# Spatio-temporal analysis of renewable electricity supply and demand for the German case

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## Abstract

While progress in reducing greenhouse gas emissions is notable in the power sector, other sectors such as transportation and often heating are lagging behind. A strategy to propagate greenhouse gas emission reductions from the power sector to other sectors is so-called "sector coupling." Against this backdrop, we ask the following two questions: (1) *To what extent does demand for (useful and final) energy match the supply of renewable energy sources in the dimensions of time and space? (2) What impacts of sector coupling pathways on future infrastructure requirements can be derived from applying spatiotemporal analyses?* For our analyses, we assume a scenario with 95% greenhouse gas emission reductions for Germany as a case study as targeted by the government for 2050. We choose a consumer-driven approach, analyzing the energy value chain backwards from consumption to supply for the different sector coupling technologies. From useful energy consumption, we derive final energy demand patterns in high temporal and regional resolution and evaluate implications for different strategies of renewable energy expansion. The key contributions of our study are twofold: Firstly, we introduce a generalizable and transferable consumer-driven analysis in high temporal and regional resolution for energy systems with high degrees of sector coupling and derive implications for the energy infrastructure. Secondly, we provide policy recommendations from our results regarding effective and efficient strategies for the integration of renewable energy sources into present energy systems.

**Keywords:** Sector coupling; renewables; electricity; heating; transportation; infrastructure; energy policy

# 1 Introduction

While progress in reducing greenhouse gas (GHG) emissions is noteworthy in the power sector, realizing such reductions in the transportation and often in the heating sectors seems much more difficult. A strategy to propagate potential GHG emission reductions from the power sector into other energy sectors is sector coupling (see Ruhnau et al. 2019). Generally, demand for useful energy (e.g., mechanical energy in the transportation sector or thermal energy in the heating sector) can be fulfilled by different types of final energy (e.g., gasoline, diesel or heating oil, natural gas, electricity). However, different pathways for the provision of final energy are associated with different infrastructure requirements for energy systems. In this context, so-called “direct” and “indirect” electrification are two strategies for implementing sector coupling. With direct electrification, final consumers directly purchase renewable electricity for their appliances such as battery electric vehicles or electric heat pumps (see Densing, Panos and Hirschberg 2016; Sugiyama 2012). With indirect electrification*,* on the other hand, consumers purchase fuels and gases such as hydrogen or artificial methane, which are produced from renewable electricity (see, for example, McDowall and Eames 2006; Welder et al. 2018). Therefore, direct electrification shapes energy infrastructure mainly towards electricity grids while indirect electrification puts the emphasis on pipelines or other means of transportation for gaseous and liquid fuels. However, different infrastructure requirements have different implications for the different strategies of decarbonization in terms of both cost and acceptance for society. Against this backdrop, we ask:

> *(1) To what extent does demand for (useful and final) energy match the supply of renewable energy sources in the dimensions of time and space?*
>
> *(2) What impacts of sector coupling pathways and the placement of renewable energy plants on infrastructure requirements can be derived from applying spatiotemporal analyses?*

We analyze different sector coupling scenarios using a systemic, consumer-driven approach considering each energy conversion stage and different end consumer appliances starting from the demand for useful energy. Subsequently, we derive the resulting final energy demand patterns. We then evaluate how different strategies for expanding infrastructure impact economic efficiency using temporally and regionally resolved time series for energy demand and supply in Germany. Based on this spatiotemporal analysis, we provide policy recommendations regarding effective and efficient strategies for the integration of renewable energy sources into the present energy system.

We choose Germany as a case study as it is, on the one hand, strongly expanding its share of renewables in the power sector, which has increased so far from 3.4% in 1990 to 42.1% in 2019, and is projected to increase even further (UBA 2020). On the other hand, Germany is lagging behind in its goal of decarbonizing the heat and transportation sector, where renewable shares increased from 2.1% to 14.5% and from 0.1% to 5.6% from 1990 to 2019, respectively (see AGEE Stat 2020; Löschel et al. 2019; UBA 2019). The results of this case study and particularly the developed methodological framework are intended to provide notable insights for international applications as well.

The remainder of this manuscript is structured as follows. First, we provide an overview of the related literature in Section 2. We then introduce our scenario framework in Section 3. Section 4 is dedicated to briefly introducing our methodology for the spatiotemporal aggregation and disaggregation of available data. Subsequently, we summarize our results in Section 5. Section 6 provides a discussion on our results given their implications for efficient political frameworks. We conclude in Section 7.

## 2 Background

In this section, we provide a short overview of relevant literature focusing particularly on energy balances and flow charts, sector coupling, and the ongoing German energy transition.

### 2.1 Energy Balances and Energy Flow Charts

Energy balances depict statistical data on the energy flow within given system boundaries. Figure 1 shows an exemplary illustration of an energy flow chart based on energy balances. Typically, energy balances differentiate between *primary energy* (i.e., energy carriers that have not undergone any man-made conversion steps such as crude oil), *final energy* (i.e., mostly energy converted from primary energy and sold to end users such as gasoline), and *useful energy* (i.e., energy that has undergone a final local conversion process in end user appliances such as motion energy). Therefore, demand for final energy is only an intermediate one corresponding mostly to commercial energy to provide utility (i.e., useful energy) such as heat and cold, mechanical energy, data processing in information and communication technology (ICT) services, or lighting to the end user (Zweifel, Praktiknjo and Erdmann 2017).

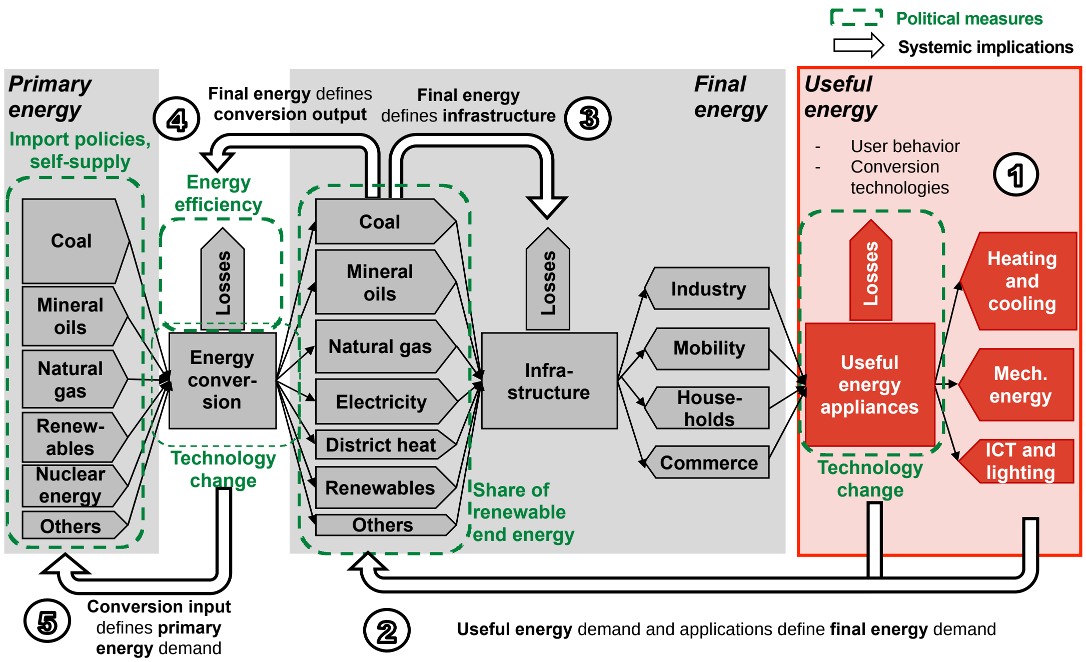



**Figure 1: Systemic Implications and Political Measures in Energy Balances of National Energy Systems Based on Zweifel, Praktiknjo and Erdmann (2017).**

In recent literature, energy flow charts are frequently used to visualize statistical data on energy production, transportation, and consumption of different forms of energy carriers. For example, Zhang and Wang (2012) represent and analyze the energy system of Jiangsu Province in the People's Republic of China (PRC) using energy flow charts, while Yang and Xu (2013) conduct a similar study focusing on Guangdong Province. Wu, Hu and Chen (2014) make use of energy flow charts on a less aggregated level to depict the energy flow of an electric bus. Energy flow charts are also used to investigate hydrogen economies, e.g., by Deng et al. (2010) for the Chinese case and by Berry and Daily III (2004) for future scenarios regarding the diffusion of hydrogen-fueled vehicles in the US.

Historically, energy flow charts have been used in particular to investigate the potentials and limits of biomass in different regions around the globe (cf. Woods 1990; Senelwa and Hall 1993; Hemstock and Hall 1997; Amoo-Gottfried and Hall 1999).

Also, energy flow charts have been adopted to flows other than energy: Fürnsinn, Günther and Stummer (2007) introduced so-called "economic flow charts" to represent monetary flows for new technologies. Further, Xie et al. (2009) expanded the scope of energy flow charts to illustrate the flux of $CO_2$. Finally, modified energy flow charts in the form of *Sankey diagrams* are often used to depict processes on a higher level of detail rather than on a systemic level (for the case of the iron and steel industry in Germany, see Schmidt (2008)).

Overall, energy flow charts have proved to be a suitable tool for analyzing relevant relationships on a systemic level as well as for more detailed mapping of processes. Thus, we consider this method appropriate to investigate the effects of sector coupling on the whole energy system. A holistic approach comparing the effects of different sector coupling pathways on a national level has not been conducted, however, to the best of our knowledge. Thus, this constitutes a substantial research gap. Additionally, energy flow charts provide a good overview on the system level but do not allow for more refined temporally and spatially disaggregated analyses. By introducing an approach to disaggregating the statistical data behind energy flow charts, we expand the scope of possible investigations.

## 2.2 Sector Coupling

Having introduced energy flow charts, we now focus on recent literature regarding sector coupling pathways. As outlined by Robinius et al. (2017a and 2017b), there are different definitions of sector coupling. In general, the term refers to "the energy engineering and energy economy of the connection of electricity, heat, mobility […], as well as their infrastructures"[1] (BDEW 2017). As

[1] Own translation from German.

mentioned in the introduction section, multiple pathways can be used to connect the aforementioned sectors: direct coupling via electrification and indirect coupling using intermediate energy carriers such as hydrogen (Ruhnau et al. 2019). Also, different combinations and pathways are discussed in the literature: The electricity sector can be connected to the heat (see Madlener, Kowalski and Stagl 2007; Henning and Palzer 2014; Palzer and Henning 2014; Nastasi and Lo Basso 2016; Nolting and Praktiknjo 2019) and mobility (see, for example, Lund and Kempton 2008; Garmsiri, Rosen and Smith 2014; Robinius, Erdmann and Stolten 2015; Rogge, Wollny and Sauer 2015; Samsatli S., Staffell and Samsatli N.J. 2016; Emonts et al. 2019) sector or both (see Welder et al. 2018; Brown et al. 2018).

In the following paragraphs, we illustrate the systemic implications of different sector coupling technologies: electric heat pumps that directly link the heat and the electricity sector, battery electric vehicles (BEVs) that link mobility to electricity, and finally fuel-cell electric vehicles (FCEVs) that indirectly couple the mobility and the electricity sectors. Particularly when considering primary energy, we focus on the rapidly changing German energy system as our use case. Starting with heat pumps, Figure 2 illustrates the effects on a systemic level using an energy flow chart as introduced in Section 2.1.

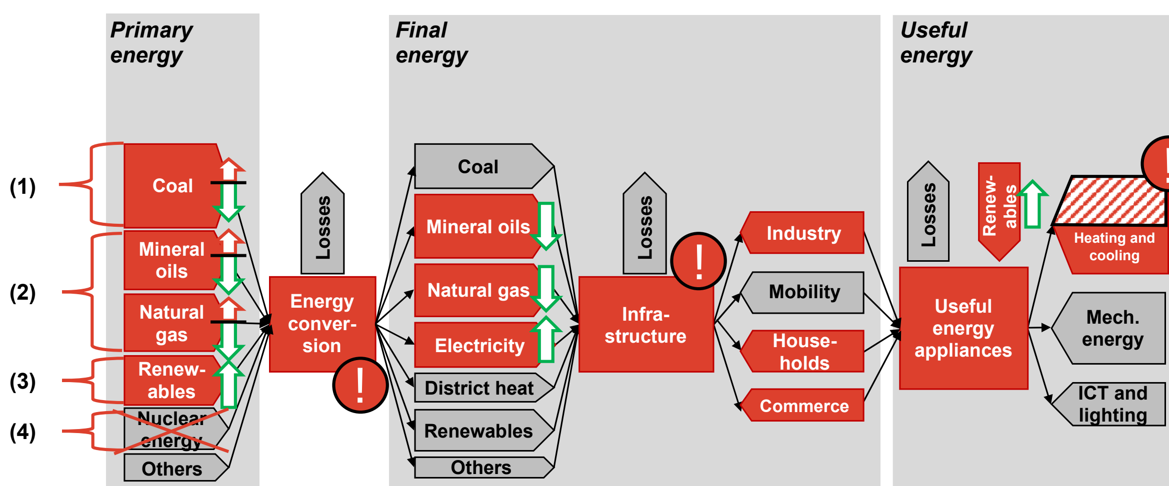



**Figure 2: Integration of Heat Pumps into the Energy System Based on Zweifel, Praktiknjo and Erdmann (2017). Abbreviation: ICT – Information and Communication Technology; 1–4 are Explained in Further Detail in the Continuous Text.**

The analysis illustrates that the integration of heat pumps has several long-term implications for the future energy system. First, the amount of renewable energy that is directly integrated into end consumer sites is increased. Second, the demand for final energy is shifted from mineral oils and natural gas to electricity, causing a change in infrastructure requirements (i.e., further expansion of the electricity grid). Third, the composition of primary energy sources and thereby the required energy conversion plant portfolio is changed as follows: (1) the demand for coal is increased due to increased demand in electricity;[2] (2) the demand for mineral oils and natural gas is reduced as conventional heating appliances are replaced; however, increases in the electricity demand partially compensate for this; (3) the amount of renewables increases due to the increased demand for electricity produced from renewable sources such as wind and solar.

BEVs are another relevant technology that is discussed in the literature as already mentioned above. They serve to directly link the electricity and the mobility sectors. The systemic implications of a future diffusion of electric vehicles are summarized in Figure 4.

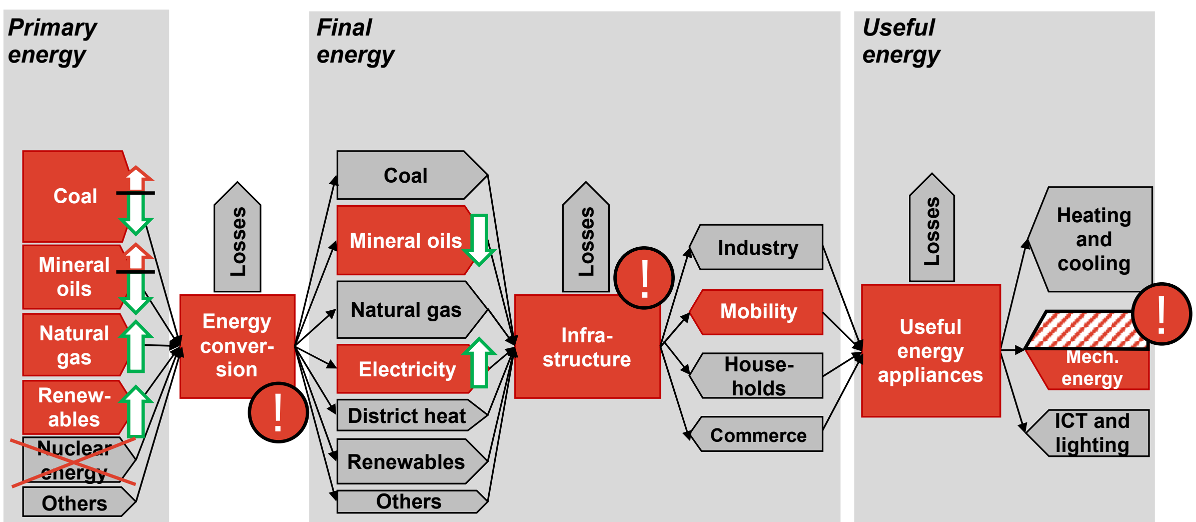



**Figure 3: Integration of Battery Electric Vehicles into the Energy System for the Case of Direct Electrification Based on Zweifel Praktiknjo and Erdmann (2017).**

Here, it can be observed that the diffusion of BEVs reduces the demand for mineral oils as a final and primary energy source, while the importance of electricity is increased. Again, the share of

[2] However, *exogenous effects* such as a compulsory phase-out of coal-fired power plants in Germany reduce the demand for coal as a primary energy carrier. The nuclear phase-out in Germany constitutes a further exogenous effect erasing nuclear energy as a primary energy source.

renewables as primary energy carriers can be increased through direct coupling of the electricity and the mobility sector.

FCEVs constitute an opportunity to indirectly couple the electricity and the mobility sectors. Electricity is converted to hydrogen before it is transported to the end consumers. Figure 4 summarizes the systemic implications.

Figure 4 illustrates that the importance of mineral oils in providing mobility and transportation services is decreased, while the share of gas among final energy carriers is increased. Here, indirect electrification can serve to transfer the potential of renewable electricity to other sectors. We conclude that the demand for energy conversion (i.e., additional demand for electrolyzers) and transportation (i.e., gas grid instead of electricity grid) infrastructure substantially differs from the direct electrification of the mobility sector.

The sheer amount of literature on the subject of sector coupling and the multitude of different pathways to integrate renewable electricity into other sectors underline the need to develop insights into the effects of sector coupling technologies at the system level. The spatiotemporally disaggregated analysis of the effects of sector coupling technologies on the energy system constitutes a substantial research gap. Our work is intended to provide a contribution to further narrow down this gap.

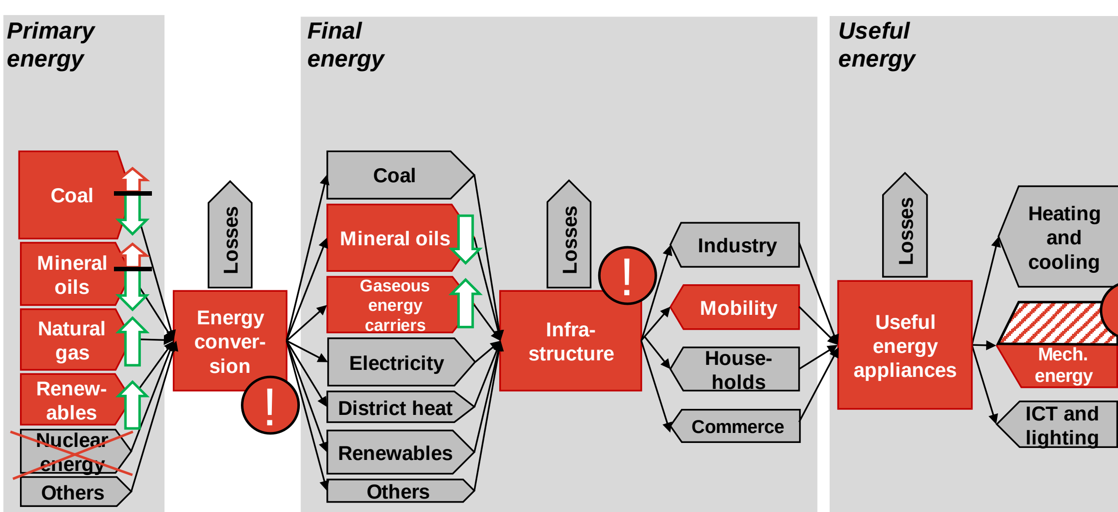



**Figure 4: Integration of Hydrogen-Fueled Vehicles into the Energy System for the Case of Indirect Electrification Based on Zweifel Praktiknjo and Erdmann (2017).**

## 2.3 German Energy Transition

Having introduced energy flow charts as a useful tool for depicting changes in the energy system and having demonstrated the implications of the diffusion of different sector coupling technologies, we will now underline their importance for the German energy transition and address the transferability to the Asian case.

The German government has defined ambitious GHG emission reduction targets to mitigate climate change: By 2050, the German energy system is planned to be largely GHG emission neutral with reductions of 80% to 95% compared to 1990 (BMWi 2018). To achieve these ambitious targets, distinct goals for the share of renewables in the total final energy consumption as well as for the share of renewables in the electricity sector have been defined, as shown in Figure 5. Further, it can be seen that the goals for electricity generation are even more ambitious (more than 50%, 65%, and 80% by the years 2030, 2040, and 2050, respectively) than for the overall final energy consumption (30%, 45%, and 60%). This takes account of the fact that the integration of renewables in electricity generation is easier to achieve than in other sectors such as the heating and cooling sector as well as the mobility sector. The historic development of the shares of renewables in Germany underlines that the share of renewables in the electricity consumption has been at similar levels to the overall final energy consumption in 2010 but has increased much stronger since then. Now, the share of renewables in the electricity sector is more than twice as high as the overall share of renewables in the final energy supply (38% vs. 17%).

The following thought experiment emphasizes the importance of sector coupling technologies in achieving the German national targets: If the entire electricity production from nuclear and coal-fired power plants was to be replaced by renewable electricity generation units, the share of renewables in the electricity sector would increase to ~80%; however, the overall share of renewables in the final energy consumption would only increase to ~25% (this calculation is based on data provided by AGEB (2017)). This demonstrates that sector coupling technologies and their potential to propagate high shares of renewables from the electricity sector to other sectors are needed to achieve climate targets.

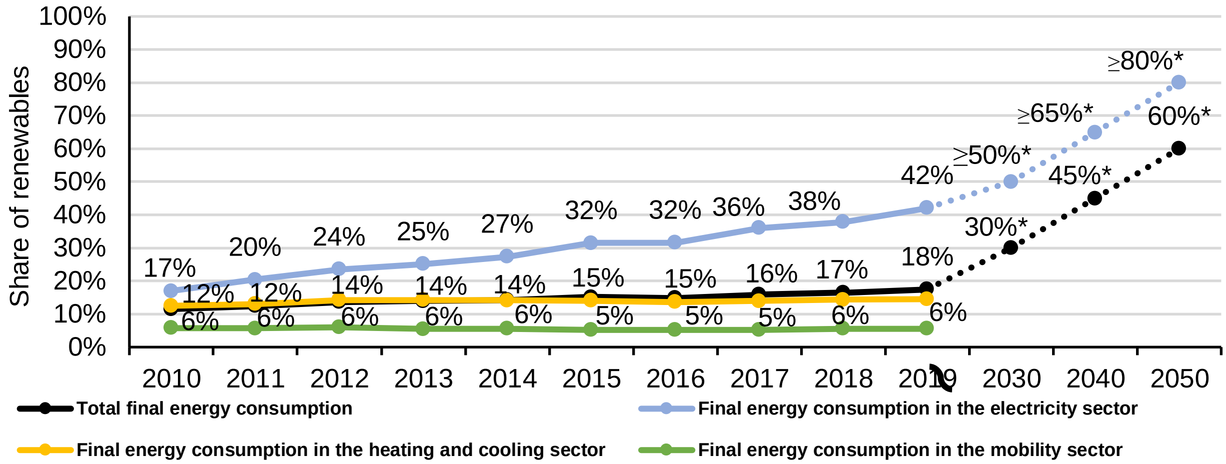



**Figure 5: Share of Renewable Energy in the Electricity, Heating and Cooling, and Mobility Sectors of Germany. *: Targeted Shares of Renewables According to the Coalition Agreement of the Governing Parties (Governmental Parties 2018) and the Annual Reports Published by the German Federal Ministry for Economic Affairs and Energy (BMWi 2018).**

**Source of data for historic development in the period 2010 to 2019: AGEE Stat (2020).**

## 3 Scenario Framework and Input Data

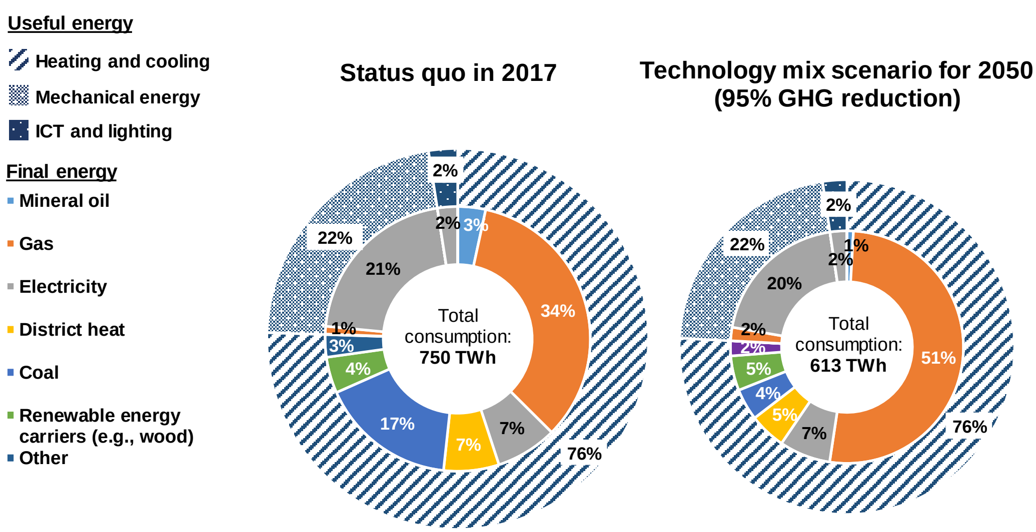
After the relevant background has been introduced, we will focus on the scenario framework under investigation and describe relevant input data for our analysis. To depict major changes, we focus on the scenario year 2050 and investigate the ambitious goal of a 95% GHG emission reduction in comparison to 1990 by the German government. As we want to investigate both *direct* and *indirect* electrification by means of different sector coupling technologies, we emphasize a so-called "technology mix scenario." The German Energy Agency (DENA) has introduced a set of three scenarios for the future development of Germany by 2030 and five scenarios focusing on 2050 (DENA 2018). As the technology mix scenario targeting a 95% emission reduction fulfills all the above-mentioned criteria, we conduct our further analyses using this scenario. The scenario will be described in further detail in the following sections.

### 3.1 Scenario for Future Energy Demand

In general, the study predicts future final energy demand to be below current levels. Two opposing effects need to be accounted for: On the one hand, energy serves as a relevant input factor for gross domestic production. Therefore, the demand for final energy is directly linked to an increasing gross domestic product (GDP) over time. On the other hand, efficiency measures weaken this relation and even overcompensate for the increases. For example, renovations and increased insulation substantially reduce the need for heating.[3] In the following subsections, we illustrate the final energy demand in different sectors based on the DENA technology mix scenario with a 95% GHG reduction.

### 3.1.1 Industry

The largest demand for final energy carriers is caused by industrial processes. As shown in Figure 6, the importance of gaseous energy carriers increases compared to current levels while the total final energy demand is reduced from 750 TWh to 613 TWh. Renewable gases constitute a major levy in decarbonizing industrial processes. Due to cost degression, high shares of the gas demand can be economically covered by synthetic gaseous energy carriers such as hydrogen and methanol. According to DENA (2018), these fuels will (1) be supplied in Germany and Europe using electrolyzers, direct air capture units, and methanization facilities; and (2) be imported as synthetic liquid natural gas from non-European foreign countries with high amounts of (cheap) excess electricity from renewables (e.g., Algeria).




[3] According to the energy efficiency strategy of the German government (cf. Thamling, Pehnt and Kirchner 2015), the useful energy demand for heat should be reduced by 45% by 2050 compared to current levels.

Figure 6: Industrial Final Energy Demand. Own Calculation and Illustration, Based on DENA (2018) and AGEB (2018).

### 3.1.2 Trade and Commerce

A similar picture emerges for the trade and commerce sector (see Figure 7). Again, final energy demand is assumed to be decreasing, while the significance of gas to cover useful energy demand increases.

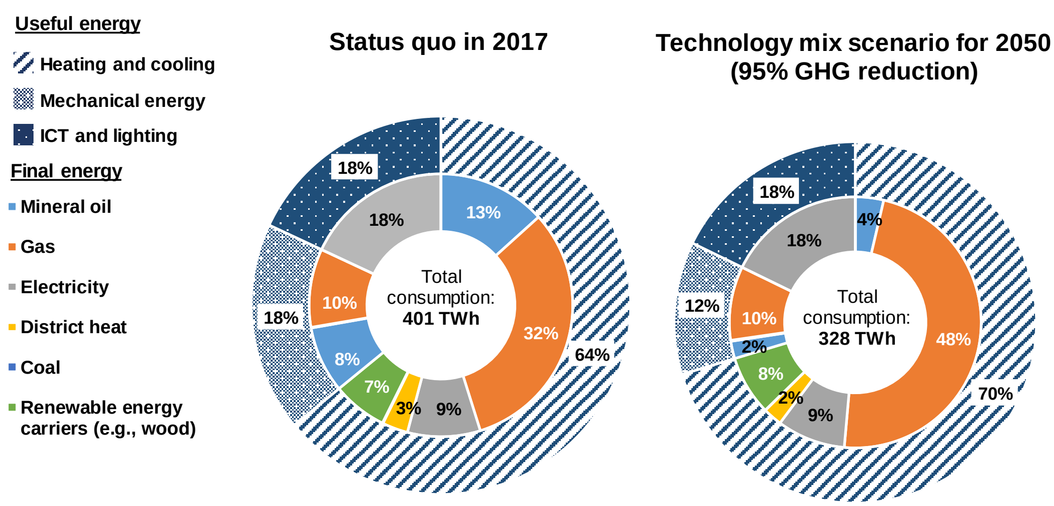



Figure 7: Final Energy Demand in the Trade and Commerce Sector. Own Calculation and Illustration, Based On DENA (2018) and AGEB (2018).

### 3.1.3 Residential

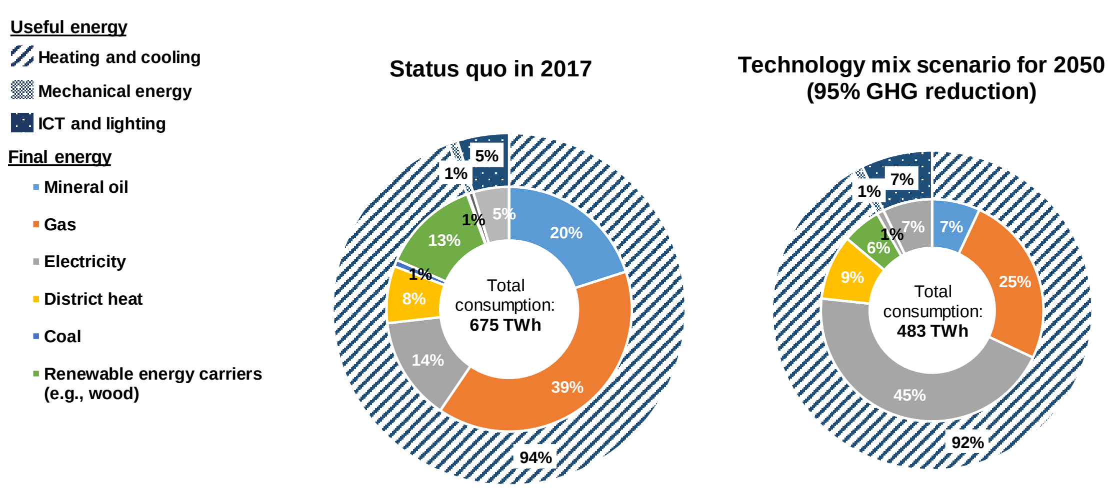



Figure 8: Final Energy Demand in the Residential Sector. Own Calculation and Illustration, Based on DENA (2018) and AGEB (2018).

For the residential sector, decreases in final energy demand are very prominent (cf. Figure 8).

This is due to the fact that the demand for heating of buildings is predicted to be reduced significantly due to insulation measures.

### 3.1.4 Mobility

As new sector coupling technologies emerge, the final energy demand in the mobility sector is reduced substantially. Fuel demand shifts almost entirely from conventional mineral oil products to electricity and particularly gas, which can be seen in Figure 9. Both gas- and electricity-fueled vehicle types have a higher efficiency in the conversion of final into useful energy than conventional combustion engines based on mineral oil products. Hence, the overall final energy demand in the mobility sector is reduced. However, the efficiency of electric vehicles is in turn significantly higher than the efficiency of gas fuel vehicles. Therefore, the share of gas as the final energy carrier in the mobility sector is higher than the share of gas-driven vehicles in the overall vehicle fleet.

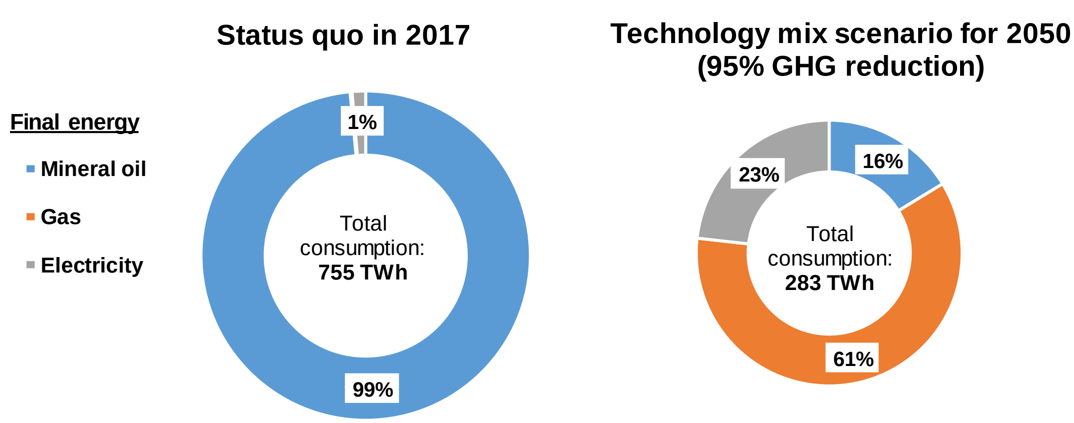



**Figure 9: Final Energy Demand in the Mobility Sector. Own Calculation and Illustration, Based on DENA (2018) And AGEB (2018).**

## 3.2 Scenario Framework for Generation Capacity

To achieve the emission targets by 2050, the electricity sector in Germany will transition into a system dominated by renewable energy sources according to our scenario framework as shown in Figure 10.

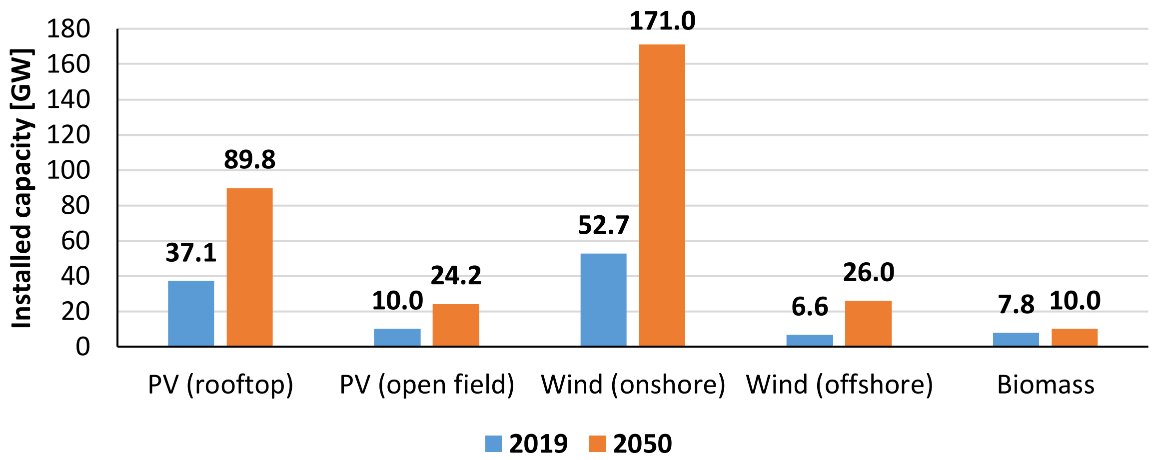



**Figure 10: Renewable Power Generation Capacities for the Status Quo and the Scenario Under Investigation. The Capacity Data for 2019 are Derived from BNetzA (2019b). The Capacity Data for 2050 are Based On DENA (2018).**

# 4 Methodology: Temporal and Spatial Disaggregation

For our analysis, we model hourly and regionally resolved time series for useful and final energy demand and renewable energy supply by combining *top-down* with *bottom-up* modeling methods. Here, we make use of comprehensive data sets stemming from publicly available data sources such as population and employment figures, land eligibilities for renewables, GDP figures for eight industry and four commerce subsectors, energy intensity per subsector based on input-output tables, weather data, building characteristics, and driving profiles per vehicle type. Top-down and bottom-up data are consolidated at interfaces to ensure the validity of our data sets.

For the spatial resolution, we use the unique identification *Nomenclature des unités territoriales statistiques* (NUTS) of the European Union – a hierarchical system in which regions are administrative levels or units. Our top-down approaches start at the state level NUTS0, which in our case corresponds to Germany. The NUTS2 resolution comprises 38 regions in Germany and corresponds to administrative districts. Since, on this level, regional policies can be applied, we choose this resolution as the interface for our combined top-down and bottom-up analysis. The NUTS3 level is an even finer resolution comprising 401 regions that represent mostly counties or bigger cities. For the bottom-up approaches, data on the NUTS3 level as well as geodata are utilized. Figure 11 depicts the different resolutions.

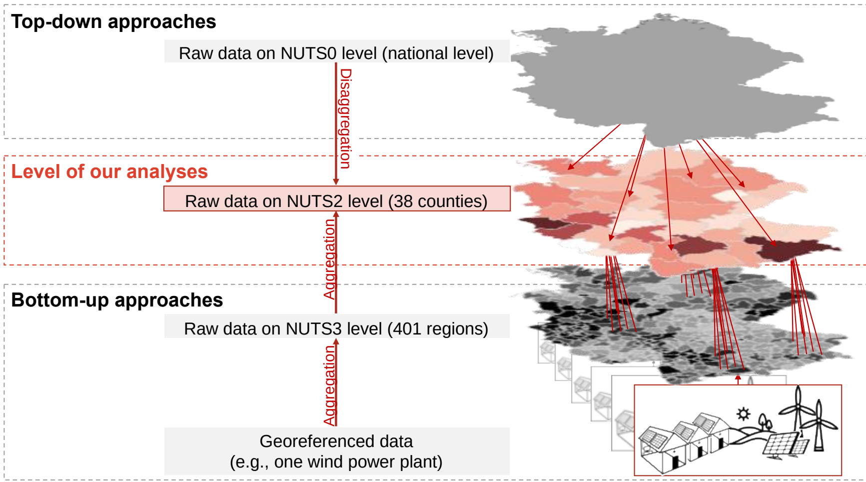



**Figure 11: Illustration of Bottom-Up and Top-Down Approaches.**

## 4.1 Useful Energy Demand in Germany

As outlined in Section 2.1, useful energy can be divided into the following: demand for (1) space heating, (2) warm water, (3) other process heating, (4) cooling applications, (5) information and communication technology and lighting, and (6) mechanical energy. Depending on the sector, the demand for useful energy results from various applications with differing significance. Therefore, the data acquisition and its preparation are described in detail for the residential, the industry and commerce, and the mobility sector in subsections 4.11, 4.12, and 4.13, respectively. The following methods can be applied generically and are not limited to the German case. To ensure the reproducibility of our results and to make further analyses beyond the scope of this work possible, we have made the data on useful energy demand patterns in Germany publicly available along with comprehensive data descriptors. For the descriptions, please refer to Priesmann et al. (2021). Data can be retrieved from https://doi.org/10.6084/m9.figshare.c.5245457. Visualization of data can be found here: https://jericho-energy. de/vesl/jericho-e-usage/.

For the top-down approaches, the most recent energy balances for Germany from 2017 can be used as a basis and validation data for all sectors and their useful energy demands (AGEB 2018). The bottom-up approaches are first carried out at NUTS3 level before being aggregated to a common interface at NUTS2 level. In particular, the heat demand depends on the regionally specific climate. The differences within Germany can be represented by the 15 climate zones of Germany (DWD 2017). The observed NUTS regions are allocated to the climate zones and the demand is scaled accordingly. For the temporal resolution, the time series of the regions are adapted with the help of climatic zone-specific temperature and occultation time series predicted for the year 2050. In addition, the time series are created according to the calendar of the year 2050, i.e., distribution of weekdays and Saturdays, as well as Sundays and public holidays.

### 4.1.1 Residential Sector

In the residential sector, we identify the demand for heating and cooling as being the main driver for useful energy demand. We distinguish between the demand patterns of single-family and multi-family houses. The distribution of the useful energy demand for the residential sector is modeled with a bottom-up approach. Depending on the year of construction, the size, and the number of residents and apartments, different annual energy consumptions are allocated to the building types in accordance with Loga et al. (2015) and Verein Deutscher Ingenieure (VDI) (2008). The spatial distribution is determined by the distribution of the different residential building types in the respective districts (Statistische Ämter des Bundes und der Länder 2011).

The temporal distribution is based on measured load profiles of different types of residential buildings in hourly resolution (Verein Deutscher Ingenieure (VDI) 2008).

### 4.1.2 Industrial and Commerce Sector

For the industrial and commerce sectors, we calculate the useful energy demand with a top-down and bottom-up approach.

Starting with the useful energy demand for the whole of Germany for the commerce and industrial sector by AG Energiebilanzen e.V. (2018), we disaggregate the data spatially based on employment figures and energy intensities within the subsectors. Those subsectors comprise agriculture, trade, public sector, and finance for the commerce sector and food industry, manufacture of glassware and ceramics, car industry, mechanical engineering, chemical industry, paper industry, metal production and processing, and other industry for the industrial sector.

Furthermore, the temporal distribution is based on a bottom-up approach, in which representative time series for each subsector are determined according to typical days for industry based on Gobmaier (2011) and for the sector commerce based on Meier et al. (1999).

### 4.1.3 Mobility Sector

We estimate the demand for useful energy in the mobility sector differentiated by vehicle and road type.

The spatial disaggregation and distribution of vehicle mileage are based on (1) the type of vehicle, (2) the average mileage of the vehicle type, and (3) the mileage share on urban and nonurban roads of the vehicle type. After having spatially distributed the annual mileage for the different vehicle types to the NUTS3 regions, we further temporally disaggregate the yearly values to an hourly resolution. After having calculated the hourly mileage for NUTS3 regions, we again aggregate the data to the NUTS2 level. We then validate our approach based on the status quo by translating the hourly mileage profiles into refueling and recharging profiles.

## 4.2 Renewable Electricity Generation Capacities and Feed-in Time Series

Based on the scenario framework presented in Section 3.2, we distribute the RES capacities to the NUTS3 regions according to two different strategies: (A) *supply-driven* (i.e., the regional feed-in potentials and associated levelized costs of electricity (LCOE)) and (B) *demand-driven* (i.e., the regional electricity load).

Besides feed-in potentials and electricity load, the disaggregation is supported by further indicators such as area eligibility, building stock (i.e., roof potentials), the current regional distribution of capacities, availability of power supply lines, availability of resources, and equitable use of available potentials. The currently installed capacities are accounted for in the distribution of future capacities.

The feed-in time series are calculated based on raster data, data collected by research platforms in the North Sea and Baltic Sea, and predictions on climatic change for the year 2050.

### 4.2.1 Rooftop and Open-Field Photovoltaic

The PV capacities are disaggregated using the indicators i) equitable use of available potentials and ii) the regional LCOE, respectively the regional electricity load subject to the regional maximum area and roof. Roof potentials are taken from the 2011 census in Germany (Statistische Ämter des Bundes und der Länder 2011) and calculated according to the method proposed by Lödl et al. (2010). For the open-field capacities, a land eligibility analysis is conducted using the GLAES framework to account for area restrictions (cf. Ryberg, Robinius and Stolten 2018).

#### 4.2.2 Onshore and Offshore Wind

Onshore wind capacities are disaggregated using the indicators i) equitable use of available potentials and ii) the regional LCOE, respectively the regional electricity load subject to the regional maximum area potentials that are again calculated using the GLAES framework. For the offshore wind capacities, we decided to assign the capacities to those regions where the onshore network interconnection point is situated. The disaggregation is based on the current offshore line expansion plan and is subject to the maximum area potentials in the Northern Sea and the Baltic Sea (BNetzA 2019b).

#### 4.2.3 Biomass

We disaggregate biomass power plant capacities according to the regional availability of biomass resources provided by AEE (2013).

## 5 Results

In the following, our regionalized results for energy demand and future generation for the 2050 scenario and the resulting residual loads are presented.

### 5.1 Future Scenarios for Electricity Demand in Germany

Figure 12 depicts the results of the regional disaggregated useful energy demand in Germany for the industry, commerce, residential, and mobility sectors based on the 95% GHG emission reduction scenario. As described above, the useful energy demand can be divided into the subcategories heating and cooling, mechanical energy, ICT services, and lightning. For the mobility sector we focus on mechanical energy as the main useful energy demand form.

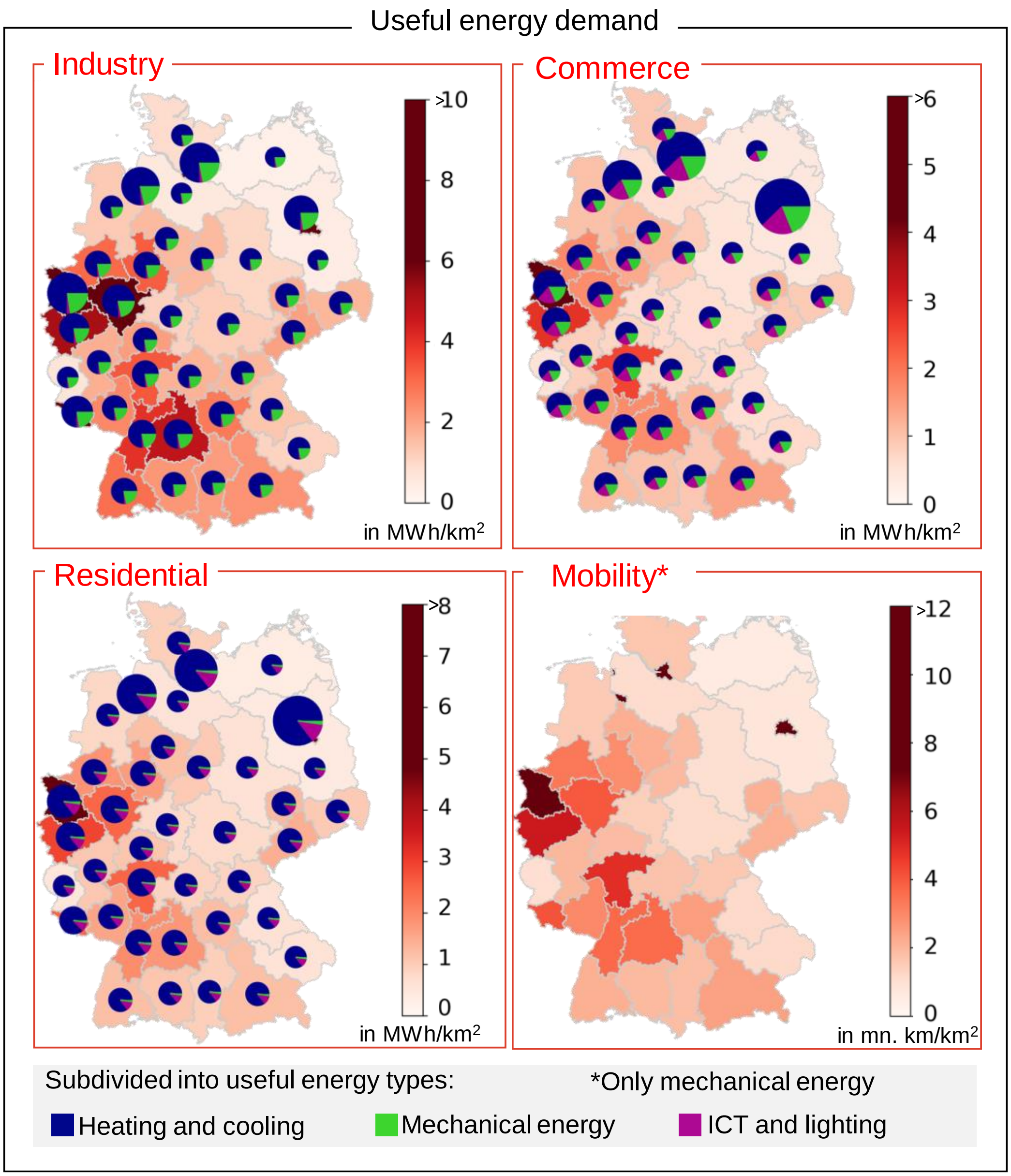



**Figure 12: Regional Distribution of Useful Energy Demand for the Different Sectors in Germany for the 95% GHG Emission Reduction Scenario Divided into Useful Energy Types Except for Mobility (Only Mechanical Energy).**

In our scenario, sector coupling technologies such as heat pumps, hydrogen fuel cells, and battery electric vehicles are used in particular to provide heat and mechanical energy (i.e., mobility) to electrify those sectors. The derived regional demand for electricity for the scenario is shown in Figure 13 for the different sectors.

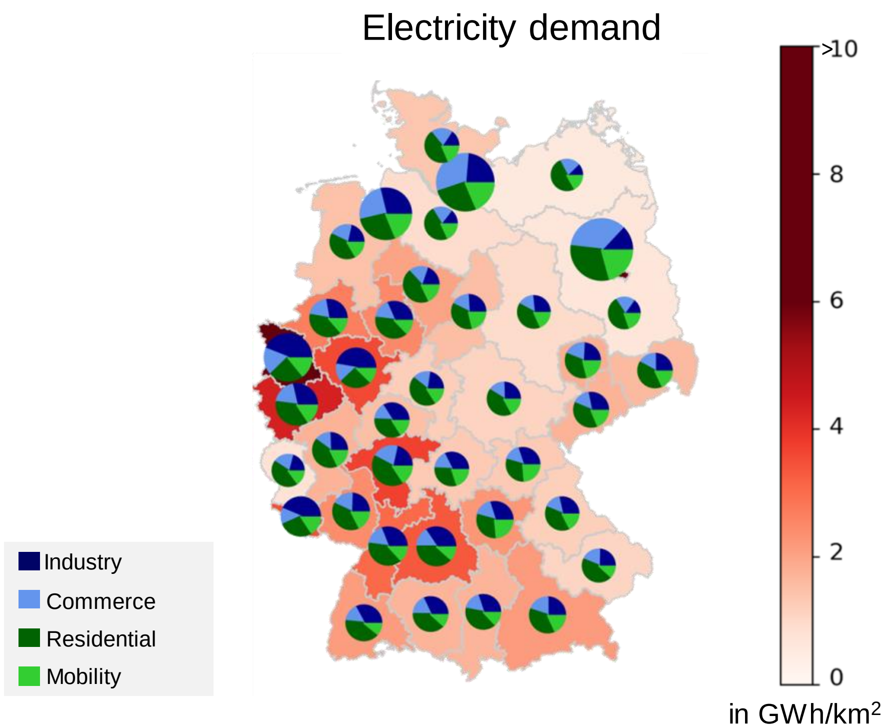



Figure 13: Electricity Demand per Sector for the 95% GHG Emission Reduction Scenario.

## 5.2 Future Scenarios for Renewable Electricity Generation Capacities

The capacities for RES-based electricity generation are disaggregated according to the methodology described in Section 4.2.

To demonstrate the effects of different placement strategies for renewable energy sources, we introduce two strategies in the following: a demand-driven strategy, which represents an allocation of renewables, where locations that are close to electricity demand are preferred, and a supply-driven strategy, representing an allocation of renewables, where locations with high generation potentials are preferred.

The results can be seen in Figure 14. The total capacities being replaced from a site-driven placement in the supply-driven strategy to a load-driven placement in the demand-driven strategy sum up to 18.2 GW of wind onshore capacities, 9.1 GW of rooftop PV capacities, and 2.2 GW of open-field PV capacities.

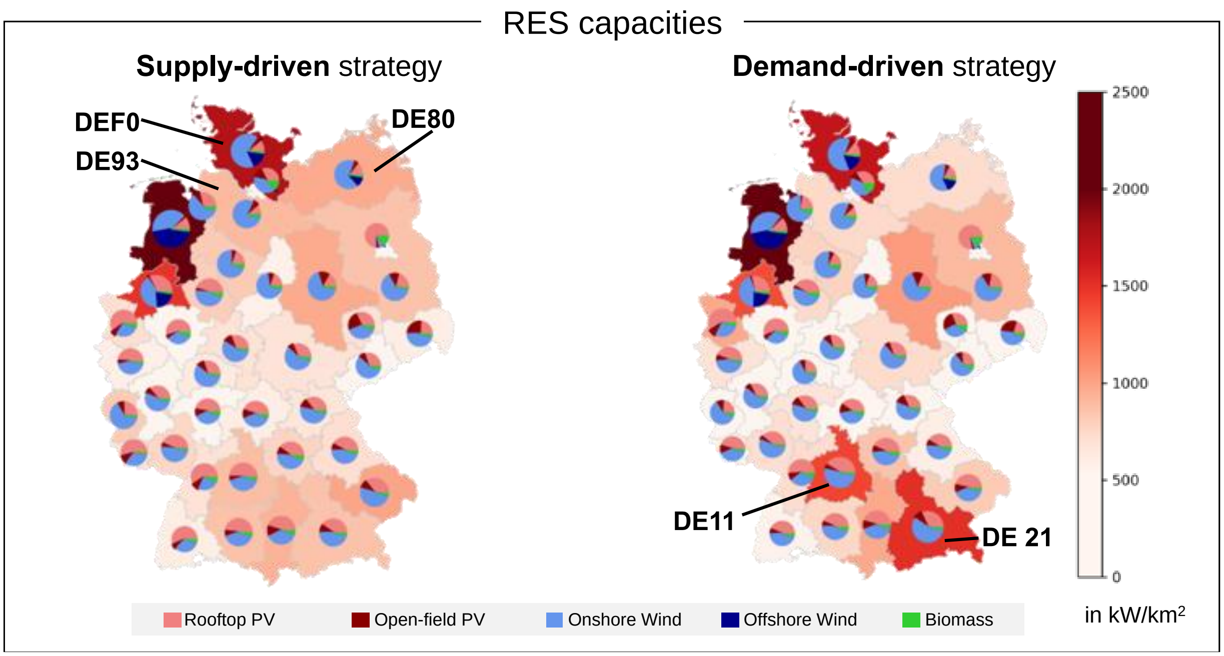



**Figure 14: Renewable Electricity Generation Capacities According to the 95% GHG Emission Reduction Scenario for the Supply-Driven Strategy and the Demand-Driven Strategy.**

## 5.3 Residual Loads and Energy not Covered by Renewable Electricity Generation

Based on the calculated regionally and temporally resolved electricity load and electricity generation (cf. Sections 5.1 and 5.2) we calculate the residual loads and the average residual load for the *supply-driven strategy* and the *demand-driven strategy*. Figure 15 shows the average residual loads for the NUTS2 regions in Germany for the *supply-driven* and the *demand-driven* capacity allocation strategy. While the western and eastern regions are less influenced by the capacity expansion strategy, the northern regions show a strong decrease in surplus generation and the southern regions show a strong decrease in generation shortfall. The downside of the more balanced electricity generation and demand within the regions in the *demand-driven strategy* is a decrease in total generation as capacities are placed according to regional electricity load. In the *supply-driven* strategy, in which capacities are placed according to regional generation potentials, 33.7 TWh more electricity per year can be generated than in the *demand-driven* strategy.

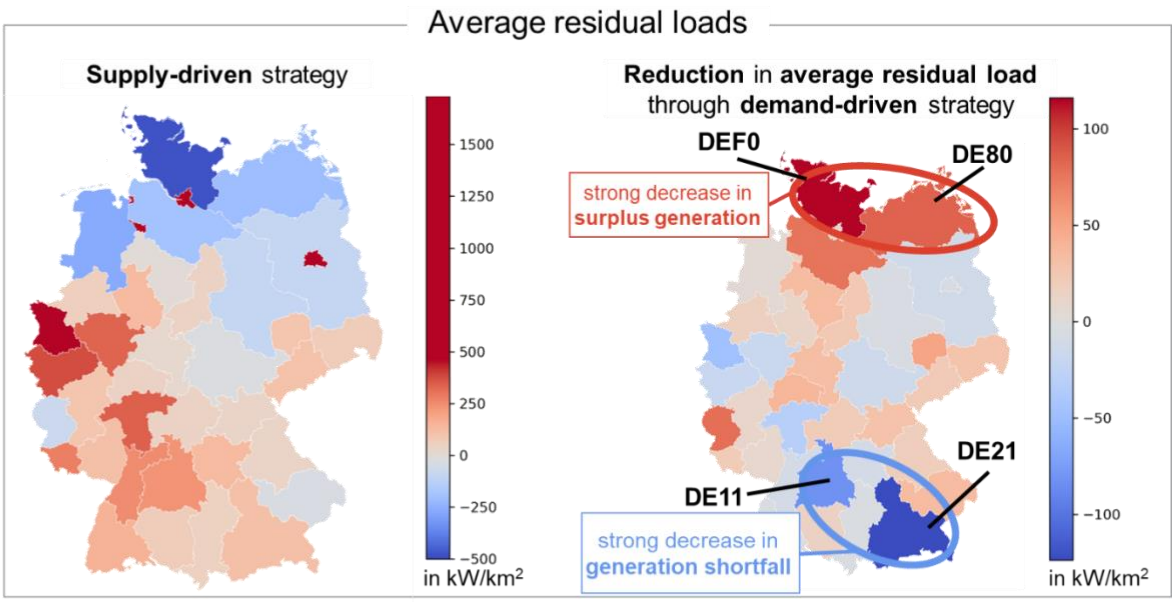



**Figure 15: Average Residual Load for 95% GHG Emission Reduction Scenario for the Supply-Driven and Demand-Driven Strategy.**

The distribution of residual loads in the southern regions DE11 and DE21 as well as in the northern regions DE80 and DEF0 is shown in Figure 16. For the southern regions, the medians and upper and lower quartiles of the residual loads decrease. For the region DE21, large shares of the residual loads become negative, indicating surplus generation due to additionally placed wind and PV capacities. For the northern regions, the medians and upper and lower quartiles of the residual load increase, which indicates lower surplus electricity generation in these regions.

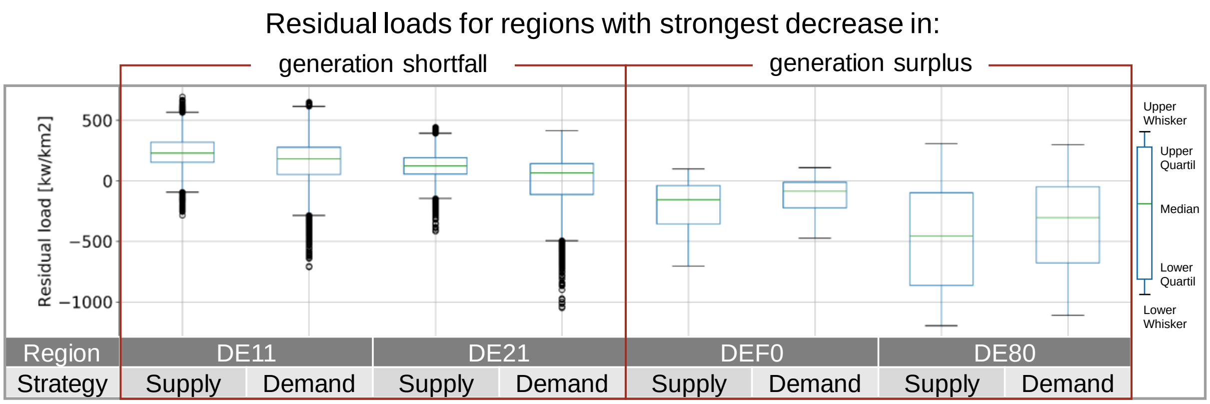



**Figure 16: Boxplots for the Resulting Residual Load in Four Exemplary NUTS2 Regions for Supply-Driven and Demand-Driven Strategy (Here Shortened to Supply and Demand).**

Overall, we find an average relative reduction in negative residual load of 31% when comparing the *demand-driven* placement strategy to the *supply-driven* strategy. This indicates cost reduction potentials as less redispatch and curtailment of renewables is required when decreasing the absolute value of residual load. In 2019, the costs associated with curtailing renewable electricity generation units due to grid congestions (so-called *Einspeisemanagement*) in Germany amounted to 709.5 mn. euros (BNetzA 2020). These costs are allocated to end users via network charges. While most of these measures were conducted in distribution grids, they were caused by bottlenecks in the transmission grid. Hence, a reduction of these costs by the efficient allocation of renewables would be feasible. With the increasing share of renewable electricity units in the German energy system and particularly with the growing amount of wind energy in northern coastal regions, these costs are likely to increase in future. Using the regression model published by Höfer and Madlener (2020), we find that these costs can be predicted to increase to ~4.6 bil. euros for a scenario with a total of 197 GW installed wind capacity (this reflects our 95% GHG reduction scenario for 2050; see Figure 10). Hence, we can calculate the savings potential of an efficient allocation of renewable energy sources to be ~1.4 bn. euros.[4]

## 6 Discussion and Policy Recommendations

Having shown the results of our spatiotemporal analysis, we now derive policy recommendations and discuss adequate political frameworks to provide incentives for the efficient allocation and integration of renewable energy sources.

First, we found that the electrification of the mobility and heating sectors via sector-coupling technologies is helpful for propagating renewable electricity and hence supports the decarbonization of energy systems. To support efficient sector-coupling pathways, a *level playing field* and *technology-neutral market mechanisms* such as $CO_2$ pricing are preferable to technology-specific quotas or subsidies (Löschel et al. 2019). The latter come with high risks of *lock-in effects* and unintended interactions with other technologies (see, for example, the integration of highly subsidized combined heat and power technologies in Germany and their

[4] For a more accurate calculation, it would be necessary to use a grid model. However, our results can serve as a first indication.

unintended interference with the expansion of wind energy as discussed by Dittmar and Erdmann (2010)).

Second, we demonstrated substantial temporal discrepancies between useful energy demand and renewable electricity supply. When high shares of useful energy demand are covered by means of electricity and the electricity supply is mainly stemming from intermittent renewable energy sources, an urgent need for flexible demand arises. Flexible demand for electric energy and the expansion of storage capacities can be incentivized by introducing sufficiently dynamic end user prices, e.g., by establishing *time-varying instead of static levies* (see, for example, the potential of flexible heat pump controls and current obstacles due to fixed components in the end consumer price as discussed by Nolting and Praktiknjo (2019), and the systemic potential of storage technologies in terms of flexibility that can result in a reduced need for network expansion as discussed by Child et al. (2019).

Third, we revealed regional discrepancies in electricity demand and supply due to the deviation of electricity demand centers (demographic and industrial centers in the west and south of Germany) and supply centers with high potential for renewable electricity generation (especially northern regions with the potential for high winds). This implies the need to adjust energy infrastructures. In unbundled markets in particular, *reliable and consistent policy frameworks* are required that allow potential investors in grid infrastructure for the necessary planning security that is needed due to long periods of amortization for such investments (for a Delphi process-based view on investment barriers as perceived by the private sector, see Jones (2015)).

While our analysis focuses on the German case, our policy recommendations are transferable to the global integration of renewable energies as they point towards general challenges that to come with the integration of intermittent renewables with regionally distributed feed-in potentials and the electrification of end user demand by sector coupling.

## 7 Conclusion and Outlook

In our work, we introduced and applied a comprehensive framework for the spatiotemporal disaggregation of energy demand and supply. In our case study, we have shown that decarbonizing the energy system comes with a trade-off between placing generation capacities at locations (1) where the generated electricity is maximized and (2) where the electricity demand can be covered at low transmission distances. Our results indicate that costs associated with curtailing renewable electricity generation units due to grid congestions can be reduced dramatically if this trade-off is accounted for in the placement of renewable generation capacities. We have further found that:

- the electrification of the mobility and the heating sector is helpful for the propagation of renewable electricity and decarbonization,
- useful energy demand and renewable electricity supply show substantial temporal discrepancies, and
- sector coupling increases regional discrepancies in electricity supply and demand, which requires an adjustment of energy infrastructure, particularly in unbundled markets.

We have presented multiple policy recommendations for incentivizing system-friendly investments, such as:

- technology-neutral market mechanisms such as $CO_2$ pricing,
- incentivizing flexible electricity demand with sufficiently dynamic end user prices, and
- consistent policy frameworks that allow potential investors in grid infrastructure for the necessary planning security.

Our analysis is based on a consumer-driven approach that starts with the energy demanded by the consumer (useful energy) and then derives final and primary energy by incorporating multiple sector-coupling pathways. For our spatiotemporal analysis, we apply a combined top-down and bottom-up approach that merges highly resolved bottom-up data with disaggregated top-down data at an interface of 38 regions in Germany.

For future work, it would be extremely interesting to transfer our framework to different regions of the world as it provides high generalizability. Further, it might provide additional insights to assess effects on the gas grid as our study was mainly focused on effects regarding the electric infrastructure.

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