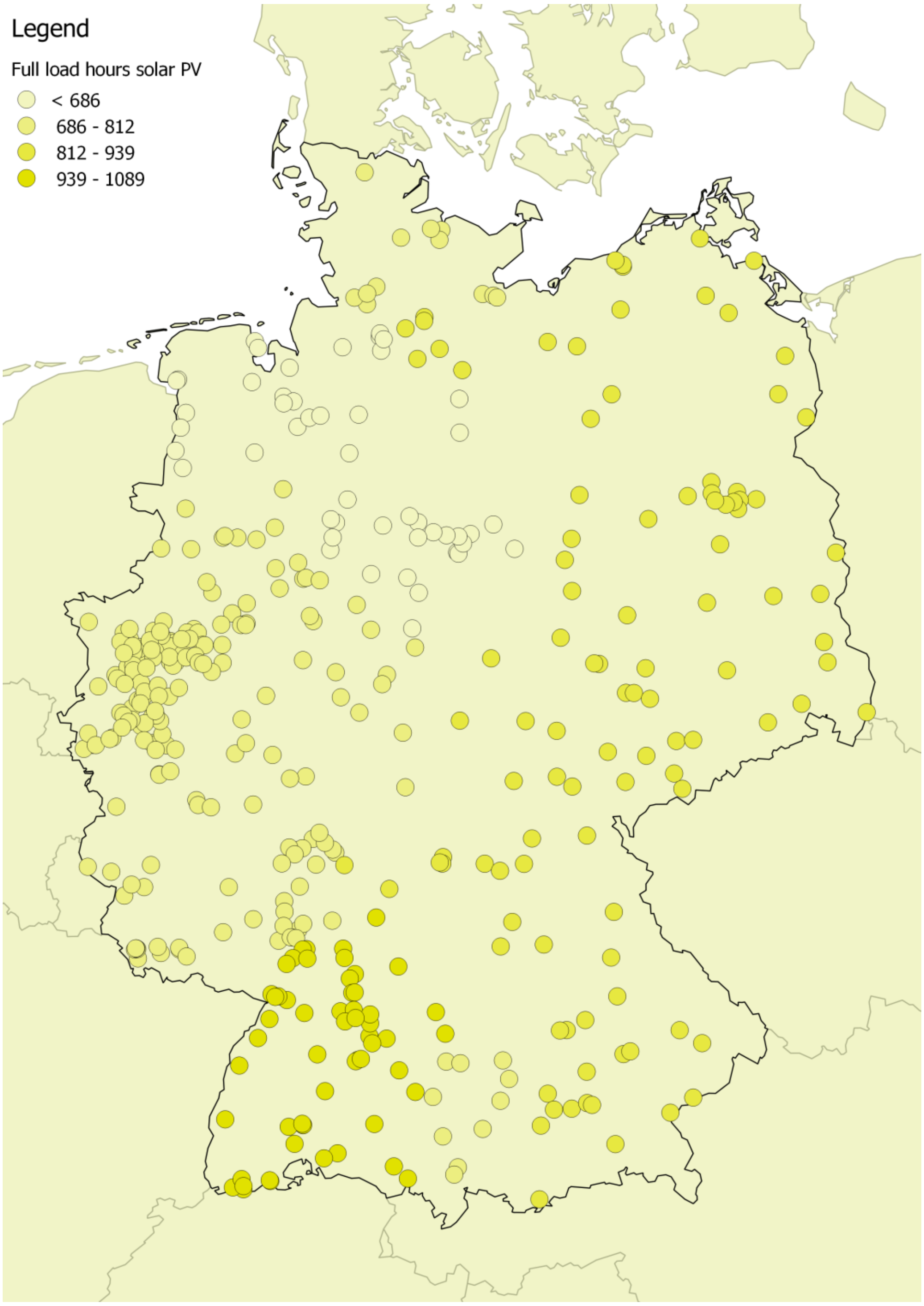


Figure 10: Spatial distribution of full load hours for solar PV

Source: own illustration

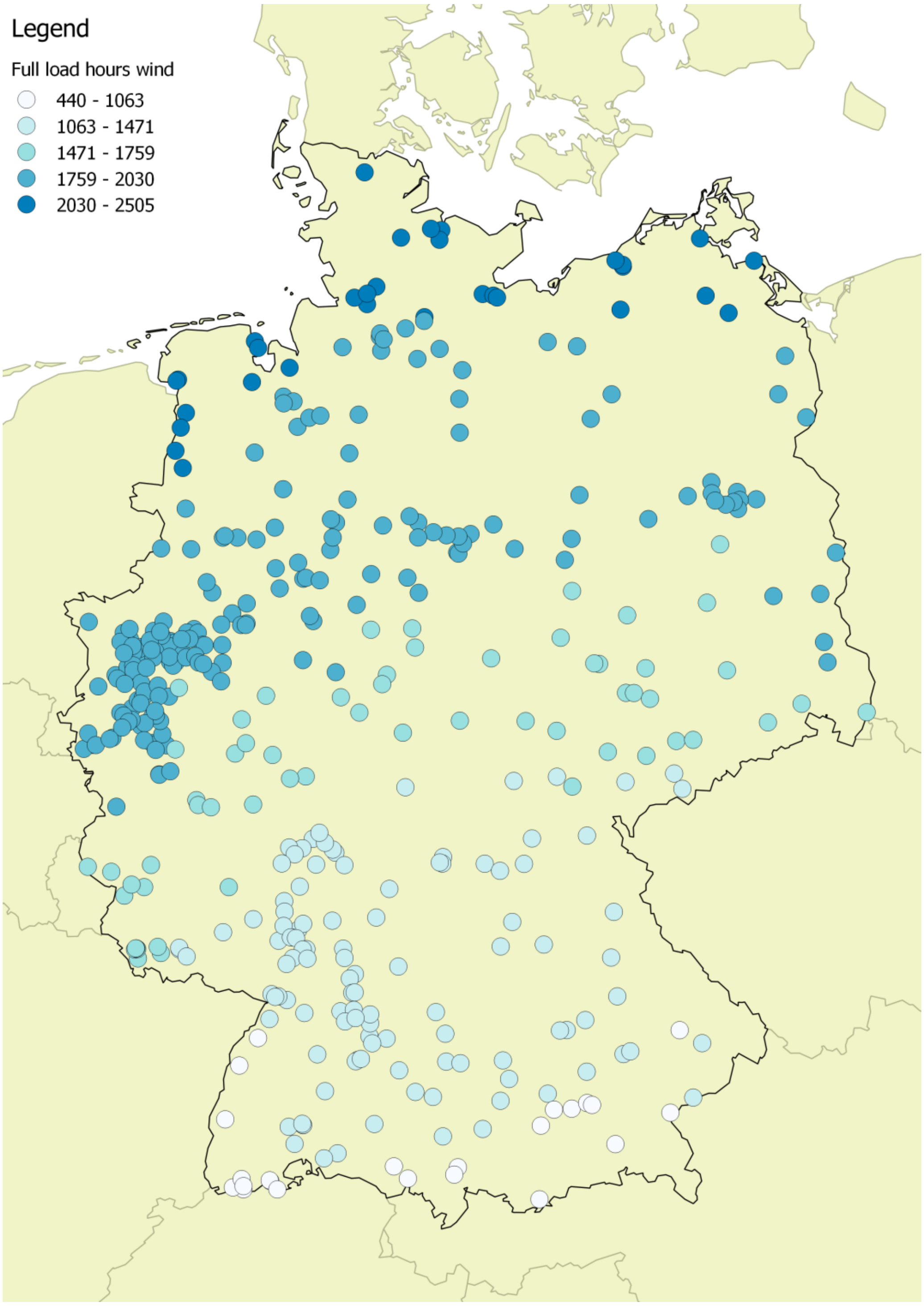


Figure 11: Spatial distribution of full load hours for wind onshore

Source: own illustration

A comparable approach could be applied to regionalize wind generation as described in Egerer et al. (2014). However, we extent this approach through the use of wind speed data to reflect the regional differences in greater detail. To do so, we use hourly wind speed data compiled within the Open Power System Data project (Open Power System Data 2017b) to regionalize historical electricity generation. We firstly translate hourly wind speed data to generation output using a typical wind turbine power curve. Secondly, we use regionalized wind capacities, as derived in Section 2.3.2, to calculate electricity generation from wind power on a national level. As we apply a single typical power curve for all wind turbines and do not account for wind farm effects, we are only partly able to reflect historical time series. The approach yields a comparable hourly generation pattern, however wind generation in windy or calm hours is over- or underestimated, respectively. Thus, increasing the accuracy of this time series would require, among others, more information on individual wind turbines as well as their exact location. Therefore, we rather use the nodal hourly wind generation derived from wind speeds, multiply them with installed nodal generation capacities, and finally scale them on a national aggregated level to historical generation volumes. We finally derive individual times series on a nodal level which closely match with reported hourly wind power generation on an aggregated national level. The annual full load hours are summarized in Figure 11 for individual nodes in the transmission network. In contrast to solar PV, full load hours of wind generators are highest in northern Germany.

2.4 Electrical load

We regionalize time series data provided by the ENTSO-E Transparency Platform for Germany (ENTSO-E 2017a) to reflect electric load at each node as shown in Figure 12. The methodology closely resembles the one described in Becker et al. (2016).

Since the given ENTSO-E time series does not match the total yearly demand as reported in official statistics, we first adjust it to total demand including losses but excluding own demand by power plants following the AGEB statistics (AGEB 2015).

In the next step the total load is distinguished into the categories household, commerce, and industry. For the first two categories we use BDEW's standard load profiles (SLP) for households (H0) and commerce (G0) (BDEW 2015a), scaled to the total demand in those categories according to AGEB energy balance. Since there is no standard load profile given for industry demand (industrial demand is usually directly metered as it falls into the category of more than 100,000 kWh per year), we assume the residual of the total (scaled) demand and the household and commercial demands to be industrial demand.

Next, we distribute the load to NUTS3 zones (Eurostat 2015) according to two indicators: the industry and commercial demand is distributed according to the share of gross value added (GVA) in each NUTS3 zone, which is taken from the national account system of the German federal states (Volkswirtschaftliche Gesamtrechnung der Länder (VGRdL) 2017). We distinguish between category WZ08-B-F for industry demand and categories WZ08-A and WZ08-G-T for commercial demand. For household demand, on the other hand, the share of population within a given NUTS3 zone is used (Eurostat 2017).

In a final step the load profiles regionalized to NUTS3 zones are mapped to the network nodes of the electricity transmission grid. When there are zones containing multiple nodes, load is equally distributed to those nodes. When there is a zone not containing a single node, load is mapped to the closest node measured in shortest distance to the centroid of the zone.

In the end some manual adjustments are necessary. Figure 13 shows two exemplarily calculated load profiles for Berlin and Ingolstadt, respectively. It can be seen that Berlin, with little industry but a large population, has a very different profile from Ingolstadt, with a smaller population but being a center of the automobile industry.

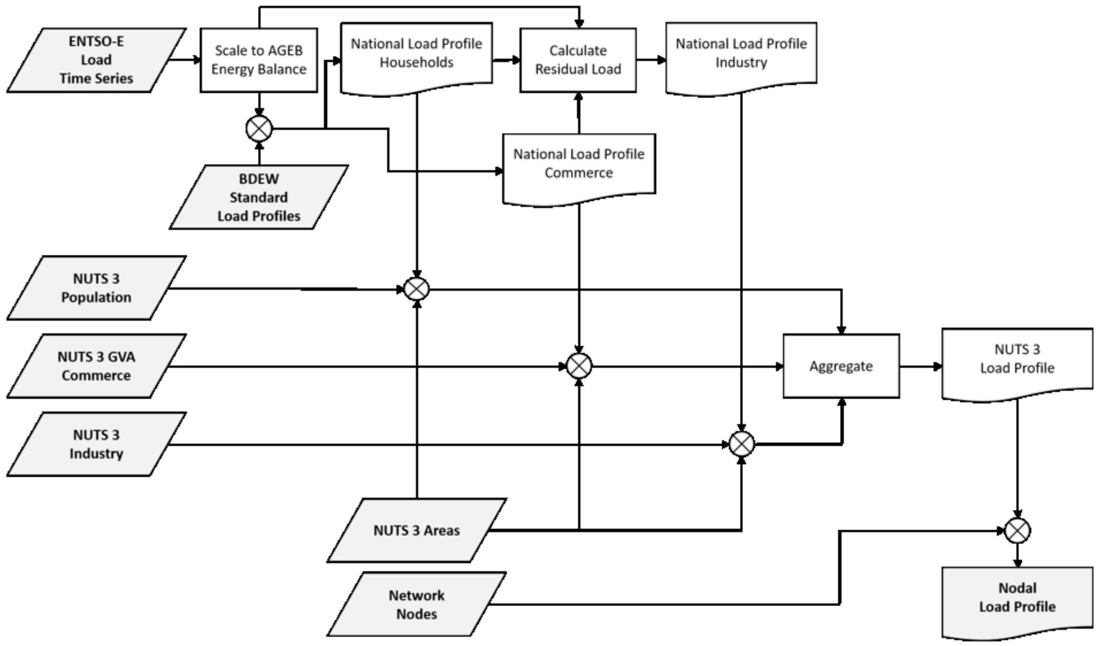


Figure 12: Calculation of nodal demand

Source: own illustration

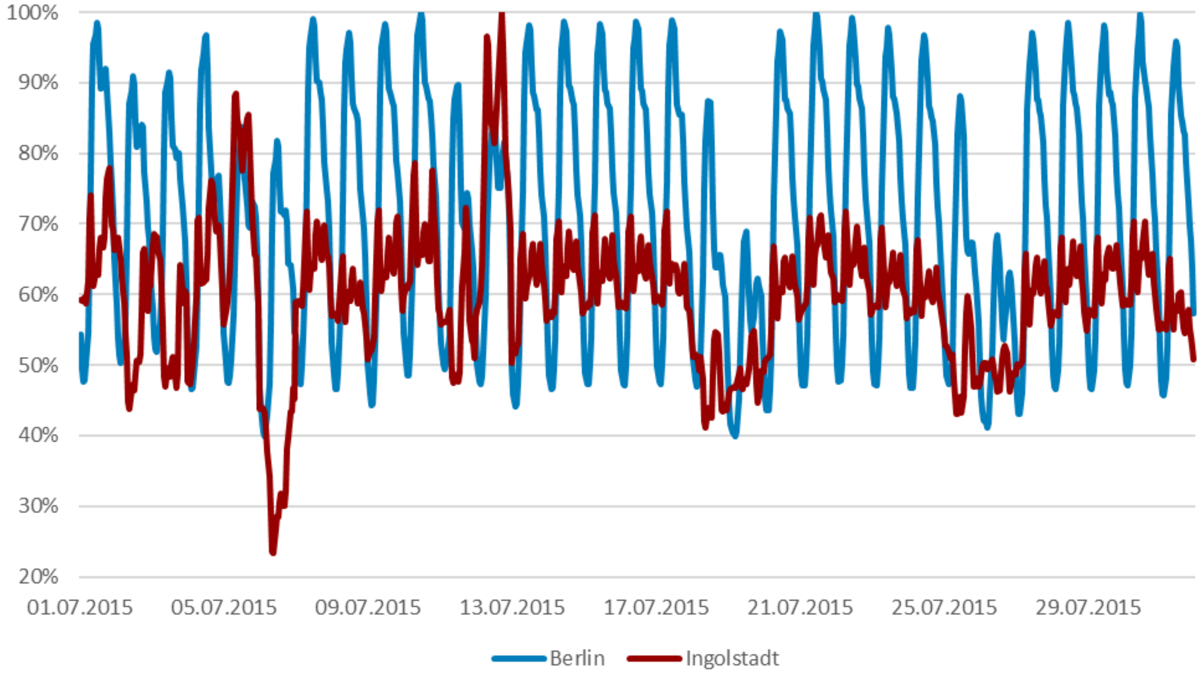


Figure 13: Exemplary load profiles for the month of July (normalized to maximum load)

Source: own illustration

2.5 Import and export

Hourly cross-border flows between Germany and neighboring countries for the year 2015 are taken from the ENTSO-E transparency platform (ENTSO-E 2017a). The published exchange data is available both for each TSO to the respective neighboring country and for an aggregated national level. While the data on TSO level is more detailed, the statistics vary significantly. As no information on the distribution of imports and exports is given by the TSOs (with the exception of 50Hertz), a regional allocation of the cross-border flows becomes necessary in case of more than one cross-border node for a given country, that is for every German neighbor. Hourly import and export flows are therefore allocated to the respective network nodes based on the capacity of the cross-border interconnectors (see Table 8).

The database of ENTSO-E is partly incomplete for the year 2015, as some hourly data points are missing, especially in the beginning of the year since the platform only opened on January 5, 2015. If only a small number of hours is missing, the data is linearly extrapolated. However, in some cases (e.g. exchange flows between Denmark and Germany), a sequence of five days is missing in the ENTSO-E transparency database. These points, and a few other sequences of more than a couple of hours, are manually added using researched data from the respective countries' TSOs.[18]

Table 8: Assumptions on flow allocation on the cross-border connections

TSO	Country	Node Neighbor	Node DE	Type	Capacity [MW]	Share [%]
50Hertz	Denmark	Bjæverskov	Kontek	DC	600	100
	Poland	Krajnik	Vierraden	2x 380 kV	3,400	100
	Poland	Mikulowa	Hagenwerder	2x 380 kV	3,400	100
	Czech Rep.	Hrader	Röhrsdorf	2x 380 kV	3,400	100
Amprion	Austria	Westtirol	Leupholz	1x 220 kV 1x 380 kV	490 1,700	50

[18] For the Danish case: https://www.energidataservice.dk/en/

TSO	Country	Node Neighbor	Node DE	Type	Capacity [MW]	Share [%]
Amprion (ctd.)		Bürs	Herbertingen	1x 220 kV	490	50
			Obermoor-weiler	1x 380 kV	1,700	
	France	St. Avoid	Ensdorf	1x 220 kV	490	13
		Vigy	Ensdorf	2x 380 kV	3,400	87
	Netherlands	Hengolo	Gronau	2x 380 kV	3,400	50
		Maasbracht	Oberzier	1x 380 kV	1,700	50
			Siersdorf	1x 380 kV	1,700	
	Switzerland	Laufenburg	Kühmoss	4x 380 kV	6,800	87
			Kühmoss	1x 220 kV	490	
			Tiengen	2x 380 kV	3,400	
			Gurtweil	2x 220 kV	980	
		Beznau	Tiengen	1x 380 kV	1,700	13
TenneT	Austria	St. Peter	Pleinting	1x 220 kV	490	67
			Altheim	1x 220 kV	490	
			Simbach	1x 220 kV	490	
			Pirach	1x 220 kV	490	
		Silz	Krün	2x 220 kV	980	33
	Czech Rep.	Hradar	Etzenricht	2x 380 kV	3,400	100
	Denmark	Klipleff	Flensburg	2x 220 kV	980	22
		Rødekro	Audorf	2x 380 kV	3,400	78
	Netherlands	Meeden	Diele	2x 380 kV	3,400	100
	Sweden	Kruseberg	Herrenwyk	DC	600	100
TransnetBW	Austria	Bürs	Herbertingen	1x 220 kV	490	100
			Dellmensingen	1x 380 kV	1,700	
	France	Fessenheim	Eichstetten	1x 380 kV	1,700	50
		Sierentz	Eichstetten	1x 220 kV	490	50
	Switzerland	Asphard	Kühmoos	1x 380 kV	1,700	67
			Eichstetten	1x 380 kV	1,700	
		Laufenburg	Trossingen	1x 380 kV	1,700	33

3 Heating networks data

Heat distributed through heating networks is generally produced in combined heat and power (CHP) plants as well as in heat plants. The generation of power and heat in CHP plants (also called cogeneration) is coupled, so that a higher overall fuel efficiency is reached as both products are produced simultaneously. While conventional condensing power plants operate based on price signals from the electricity market, operation of CHP plants is also driven by heat demand.

A part of the project LKD-EU intends to investigate the market for district heating and other CHP applications. As will be discussed later, CHP accounts for almost 70% of the total heat production delivered through heating networks in Germany. Therefore, we focus on heating networks, which are characterized by CHP plants.

Heating networks are piping systems for the distribution of heat, which is generated in a centralized location (e.g. CHP plants). Broadly three types of heating networks may be distinguished:

- district heating networks (DHN): these deliver heat to residential, commercial, and public customers (and some industry), usually to fulfill space and water heating requirements;
- local heating networks: these are similar to district heating networks, but much smaller in size. As a special case, CHP units may also serve to deliver energy just to a single object such as a hotel or a swimming pool;
- industrial heating networks: those mainly deliver process heat but also heat for space heating in industrial sites, for example in the chemical industry.

Subsequently we focus on district heating networks, as local heating networks are (at least currently) of minor importance in Germany and data for industrial networks is only sparsely available. In the following, we describe the acquisition of data that is essential for modeling cogeneration. This data includes time series of heat demands for heating networks as well as specifications of CHP plants.

The rest of this section is structured as follows: after giving a summary of the sources of data in Section 3.1, we describe the determination of annual heat demands in Section 3.2. Subsequently, Section 3.3 describes model-generated time series of heat demands while Section 3.4 deals with characteristics of CHP plants.

3.1 Data sources

The German Act on Energy Statistics (*Energiestatistikgesetz*, EnStatG) requires all operators of power and heat plants to deliver detailed data regarding their production, delivery, own consumption, as well as available production capacities. A detailed and comprehensive form of this data is not publicly available. However, aggregated data is offered on both the state and national level and published in different public reports.

This data is available on an annual basis, yet obtaining time series of heat demands requires additional calculations. Therefore, we used the model described in Felten (2016) and Felten, Baginski, and Weber (2017) to generate time series of regional heat demands. The model computes hourly time series of heat demands for heating networks based on the following inputs: annual heat demands, peak demands within heating networks, and temperature time series.

In the following sections, we describe the approach used to obtain the different input data. Table 9 summarizes the sources used for heat demands.

Table 9: Public data sources for heat demands

Institution	Type of data
AG Energiebilanzen e. V. (Working group)	• Energy balance for annual heat production in Germany
AGFW (Association)	• Annual heat production in different states of Germany
IEA – Electricity information	• Annual heat production in different countries
DESTATIS (Statistics departments of the federation and the federal states)	• Annual heat production for district heating purposes in Germany
Open Power System Data (OPSD) project	• List of conventional power plants • Identification of CHP units • Maximum heat production capacities
BNetzA (German regulator)	• List of conventional power plants • Identification of CHP units
Information provided by plant owners and DHN operators (various sources)	• Maximum heat production capacities • Further CHP plant properties • Assignment of CHP plants to DHNs

Source: own construction and Felten, Baginski, and Weber (2017)

3.2 Annual heat demand

Generally, public statistics and reports publish historical heat production. Since a district heating network is a closed and isolated system, heat production and demand (including losses) must be equal. In the rest of this document, we generally refer to heat production instead of heat demand to account for network losses (which are hardly modifiable in the short term).

To understand the publicly available statistics, the classification of heat production in these sources has to be considered. The heat is basically produced in CHP plants as well as in heat plants, and can be fed into various heating networks. The produced heat is used for industrial, commercial, or residential purposes. The general classification of heat production used in official statistics is primary as illustrated in Figure 14.

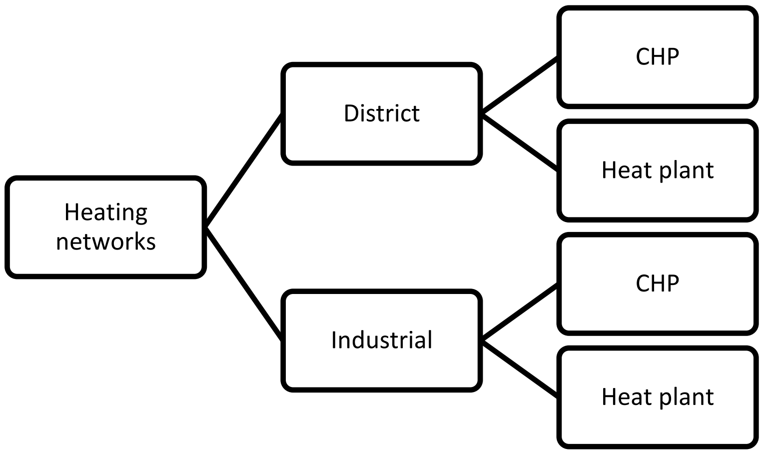


Figure 14: Classification of heat production

Source: own illustration

Subsequently, we focus on the share of the heat which is produced in CHP plants, since these plants are linked to the electricity system.

3.2.1 National heat demand for Germany

The International Energy Agency's "Electricity Information" (IEA 2016), as we discuss later, is a widely used source for annual production and supply of heat for selected countries. It contains primarily data for 2015. Moreover, due to the relevance of Germany, we investigate more details for this country.

The energy balance of AGEB (2017) records heat production in CHP plants greater than 1 MW for district heating supplies. We specifically use AGEB's Table 5.3 (heat generation per fuel in CHP plants for general supply, that is mostly residential usage) and Table 5.4 (heat generation in CHP plants for industrial supply) for our application.

Table 10 lists annual heat production per fuel in Germany in 2015 according to AGEB. This statistic is additionally illustrated in Figure 15.

The total heat production in Germany in 2014 was almost 250 TWh[19]. If we assume the same amount of heat production in 2015[20], CHP production accounts for almost 70% of the total heat production in Germany. This indicates that considering only CHP plants as a part of the heating market is an acceptable approximation.

Table 10: CHP heat production for industrial and district heating purposes in Germany in 2015

Fuel	**Annual heat production for district and local heating grids [TWh_{th}]**	**Annual heat production for industrial heating grids [TWh_{th}]**
Coal	28.20	3.10
Lignite	10.50	6.40
Oil	0.20	8.60
Gas	32.50	46.10
Renewables	11.60	11.60
Others	7.90	6.30
Total	**90.90**	**82.10**

Source: AGEB (2017)

[19] Own calculation based on the mentioned statistics.

[20] At the time of publication, the exact total production and supply of heat in Germany for the year 2015 was not available.

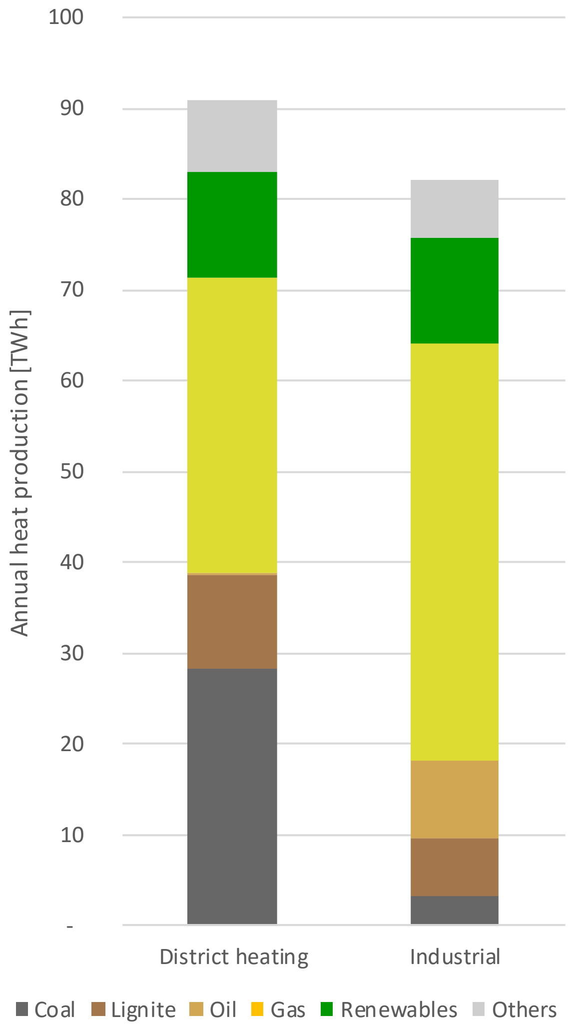


Figure 15: CHP heat production for industrial and district heating purposes in Germany in 2015

Source: own illustration

3.2.2 Heat demand for other European countries

For other European countries with important district heating markets, we use data from the IEA report "Electricity information" (IEA 2016). Specifically, the table "Electricity and heat produced for sale from combustible fuels in combined heat and power plants (CHP plants)" in the country information section of this document lists the production of heat from CHP plants in each country. As only preliminary values for 2015 were available at the time of writing, we use the data of 2014 instead. Table 11 lists the heat production for these European countries.

Table 11: CHP heat production in selected European countries in 2014

Country	Annual heat production by CHP plants [GWh_{th}]
Austria	12,217
Belgium	7,413
Czech Republic	26,708
Denmark	23,254
France	19,787
Luxemburg	948
Netherland	35,099
Norway	2,515
Poland	48,613
Sweden	34,217

Source: IEA (2016)

3.2.3 Annual heat demand for selected heating networks

Searching detailed data for all the heating networks inside Germany and neighboring countries is challenging due to the lack of information and the large number of district heating networks. The German sector association of district heating operators AGFW already counts 260 members. Moreover, identifying the units connected to each heating network would require significant effort. Therefore, we limit the number of heating networks, which we suggest to model. Moreover, we apply different approaches for Germany and neighboring countries.

Due to the specific focus on Germany, we explicitly list the ten largest district heating networks and aggregate all other district heating networks to one big network. We also aggregate all industrial heating networks to one big network since data is even sparser there.

Figure 16 summarizes our disaggregation approach for heating networks in Germany.

For all other European countries, we consider only one national district heating network per country to which all CHP units are connected.

Considering the aims of the LKD-EU project, we believe that the aggregation of heating networks as mentioned leads to sufficiently accurate calculation results.

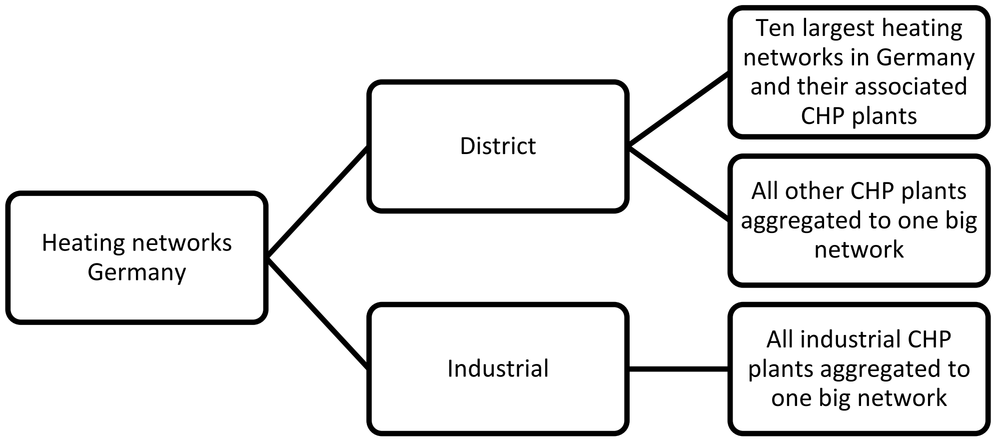


Figure 16: Considered heating networks in Germany

Source: own illustration

Several criteria may be used to identify the ten largest district heating networks in Germany:

- maximum heat production capacities of all installed CHP units within a network;
- maximum electricity production capacities of all installed CHP units within a network, since the result of the district heating modeling will be used later in the context of modeling the electricity market;
- annual heat production of a heating network.

Beside the aforementioned criteria, the availability of public data for the heating networks should also be considered.

Within the framework of the LKD-EU project, we pursue the target of extending a pure electricity market model to the joint modeling of both heat and electricity markets. Therefore, we choose the ten district heating networks essentially based on the third criterion – annual heat production of the networks. The chosen networks are listed in Table 12 and their key characteristics are given in Table 13.

Regarding the annual heat production in Germany in 2015, the heat produced from CHP plants connected to these ten networks accounts for almost 34% of the total production of heat from CHP plants for district heating purposes.

Table 12: Selected district heating networks in Germany

Name of DHN	Network name	City
Berlin	DHN Vattenfall Berlin	Berlin
Munich	DHN SW München	Munich
Hamburg	DHN Vattenfall Hamburg	Hamburg
Mannheim	DHN Mannheim	Mannheim, Heidelberg, Schwetzingen
Ruhr	DHN-Schiene Ruhr	Essen, Bottrop and others
Neckar	DHN-Schiene Mittlerer Neckar	Stuttgart
Gelsenkirchen	DHN Gelsenkirchen Uniper	Gelsenkirchen (Knepper and Shamrock, but not Stadtwerke Herten)
Dresden	DHN Dresden	Dresden
Nuremberg	DHN Nürnberg	Nuremberg
Saar	DHN-Schiene Saar	Saarlouis, Saarbrücken, Völklingen

Source: own construction

Table 13: Specification of the selected district heating networks in Germany

Name of DHN	Annual heat production [GWh_{th}]	Installed heat production capacities of CHP [MW]	Annual full load hours	Source
Berlin	10,671	3,626	2,943	(AGFW 2015)
Munich	4,298	1,698	2,531	(Stadtwerk München 2015)
Hamburg	4,241	1,337	3,173	(AGFW 2015)
Mannheim	2,280	696	3,276	(GKM-Aktiengesellschaft 2015)
Ruhr	2,185	708	3,087	(STEAG Fernwärme GmbH 2017)
Neckar	1,855	1,046	1,772	(EnBW 2017; Stadtwerke Esslingen 2015)
Gelsenkirchen	1,815	844	2,150	(Uniper Wärme GmbH 2017)
Dresden	1,528	455	3,358	(DREWAG NETZ GmbH 2017)
Nuremberg	1,056	371	2,843	(N- ERGIE Aktiengesellschaft 2015)
Saar	950	956	994	(FVS GmbH 2017)

The annual heat production of industrial (auto producer) plants is used as heat demand of the aggregated industrial heating network in Germany. Furthermore, the annual heat demand of the aggregated remaining DHN is obtained through subtraction of the national annual heat production for general purposes and the sum of the heat production within the ten biggest networks. Table 14 shows the specification for the two aggregated heating networks.

Table 14: Specification of the aggregated heating networks in Germany

Name	Annual heat production [GWh_{th}]	Installed heat production capacities of CHP [MW]	Annual full load hours
Aggregated district heating network	60,020	19,059	3,149
Aggregated industrial heating network	82,100	16,035	5,112

Source: own calculation

The AGFW report 2015 (AGFW 2015) lists annual heat production per state, making it usable for the cities of Berlin and Hamburg. For these cities, we consider the main district heating network. However, the values from the AGFW report also include small local heating networks as well as industrial heat production, which we do not consider. Therefore, we correct the annual heat production of Hamburg and Berlin to account for this deviation.

The values of the annual heat production from websites of the network operators are not in all the cases updated for the reference year of 2015. Moreover, the published values for the heating networks may contain the heat production from heat boilers in a few cases. For those reasons, the annual heat production is modified in some cases by a correction factor. The associated CHP units of each district heating network have been mainly obtained from the same sources (cf. Felten 2016; Felten, Baginski, and Weber 2017).

3.3 Time series for heat demand

3.3.1 Modeling approach

In order to model the operation of CHP units, the connection of CHP plants to different heating networks has to be considered. Moreover, time series of heat demands for individual heating networks are needed to determine the commitment and dispatch of power plants within the heating networks. We used the approach presented in Felten, Baginski, and Weber (2017) and Felten (2016) to determine these time series is described subsequently.

In a first step, heating networks are divided into district and industrial heating networks as described earlier. District heating networks provide heat to a large extent for space heating purposes, thus it is expected that their heat demands are sensitive to ambient temperature changes. Industrial networks, on the contrary, deliver heat for industrial applications and consequently are less dependent on the ambient temperature.

Yet, hourly heat demand data for networks is rarely publicly available. A search among the open sources shows that mainly annual heat demand of networks as well as their associated CHP units are available. Thus, hourly time series of heat demand need to be calculated.

We used the model of Felten, Baginski, and Weber (2017) to perform this task based on the local temperature. This tool initially uses the temperature data to determine the share of the dependency of heat demands on the temperature.

Some literature suggests the application of a sigmoid function to model the dependency between heat demand and temperature (Eriksson 2012). However, a piecewise linearization of this relationship reduces the number of parameters to be estimated and improves the calculation performance with a limited loss in accuracy. Thus, we assume a piecewise-linear temperature dependency for daily heat demand as indicated in Figure 17.

The mathematical formulation corresponding to Figure 17 is given by Equation 3.1:

$$Q(t) = Q_0 + \frac{Q_{max} - Q_0}{T_R - T_{min}} \max\left(0,\ T_R - T(t)\right) \qquad \text{(Eq. 3.1)}$$

where Q_0 is the base heat demand which occurs at temperatures above the reference temperature T_R, Q_{max} is the maximum heat demand corresponding to the minimum temperature T_{min}. The formula basically specifies that beyond the temperature T_R, Q is constant, whereas for temperatures below T_R, Q increases linearly. The fraction $\frac{Q_{max}-Q_0}{T_R-T_{min}}$ represents the slope in the Q-T diagram. Heat demand curves for district heating networks are more temperature dependent compared to industrial heating networks, driven by residential heating demands. We take this into account with a flatter Q-T diagram for industrial heating networks.

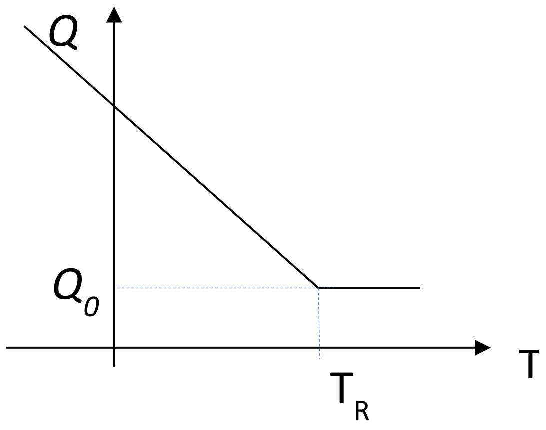


Figure 17: The relation between daily mean temperature and daily heat demand within the heat demand tool

Source: own illustration in analogy to Felten, Baginski, and Weber (2017)

The modeling tool calculates the parameters Q_0 and Q_{max} for each heating network from the annual heat demand and the annual heat peak demand using the integral of the heating degree days, that is, the sum of the term $\max\left(0,\, T_R - T(t)\right)$ over the course of the year. To derive hourly values from daily heat demands, typical season-dependent profiles are used. These have been derived from observed heat demand time series.

To sum up, for the calculation of hourly heat demands of each network the following data is essential:

- daily mean temperature in the location of heating networks,
- associated CHP plants of district heating networks and their specifications,
- full load hours for heating networks which are calculated based on the annual heat demand of district heating networks and installed capacities of CHP heat production within the networks.

3.3.2 Temperature

Temperature time series are available at the National Center for Environmental Information (NCEI 2017) which publishes information from different weather stations around the world.

For the ten district heating networks inside Germany, we use temperature data from the nearest weather stations. For the two big aggregated heating networks of Germany, we calculate an average of temperatures from a few stations around the country, representing average time series of temperature for overall Germany.

The same approach is applied for other European countries; we choose three to four stations (spatially distributed around a country) and calculate the average temperature.

3.3.3 Model results

We show the calculated curves for heat demands for the two aggregated heating networks of Germany in Figure 18 and for the Berlin district heating network in Figure 19. Both figures illustrate the temperature dependency of heat demands in the heating networks, yet the industrial network in Figure 18 shows less variations.

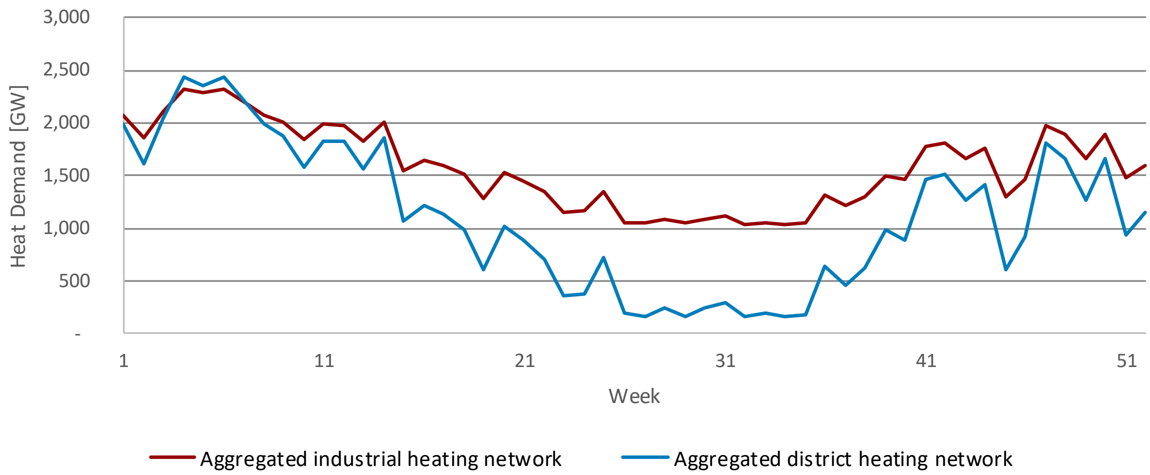


Figure 18: Weekly heat demand for the aggregated district heating network and the aggregated industrial heating network of Germany

Source: own illustration

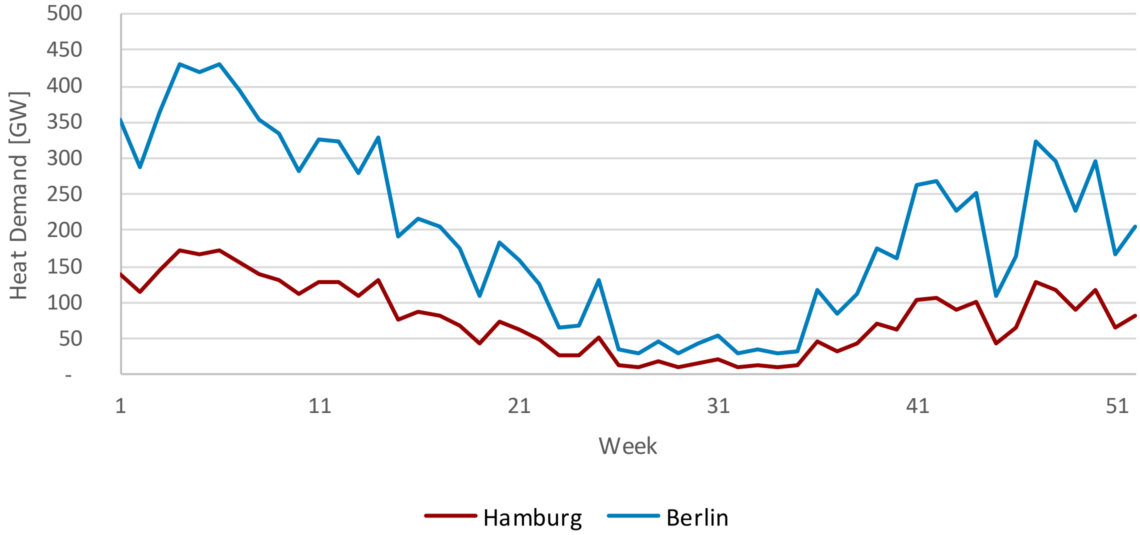


Figure 19: Weekly heat demand for the Berlin and Hamburg district heating networks

Source: own illustration

3.4 Technical characteristics of CHP power plants

To provide a suitable data basis for the modeling of CHP units we delivered an extension to the power plant list of OPSD (Open Power System Data 2016a). We re-identified the CHP units as well as their types and parameters. Table 15 lists the utilized sources.

It is a common market modeling assumption (e.g. used in P. Meibom et al. 2006) to group CHP plants into two technology classes: power plants with one degree of freedom and power plants with two degrees of freedom.

Table 15: Public data sources for CHP units

Institution	Type of data
Open power system data project	• List of conventional power plants • Identification of CHP units • Maximum heat production capacities
German regulator (BNetzA)	• List of conventional power plants • Identification of CHP units
Various information sources of power plant owners	• Maximum heat production capacities • Types of units • Associated heating networks

Source: own construction

3.4.1 Power plants with one degree of freedom

Power plants with backpressure turbines, small-scale engine based CHP plants and gas turbines with heat recovery systems have only one degree of freedom. Such units with one degree of freedom have a fixed ratio of power output P to heat output Q.[21] The power to heat ratio for these units is almost independent of the output level. In other words, a change in the power generation induces a proportional change in the heat generation (or vice versa). Such plants are especially utilized in industrial processes, where a certain quality of steam is needed at a rather constant rate. The following diagram illustrates the P-Q relation for power and heat generation.

Correspondingly the following relationship can be used to define the power-to-heat ratio:

$$c_B = \frac{P_{max}}{Q_{max}} \quad \text{(Eq. 3.2)}$$

[21] Note that in thermodynamics, usually the symbol $\dot{Q}$ is used to designate heat flows and Q describes the corresponding energy amount. For notational convenience, the symbol Q is used here as in most applied energy system literature to designate the heat flows.

where P_{max} is the maximum power production and Q_{max} is the maximum heat.

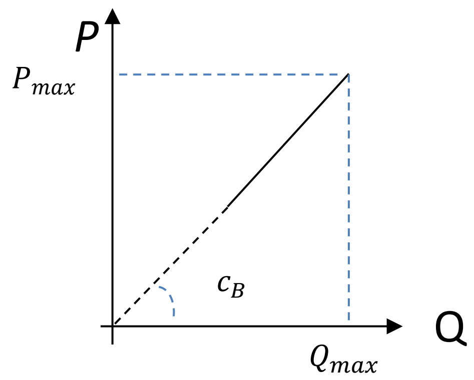


Figure 20: Power-heat diagram for units with one degree of freedom

Source: own illustration in analogy to Peter Meibom et al. (2006)

3.4.2 Power plants with two degrees of freedom

Power plants with steam cycles and extraction turbines – sometimes also gas turbines (or even motor engine) may operate as CHP units with two degrees of freedom, if they have an auxiliary cooling system. Two degrees of freedom enable these power plants to vary one product (as power), while keeping the other product (heat) constant (to some extent). The corresponding P-Q diagram is given in Figure 21 and the relation between parameters for these plants can be described as follows:

$$c_B + c_V = \frac{P_{max}}{\overline{Q}_{max}} \quad \text{(Eq. 3.3)}$$

$$Q_{max} = fct. \ \times \overline{Q}_{max} \quad \text{(Eq. 3.4)}$$

c_v is the power loss coefficient. $\overline{Q}_{max}$ is the maximum theoretical heat production capacity which can be achieved with existing c_V and c_B for an extraction turbine. In reality, the actual maximum heat production capacity Q_{max} is often smaller than the theoretical maximum value $\overline{Q}_{max}$. Equation 3.1 shows that Q_{max} is always smaller than $\overline{Q}_{max}$ by a factor fct.

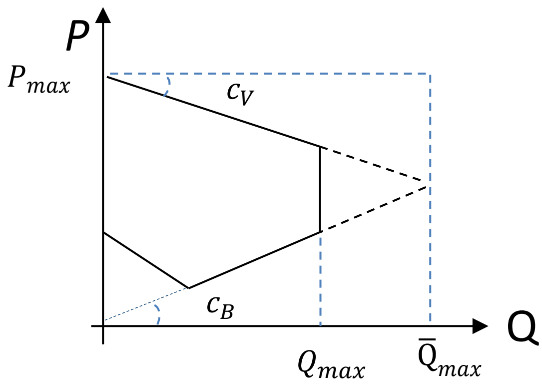


Figure 21: Power-heat diagram for units with two degrees of freedom

Source: own illustration in analogy to Peter Meibom et al. (2006)

In the power plants list of OPSD (Open Power System Data 2016a), we include additional information regarding whether the units are CHP units. For the CHP units, we also specify whether the units produce heat for district heating or industrial heating networks. In addition, we provide information regarding the type of each CHP unit as well as their thermodynamic values such as the c_B (power to heat ratio) and c_v (power loss coefficient). This information is mainly provided based on expert judgments on a unit, which are based on facts such as the year of construction, owner, usage of power plant etc.

For instance, as a general rule we use the following approach to determine typical values for the power reduction coefficients c_v:

- pure gas turbines: 0
- newly built combined cycle power plants: 0.17
- all other power plants: 0.15

The maximum capacity of heat production is either based on own research or adopted from the OPSD list or calculated based on the aforementioned c_B and c_v values.

For units with available values for maximum heat production (where the value was researched or adopted from the OPSD list), we perform a plausibility check of the computed c_B values. With available P_{max} and Q_{max} , we can compute a prima-facie c_B as follows:

$$c_B = \frac{P_{max}}{Q_{max}} - c_v \qquad \text{(Eq. 3.5)}$$

For units with one degree of freedom, c_v thereby is equal to zero.

For thermodynamic reasons, c_B is expected to be within the range of 0.2 and 1.8, with higher values corresponding to higher steam (or exhaust gas) temperatures. If the computed prima-facie c_B is larger than 1.8, the maximum heat output has to be corrected in the case of units with only one degree of freedom, since this is not thermodynamically feasible. In the case of two degrees of freedom, the explanation for the high prima-facie value might be that the actual maximum heat output Q_{max} is far smaller than the technically feasible $\overline{Q}_{max}$.

If a unit has a calculated c_B below 0.2, it is rather likely that the researched value of the maximum heat production includes some peak load boilers. Therefore, we adjust the maximum heat production for these units to get a c_B value of at least 0.2.

The new information for CHP units finally complements the power plant list described in Section 2.3.1.

4 Natural gas system data

4.1 Data sources

The availability of data on the German natural gas sector is worse compared to the electricity sector. One reason for this might be a slower process of unbundling and liberalization that causes higher non-transparency. Another explanation could be that natural gas pipelines run mostly underground. Hence, public observations that could be included in open data sets are more difficult to collect. Finally, researchers' interest in modeling detailed natural gas systems has increased only during the last years. According to European and German obligations, companies in the natural gas sector are required to collect and provide information on their websites. Table 16 lists rules and obligations to publish data in the gas sector.

The European Union passed a regulation that ensures access to the natural gas transmission pipelines ((EC) No 715/2009) and established a network code on capacity allocation mechanisms in gas transmission systems ((EU) 2017/459). In Germany, the Act on Energy Statistics (*Energiestatistikgesetz*, EnStatG) ensures the availability of data for federal states and the federal government since 2002. Natural gas TSOs are regulated by the Federal Network Agency (*Bundesnetzagentur*, BNetzA). The regulated network access model was introduced with the second amendment of the Germany Energy Industry Act (*Energiewirtschaftsgesetz*, EnWG) in 2005, which is completed by the Gas Grid Charge Ordinance (*Gasnetzentgeltverordnung*, GasNEV) and the Gas Network Access Ordinance (*Gasnetzzugangsverordnung*, GasNZV).

Based on these obligations, different types of data are publicly available. Table 17 provides an overview of institutions, associations, and private companies providing public data as well as the type of data that is published there.

Table 16: Obligations to publish data in the natural gas sector

Short version	Title	Published
European regulation		
(EC) No 715/2009	(EC) No 715/2009 of the European Parliament and of the Council of 13 July 2009 on conditions for access to the natural gas transmission networks and repealing Regulation (EC) No 1775/2005	13.07.2009
(EU) 2017/459	(EU) 2017/459 of 16 March 2017 establishing a network code on capacity allocation mechanisms in gas transmission systems and repealing Regulation (EU) NO 984/2013	16.03.2017
German regulation		
EnStatG	Energiestatistikgesetz (Act on Energy Statistics)	06.03.2017
EnWG	Energiewirtschaftsgesetz (German Energy Industry Act)	07.07.2005
GasNZV	Gasnetzzugangsverordnung (Gas Grid Charge Ordinance)	03.09.2010
GasNEV	Gasnetzentgeltverordnung (Gas Network Access Ordinance)	25.09.2005

Table 17: Public data sources for natural gas data in Germany

Institution	Type of data
ENTSOG (European Network of Transmission System Operators for Gas)	Time series on • Transmission capacity map Europe • Tariffs and Interruptions
GIE (Gas Infrastructure Europe)	• Gas storage maps Europe since 2011 (gse) • LNG maps Europe since 2011 (gle)
AGSI (Aggregated Gas Storage Inventory)	Time series on • withdrawn and injection capacity • working gas volume • injection and withdrawn rates

Natural gas system data

Institution	Type of data
EUROGAS (Non-profit organization)	Statistics on • annual gas demand • annual gas supply
FNB (German natural gas TSOs**)**	Technical and geographic information on • Transmission network map • Structural information on natural gas networks
BNetzA (German regulator)	General information on • extension of transmission infrastructure (network development plan, Netzentwicklungsplan Gas, NEP Gas) • Power plants list (BNetzA Kraftwerksliste)
BAFA (Federal Office of Economics and Export Control)	Time series on • monthly import prices for natural gas • exploration and exports of natural gas
DWD (German Meteorological Service)	Time series on • temperature data
DESTATIS (Statistics departments of the federation and the federal states)	Structural data (Destatis 2011) • Regional distribution of single-family houses and apartment buildings • Number of people employed in sectors • Regional distribution of population
PEGAS (Energy exchange)	• Daily reference price • Natural gas price in market areas GASPOOL and NCG
BVEG (Association for Natural Gas and Petroleum Extraction)	Technical and economic data on • natural gas production in Germany by federal states • annual mining royalties • reserves

Institution	Type of data
BDEW (German association of energy and water industries)	Aggregated data on • Natural gas demand • Fuel use • Security of supply statistics
AG Energiebilanzen e.V. (Working group)	Aggregated data on • Primary energy usage for natural gas
Open Street Map	Geographic pipeline information (poor quality)
Open Power System Data project	Geographical and technical information on natural gas power plants

In general, the quality of public data for the German natural gas system varies. While maps and structural data are available due to legal obligations, the development of a technical gas grid model is challenging. These challenges can be summarized in the following two points. Firstly, there is no central collection of infrastructure data as it exists at the European level, but many decentral documents and sources at different levels of technical details provided by the TSOs. Secondly, a high number of assumptions have to be made to integrate different public data sources into one consistent gas grid model.

The aim of the next sections is to point out the available data for each data category and to describe the methodologies used for (dis-)aggregating missing data.

4.2 Natural gas transmission system

4.2.1 Data on natural gas transmission networks

The infrastructure data is mainly based on TSO data. In total, 16 TSOs are operating the natural gas network in Germany. Moreover, they are part of two main market areas namely Gaspool and NetConnect Germany (cf. Table 18).

To our knowledge, there is no centralized open data collection covering all infrastructures of the German natural gas transmission system. However, according to transparency obligations of the TSOs, some public data is available.

The gas grid model is based on both publicly available data and methodologies to break-down assumptions and aggregated data. Table 19 provides an overview of grid information that is published and methodological needs to derive further information.

Table 18: Allocation of TSOs to market areas Gaspool and NetConnect Germany

Gaspool	NetConnect Germany
Gascade, Gasunie Germany , GTG Nord, Jordgas, Nowega, Ontras	bayernets, Fluxys TENP, GRTgaz Germany, Open Grid Europe, Terranets BW, Thyssengas

Source: VKU and BDEW (2017)[22]

Table 19: Overview about data for the gas grid model and their data origin

Data category	Origin of data
Transmission network topology	Available data: • TSO maps with nodes and pipelines according to § 40 GasNZV (BMWi, NEP Gas of TSOs) • data on exit and entry points depends on TSO region Methodology necessary for: • pipeline connections within the grid • determination of entry and exit points
Technical grid characteristics	Available data: • Aggregated data of pipeline classes A-G according to § 27 (2) GasNEV) • Gas quality (low or high-caloric natural gas) • Sample pipelines with pressure and diameter Methodology necessary for: • Allocation of technical data to pipelines

[22] FLUXY Deutschland, NEL Gastransport, Lubmin-Brandov, OPAL Gastransport are not allocated to market areas in this source

Data category	Origin of data
Location of natural gas facilities in the gas grid	Available data: • Storages • Power plants • Production facilities Methodology necessary for: • Assignment of natural gas facilities to network nodes

The data provided by TSOs differs with respect to quality and extent of technical details. An overview of the available data is provided in Table 20 to Table 24. The NEP Gas is the long-term natural gas network development plan jointly developed by all TSOs and approved by the BNetzA. All TSOs are obligated to jointly publish the network developments which describe all necessary measures to take in order to guarantee a secure and reliable network system (§ 15a (1) EnWG).

The NEP Gas (FNB 2015) contains the following types of information for modeling the gas grid:

- aggregated data of 16 TSOs on length of pipelines, number and capacity of compressors, number of cross-border points, number of exit points and information about peak demand, and total amount of delivered energy for final consumption and distribution
- information on system relevant power plants
- investment costs for pipelines and compressor stations
- transmission map for H- and L-gas in Germany
- analysis of historical interruptions
- information on the current status of the conversion from L-gas regions to H-gas regions

The next section provides an overview of available transmission system maps that can be distinguished in specific maps of all 16 TSOs in Germany and maps that contain the entire German natural gas grid.

Table 20: Natural gas transmission network for Germany and Europe

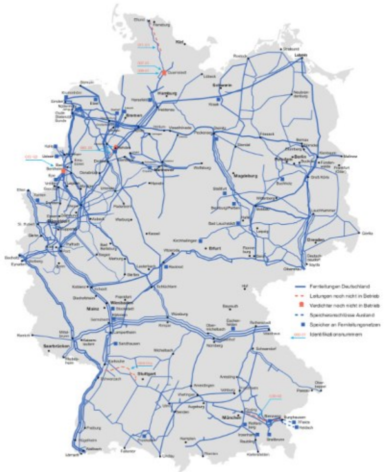
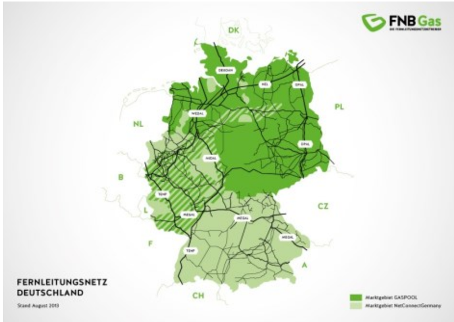
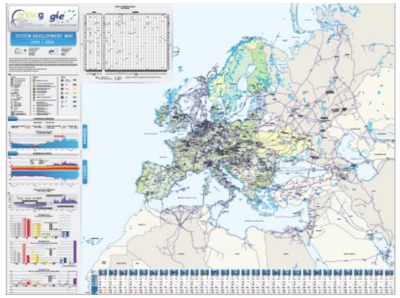
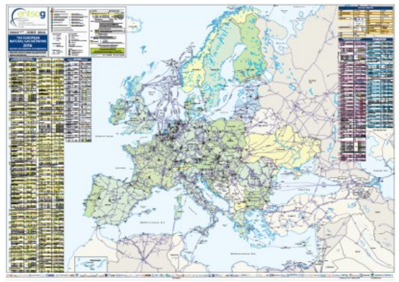
Publisher	BMWi	FNB	ENTSOG
Network topology map	 (BMWi 2017)	 (FNB 2013)	  (ENTSOG 2016a), (ENTSOG 2016b)
Information content	Topology, but simplified representation	Topology, but simplified representation of market areas	Topology and individual data to cross-border connections
Other sources			Gas infrastructure Europe (gie) Gas transmission Europe (gte) Gas Storage Europe (gse) Gas LNG Europe (gle)

Table 21: Information on TSO network data (bayernets GmbH, Fluxys Deutschland GmbH, Fluxys TENP GmbH, GASCADE Gastransport GmbH)

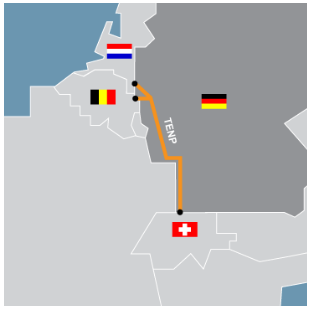
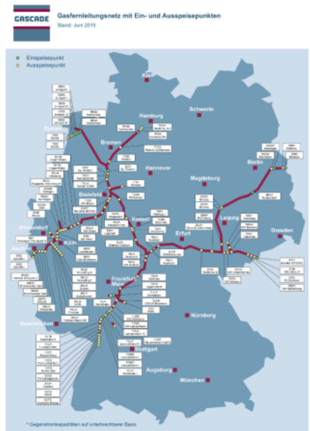
Operator	(1) bayernets GmbH	(2) Fluxys Deutschland GmbH	(3) Fluxys TENP GmbH	(4) GASCADE Gas-transport GmbH
Network topology map	  (bayernets 2017a)	 (Fluxys NEL 2017)	 (Fluxys TENP 2017a)	 (Gascade 2017)
Information content		Participation (23,9 %) of NEL-pipeline	Participation (49 %) of TENP-pipeline	
Other sources	MONACO pipeline (bay-ernets 2017b)	(Gasunie 2017b)	(Fluxys TENP 2017b)	

Table 22: Information on TSO network data (Gastransport Nord GmbH, Gasunie Deutschland Transport Services GmbH, GRT gaz Deutschland GmbH, jordgas Transport GmbH)

Operator	**(5) Gastransport Nord GmbH**	**(6) Gasunie Deutschland Transport Services GmbH[23]**	**(7) GRT gaz Deutsch-land GmbH**	**(8) jordgas Transport GmbH**
Network topology map	 (GTG Nord 2017)	 (Gasunie 2017a)	 (GRTgaz 2017)	 (Jordgas 2017)
Information content	-	Participation (25,1 %) of NEL-pipeline Participation (75 %) of Deudan	Participation (49 %) of MEGAL	-
Other sources	-	(Gasunie 2017b) (Gasunie 2013)	(GRTgaz 2015)	-

[23] Netzentwicklungsplan 2015 (FNB 2015) also contains Gasunie Osteseeanbindungsleitung GmbH (GOAL) that was merged with Gasunie Deutschland Transport Services GmbH on September 1, 2015.

Table 23: Information on TSO network data (Lubmin-Brandov Gastransport GmbH, NEL Gastransport GmbH, Nowega GmbH, ONTRAS Gastransport GmbH)

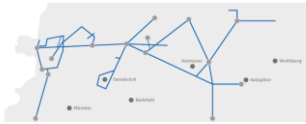
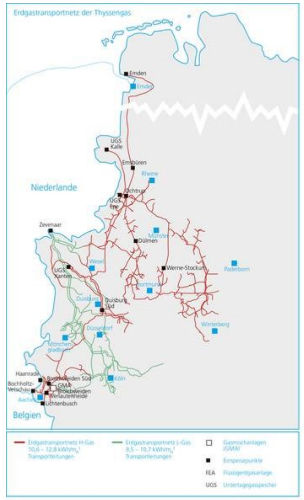
Operator	**(9) Lubmin-Brandov Gastransport GmbH**	**(10) NEL Gastransport GmbH**	**(11) Nowega GmbH**	**(12) ONTRAS Gas-transport GmbH**
Network topology map	 (LBGT 2017)	 (NEL 2017)	 (Nowega 2017)	 (ONTRAS 2017)
Information content	Participation (20%) of OPAL	Participation (51 %) of NEL		
Other sources	(OPAL 2016)	(Gasunie 2017b)		

Table 24: Information on TSO network data (OPAL Gastransport GmbH & Co. KG, Open Grid Europe GmbH, terranets bw GmbH, Thyssengas GmbH)

Operator	(13) OPAL Gastransport GmbH & Co. KG	(14) Open Grid Europe GmbH	(15) terranets bw GmbH	(16) Thyssengas GmbH
Network topology map	 (LBGT 2017)	 (OGE 2017)	 (Terranets, 2017)	 (Thyssengas 2017)
Information content	Participation (80%) of OPAL	Participation (51 %) of MEGAL Participation (25 %) of Deudan Participation (49 %) of TENP		
Other sources	(OPAL 2016)	(OGE 2016)		

4.2.2 Methodology

The pipeline system of the German natural gas grid is modeled using the directed graph theory. Using this methodology, branches represent pipelines and nodes represent exit points and/or entry points of the network. The topology data is based on schematic figures of TSOs that were integrated in a Geographical Information Systems (GIS) environment using the software QGIS (QGIS Development Team 2017).

As described in the section above, topology data is limited for some grid elements and there are limitations to the digitalization of schematic network maps. Hence, we make subjective decisions in the process of data preparation in order to model the principal features of the German natural gas network.

The physical natural gas flow in gas grids mainly depends on different levels of pipeline pressure that can be controlled by compressor stations. There are some non-linear models that consider technical parameters to optimize technical gas flows(De Wolf and Smeers 2000; Rövekamp 2015). Latest approaches investigate simplifications in order to achieve a linear description of the gas flow (Hennings 2017). However, in a first step, we use a simplified transport model approach for energy units, while the capacity of pipelines is restricted. Therefore, a conversion of pipeline characteristics (pressure and diameter) is needed to calculate the maximum transport capacity of each single pipeline. The maximum (energy) transport capacity of each pipeline is estimated using the nominal pipeline pressure and diameter (cf. Table 25) and assuming a maximum mass flow speed of 10 m/s at a net caloric value of 49.725 MJ/kg under ideal gas conditions. These maximum (energy) transport capacities can be interpreted as an upper bound for real world transport capacities.

There are three different levels of pipeline with respect to pressure:

- high pressure level (> 1 bar)
- medium pressure (> 100 mbar to 1 bar)
- low pressure (<= 100 mbar)

All TSOs have to publish the individual lengths of their high-pressure pipelines according to pipeline diameter classes A to G (§27 (2) GasNEV). This data can be used to validate both the grid model and the aggregated capacity of pipeline classes within the gas model.

In order to calculate energy transport capacities, we used the maximum values of pressure and the individual diameter of each pipeline for each class, based on TSO information or own assumptions. The classification G is assigned to low caloric gas pipelines (L-gas) that are mainly located in the north-west of Germany and transport gas from German and Dutch gas fields. The current version of the reference dataset includes the topology of these kinds of pipelines. However, at the time of writing we have no information about the technical characteristics of these pipelines. The detailed technical values for high pressure pipeline classes as well as the calculated ranges for maximum and minimum transport capacities are shown in Table 25.

Table 25: Technical pipeline characteristics for high pressure pipelines

Classifications	Pressure [bar]	Diameter [mm]	Transport capacity [GWh/d]
A	100	x >= 1000	651 - 1275
B	25 – 100	700 <= x < 1000	80 - 651
C	25 – 63	500 <= x < 700	41 - 201
D	25	350 <= x < 500	20 - 41
E	16 – 25	200 <= x < 350	4 - 20
F	63	100 <= x < 200	4 - 16
G	63	x <= 100	<= 4

Source: FNB (2015, 2016)

As TSOs provide only stylized transmission maps, it is challenging to allocate pipelines to pipeline diameter classes. Starting from grid elements with known technical parameters, for example compressor stations or cross-border points, a heuristic approach is used to allocate pipelines to classes. Starting from these well-known points, the connected pipelines are allocated to classes with similar technical characteristics. The remaining pipelines are assigned to the best fit classification using the following three principal rules:

1. Start at well-known points and their technical characteristics (e.g. compressors, power plants etc.) and allocate to connecting pipelines classes with similar technical features.
2. If there is a crossing point (entry /exit node) with only two connecting pipelines, both have the same characteristics.
3. In contrast, a stub pipeline has a lower class than a main pipeline.

The overall goal of the heuristic approach is to reproduce the distribution of pipeline distribution classes that is given in aggregated form by each TSO.

TSOs have to publish essential points in their network. A list is provided by FNB (2015). The model takes this information into consideration and adds additional entry and exit points for NUTS-3 regions. Exit points are, for example, natural gas power plants, connections to subnetworks or neighboring grid operators and cross-border points to neighboring countries. Entry points represent biogas plants, connections to import pipelines and domestic natural gas productions. Nodes with storage facilities are assigned as entry and exit points.

All natural gas facilities that represent exit and/or entry points are integrated in the model and assigned to existing grid nodes by calculating the shortest distance.

4.2.3 Comparison of modelled grid elements with data sources

The total modeled length of pipelines amounts to 32,075 km and is thus lower than the length of 36,843 km documented by TSOs. One reason for this deviation is that modeled pipelines follow the schematic network map and neglect curves of pipelines. Another reason might be parallel pipelines in the transmission maps that are drawn as one single line. The allocation of pipelines to pipeline diameter classes in the gas grid model and the aggregated information of each class given by TSOs is listed in Table 26.

Table 26: Quantitative natural gas network statistics (pipelines)

Classifications	Length in Model [km]	Length based on TSO data [km]
A	10926	7448
B	8992	8981
C	5967	7972
D	3493	4524
E	2169	4666
F	529	2954
G	0	298
Total	**32075**	**36843**

Source: own calculation

Figure 22 shows the allocation of lengths for each TSO in the model compared to the TSOs' information of aggregated lengths of each pipeline diameter class. According to the absolute and relative differences between the data in the model and information of TSOs, the biggest error occurs for OpenGridEurope and Thyssengas (cf. Figure 23). There are several reasons for these errors. Firstly, these networks are the biggest ones in Germany and for smaller TSOs as GTG Nord or Terranets the errors are much lower. Secondly, the transparency of these networks, especially the course and number of systems per pipeline, is lower. It might be possible that there are several routes of pipelines with two or more pipeline systems in parallel that double or triple the length. Finally, the L-gas grid (e.g. in the network of OpenGridEurope) is depicted in lower detail than the high-caloric pipeline grid. Hence, curves are not considered, causing shorter pipeline distances.

An overview of the numbers of nodes and their classifications in the model as well as benchmarks based on public sources is given in Table 27.

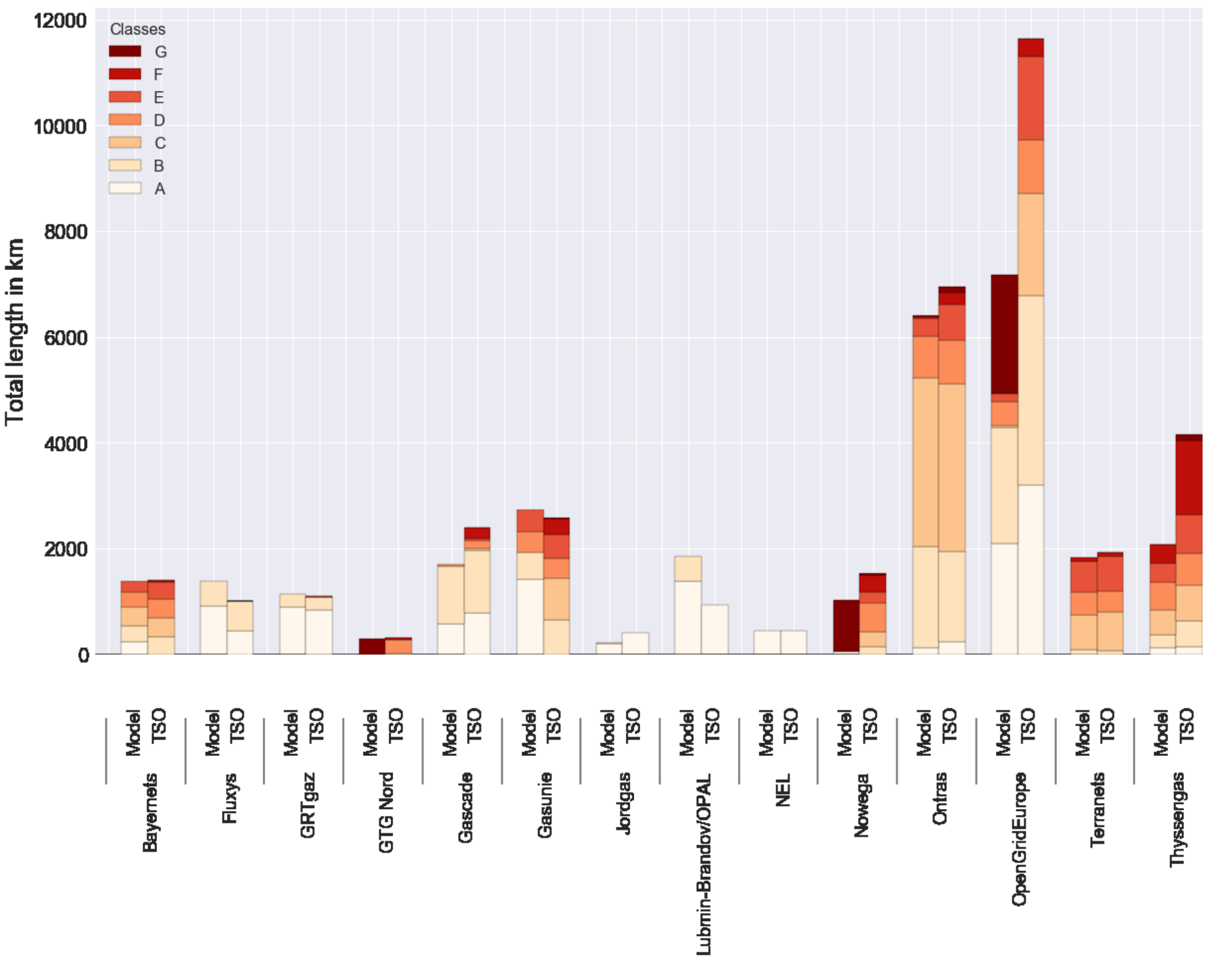


Figure 22: Classification of pipelines in categories A-G in the model and based on TSO data

Source: own illustration

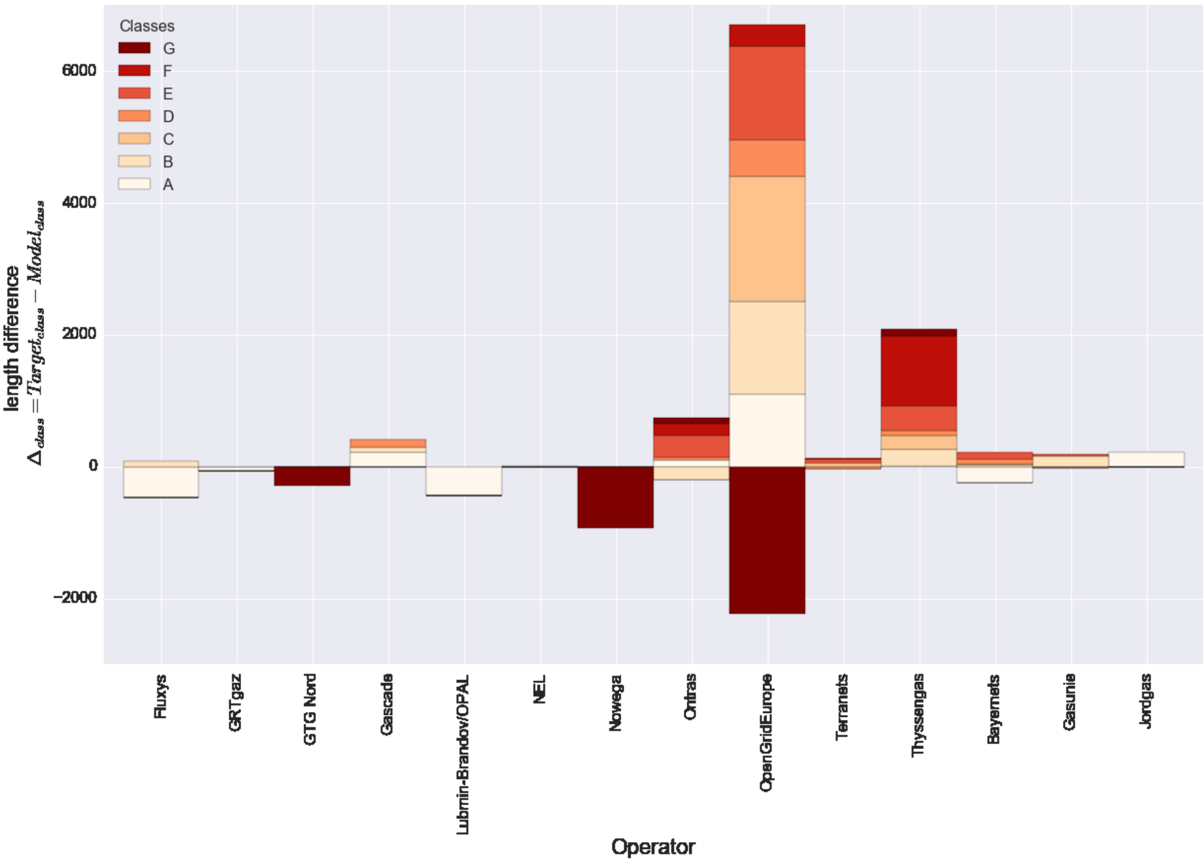


Figure 23: Relative differences between TSO information and model data

Source: own illustration

Table 27: Quantitative natural gas network statistics (nodes)

Classification	Number of elements in model	Number of elements based on sources	Source
Exit Point	882	ca. 3530	TSO data (NEP 2015) and own assumptions
Entry Point	131	126	BNetzA 2015 and own assumptions
Storages	25 nodes with 64 storages	66 64	Rövekamp 2015 ENTSOG 2017
Domestic production	8	9 8	Rövekamp 2015 ENTSOG 2017
NG power plants	265	265	Power plants that use natural gas as fuel as listed by BNetzA and UBA and operated in 2015
Cross Border points	62	62 89	ENTSOG 2017 Rövekamp 2015

Source: own calculation

Figure 24 depicts the model of the German natural gas transmission system including pipelines, nodes, and connected pipelines to neighboring countries.

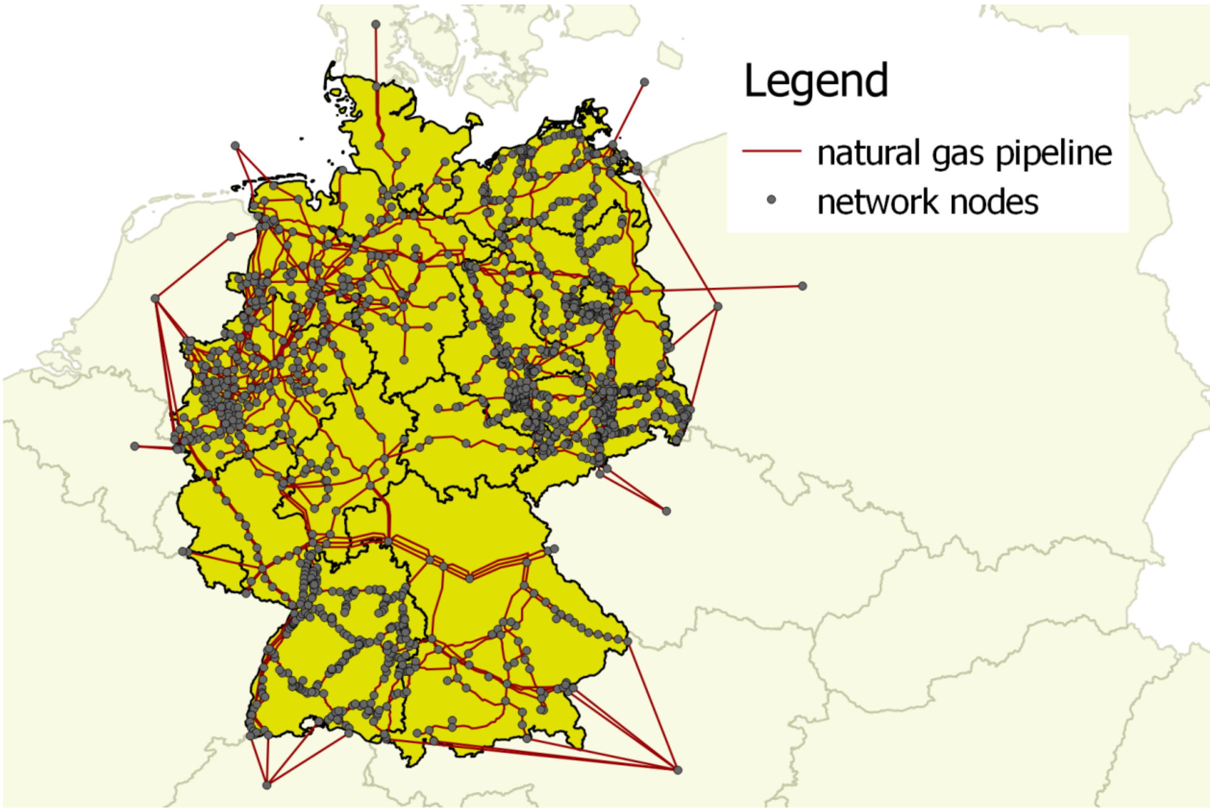


Figure 24: The German natural gas transmission system in 2015

Source: own illustration

4.3 Natural gas demand

4.3.1 Data on natural gas demand

Aggregated data for German primary energy demand for natural gas is provided by different institutions listed in Table 28 on different resolution levels.

Table 28: Overview about data for natural gas demand

Source	Resolution of natural gas demand
AGEB	Annual primary energy consumption of natural gas
ENTSOG, TYNDP 2015	Annual actual gas consumption of natural gas
Websites of federal states	Monthly data for federal states, clustered by sectors according to § 4 EnStatG
NEP 2016	Annual natural gas demand in industry for Germany
Destatis	Classification of NUTS-3 level, aggregated data

A challenge arises from the objective to integrate natural gas demand in a high spatial and temporal resolution into a gas grid model. Hence, specific methods are necessary to break down total demand according to three dimensions:

- time (from annual or monthly demand data to daily or hourly time series)
- space (from a country based demand to regions, e.g. NUTS-3 level)
- sectors (from a primary natural gas demand to a natural gas demand based on sectors, i.e. heat, industry and electricity)

4.3.2 Methodology

In industry and academia, many approaches are used to forecast natural gas demand, among them ARIMA modeling (Erdogdu 2010), decomposition approaches on a daily base (Sánchez-Úbeda and Berzosa 2007), or heuristic approaches based on economic indicators, for example GDP or population (Gümrah et al. 2001). In contrast to these econometric approaches, we aim to explain the natural gas demand based on fundamental data.

In general, there are two approaches to calculate these spatially resolved natural gas demands: A top-down approach allocates the total natural gas demand according to specific parameters on the aforementioned dimensions. In contrast, a bottom-up approach starts on a level with higher resolution and calculates a high number of specific parts of the natural gas demand. The sum of these single parts represent the total natural gas demand.

We use the top-down as well as the bottom-up approach to resolve the total natural gas demand for the gas grid model. The following sections describe the general approach and specific assumptions for heat, electricity, and industry based natural gas demand.

The energy balances of the federal states describe the total gas demand as the primary energy consumption of natural gas, consisting of final energy consumption of natural gas (74%) and the conversion input for natural gas power plants (21%) as well as losses and others (5%).

According to Figure 25, we expand this categorization and divide the total natural gas demand into three final energy categories of natural gas (heat 46%, transportation 0.2%, and industry 28%), the demand of natural gas power plants (electricity 21%), and finally losses and others (5%) (AGEB 2015). The highest share of the gas consumption in 2015 is represented by heating[24]. Due to the low share of natural gas demand in transportation (0.2%), we neglect this sector.

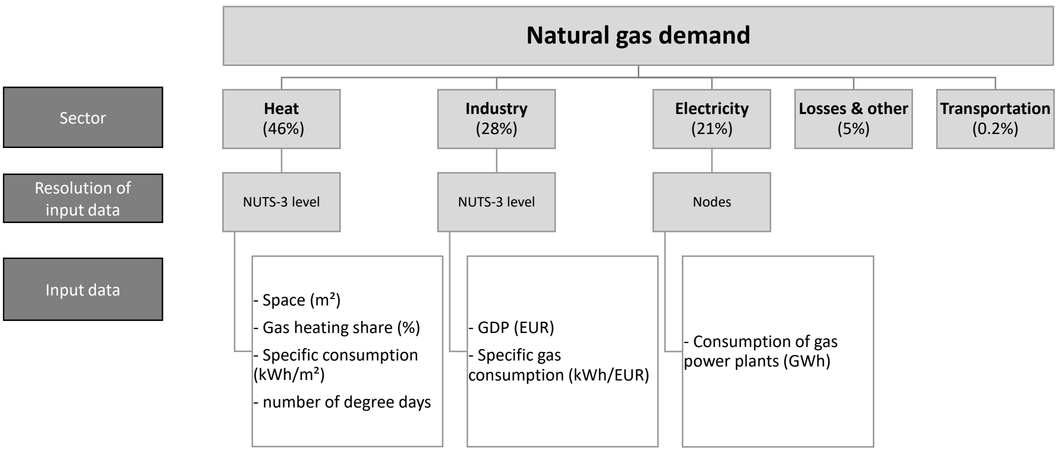


Figure 25: Composition of natural gas demand in Germany

Source: own illustration based on the German energy balance (AGEB 2015)

[24]This includes space heating in all buildings, also public buildings, but excludes process heat in industry.

Based on Figure 25, our method for fundamentally modeling the natural gas demand concentrates on three sectors: industry, electricity and heat (cf. Figure 26).

The spatial allocation of natural gas demand can be done on different levels. Table 29 shows four alternatives.

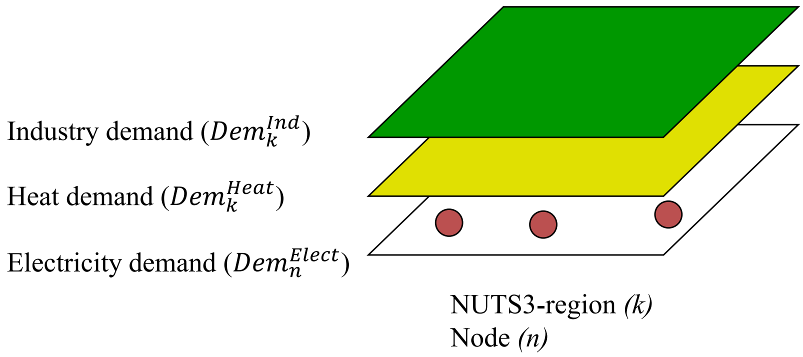


Figure 26: Layer to define natural gas demand

Source: based on Hauser et al. (2017)

Table 29: Spatial aggregation levels of natural gas system

Nodes	Zones		Uniform
	NUTS-3	NUTS-1	
			

Source: Own illustration based on Egerer et al. (2014) and Eurostat (2015)

One option would be to divide Germany into the two market areas Gaspool and NetConnect Germany. As there is no clear border between both market areas, it is challenging to implement these zones into a GIS-based model. FNB (2017) gives an overview for an allocation to market areas. It can be expected that in the future both market areas will be combined in one uniform market zone (Enet 2011). However, in order to investigate regional effects, a high spatial resolution is aspired. As the data is only published on federal states level, there is a lack of detailed spatial gas consumption data for example for individual districts.

Hence, the demand is clustered according to regions using the NUTS-3 level. The latest NUTS classification is from 2015 for the European Union (Destatis 2017). The selection criteria for one NUTS-3 area is the number of inhabitants in a specific region. While NUTS-1 describes the level of countries and NUTS-2 the level of federal states, the NUTS-3 area is defined by a minimum number of 150.000 inhabitants and an upper bound of 800.000 people[25].

4.3.2.1 Industrial natural gas demand

Beside the use of natural gas in the conversion sector to produce heat and electricity, natural gas is used in many other industrial sectors such as chemical processing (48 TWh_{th}), metal industries (42 TWh_{th}), food and tobacco (31 TWh_{th}), paper (22 TWh_{th}), glass and ceramics (17 TWh_{th}), and other smaller industries. The natural gas consumption is reported by AGEB (2017) for 2015 and amounts to 216.4 TWh_{th}. Figure 22 shows the consumption of all the reported sectors.

[25] It is worth mentioning that the German postal codes are on a different level than NUTS-3. Therefore, a referencing from postal codes to NUTS-3 is used.

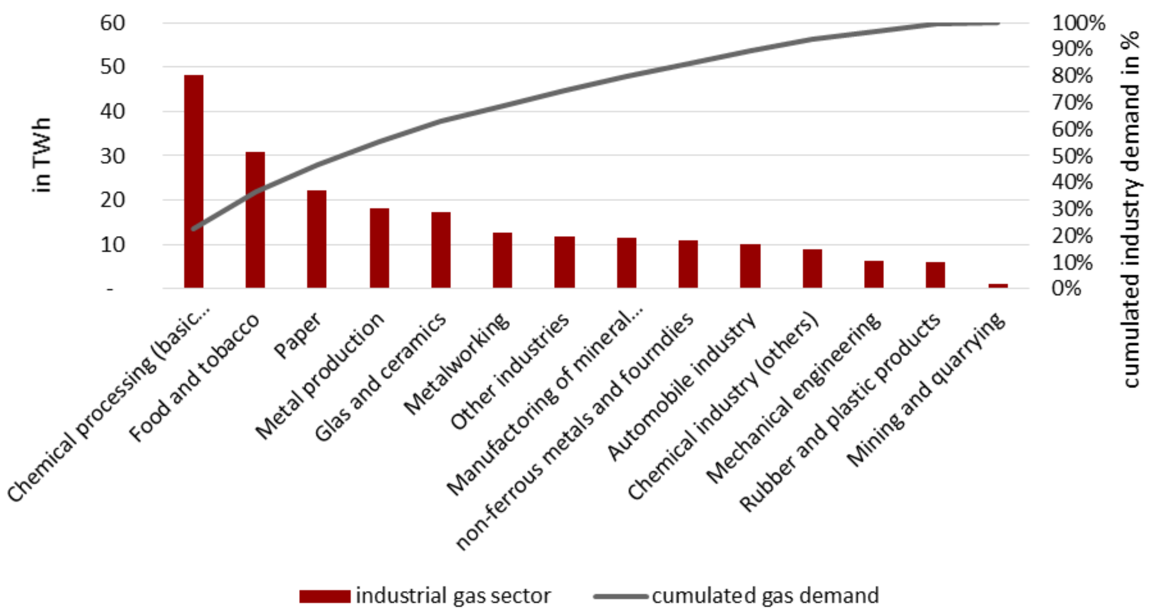


Figure 27: Reported natural gas consumption in industry sectors in 2015

Source: based on AGEB (2017)

Table 30: Data sources for industrial natural gas demand and company locations

Association	Type of data and considered companies
Euro Chlor – association of chloralkali process plant operators in Europe	Chlorine: 19
Bundesverband der deutschen Ernährungsindustrie (BVE)	Food: 161
Verband der deutschen Rauchtabakindustrie (VdR)	Tobacco: 19
Bundesverband der deutschen Glasindustrie	Glass: 68
Bundesverband Keramische Industrie e.V.	Ceramics: 148
Verband deutscher Papierfabriken (VDP)	Paper: 153
Stahl Zentrum Düsseldorf	Steel: 26
Gesamtverband der Aluminiumindustrie e.V.	Aluminum: 4

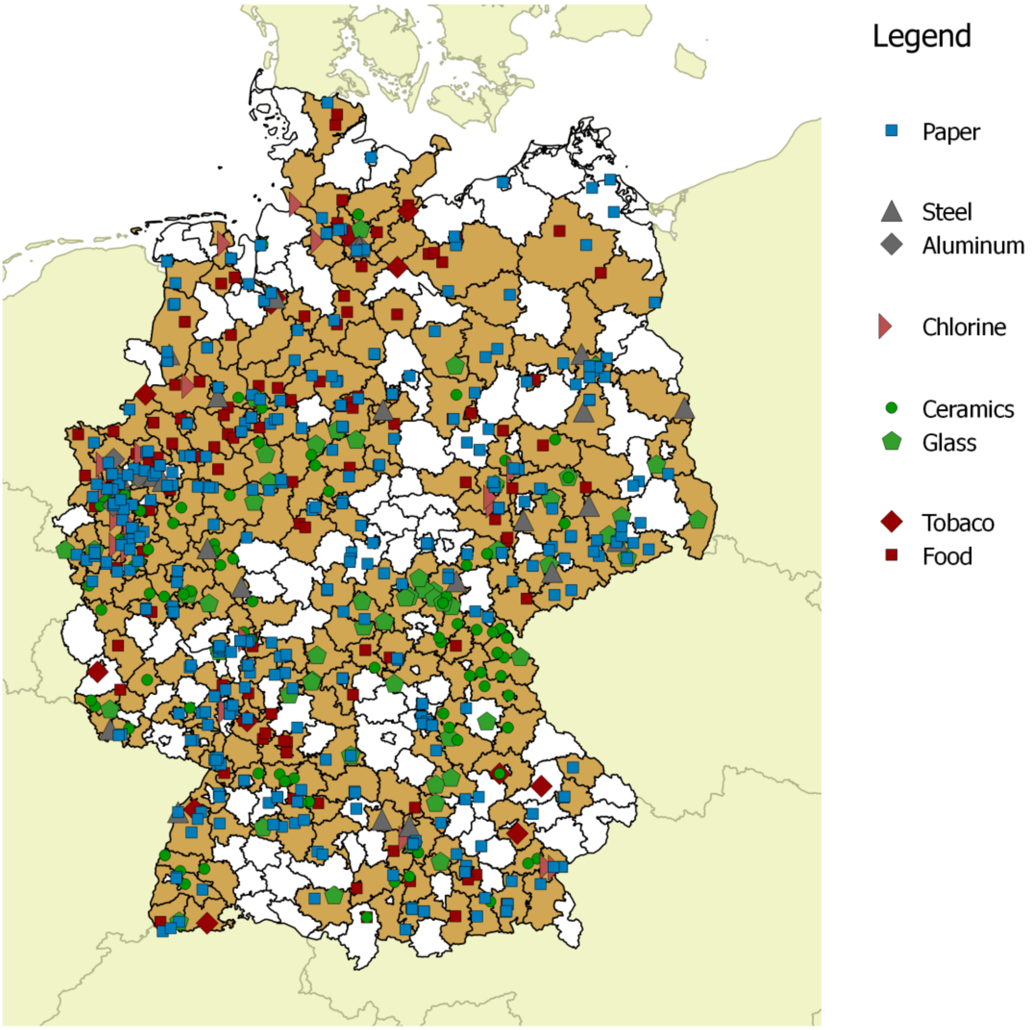


Figure 28: Map of natural gas-intensive industries in Germany

Source: own illustration

Here, a methodology for spatial and temporal resolution is needed. The distribution to regions follows a top-down approach, whereas the sector-specific gas consumption is distributed to regions according to the number of firms per region. The total natural gas demand in 2015 is reported and clustered according to usage in different industry sectors by AGEB (2015). The locations of companies in the particular industries are reported by industry associations (cf. Table 30). The locations of gas-intensive industries as paper, steel, aluminum, chlorine, ceramics, glass, tobacco, and food are depicted in Figure 28.

The remaining non-depicted natural gas consumption in other industries (58 TWh_{th}) is allocated to regions according to the gross value added (GVA). The results of allocated annual industrial demand of natural gas is depicted in Figure 29. The industrial natural gas consumption is concentrated in western regions of Germany in North Rhine-Westphalia as well as parts of Baden-Wuerttemberg, Bavaria and Saxony. Concerning the temporal resolution, we use the time series of the German industry heat demand (cf. Section 3).

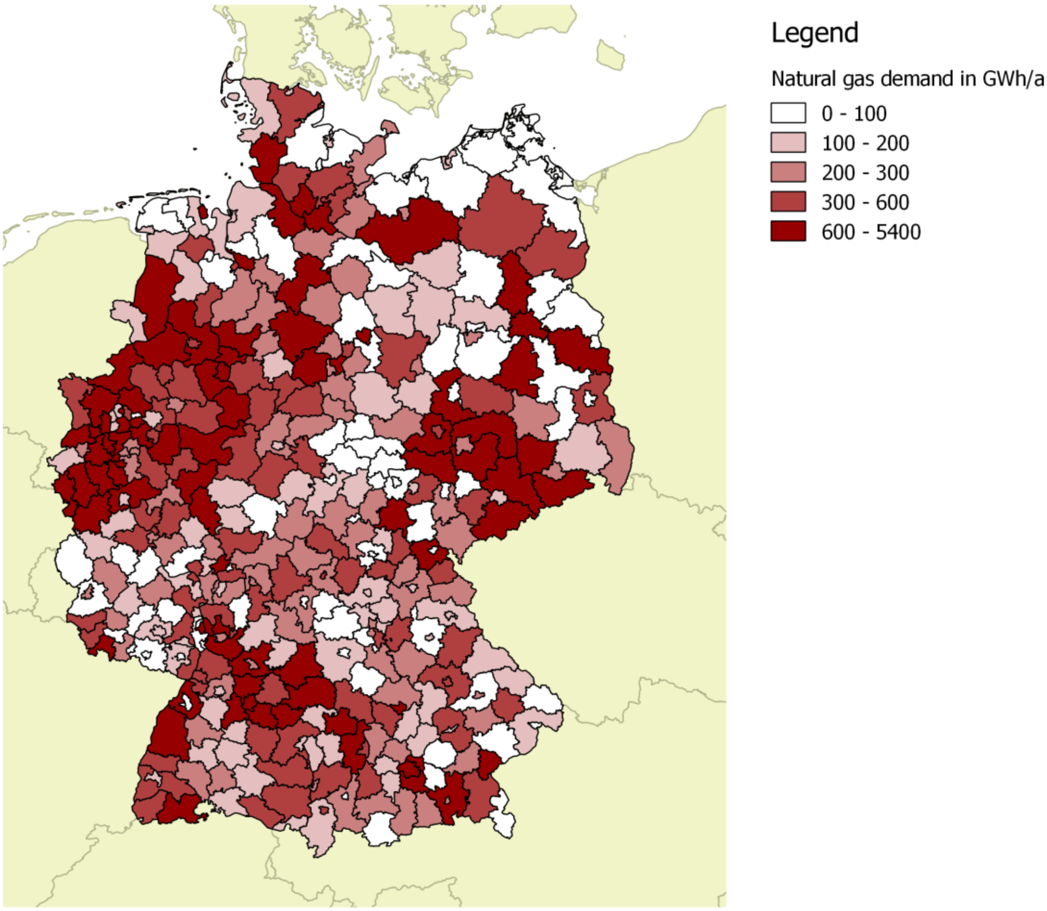


Figure 29: Allocation of industrial natural gas demand in Germany

Source: own illustration

4.3.2.2 Natural gas demand for electricity generation

The natural gas demand for electricity generation refers to German natural gas power plants. Here, two integration methodologies are possible: (i) exogenous, historic gas consumption time series of gas power plant or (ii) gas consumption time series of gas power plants based on results of a dispatch model like ELMOD-DE (Egerer 2016). In both cases, the location and operation of gas power plants is already given. Therefore, the spatial and temporal resolution is already given as well and the modeled natural gas demand follows a bottom-up approach. Setup B provides an option to couple an electricity and gas model.

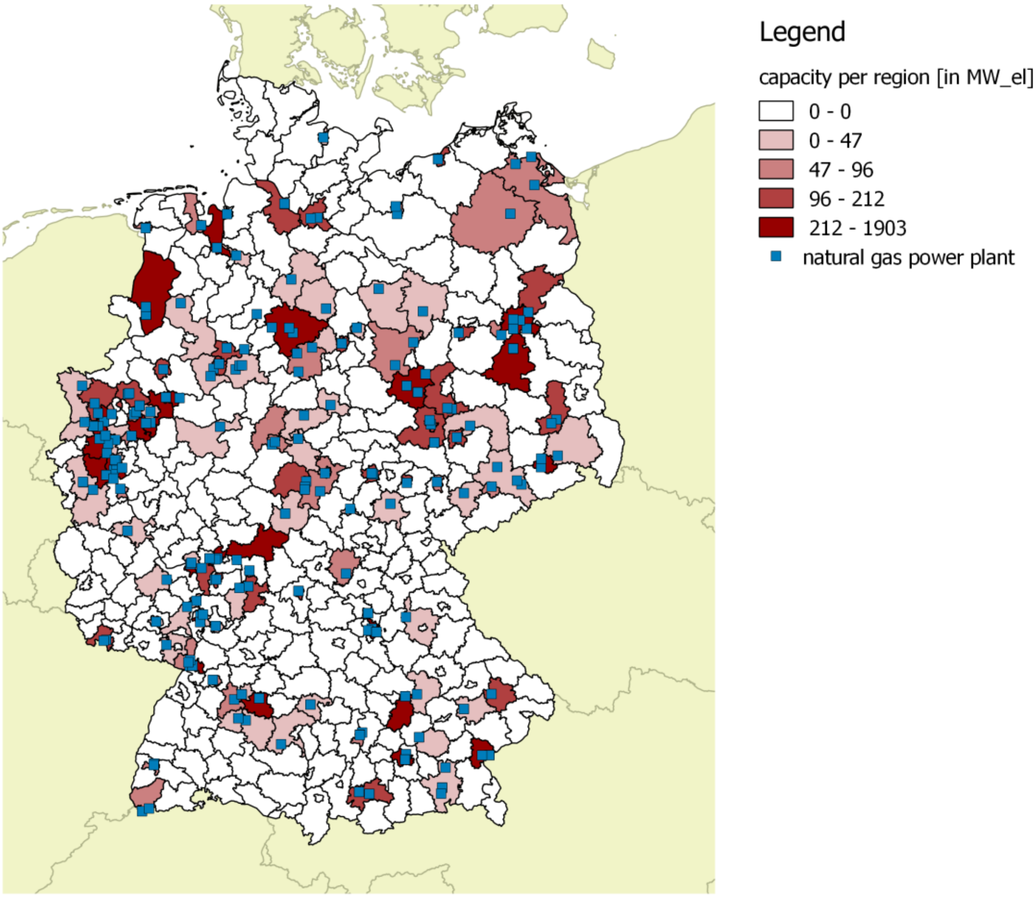


Figure 30: NUTS-3 level grouped nominal capacities of gas power plants

Source: own illustration

Due to the fact that the gas grid nodes do not always match gas power plant locations, an allocation of natural gas power plants to exit nodes is needed. We determine the nearest distances between power plants and exit nodes. Figure 30 illustrates the regional distribution of gas power plants in Germany and gives an overview of the installed net capacity per region.

4.3.2.3 Natural gas demand for heating

The natural gas demand for heating is the most challenging task with respect to modeling its spatial and temporal resolution. The two reasons are, firstly, that the production of heat can be provided by different technologies and depends on building structures and population and secondly, the temporal resolution is also challenging due to a dependence on temperature.

Table 31 provides an overview of available data on natural gas demand for heating.

Based on the available data we use a bottom-up approach to calculate the natural gas demand for heating. The spatial resolution is calculated using regional structures of buildings and heat technologies.

Table 31: Data sources to calculate natural gas demand for residential heating

Type of data	Source
For spatial resolution	
Structure of buildings by German regions	Destatis (2011)
Energy consumption in private buildings in Germany	Fraunhofer ISI et al. (2014)
Heat technologies by German regions	Bundesverband der Energie- und Wasserwirtschaft e.V., BDEW (2015b)
Natural gas consumption for heating in federal states	Länderarbeitskreis Energiebilanzen, LAK, (2017)

Type of data	Source
For temporal resolution	
Hourly temperature times series by German weather stations	Deutscher Wetterdienst, DWD (2017)
Standard load profiles and corresponding parameters	Bundesverband der deutschen Gas- und Wasserwirtschaft, BGW (2006)
Methodology to calculate daily heat demand, based on temperatures	Schaber (2014)
Methodology and tool to calculation of degree days	Institut Wohnen und Umwelt, IWU (2017)

Equations 4.1 to 4.3 show the principal methodology to determine the gas consumption for households. The gas consumption for households ($gasConsHous_k$) mainly arises from heating activities. For a specific day, the consumption in a region *k* can be calculated using Equation 4.1 and depends on living area a_k, the average gas consumption $\overline{gasConsHous_k}$, the share of gas using households *share_guh*, and the share of days in a year, where heating is used ($share\_hd_k$). The *share_guh* is calculated according to Equation 4.2, based on Destatis (2011) data and takes all heat technologies into account that use natural gas. We consider the reported categories self-contained heating *selfH,* central heating *centralH*, and block-type thermal power stations (BTTP) *blockH*. Degree days (dd_t) are such days that have a lower temperature than a defined level (i.e. 15°C for existing buildings and 12°C for new buildings). Heating starts only when temperatures are below this level. The calculated value is related to the long term average $N_{dd,longterm}$.

$$gasConsHous_k = a_k * \overline{gasConsHous_k} * share\_guh_k * share\_hd_k \qquad \text{(Eq. 4.1)}$$

$$share\_guh_k = \frac{selfH + centralH + blockH}{all\ heating\ systems} \qquad \text{(Eq. 4.2)}$$

$$share\_hd_k = \frac{\sum_{t=1}^{365h} dd_t}{N_{dd,longterm}} \quad \text{(Eq. 4.3)}$$

The temporal resolution follows the approach of standard load profiles described by BGW (2006, 29 ff) and takes the daily temperature and the calculated *gasConsHous*$_k$ into account.

4.3.3 Calculation of total gas demand and comparison with data sources

The introduced approach aims to model the natural gas demand using different methodologies for temporal and spatial resolution in three sectors. The previous sections laid down the methodologies to calculate the natural gas demand based on final usage in the industry sector, in the electricity sector, and in the heating sector. This section now validates the results, aggregates the sectoral natural gas demands and explain the allocation from regional (NUTS-3 level) to nodal natural gas demands.

The deviations of calculated natural gas demand for heating to public information for all federal states are shown in Figure 31. While the total deviation in most states is less than 10%, the used approach shows high deviations for Berlin. One reason might be the higher share of buildings that are supplied by district heating networks that is not considered in this approach. In total, our approach overestimates the residential natural gas demand. The temporal resolution for heating-related natural gas demand refers to daily temperatures.

For industry processes that use natural gas, a relation to temperature can observed as well. We use a uniform time series, based on the industry heat pattern (cf. Section 3) in order to distribute the total industrial natural gas demand over the year with regard to seasonal effects. Natural gas demand for electricity generation can be a result of a dispatch model like ELMOD-DE and has the highest temporal and spatial resolution as all power plants are assigned to natural gas network exit nodes. Figure 32 shows the summarized results of the demand modeling approaches and depicts the total natural gas demand pattern for 2015 in Germany.

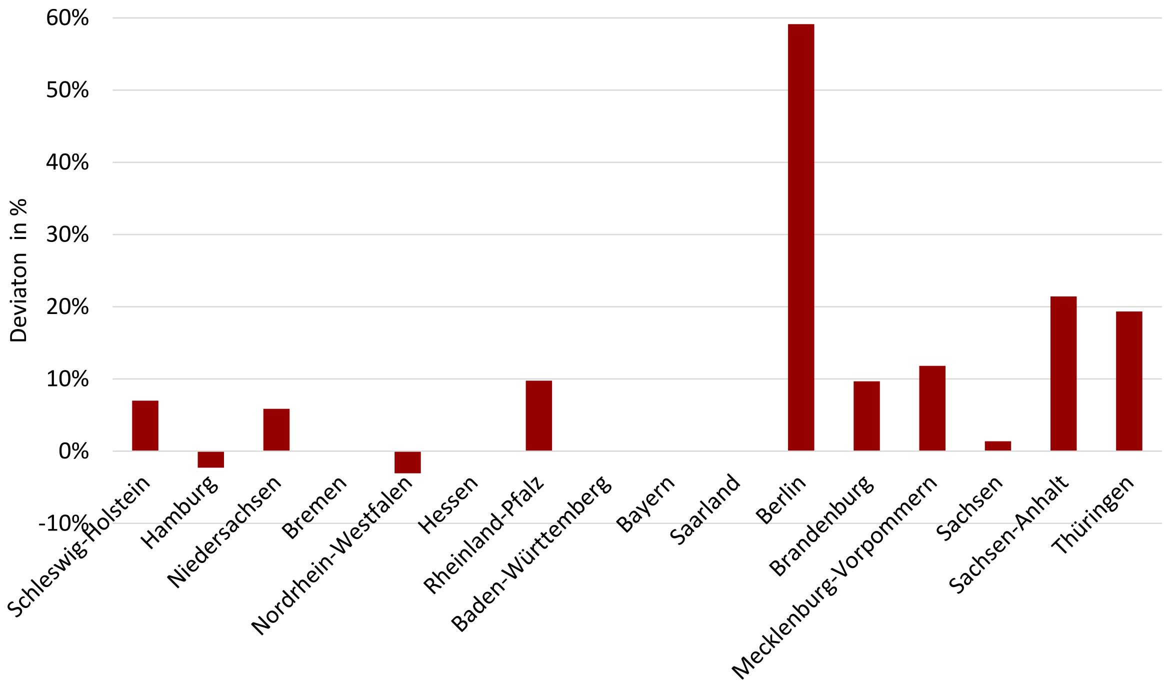


Figure 31: Deviation between calculated and actual household gas consumption for the federal states in the year 2013

Source: own calculation

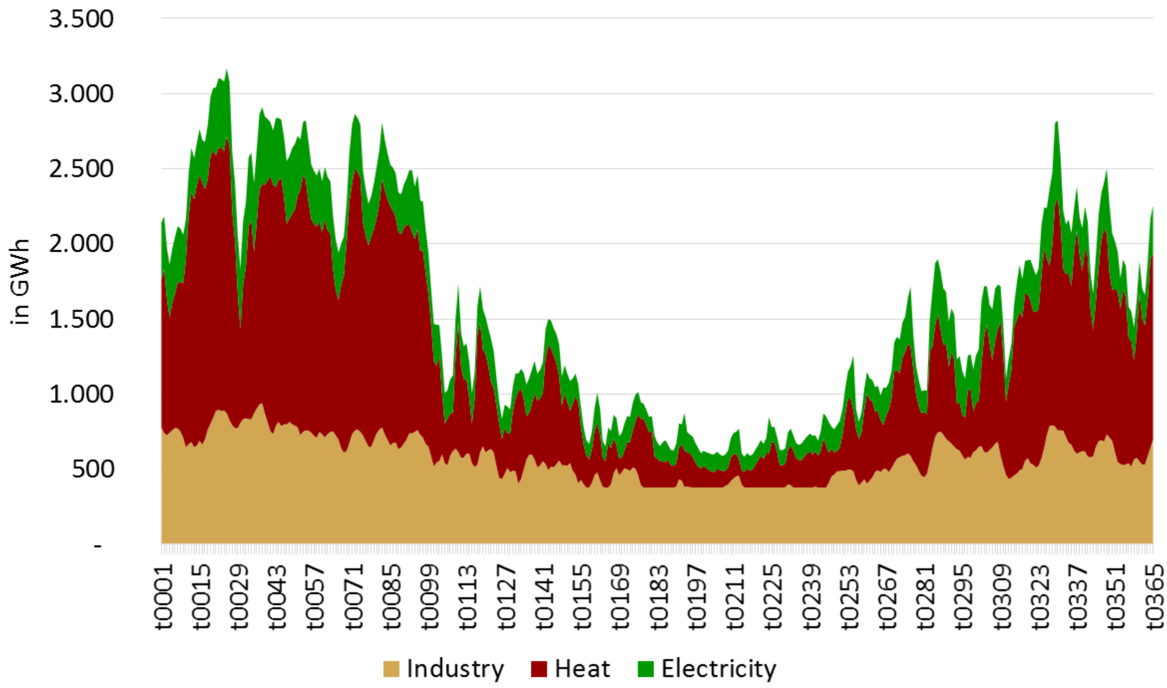


Figure 32: Natural gas demand pattern for Germany in 2015

Source: own calculation

In the next paragraph, the assumptions for spatial resolution are described. The industrial and heating-related natural gas demand (Dem_k) for one region k is calculated according to Equation 4.4 using spatial data of each region within Germany.

$$Dem_k = Dem_k^{Ind} + Dem_k^{Heat} \; \forall \; k = 1, \dots, 402 \qquad \text{(Eq. 4.4)}$$

$$Dem_n = \frac{Dem_k}{N_k} + Dem_{n,p}^{Elect} \qquad \forall \; p = n \qquad \text{(Eq. 4.5)}$$

k	NUTS-3 areas
n	exit node
N_k	Number of exit nodes in NUTS-3 area k
p	natural gas power plant node

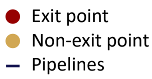
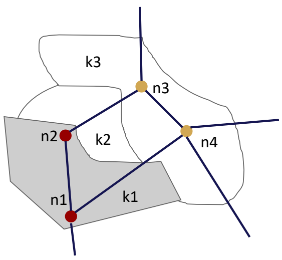
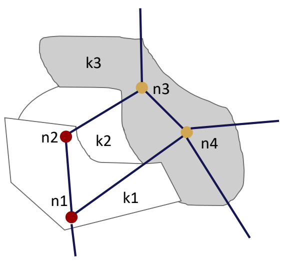
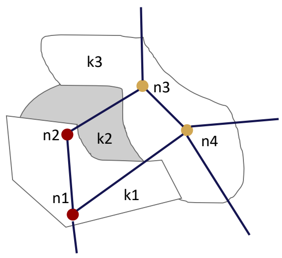
However, as the model operates with pipelines and nodes, it is necessary to allocate regional demand to the respective nodes located in each region. In the case that more than one exit node per region exists, the natural gas demand Dem_k of the NUTS-3 area k is distributed equally to all exit nodes according to Equation 4.5. If a natural gas power plant is located at the exit node n, the electricity based natural gas demand is added as well.

In the model, there are three different relations between nodes and NUTS-3 areas:

1) NUTS-3 areas where more than one exit point exist
2) NUTS-3 areas without any exit points, but other points
3) NUTS-3 areas without any points

For the first case, demand can be easily assigned to respective exit nodes. In the second case, one node inside the area is chosen randomly and is considered as an exit point. In case there is no node inside the NUTS-3 area, the closest node to the NUTS-3 area is considered to be the exit point. This relation is calculated by the minimum Euclidian distance between the centroid of the NUTS-3 area and all neighbor nodes of this centroid, using QGIS. Consequently, the natural gas demand in all NUTS-3 areas can be allocated to at least one exit node.

Table 32: Allocation of NUTS-3 demand to nodes

Case	1) areas where more than one exit point exists	2) areas without any exit points, but other nodes	3) without any points
Number of NUTS-3 zones	221	25	156
Number of exit nodes	905	25	0
Stylized example 	 Demand of k1 is equally allocated to the nodes n1 and n2	 Demand of k3 is allocated to the nodes n3 or n4, that becomes an exit point	 Demand of k2 is allocated to the closest exit point n2
Example Regions	Duisburg	Nuremberg	Berlin

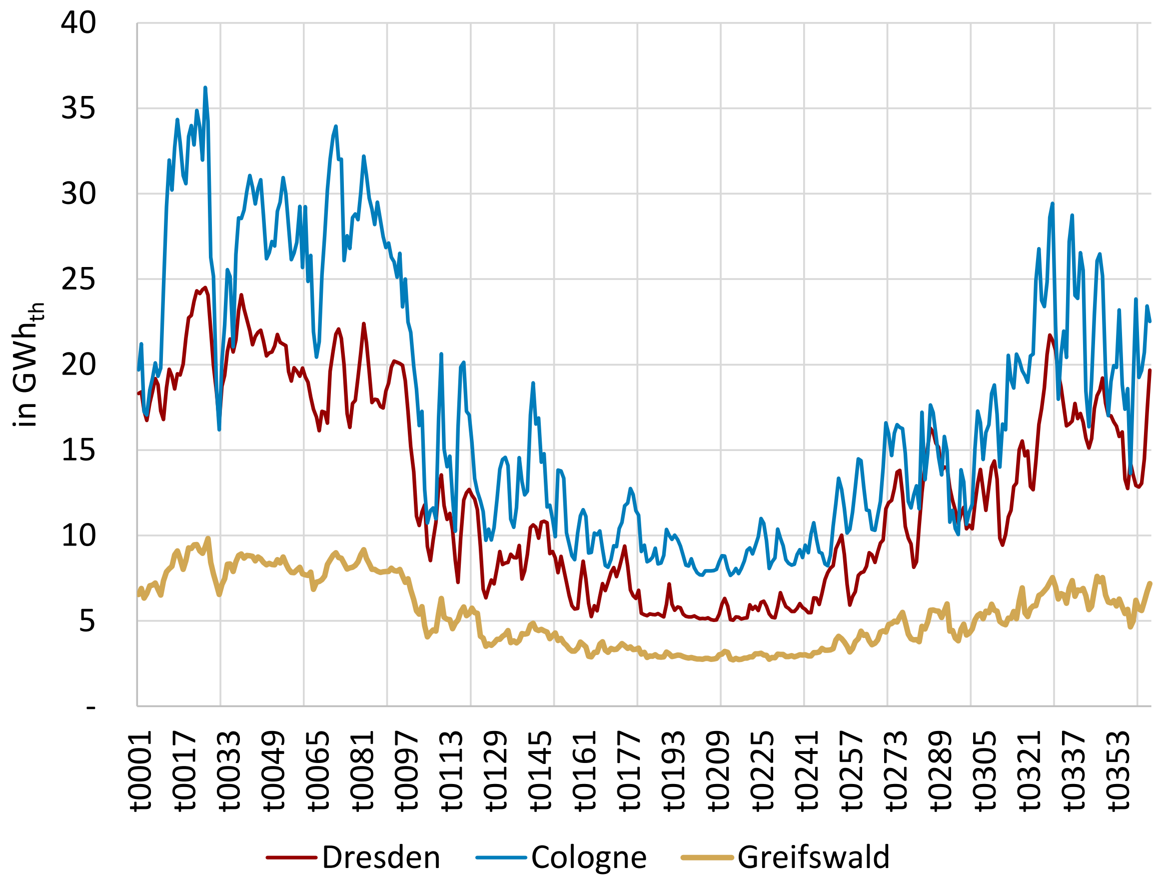


Figure 33: Exemplary calculated load profiles for Dresden, Cologne and Greifswald in 2015

Source: own calculation

4.3.4 Limitation of gas demand modeling approach

The introduced methodology enables modelers to represent the German natural gas demand in a high spatial and temporal resolution differentiated by heating, industry, and electricity generations. The results show typical load profiles for different locations in Germany. However, as described in the previous sections, our approach requires a range of assumptions and simplifications. Focusing on the three sectors industry, heat, and electricity neglects other sectors as transportation or losses. Secondly, there is some overlap between heat, electricity, and industry. For instance, CHP plants produce heat and power simultaneously. Another example are industry processes that use natural gas for both heating processes and as raw material.

With respect to heating-related natural gas demand, we focus on private households. Public buildings are underrepresented and hence also their respective natural gas demand. The distribution of industrial natural gas demand follows a detailed research of special industries that use natural gas. The remaining gas-using industries “others” are allocated by using the simplified approach of using GVA as a distribution key. This may lead to distortions, especially in urban areas as Berlin, where the real natural gas demand is overestimated.

4.4 Natural gas supply

4.4.1 Data on natural gas supply

The following subsections describe the data availability for natural gas supply. TSOs have to publish data about in- and outflows to/from their grids according to §4 (2) 2, EnStatG. Table 33 gives an overview about available data.

Table 33: Overview about data for natural gas demand

Source	Type of data
BAFA	Annual production of natural gas
BVEG	Technical data of natural gas production in Germany
DENA	Aggregated data on biogas production
ENTSOG	Time series of natural gas imports and exports
EUROGAS	Statistics on annual indigenous gas production

The spatial distribution of supply data to grid nodes is straightforward, as locations can be assigned to gas grid nodes by geographical information. Time series for imports and exports are available. More challenging are time series of biogas and conventional gas production.

4.4.2 Domestic production

In total, there are five different operators which produce natural gas, which is mainly L-gas, according to the ENTSOG API (ENTSOG 2014): Gasunie, Thyssengas, Ontras, Nowega, and Open Grid Europe (cf. Table 34). The mapping is done by comparing the natural gas production facilities of Rövekamp (2015, 117) shown in Figure 34 with our GIS model.

Table 34: Conventional natural gas production in Germany

	Production [TWh_{th}/a]
ONTRAS	1.080
Thyssengas (H-gas)	0.062
Thyssengas (L-gas)	0.000
Nowega	28.280
Gasunie Deutschland (H-gas)	14.875
Gasunie Deutschland (L-gas)	22.887
Open Grid Europe	6.850
Total	**73.962**

Source: ENTSOG (2017)

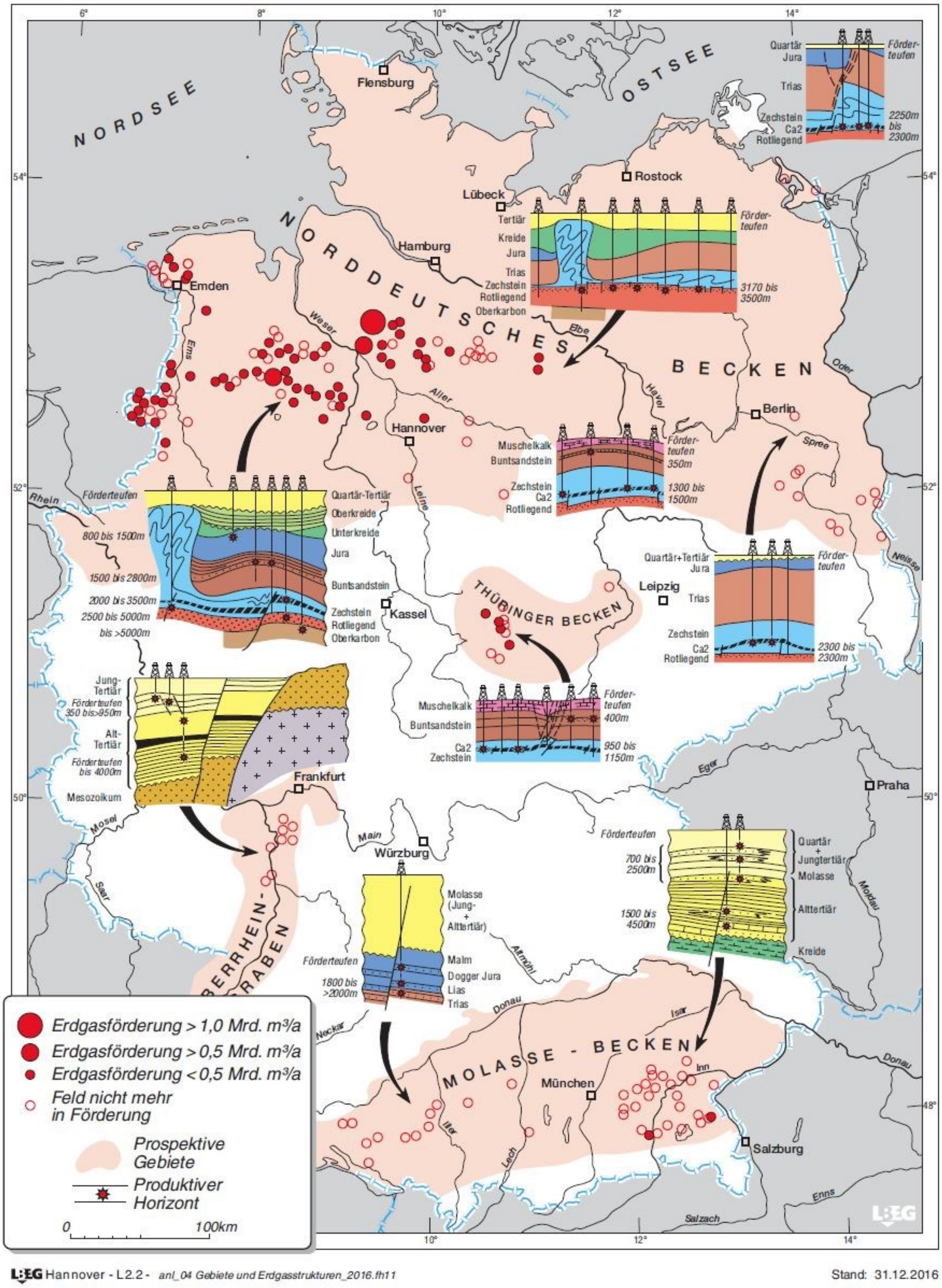


Figure 34: Natural gas production Germany

Source: LBEG (2017)

These production capacities are assigned to grid nodes in the model as shown in Figure 35. During the shale gas boom in the USA, the relevance of shale gas production in Europe was discussed as well. Due to geological conditions, the exploration of European shale gas is more expensive than for example in the United States. Riedel et al. (2016) provide a meta-analysis on European shale gas formations and show that estimated production costs cannot compete with conventional natural gas. Additionally, the current policy in Germany does not allow shale gas explorations to a larger extent. Therefore, shale gas is not considered in this reference data set.

There is only limited data on production costs in Germany as companies do not publish their original cost data.Lochner (2012, 74) assumes production costs of 6.28 EUR/MWh_{th} for European natural gas producers.

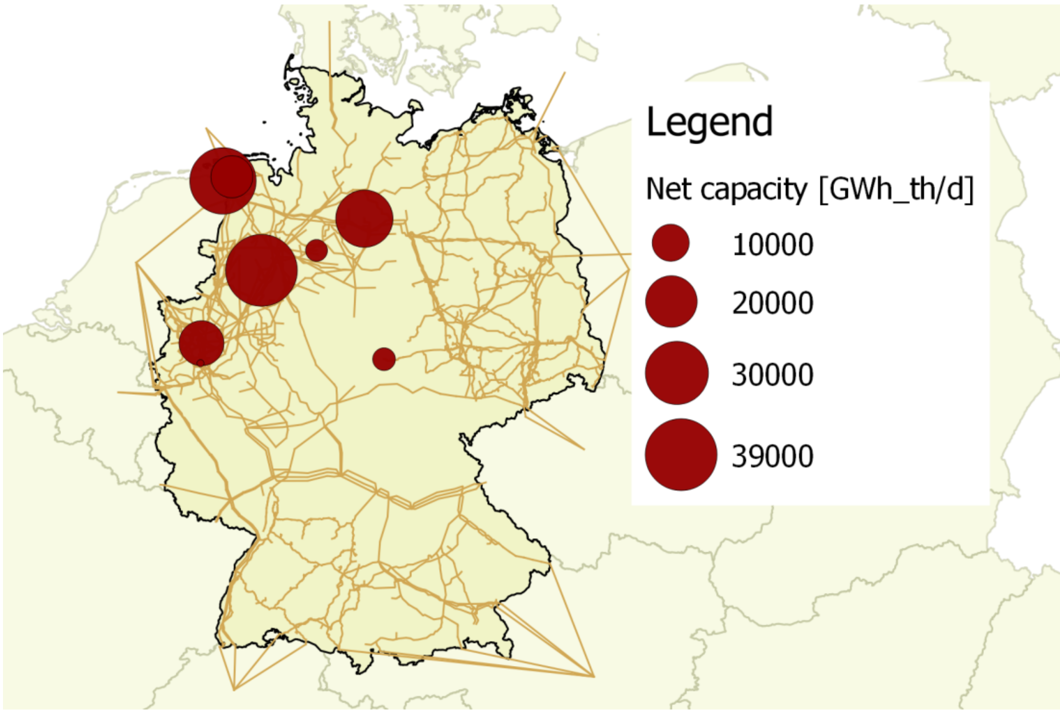


Figure 35: Allocation of German natural gas production to nodes

Source: own illustration

4.4.3 Biogas

Biogas was a growing renewable energy resource in the last decade. After political debates about the food-energy nexus, political support for bioenergy has been reduced. Only a small number of biogas plants inject directly into natural gas pipelines. Mostly, biogas is used to produce heat and electricity in small CHP plants. In 2015, 10 TWh of biogas were injected into the natural gas pipeline system. Hence, the share of biogas from the total natural gas demand (2015: 630 TWh) is only 1,5% (FNB 2015, 23). Accordingly, the data for biogas is neglected in this version of the reference data set. However, data regarding biogas plants that are connected into natural gas pipelines can be found at DENA (2017).

4.4.4 Imports and interconnectors

Germany heavily depends on natural gas imports, as the domestic reserves are limited. Figure 36 shows that the domestic production covers only 7% of the German natural gas volumes[26].

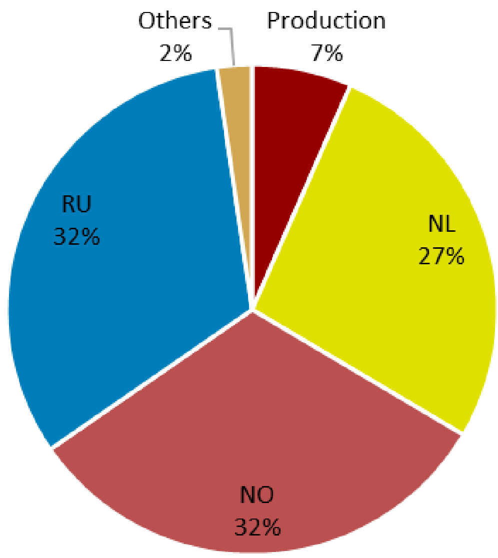


Figure 36: German natural gas volume in 2015

Source: ENTSOG (2017)

[26] The German natural gas volumes describe the sum of all gas imports to Germany and the German domestic production.

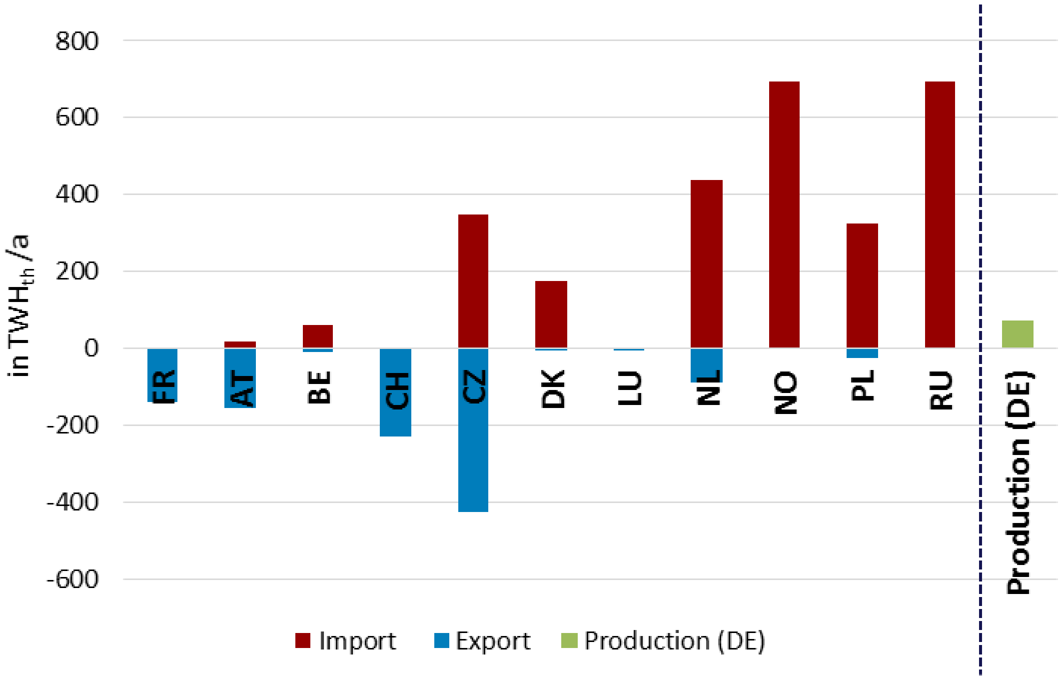


Figure 37: Comparison of German production and physical flows in the year 2015

Source: ENTSOG (2017)

Germany is connected by pipelines (interconnectors) with all neighboring countries (cf. Figure 37). Russian gas flows indirect via Austria (AT), Czech Republic (CZ) and Poland (PL) as well as direct via the Nord Stream pipeline to Germany. Dutch gas flows direct from the Netherlands (NL) and via Belgium (BE) to Germany and Norwegian (NO) gas enters Germany directly and via Denmark (DK). The depicted exports from Germany in Figure 37 shows that Germany is also a transit country for natural gas. With respect to the extension of the Nord Stream II pipeline it can be expected that transit gas volumes will increase (cf. Hauser et al. 2017).

The European natural gas transmission system connects Western European countries with non-European sources in Russia, North Africa, and the Caspian Region. Therefore, all connection points to neighboring countries (also called interconnectors) are modeled. Table 35 lists the import and export capacity of the interconnectors.

Table 35: Import and export capacities of German interconnectors

Country	Import [GWh_{th}/d]	Export [GWh_{th}/d]
Poland	931.6	117.6
Czech Republic	1,104.4	1216.5
Austria	485.7	467.3
Switzerland	0.0	554.4
France	0.0	571.8
Belgium	313.0	320.1
Luxemburg	0.0	38.7
Netherlands	2,356.5	1,616.0
Norway	1,710.2	0.0
Denmark	32.7	60.6
Russia	1,743.0	0.0

Source: ENTSOG (2014) GIE (2017)

4.4.5 Storages

Storages provide flexibility in natural gas grids. Since the demand shows a seasonal fluctuation between summer and winter times, natural gas storages enable a smoother operation of production and import facilities. AGSI (2016) provides daily updated data about gas in storage, storage level in percentage, level trends, injected and withdrawn capacities and rates (in GWh_{th}/d), and the working gas volume. Germany holds the highest storage working gas volume in Western Europe (232 TWh_{th}), followed by Italy (193 TWh_{th}), France (134 TWh_{th}), and the Netherlands (130 TWh_{th}). An important country for the natural gas security of supply is Ukraine that holds, as a non-EU country, the highest storage volumes (323 TWh_{th}).

There are different storage operators in Germany. All data of single storages are listed on the website of AGSI. One of the biggest storages in Germany is Rehden, located in the north west of Germany. It has a storage volume of more than 48 TWh_{th} and is owned by Gazprom.

Smaller-scale storage technologies such as LNG tanks or gasometers above ground are neglected here. In addition, pipelines have the ability to store natural gas in the short term by increasing the pressure of a pipeline. This is called line packing that is not considered in the model so far. However, the largest storages are geological formations located underground and can be distinguished in depleted gas fields, aquifer reservoirs or salt formation. Depending on rock formations (i.e. pore or cavern storage facilities) the injection and withdrawn rates vary. Figure 38 shows the injection capacities distributed in Germany and Figure 39 shows the maximum withdrawal capacities.

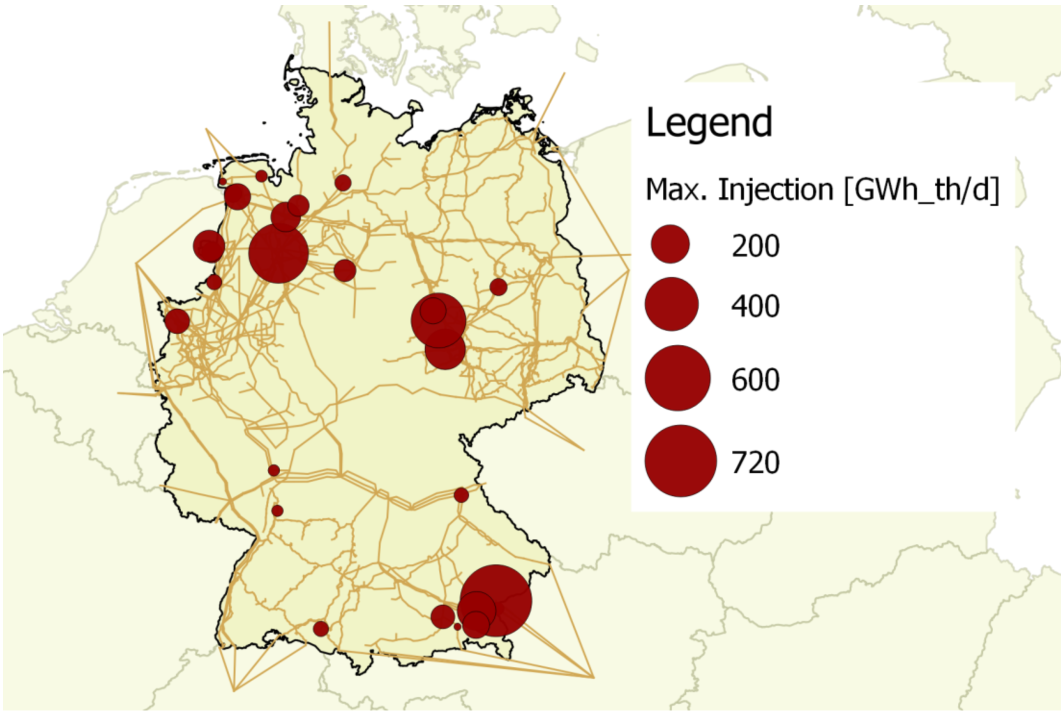


Figure 38: Storage injection capacities in Germany

Source: own illustration

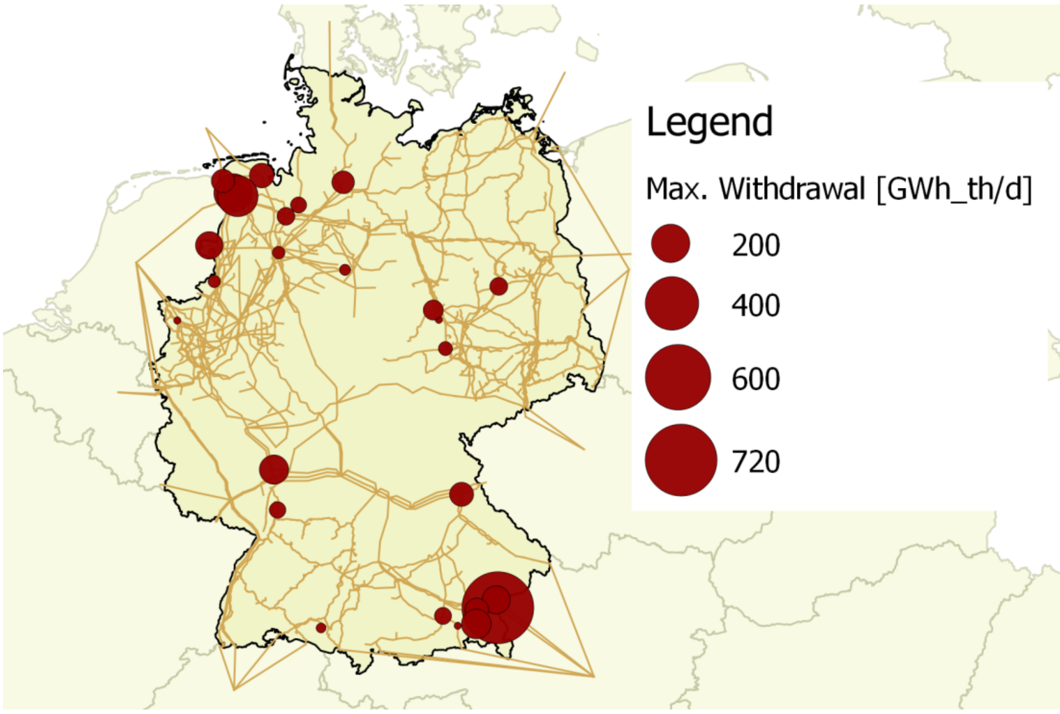


Figure 39: Storage withdrawal capacity in Germany

Source: own illustration

5 Final remarks and outlook

5.1 Limitations of this data set

The data set described in this data documentation draws on publicly available data in the German electricity, heat, and gas systems. It is intended to facilitate appropriate and policy-relevant modeling of the German energy system, which can contribute to answering various research questions in the field of German energy markets and infrastructure. There are some limitations of the presented data set, though.

For the presented data of the electricity system (Section 2), some detail is missing with respect to the technical representation of conventional generation capacities. An example is the rate and cost of changing output levels of conventional generating units. Also, the given seasonal availability factors reflect exogenous assumptions on revision times during the summer months and abstract from uncertainty, neglecting unscheduled outages of power plants and other system infrastructure. Technical power line characteristics are only approximated with the voltage level and line length. Some of the German TSOs have published technical information on individual transmission lines, which could be used to improve the representation of the transmission system. Further, a large share of small-scale generation and demand is connected to lower voltage levels. Yet, the data set connects those to network nodes of the 220 kV or 380 kV grid. Alternatively, renewable generation and demand of underlying networks of lower voltage levels could be replaced with vertical load at connecting transformer stations. As regards electricity demand, time series are currently represented by a mixed bottom-up and top-down model that works with some assumptions. The spatial and temporal distribution of load could be improved using specific data on the spatial distribution of demand from large industrial consumers for different sectors.

The described data for heat production (Section 3) is provided as demand time series, based on model-generated time series and not on an actual data set. While there is a large number of heating networks in Germany, this data set only considers the ten largest ones, accounting for only 34% of the German heat demand. Further, the maximum heat production capacities for some CHP plants may include peak load boilers and storages that are currently not included in the data set. Those boilers and storages would affect the flexibility of power plants regarding the satisfaction of heat demand and co-generated electricity in a model application.

The provided data and methodology concerning the natural gas system (Section 4) face limitations especially with respect to the available infrastructure data. TSOs provide only limited details of technical features (diameter, pressure, number of lines, and location of entry/exit nodes). Additionally, the capacities are calculated based on the assumed pressure and diameter information provided in $GW_{th.}$ The gas demand focuses on electricity, industry, and heat in private households, while other sectors like transportation or losses are neglected. In the case of economic data, hardly any reliable sources on production costs for natural gas are available. Hence, assumptions based on import prices and mark-ups are necessary. Renewable "green gas" and biogas are neglected in this data set, as well.

5.2 Outlook and possible applications

This data documentation and the underlying dataset may serve as a starting point to model studies which answer a range of research questions, for example:

- How do interactions between electricity, heat and natural gas markets and infrastructures change in the context of the Energiewende?
- Does congestion in natural gas networks exist – and if not, will the risk of congestion increase by rising transit gas flows during the coming decades?
- Which interdependencies between heat production and electricity and gas system do exist in Germany, and how will these evolve?
- What is the influence of properly considering heat production when modeling dispatch and operation of power plants?
- How do electricity prices change in the context of the Energiewende?
- Does sector coupling increase the security of supply in natural gas and electricity systems?

All of these research questions touch upon important uncertainties and risks in the German energy system. Answering them with proper model-based analyses, making use of adequate input data, may contribute to achieving sustainable energy system in Germany.

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Kurzzusammenfassung

Diese Dokumentation beschreibt Daten zum deutschen Strom- Wärme- und Gassektor und ermöglicht eine modellgestützte Abbildung dieser Energiesysteme. Die Aufbereitung der Daten erfolgte im Rahmen des vom BMWi geförderten Forschungsprojekts LKD-EU (Langfristige Planung und kurzfristige Optimierung des Elektrizitätssystems in Deutschland im europäischen Kontext, FKZ 03ET4028C), in Zusammenarbeit mit dem Deutschen Institut für Wirtschaftsforschung (DIW), der Arbeitsgruppe Wirtschafts- und Infrastrukturpolitik (WIP) der Technischen Universität Berlin (TUB), dem Lehrstuhl für Energiewirtschaft (EE2), der Technischen Universität Dresden (TUD) und dem House of Energy Markets & Finance der Universität Duisbrug-Essen (UDE). Ziel des Dokumentes ist es, Referenzdaten zur Verfügung zu stellen, die den aktuellen Zustand des deutschen Energiesystems repräsentieren. Das Bezugsjahr ist 2015. Diese Dokumentation trägt dazu bei, die Transparenz in der Verfügbarkeit von Daten zum deutschen Energiesystem zu erhöhen.

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