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Pathways for Germany's Low-Carbon Energy Transformation Towards 2050

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Abstract: Like many other countries, Germany has defined goals to reduce its CO_2-emissions following the Paris Agreement of the 21st Conference of the Parties (COP). The first successes in decarbonizing the electricity sector were already achieved under the German Energiewende. However, further steps in this direction, also concerning the heat and transport sectors, have stalled. This paper describes three possible pathways for the transformation of the German energy system until 2050. The scenarios take into account current climate politics on a global, European, and German level and also include different demand projections, technological trends and resource prices. The model includes the sectors power, heat, and transportation and works on a Federal State level. For the analysis, the linear cost-optimizing Global Energy System Model (GENeSYS-MOD) is used to calculate the cost-efficient paths and technology mixes. We find that a reduction of CO_2 of more than 80% in the less ambitious scenario can be welfare enhancing compared to a scenario without any climate mitigating policies. Even higher decarbonization rates of 95% are feasible and needed to comply with international climate targets, yet related to high effort in transforming the subsector of process heat. The different pathways depicted in this paper render chances and risks of transforming the German energy system under various external influences.

Keywords: decarbonization; energy system modeling; GENeSYS-MOD; renewables; energy policy; energy transformation; Energiewende

1. Introduction

Human activities have already caused approximately 1.0 degree Celsius of global warming above pre-industrial levels by 2017 [1]. Based on the analysis conducted by the Intergovernmental Panel on Climate Change (IPCC) [1–4], the global carbon budget to limit the temperature rise to 1.5 °C will soon be exhausted. With an increasing global mean temperature, the risk of abrupt and major irreversible changes will grow and impact human life in many ways [1,5]. Therefore, the global community must undertake measures to find a collective climate policy towards decarbonization.

To get the world mobilized, all (then) 197 United Nations (UN) member countries agreed to the 2015 UN Climate Change Conference held in Paris [6,7]. Thereby, policymakers ratified their Nationally

Determined Contributions (NDCs) in the so-called Paris Agreement. The are the nations self-defined emission reduction goals, aiming to keep the global mean temperature increase well below 2 °C and limit the share of carbon dioxide equivalents to less than 450 parts per million (ppm) within the atmosphere [7]. They are, however, not sufficient to reach the climate target.

Induced by the German Energiewende, there is a remarkable uptrend in using renewable energy sources in Germany: Since 2010, in the framework of the Energiewende a series of decisions where made to decarbonize and decentralize the German energy system and more general, find a concept of a future energy system [8]. Nevertheless, there are still doubts if an energy system based on 100% renewable energy is viable and achievable, both in technical, as well as economic terms, illustrated in the debate of Heard et al. [9] and Brown et al. [10]. A correlating attribute for realizing a renewable energy integration is the consideration of technology-specific storage aspects. However, there are still conflicting opinions on the necessity and size of electric storages in the power grid, as exemplified in the dispute between Sinn [11] and Schill et al. [12] (See also Section 1.3).

Thus, it is crucial to elaborate scenarios, driven by different storylines that target a rather holistic perception than solely absolute numbers [13]. To do so, this paper examines three different scenarios for Germany's low-carbon transformation concerning the ratified NDCs. To establish a differentiated impact assessment, those are implemented into the Global Energy System Model (GENeSYS-MOD) v2.0 [14,15]. This multi-sectoral energy system model is used to analyze national trajectories for the sectors electricity, heat, and transportation until 2050 by applying a cost-optimization algorithm. Based on its federal system, Germany is divided into 16 sub-regions to indicate bottlenecks and potentials for a sophisticated recommendation for action. Despite a limited transferability to other countries, a close consideration of the German case bears insights on its past and future development and might offer some lessons and best practices for other nations, because of Germany's fruitful start and the *Energiewende's* success in laying down a base for an decarbonized energy system [8], its close interdependence with other European nations and a certain maturity of the idea of renewable energy supply [8]. Section 1.1 gives a brief overview on the status quo of Germany's climate policy and energy system within its national and international context. Sections 2.1 and 2.2 introduce three different scenarios and their implementation in GENeSYS-MOD. The model results of the scenarios are displayed and discussed in the following Section 3 to provide holistic recommendations for political action. Section 4 concludes the paper.

1.1. German Climate Policy

Germany takes part in the United Nations Framework Convention on Climate Change (UNFCCC) since its foundation. The first Conference of the Parties (COP) took place in 1992 in Berlin, the capital of Germany. Since then, Germany took part in various multilateral agreements and programs for global climate protection, like the Montreal Protocol to protect the ozone layer [16] and the Kyoto Protocol [17]. As part of the European Union (EU), Germany commits itself to a number of further climate protection measures and targets. Since 2005, for example, emissions from the domestic energy industry and heavy industry have been covered by an Emissions Trading System (ETS). This accounts for 45% of European emissions [18]. A second approach to reducing greenhouse gas (GHG) emissions on a European level is pan-European reduction targets, which should include emissions outside the ETS. These targets are also included in the Paris Agreement and state that by 2020, greenhouse gas (GHG) emissions should be reduced by 10 percent compared to 2020 [19] and by 30 percent compared to 2030 [20]. In order to balance the burden between the countries according to their economic performance, the Effort Sharing scheme is implemented. Hence, relatively underdeveloped countries can even increase their emissions by a certain amount, while other countries have to reduce beyond the European target. Germany is to reduce its emissions by 14 percent by 2020 compared to 2005 [19] but will miss this European target [21]. Aside the European targets, Germany has set itself own targets for 2030 and 2050, based on the reference year of 1990. These targets are also subject to the Paris Agreement ratified by Germany. The main goal is to provide a reduction of GHG emissions of at least 55% until 2030 and

80–95% in 2050 compared to 1990-levels. Additionally, renewable energy sources are prescribed to account for at least 60% of the energy consumption in 2050, while efficiency rates should increase by 50% [22]. The final decision to phase out nuclear power by 2022 has already been cushioned by the addition of renewable energy plants. The annual nuclear power production fell from 170 Terawatt Hours (TWh) in 2000 to 76 TWh in 2018 while at the same time renewables rose from 38 TWh to 229 TWh. However, power production with coal decreased only from 291 TWh to 229 TWh in the respective timespan [23]. Hence, there is a large gap between the own decarbonization targets and the actual implementation so far. In 2018, the German government convened a commission "Growth, Structural Change, and Employment" ("Coal-Commission") for the purpose of implementing practical measures to concretize the goals set out in the climate protection plan. In January 2019, their final report on the gradual reduction and cessation of coal-fired power generation was published [24]. This report suggests that by 2022, coal-fired power plant capacities have to be reduced gradually to around 15 Gigawatt (GW) of lignite and 15 GW of hard coal. Phasing out coal is recommended at the latest by 2038 [24]. In the second half of 2018, a new global movement gained medial presence: Every Friday, schoolchildren, supporters from universities, and the scientific community protest for a more decisive approach of politics in climate questions. The German branch of the "Fridays for Future" movement demands Germany shall have no net emissions of carbon dioxide (CO_2) by 2035 and complete phase-out of coal by 2030. Also, they demand an electricity supply that is entirely renewable by 2035. By the end of 2019, the movement further demands to shut down one-quarter of capacity of coal-fired power plants an end to all subsidies on fossil fuels and a pricing scheme for CO_2 that internalizes all external effects and thus they refer to the German Environment Agency which estimates a price of 180 € per ton of CO_2 [25].

Further insights on the regional differences, stakeholders in Germany, and the division of competences among the ministries can be found in the Appendix A.

1.2. Energy System

The German energy system is undergoing fundamental restructuring intending to achieve a renunciation of fossil fuels, a switch to renewable energies, and more efficient use of energy. The driving force behind this transformation is the man-made global climate change through the emission of GHG and the climate protection targets developed in response [26].

The current supply structure of the power, heating, and transport sectors, as well as the transmission grid and the final energy demand, serve as a starting point for modeling the future energy system of Germany.

Even though electricity generated by renewable technologies reached a share of approximately 37.8% in 2018, the four conventional sources coal (hard coal and lignite), oil, fossil gas, and nuclear are still dominating [23]. This translates to 313 million tons of CO_2 equivalents released in the atmosphere in the year 2017 [27]. Lignite and hard coal account for the highest share (35.4%) of electricity produced in Germany in 2018. Gas fired power plants are held as a flexible reserve to cushion the renewables' volatility and grid compensatory measures. Most of the renewable power generation comes from wind and solar with wind energy already providing 17.2% of the total electricity production [23]. With the further development of offshore capacities in the Baltic- and North Sea, as well as onshore wind turbines focused in northern Germany, this share will increase. Among more cost-intensive technical requirements [28], the maximum potential for offshore installations of 85 GW [29] is lower compared to the potential of onshore installations, which is set at 200 GW [30]. Photovoltaics (PV) are another important pillar of Germany's future electricity supply, contributing about 7% of the electricity supply today [23]. Braun et al. [31] calculated a potential for open-field PV of 297 GW following the target set in German Renewable Green Energy Act (EEG) 2017 of locating open-field PV plants along traffic routes [32]. Storing the generated electrical energy will become a challenge concerning the volatility of the feed-in of power into the grid by solar and wind plants. Storage technologies, such as batteries, pumped hydro power plants, or gas- and heat storages can be used to effectively reduce the fluctuating power feed in by renewables. CCS technology will not play a role in the German nor European power sector in the future. It has turned out that the implementation is technologically too demanding, very expensive and not needed [33–35].

Compared to the power sector, the heating sector faces more difficulties to become renewable. In fact, the transition of the heating sector towards less carbon dioxide emissions requires a renewable electricity sector, as electric heating alternatives are only renewable if the electricity used is renewable. The heating sector consists of space and water heating but also implies process heating in the industry. Fossil fuels still play a major role in heat generation, particularly fossil gas. In 2018, 49% of German households were supplied with heat by direct gas heating and 13% by district heating [36]. In the industry, coal and gas are mainly used for the supply of process heat [37]. The use of renewable energy sources for heat generation is not yet as established as in the electricity sector, although their share in heating and cooling in Germany rose from 4.4% to 13.9% between 2000 and 2018 [38]. Also, the application of renewables is mainly used for generating low-temperature heat, lesser for process heat in the industry. The share of renewables is at only 5.3%, while coal and gas remain the dominating energy sources [39]. Further deployment of renewables could be implemented through electric furnaces and renewable gas, produced via renewable energy inputs. In the low-temperature heating sector, heat pumps, as an electric alternative to fossil boilers, can contribute to the decarbonization. The efficiency of heat pumps is higher for small differences in temperature. Therefore, they are primary only used in the low-temperature heating sector. Contrary, process heat also demands temperatures above 1000 °C. Therefore, renewable gas is the only option to decarbonize specific processes, according to Naegler et al. [40]. As a result, Biogas and Biomass are getting more relevant but are limited by the existing arable lands and grasslands [41]. Also, a renewable heating sector will rely on direct electric heat generation (e.g., heat pumps or electric (arc) furnaces) and thereby coupling the sectors electricity and heat. Furthermore, synthetic hydrogen has substantial potential in the heating sector, as well as in the transportation sector. Still, this would lead to a higher total electricity demand because of increased need for hydrogen produced by electrolysis. Consequently, the higher demand for electricity will also possibly generate the need for an expansion of the electricity grid.

Currently, the German electricity distribution networks have a line length of 1.7 million kilometres (km) in total and are operated by approximately 880 Distibution System Operators (DSOs) [42]. The existing transmission grid has a length of 35,000 km and is operated by four privately organized Transmission System Operators (TSOs) [43]. The transformation of the energy supply to renewable energies involves a profound change in the German electricity supply structure [44], which leads to new challenges for the grid infrastructure.

The final energy demand in Germany amounted to 9329 petajoules (PJ) in 2017, in which power and heat applications accounted for 70.5%. The remaining energy demand was caused by the transportation sector [45]. Even with efficiency improvements and climate goals, the final energy demand in the household sector increased slightly from 2383 to around 2430 PJ in the past 27 years [45]. Finally, the energy demand in the mobility sector increased by almost 376 PJ from 1990 to 2017 [45].

1.3. Literature Review

Since Conference of the Parties (COP) 21 in 2015 at the latest, limiting the effects of climate change and decarbonizing and decentralizing the existing energy systems has become a topic and a task not only for scientists but also for states and subnational state institutions. As the Renewable Energy Policy Network for the 21st Century (Ren21) stated in its annual report of 2018 [46], 169 countries have already set their own targets for renewable energies. The transformation of energy systems is underway around the world with varying degrees of ambition, as shown, among other things, by the large volumes of investment in renewable energy plants. Nevertheless, the Ren21 report also shows a slightly reduced effort globally: Compared to 2017, global investment has fallen, CO_2 emissions increased by 1.7% last year, some countries have retired from their own climate targets, and overall efforts are insufficient to meet the climate targets of the Paris Agreement [46]. That is why it is important that research continues on a global, supranational, national, and regional level in this area and that studies are being published that demonstrate the relevance of the issue and can put pressure on decision-makers.

There is a variety of studies available that analyze possible pathways for decarbonized energy systems. While some studies are focusing on a global context [47,48] or on a European level [49–53]. Connolly et al. [53] used the 2013 version of the EU reference scenario [54] to calculate a European energy system in 2050 with integrated transportation, heating and cooling and industry sectors, which relies on renewables by 100%. They conclude, that it is possible without using unsustainable amounts of biomass and by additional system costs of 12%. Following the question of technical feasibility and the burden that lies on the power sector and the European transmission grid, Zappa et al. [52] used various reference scenarios determining future power demands and data from entso-e, to conclude that the installed power generation capacity has to increase from 1 Terawatt (TW) to 1.9 TW in 2050. Around 8.5 Exajoule (EJ) from Biomass will be used in the power sector, compared to Connolly et al. [53] 13.5 EJ in the whole European energy system. Also using GENeSYS-MOD, Hainsch et al. [49] model a low carbon energy system for Europe. They conclude that achieving a target where global warming is limited to 1.5 is only feasible under certain conditions while staying below 2.0 will only generate 1.5% additional costs compared to the business as usual case. Using the Dynamic Investment and Dispatch Model for the Future European Electricity Market (dynELMOD), Gerbaulet et al. [50] calculate that PV throughout Europe, as in Germany, is only used half as much as wind power in 2050. Also, they figure out that by 2050, a 98% decarbonization can be achieved, which goes hand in hand with levelized costs for electricity of around 27–32 € per MWh.

Considering a global level with some regional detail, Ram et al. [48] conclude that 100% renewable energies are feasible, as well as levelized costs in electricity are falling, but are rising in heat supply. In contrast to Gerbaulet et al. [50], their calculations suggest that Germany's renewable energy system will be based primarily on solar energy generation.

Considering the issue of imports and exports, the role of individual countries plays a decisive role. A breakdown for European countries is provided by Child et al. [51] who use the LUT Energy System Transition model also used by Ram et al. [48]. They come to the conclusion: power trade within Europe is increasing massively from 63 GW to 262 GW. They calculate that the United Kingdom, Ireland, Norway, Denmark, and the Baltic states will be exporters of electricity, while Germany will import 1% of its requirements.

The same questions arise also in the national context of Germany: numerous studies consider pathways towards a possible decarbonization of the German energy system [11,12,55–59]. However, the German studies are usually done on a national level and only seldomly in a federal context.

Pregger, Nitsch, and Naegler's [55] study compares necessary developments for achieving the aims of the German federal government's "Energy Concept" under different costs for technologies and resources. To accomplish the lower boundary of 80% emission reductions until 2050, they find that an increase of renewable power generation is needed, accompanied by the need for substantial efficiency gains across the sectors. In their base case scenario, they compute a rather moderate amount of installed renewable capacity of 179 GW in 2050.

Palzer and Henning [56] take a look at the electricity and heating system and conclude that given significant efficiency gains in the heating sector (40% to 50% of heat demand compared to 2010), both sectors can be decarbonized by 2050– with an installed renewable energy generation capacity of 465 GW. In another study, Henning and Palzer [57] also include the sectors transportation and industry and conclude that a transformation towards 80% GHG emission reduction is theoretically feasible, although additional costs would be around EUR 30 billion annually, compared to the reference case. Regarding the nearer future, Oei et al. [60] conclude in their study that Germany will not meet its intermediate targets for 2020 and 2030 if it keeps the current trends (and limited efforts). One main message is the fact that an extensive phase-out of coal-generated electricity until 2030 to meet the targets could be feasible without endangering the security of electricity supply.

While these studies do not put much weight on electricity import and export, Samadi et al. [58] point out that usual scenarios are relying on high values of net imports of electricity, thus needing fewer storage capacities but increasing technological, financial, and political complexity [58]. However, Pleßmann et al. [47] conclude that after modeling the demand for energy storage for a 100% renewable and thus fluctuating electricity supply, the integration of electricity storages will not increase the levelized costs of electricity (LCOE) in comparison to conventional energy sources. The question as to how important energy storage is for a 100% renewable energy system is also extensively discussed in a German context: In a comparing study, Cebulla et al. [61] found a large variance between the estimated requirements for electric energy storage in an energy system relying heavily on renewables: One cited study estimates a storage capacity of up to 83 TWh in a system that is 100% renewable (or 6.3 TWh in the case of 80% market penetration) [62]. By 2050, Child et al. [51] estimate that up to 147 TWh of storage capacity have to be built in Germany to compensate for grid fluctuations which is far higher than Hartmann's estimate which is even more astonishing, when having in mind, that this study calculated a fully integrated European power sector. Concentranting on Germany, Sinn [11] calculated a need for electric storages of around 16.3 TWh Schill et al. [12] however, argue that with the regulation of generation peaks from renewable energy plants, as well as sector coupling, there would be no need for large electricity storage additions. Today, there exist multiple storage technologies and solutions that can play a role in compensating the strong fluctuations in the feed-in of renewable energies. In this context, Zsiborács et al. [63] argue that European energy storage market developments and regulations which motivate the increased use of stationary energy storage systems are of importance for a successful renewable energy integration. Decentralized power storage systems, for example, can contribute to increasing local self-consumption and thus to relieving the pressure on distribution networks, as decentralized systems become more widespread [64].

With focus on the power sector and technical feasibilty within the transmission grids [65,66] also modeled the German energy system including demands for the transportation, heating and industry sectors. Different from other approaches, they chose to model in different steps which allowed them not only to have a simple cost optimization but also include some market and grid simulations. In both papers they conclude, that with a sufficient electrification of the non-power sectors an energy system largely decarbonized is feasible and that power to gas will pose as a main driver [65]. Furthermore, Müller et al. [65] also looked at cross-border power trade and conclude, that Germany will become a net importer on at the norther borders and a net exporter on all borders, making Germany a net exporterin 2050.

Regarding the electrification of the mobility sector, and the possible effects on the German power sector and grids, some studies have been published in recent years. Hanemann et al. [67] found out that vehicle-to-grid (V2G) charging mechanisms would be supportive for the stability of German power grids, would help to decrease electricity costs from renewables by increasing rates of utility and that a high CO_2-price would support the two aforementioned points. Furthermore, transnational powertrade could be reduced and the electrification of the transportation sector could go in hand with the decarbonization of the power sector [67]. More general, Schill and Gerbaulet [68] point out that not scarcity of energy should be of the policymakers' concerns but demand peaks. This means that a user-driven charging scheme will endanger the grid stability and support coal fired power plants, as they are used as a back up reserve. Further, price-driven or market-driven charging schemes will only work if an adequate CO_2-price is deployed. Just like V2G, a controlled charging would increase grid stabilities and support higher rates of utilisation of renewables thus, decrease the overall costs for electricity. In contrast to that, Loisel et al. [69], who examined different grid-to-vehicle and V2G-schemes, point out, that, as of today, battery technology is not mature enough to support such schemes and that in current pricing regimes of the power and mobility sector, electricity simply is worthier in the latter. Hence, a full integration of both sectors, as projected is still a far- away goal.

Considering the issue of imports and exports, the role of individual countries plays a decisive role.A breakdown for European countries is provided by Child et al. [51] who use the LUT Energy System Transition model also used by Ram et al. [48]. They come to the conclusion: power trade within Europe is increasing massively from 63 GW to 262 GW. They calculate thatthe United Kingdom, Ireland, Norway, Denmark, and the Baltic states will be exporters of electricity, while Germany will import 1% of its requirements.By 2050, they estimate up to 147 TWh of storage capacity will be built in Germany to compensate for grid fluctuations. Similar considerations are also carried out with the heating sector in connection with the electricity sector. Thus, Bloess [70] in her investigation of possible electrification mechanisms of space heating has determined that, similar to the mobility sector, flexibility options arise. Flexibilities in turn help the market penetration of renewables. On the other hand, there is great pressure on the electricity sector, with an additional demand for about 200 TWh of electricity by 2030 [70].

The high number of studies focusing on different sectors and regions and their interactions in the next decades presents how important this field of research is. Nevertheless, only a few studies try to have a holistic look and to model an energy system as a whole. One of the most recent studies that did that is published by Hansen et al. [59]. They conclude that even full decarbonization is possible by 2050 utilizing only domestic energy sources. This is achievable by strong sector coupling but at high costs of more than EUR 400 billion per year. Interestingly, decarbonizing the transport sector would make up 55–65% of the total costs. Touching on overall costs of the energy transformation, it becomes apparent that any non-implementation of measures would lead to even higher expenses in the long run. According to Stern [5], not acting would intensify climate change and lead to severe consequences for human life on this planet such as access to water, food production, health, and the environment. In sum, the costs and risks for not acting will be equivalent to losing at least 5% of global Gross Domestic Product (GDP) per year, respectively 20% if a wider range of risks is taken into account. However, reducing GHG emissions, in contrast, would limit the cost burden substantially to 1% [5].

Although a large number of different studies examine the German energy system and its future developments, a quantitative approach at the federal level is not yet comprehensively covered. In particular, data on the heating sector accurate to the federal state, as well as a desirable high level of detail for the location potentials of renewable energies are capable of extension and improvement is missing in these studies.

1.4. Research Question

This work aims to give further insight into the development of the German energy system by computing the sectors of power, heat, and transportation endogenously and coupled. The developed scenarios, which are described in the next chapter, shall stretch out a space of possible pathways. Results shall represent the techno-economical optimum and provide information on future technology mixes and pathways towards a 100% renewable energy system. Furthermore, this work intends to offer new insights to policymakers and the modeling community by contributing to existing literature gaps.

2. Methodology

2.1. Description of the Model

The next paragraphs provide some insights into the applied model. However, a detailed description of the mathematical formulation is not provided; at relevant passages, a reference to the respective literature is given.

2.1.1. Summary of GENeSYS-MOD

This study uses the Global Energy System Model (GENeSYS-MOD) v2.0 described by Löffler et al. [14] and Burandt et al. [15]. It is an open-source tool for the modeling of energy systems based on the Open Source Energy Modelling System (OSeMOSYS) by Howells et al. [71]. The model uses a system of linear equations to minimize total system costs while meeting energy demands and respecting externally defined constraints (see Appendix B for a more detailed description of the model structure and workings). GENeSYS-MOD allows to model multiple regions, time periods, and sectors.

Therefore, it enables to show the development of an energy system, encompassing the sectors power, heat, and transport for Germany on a federal level until 2050.

2.1.2. Basic Structure of the Model

Essentially, GENeSYS-MOD can be defined as a flow-based optimization model. Its structure is made up of a network of nodes which are connected with each other, as illustrated in Figure 1. The nodes, called technologies, represent all entities producing, using, or transforming energy, for instance, power plants, vehicles, storages, and heat pumps. The different technologies are connected by fuels, which represent all energy carriers, electricity or fossil fuels, or their proxies, such as transport.

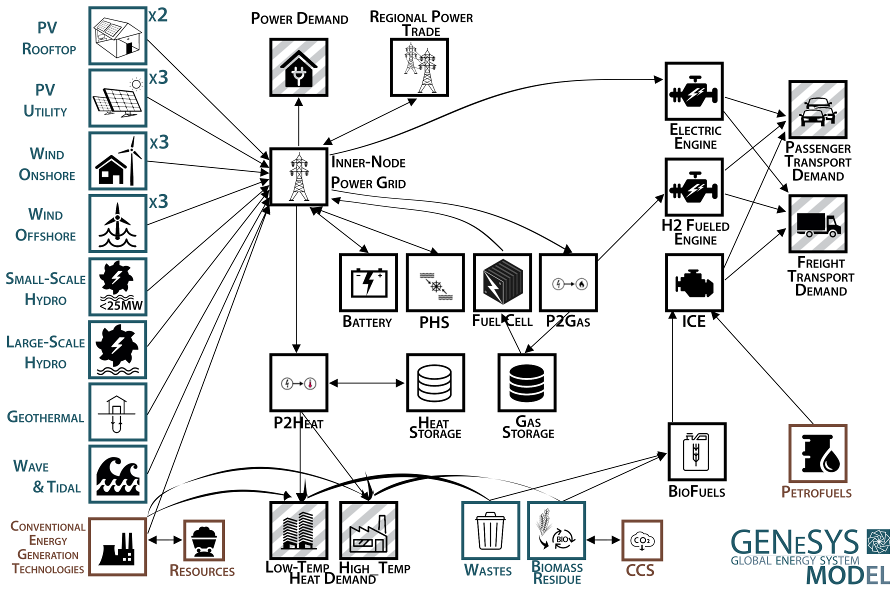

Figure 1. Structure of GENeSYS-MOD v2.0.

Energy demands are endogenously defined for every year and region and can be classified into heating, electricity, and transportation. Using a mixture of technologies and trade between different regions, GENeSYS-MOD aims to meet the given demands. The model seeks the minimization of total system costs, which are defined as the discounted costs of all regions over the model period. This includes investment costs, operating costs of technologies, trading costs of fuels, expansion costs of trade capacities, and penalties for the emission of CO_2. This objective is restricted by several constraints, which aim to depict real-life restrictions of an energy system, including maximum capacities and operational life spans. Furthermore, phase-out plans of several fossil fuels, as well as emission limits, are included under the given scenario.

For a more elaborate description of GENeSYS-MOD see the Appendix B, as well as Löffler et al. [14] and Burandt et al. [15].

2.1.3. Node Split

To analyze the development of the German energy system on a regional level, Germany was divided into a network of 16 nodes, each representing one federal state. Every node has its own energy demand, renewable potential, and existing capacities. Furthermore, there exist power transmission capacity limits between these notes according to the existing power transmission grid. In addition to the 16 nodes in Germany, neighbouring countries that are connected to Germany via a transition line are also represented by 9 nodes, to model the interlinking between Germany and its surrounding countries (following Hainsch et al. [49]). These nodes represent Denmark, Poland, the Czech Republic, Austria, Switzerland, France, and the Netherlands. Belgium and Luxembourg are gathered into one node—the BeLux node. The Scandinavian node combines Sweden, Norway, and Finland. Even though most constraints apply for each node individually, there are some constraints that apply to Germany as a whole. for example the emission targets are defined on national level not on state level.

2.2. Elaboration of the Scenarios

In the following paragraphs, three different scenarios for the energy system of Germany until the year 2050 are developed—namely European Island (EI), Green Democracy (GD), and Survival of the Fittest (SOTF). Each scenario draws up a different storyline regarding the global, European, and German trends in climate politics and the economy. The storylines were developed in a workshop with experts from governmental consultants, researchers and the business world, based on Europe's NDCs. Detailed information about the definition and elaboration of the narratives can also be found in [13]. Each scenario gives certain implications on the German energy system and thus, for the model. Developments for the global fuel prices, a price for CO_2—emissions, phase-out dates for certain technologies, and different energy demands in the sectors are derived from the storylines and implemented into the model. Relevant input data can be found in Appendix C.

It is important to say, that the narratives were designed on a global scale without specific implications for regions or nations. The derived scenarios then were designed after the model's aim and features were recognized. Therefore, forecasts or predictions of subjects that are not directly entangled with the model are not included. In this way, assumptions regarding the economic development and job markets are left untouched as well as possible policy measures that could not be integrated into the model's structure. Nevertheless, a brief examination of the stakeholders in politics, industry, and society was carried out to validate the legitimacy of the scenarios' assumptions (see Appendix A). Further, the aforementioned points are mapped via the different developments of energy demands in the various sectors. In light of these aspects, a comparison with European reference scenarios is generally difficult. Nevertheless, all scenarios are based on data and forecasts available and usually published by the countries' ministries or statistic authorities. Therefore, the baseline of this model is consistent in some aspects with, for example, the Reference Scenario of 2016 by the European Commission (*EC Ref16*) [54] or the EUCO scenarios (*EUCO323232.5*, *EUCO30*, and *EUCO27*) [72–74]: The efficiency gains in the individual scenarios are fairly consistent with the EUCO scenarios, with EI roughly correlating with *EUCO30* and GD with *EUCO323232.5*. Commodity prices here are based on world market prices and therefore differ somewhat from *EC Ref16*, especially in the gas sector, which has implications on resource prices paid in Europe. Technology costs and costs developments are largely identical to *EC Ref2016* (and not further modulated between scenarios). The assumptions on the development of the CO_2 price in the *EC Ref2016* scenario are fairly identical to the EI scenario, with neither scenario reflecting recent developments. However, the Weighted Average Cost of Capital (WACC) in our scenarios is assumed to be 5% compared to 7.5% in *EC Ref2016* [54]. In general, this study shows an increased sector coupling compared to the European average, with an accompanying increase in electricity consumption. Since SOTF and GD are not alternations of the baseline scenario but explorations of alternatives or extremes, commonalities to the European reference scenarios are fewer.

2.2.1. European Island Scenario

The EI scenario serves as the baseline scenario of this paper and is characterized by a strong European alliance, while global conflicts continue. Due to a strengthening of European institutions and greater influence of green parties, mutual politics focus on previously set climate goals. Countries within the EU are committed to enabling the EU to push for the fulfillment of the lower bounds of their climate goals, which is in the German case, an emission reduction of 40% in 2030, and 80% in 2050 compared to 1990. To realize these goals, phase-out dates for fossil fuels are set. The planned nuclear phase-out is enforced and carried out in 2022. Besides, the phase-out of hard coal and lignite for power production is set to 2035, and fossil gas and oil for power production to 2045. The heating sector and the transport sector continue to use fossil fuels. However, in terms of decarbonization, it is hoped for a spillover effect (E.g.: The heating sector is retrieving energy from a decarbonized power sector. Hence, the decarbonization in this sector is advancing, even without changing technology mix.) with increasing sector coupling.

As part of the mutual climate politics, an EU-wide CO_2 price is set (see Table 1) which rises rather slowly until 2035 but increases momentum afterward, until it reaches 85 € per t CO_2 in 2050 (With an increase of 1.50 € per year, a ton of CO_2 would cost 12.50 € in 2019. However, the European Energy Exchange (EEX) lists European Emission Allowances varying between 18–26 € per t CO_2 in 2019. www.eex.com/en/market-data/environmental-markets/spot-market/european-emission-allowances#! Last accessed: 25 May 2019). World market prices for fossil fuels hard coal, oil, and fossil gas are influenced by two opposing trends: Due to increasing worldwide demand, decreasing availability, and political instability outside the EU, prices for fossil fuels increase. However, a decrease in demand in the EU and the effect of governmentally set phase-outs reduces the price increases slightly (see Table A2). These assumptions are based on the "450 ppm scenario" from the World Energy Outlook 2016 [75] and are adapted to the following scenarios as well.

Table 1. Overview of policy measures implemented in the model for the three different scenarios.

	European Island [EI]	Green Democracy [GD]	Surfival of the Fittest [SOTF]
linear increase of the CO_2 tax from €5 per t in 2015	to €35 in 2030 and to €85 in 2050	to €130 in 2050	to €15 in 2035 to €50 in 2050
limit the CO_2 emissions compared to 1990 by	40% in 2030 80% in 2050	55% in 2030 95% in 2050	no limit
phase-out in the electricity sector	Lignite in 2035 hard coal in 2035 gas/oil in 2045	Lignite in 2025 hard coal in 2030 gas/oil in 2035	no phase-outs

2.2.2. Green Democracy Scenario

Characterized by a reduction of international tensions, increased communication between stakeholders, and a holistic approach, the GD scenario visualizes the effects of fast action towards a sustainable energy system.

Within this scenario, the public opinion plays a vital role, as they put pressure on policymakers to advance climate protection, comparable to what the "Fridays for Future" movement achieves currently. Therefore, Germany sets itself a CO_2 reduction goal based on the NDCs. With 55% (2030) and 95% (2050), less CO_2 emissions compared to 1990 levels, Germany focuses on the more ambitious targets. This includes the sector-specific goals of an emission reduction by 2030 in the transport sector by 40% and in the space heating sector by 67%, both compared to 1990 [22].

Derived from those developments, Germany carries out its nuclear phase-out until 2022. In comparison to the EI scenario, fossil fuels phase-out are earlier due to prior interventions and increasingly cost-effective renewable energies. The phase-out of fossil fuels for power generation is set in 2025 for lignite, in 2030 for hard coal, and in 2035 for fossil gas and oil.

The growing efforts for climate protection, and therefore, a related decrease in demand for fossil fuels leads to a slightly falling price for conventional energy sources (likewise to EI). At the same time, the CO_2 price increases from €5 in 2015 to €130 in 2050 in a linear manner. This increase is due to the strong focus on climate action, which includes that all sectors are covered with emission prices. Especially in previously excluded sectors, effects will become noticeable, such as the transportation sector. Due to increasing urbanization and population, metropolitan areas will drastically change, which makes a holistic planning process for sustainable energy supply and infrastructure necessary.

2.2.3. Survival of the Fittest

In the SOTF scenario, the world is presented as one that has regressed from current climate policies to go back towards a more protectionist and nationalist environment. The scenario does not represent a world that is in complete refusal of climate problems, but rather one that prioritizes other issues, like national conflicts, conservative movements, and breakdowns of partnerships, until the effects of abrupt climate change are immediate and drastic.

Until 2035, the main driver is the need for energy security and independence, while the NDCs are mostly ignored. Interruptions in global trade as a result of protectionism lead to high prices for fossil fuels as well as imported technologies. Governments may choose to use renewables to gain energy independence but have no preference over conventional energy carriers.

In Germany, this scenario is marked by increasingly high prices for gas and other fossil fuel imports (see Table A2), as well as a slower rate of technological innovation. Consequently, already existing resources and infrastructures is used more than in the other scenarios, including reviving Germany's lignite reserves. Government-based emission initiatives are non-existent in the first half of the modeled period, while the carbon price is kept low at only €5 per t CO_2 in 2015, increasing to €15 per t CO_2 by 2035. (This increase is smaller than the actual increase of the CO_2 price from 2015 to 2019 reaching €25 per t CO_2).

From 2035 on, when the negative effects of climate change are even more visible, the focus starts to shift towards climate policy to mitigate further damages. From then on, the carbon price is increased linearly up to €50 per t CO_2 in 2050. Renewables are supported, leading to falling prices, however, no phase-outs for fossil fuels are set. This can be traced back to a growing focus on more acute global conflicts. Hence, the development of the energy system and eventual fossil fuel phase-outs are fully market-driven, given the cost assumptions.

3. Results

In the following chapter, the model results of the scenarios are discussed. In doing so, respective figures specifying the power, heat, and transport sector are presented and elaborated on. The graphs are resolved in five-year time steps and show the trend of the investigated sector in the period from 2015 to 2050, in accordance with the model calculations.

3.1. Final Energy

As Figure 2 illustrates, Germany's final energy consumption decreases along the scenarios' development paths by 2050. The decrease in final energy demand is due to decreasing demands in the different sectors: better insulation of the housing structure (see Figure 6), market penetration of electric vehicles, more efficient electric applications and a slow reshaping of the industry landscape (see Figure 7) have a significant impact on the amount of energy needed. On the other hand the electrification of different sectors plays a key role, which is reflected in increasing electricity production (see Figure 3). The paths displayed have significant points and trends for the various scenarios that represent the cornerstones of the transformation of the energy system. All scenarios are affected by the phase-out of nuclear power production set for each scenario. However, the gradual trend towards the decommissioning of coal-fired and fossil-fired energy generation and its use in different sectors is reflected in individual phase-out dates for the scenarios. Common in all scenarios is the nearly constant use of biomass and hydropower until 2050, as its potential is almost at its maximum at the beginning of the model period. A more detailed overview of the sector transformations is presented in the following model results.

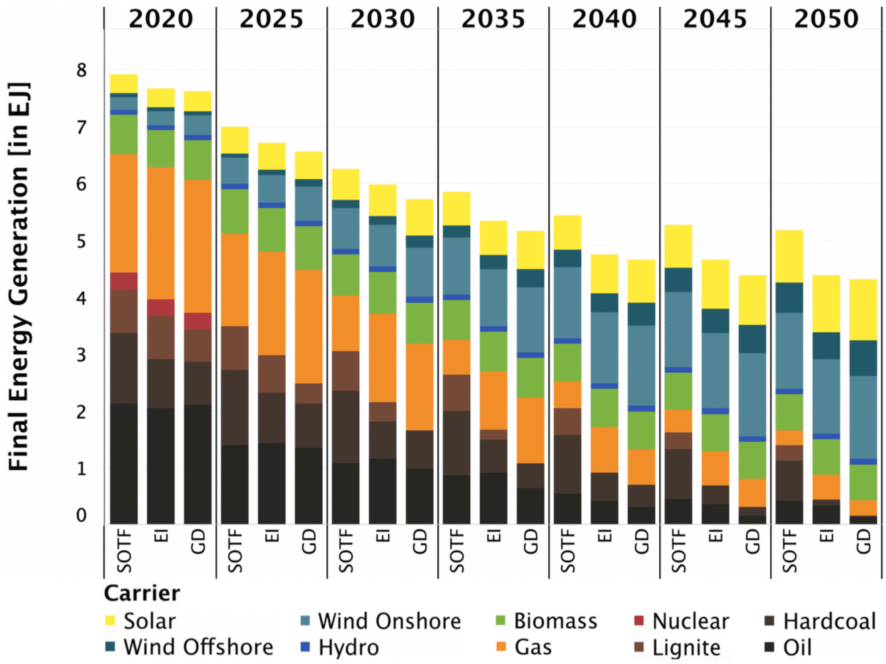

Figure 2. Development of Germany's final energy generation according to the respective scenario.

Survival of the Fittest The SOTF scenario has the most carbon-intensive transformation path and, at 5180 PJ, has the comparatively highest final energy demand in 2050, which is attributed to assumed low efficiency gains. Also, in this scenario, there are hardly any policy-driven restrictions such as phase-outs, so that model decisions, in this case, are primarily price-driven. Although the consumption of lignite (−70%), oil (−85%), and gas (−88%) are significantly reduced by 2050 compared to 2015, the use of hard coal decreases only slightly (−34%). The primary purpose of hard coal in the energy system of 2050 is to provide industrial high-temperature heat. Even though there is no phase-out date set for hard coal, it does no longer play a role in the electricity sector from 2040 on (see Figure 3). Compared to the other scenarios, renewable technologies are the last and least to expand in this scenario. Until 2050, the production of solar energy increases by 724 PJ (+370%) and wind energy by 1663 PJ (+780%).

European Island The EI scenario, as a reference case, accounts for only about half of final energy consumption in 2050, with 4388 PJ, compared to the base year 2015. Lignite is being phased-out in 2035. From 2035, hard coal no longer plays a role in the electricity sector, but is then only used for the medium- and high-temperature industrial heat generation, with decreasing volumes. The consumption of hard coal is reduced by 717 PJ (−87%) by the end of 2050. Oil as an energy carrier is drastically reduced by 2365 PJ (−86%) until 2050, in particular in the transport sector and residential low-temperature heat generation. However, it is still used for transportation to a limited extent in 2050. The use of gas (particularly fossil gas) also falls by 1962 PJ (−82%). Accordingly, the consumption of fossil gas in the industrial sector is steadily decreasing, but is being replaced to a low extent by synthetic gas. On the renewable technology side, the expansion of wind power generation is the most important. Power production from offshore wind will increase by 453 PJ (+1562%), for onshore wind even by 1120 PJ (+602%) until 2050. Solar energy generation is used for power generation through open field PV and rooftop PV systems. Furthermore, solar thermal systems are applied in residential low-temperature heat generation. With an increase of 797 PJ (+387%), solar energy likewise plays a major role in the renewable transformation path.

Green Democracy The GD scenario, which reflects the most ambitious transformation path, shows a reduction of the final energy demand by 48% (4317 PJ). The reduction rates of conventional technologies, over the entire model period, are only slightly lower than in the reference scenario (EI). However, due to strict guidelines regarding the reduction path, these reductions are achieved earlier, which goes hand in hand with the expansion of renewable technologies. As early as 2030, lignite is completely substituted by renewable sources and coal technologies are no longer used for power production (see Figure 3). By 2050, hard coal, which previously played an important role in high-temperature industrial heating, is phased out in this sector. Even stronger than in the other scenarios, oil experiences a significant drop of 2634 PJ (−96%), primarily through reductions in the transport sector. Further, it loses its role in the area of low-temperature heat generation in 2030 and from then on is only used in the transport sector. Concerning gas, it is noticeable that the utilization of fossil gas in the individual sectors is strongly declining while small quantities are substituted by the use of synthetic gas. In total, however, gas consumption declines by 2166 PJ (−89%) by 2050.

On the contrary, the technologies of wind power and solar energy have significantly higher growth rates. Led by onshore wind power with growth of 1292 PJ (+783%), and followed by solar power 860 PJ (+395%) and offshore wind power 591 PJ (+1555%), the renewable expansion in total lies slightly higher than in the other scenarios considered.

3.2. Power Sector

In all three scenarios, the energy system of Germany experiences a strong coupling of the power sector with the heat and transportation sector. This can be observed in the increasing generation of power see Figure 3. Among the scenarios, there are some variations in the power sector which are depicted more detailed in the following paragraphs. Again, biomass and hydropower contribute to the system in all scenarios but stay rather constant in generation due to almost exhausted hydro potentials in Germany and no added capacity for biomass in the power sector.

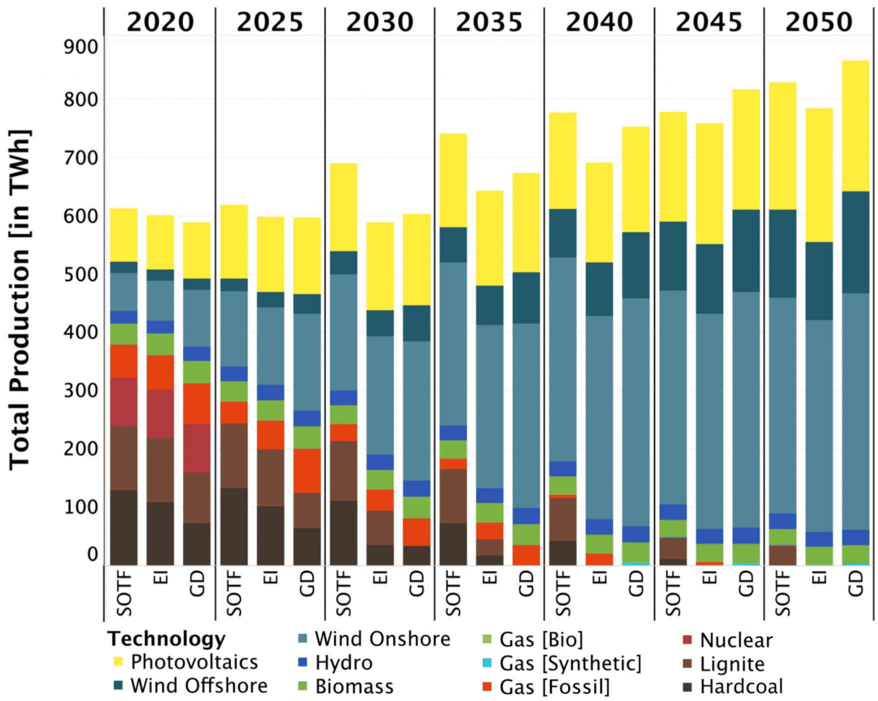

Figure 3. Development of Germany's power production according to the respective scenario.

When looking at electricity exports and imports of the federal states, it is noticeable that not only the electricity transported across federal state borders increases per year but also the inter-temporal fluctuations of the values between individual time slices. The model has two options available for absorbing strong volatilities in electricity production with high shares of variable renewable energy sources and for keeping the electricity grid stable even in dark lull periods. On the one hand, the model is allowed to expand the power grid to a certain percentage. To count in local resistance and lengthy approval procedures, the grid expansion was limited to 20% existing capacity per 5-year period. The second option is the use of intermediate storage facilities. Since the potential of pumped storage power plants in Germany is low and completely exhausted early on, lithium-ion battery storage systems are being introduced into the power grid. Depending on the scenario, large quantities of electricity will be temporarily stored in 2050. In GD this is 50.7 TWh in 2050, in EI 30 TWh, and in SOTF 20 TWh. Power-to-Gas technologies are another measure, as discussed in more detail in Section 3.3.

Survival of the Fittest The transformation of the power sector is slower than in the other two scenarios. The generation from hard coal and lignite stays rather constant in the first ten years. Nevertheless, in 2025 more than 50% of the electricity generation comes from renewable sources. The total electricity demand of SOTF is the highest among the three scenarios, due to fewer incentives to save energy, mainly in the heating sector, but also in general. Therefore, the added capacity of renewables in SOTF and EI is comparable. Overall, the generation by conventional sources declines. Lignite stays the prevalent conventional source, due to the comparably lower costs to hard coal, and fossil gas. In 2050 hard coal is phased out due to rising global prices for coal. In 2050, the electricity generation is 95% renewable even in this scenario without CO_2—targets, due to cost advantages.

European Island The development in the first 20 years is characterized by the phase-out of one energy carrier each timestep of five years: nuclear in 2025, hard coal in 2030, lignite in 2035, and fossil gas in 2040. The renewable sources wind and PV replace this conventional power generation. Already in 2035, the energy system in EI is 95% supplied with electricity from renewable sources; only fossil gas remains as a conventional source. From 2030 onwards, the total power generation increases by around 10 TWh each year, due to the increasing sector coupling, resulting in a generation of 875 TWh in 2050. In 2050 for Germany the generation from wind turbines is twice as high as the generation from PV.

Green Democracy Until 2025, the nuclear phase-out and the reduction of power generation from hard coal and lignite by 50% is replaced by power generation via wind and sun. Therefore, additional capacities of 85 GW are installed. The abandonment of lignite for electricity production is connected with a decrease in hard coal or fossil gas generation, with a reduction of fossil gas and hard coal of nearly 50% by 2030. In 2035 hard coal is phased out without resulting in a temporary increase of fossil gas. Instead, the more volatile electricity generation from wind turbines and PV is balanced via power trade, hydropower, and battery storage. In 2040, the electricity generation in Germany is 100% renewable and decarbonized. Electricity production via wind turbines contributes two thirds to the generation, PV a quarter. Synthetic gas is mainly used in the industry heavy region of North Rhine-Westphalia. After 2040, only onshore wind turbines and PV utilities are built, increasing the power production by additional 100 TWh. The expansion of renewable energy sources adds up to 180 GW onshore wind, 39 GW offshore wind, and 99 GW capacity connected to the grid in 2050. In the same time, the demand for electricity in the heat and transport sector increases by 130 TWh. In general, since low-carbon electricity generation technologies are available at low costs, the electricity sector is the first to be decarbonized.

Figure 4 shows the regional breakdown of the power production for 2020, 2030, and 2050. It can be seen, that, over the years, each federal state will have increased power production. However, the change in the coastal states might be the biggest: Yielding the potential from offshore windpower, Lower Saxony, Schleswig Holstein, and Mecklenburg-Vorpommern will become net exporters of energy. Especially the exchange of power between Lower Saxony and North Rhine-Westphalia is very important, as North Rhine-Westphalia is depending on large amounts of electricity produced by wind turbines from the north. Furthermore, in 2030, North Rhine-Westphalia will be one of the last states with significant shares of conventionally produced power. Another state with conventional generation is the city-state of Bremen, which is close to the global coal markets with its harbor. Furthermore, states like Hesse, Thuringia, and Saxony-Anhalt, which have low production rates in 2015 will increase their production by the factor three or higher. This change in production rates is a consequence of the different technologies used for electricity generation. In 2015 with a high share of fossil generation, the power plants are located near demand centers or mining areas. Contrary, in 2050, with mainly electricity generation from wind and PV, the place of the generation is determined by renewable potentials and available space. Consequently, city states like Berlin or Hamburg, Hamburg or Bremen will be more dependent on importing electricity from neighboring states, as they will shut down own production capacities (The 2019-elected local government of Bremen note in their coalition agreement of July to phase out of coal already in 2023. This would affect three powerplants in Bremen [76].). These developments go along with an increase in electricity transmission and storage.

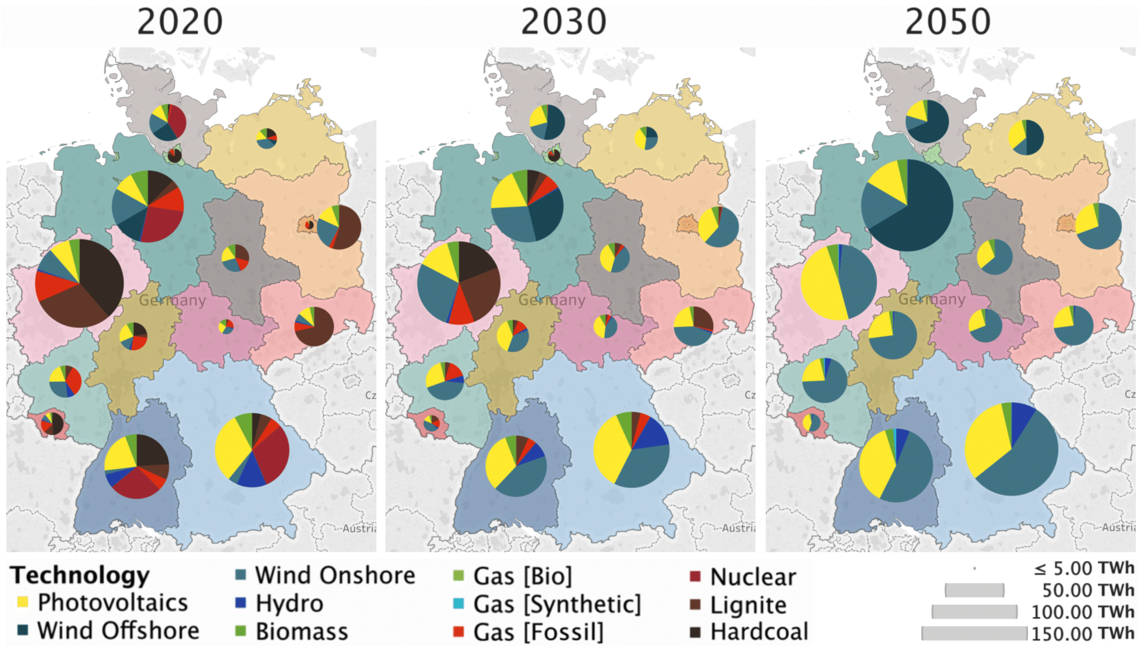

Figure 4. Regional development of Germany's power production for the Green Democracy scenario.

3.3. Sector Coupling

With increasing decarbonization of the sectors of heat and transportation, they also demand more electricity. As Figure 5 demonstrates, in 2015, the power demand from sector-coupling is well below 100 TWh per year, consisting mainly of demand in the industry sector. Over the next 15 years, the power use in sector coupling increases due to the electrification of space heating in the residential area and to a smaller extent by the market penetration of Battery Electric Vehicles (BEVs) and an increase of electric trains. By 2030, SOTF has the highest amount of electricity used in other sectors, due to less energy efficient buildings and overall energy savings. This electrification is also linked to an increase in fossil fuel prices on the world market. However, in 2050, the lead of SOTF is overtaken by EI and GD, where stricter mitigation goals have to be achieved. While the power demand in residential applications stays rather constant over the latter 20 years, the industry sector becomes decarbonized to a high extent, with a five fold power demand in the GD scenario. Passenger transport is already relying on electricity in the 2030s, with an increasing power demand until 2050. Freight transport has the same, but delayed development. At the end of the modeled period, hydrogen produced by electrolysis plays a significant role. The produced hydrogen is either used directly in the transportation sector or reformed into synthetic gas. In the GD scenario, hydrogen and synthetic gas are used primarily in low-temperature heating. Furthermore, small parts of high temperature heat are generated by synthetic gas in the EI and GD scenarios. In general, the energy that is transferred from the power sector to the transport and heating sector exceeds the 50%-mark of total power production in 2045 in GD, in 2050 in EI and reaches 46.3% in the SOTF scenario at the end of the model period.

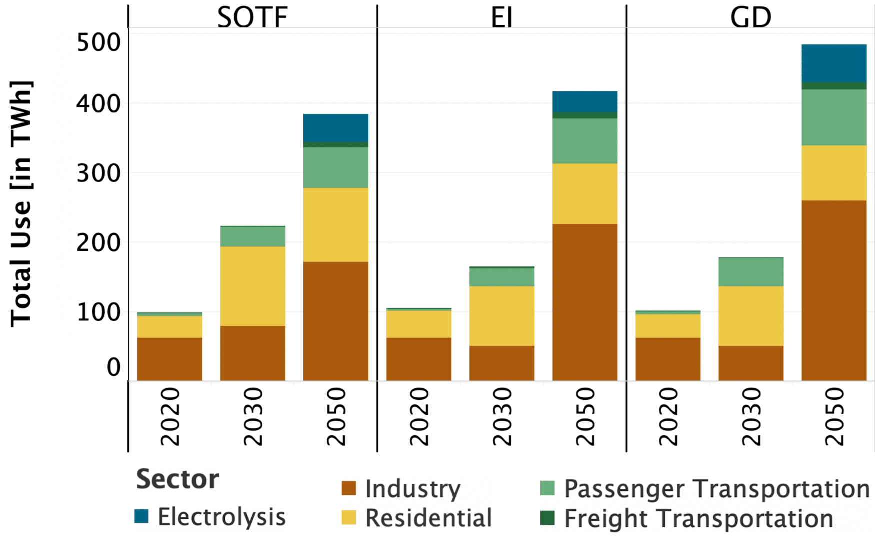

Figure 5. Use of power for sector coupling technologies by type according to the respective scenario.

3.4. Heat Production

The model results concerning heat production are displayed using the GD scenario as it provides the most drastic changes. The heating sector is divided into residential heating (warm water and space heating) and industrial heating, which is broken up into demands for low temperature heat (process heating and space heating below 100 °C), medium temperature heat, and high temperature heat (above 1000 °C).

Residential heat demand The demand for residential space heat, warm water, and energy for food preparation is with 750 TWh higher than the total heat demand in the industrial sector. However, due to the expected improved insulation of the German building structure, the demand will decrease until the end of the model period by one third, as Figure 6 shows. In 2015, the vast majority of demand is met using oil and fossil gas. Only small fractions are supplied by heat pumps or biomass. Until 2030, oil will be phased out, while the share of fossil gas stays rather constant. Air-based heat pumps are constantly gaining in importance but will soon reach their potential limit. Ground-based heat pumps will have their first appearance in 2030, but will also not reach higher market penetration rates. Close to the end of the model period, solar thermal technologies will also be helpful to decrease the share of fossil gas in this sector. However, solar thermal has to compete against PV modules on a limited space on roofs, which makes them interesting solutions only in regions, where electricity is rather abundant. To decarbonize this sector further in 2050, with decreasing costs for electrolysis and methanization, synthetic gas might also be a possible substitute for fossil gas.

Industrial heat demand In 2015, the total demand for industry heat was about 570 TWh per year, of which, low and medium temperature heat demand was at 220 TWh each. This number declines to 370 TWh per year in 2050, supported by efficiency gains from the use of power to heat technologies, as Figure 7 presents. In the first years, a slight overproduction of low temperature heat is measurable as the model can produce heat as a byproduct of the power generation of industrial power plants. Overcapacities will soon be eliminated as the expensive oil firing and emission-heavy lignite firing heating applications are dismantled. Interestingly, the share of the more expensive fossil gas is decreasing earlier than hard coal. This is partly due to the fact that hard coal is extensively used in high temperature applications (e.g., blast furnaces for steel melting), where alternatives are rather expensive and thus, decarbonization is more difficult. In the low and medium temperature range, biomass poses as a good substitute to conventional energy carriers, but availability is limited and this sector is in competition with the other sectors as well. From 2030 on, solar thermal modules are installed on roofs, but also here, the heating sector is in direct competition with the power sector due to limited roof space. In the medium temperature range, direct electric applications become very important in the second half of the model period. In the high temperature range, molten (steel/aluminium) electrolysis substitutes the remaining coal fractions in the later years. Synthetic gas is only used in small shares, mostly in low temperature heat applications.

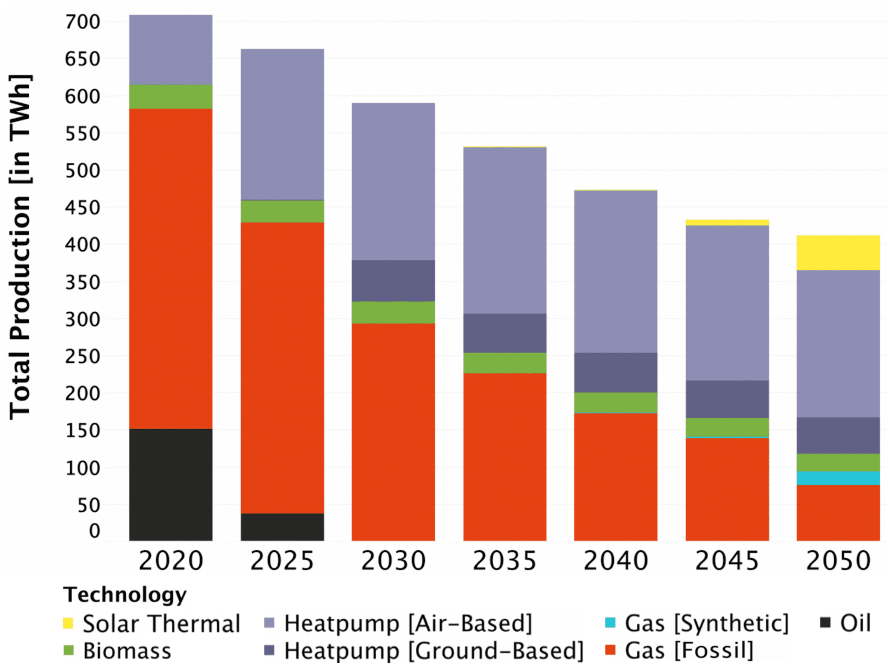

Figure 6. Development of residential low temperature heat production by carrier for the Green Democracy scenario.

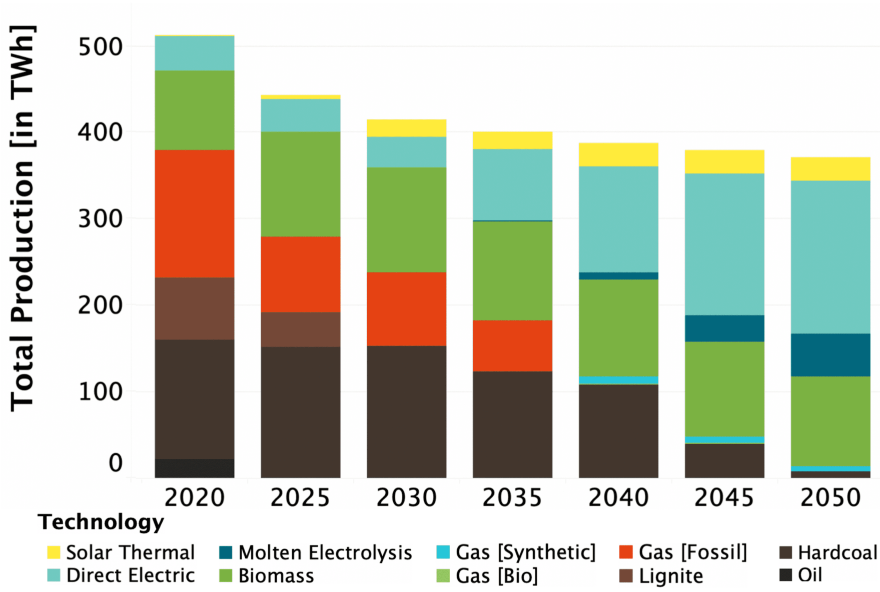

Figure 7. Development of the industrial heating sector, including the low, medium, and high temperature heat range for GD.

3.5. Transportation

The transportation sector is split up in passenger and freight transport, each of which has three different modal types: Road, rail, and air for passenger or ship for freight transport. To present the results, only the GD scenario is depicted. However, the other two scenarios have resembling results. For a visualization of the result refer to the Appendix D Figures A2 and A3.

Freight Transport The total volume of tons of freight transported in Germany will be steadily increasing by 50% until 2050. To cope with the rising traffic, an increasing share of freight will be transported via train. However, the preferred fuel for rail transport will be petrofuels until the ’30s. After that, the share of electrified rail transport will increase sharply in relative as well as in total numbers. In 2050, 32% of freight kilometers are by rail with electric trains, only 3.5% by conventional trains. The road-based freight transport is also growing in total numbers in the first half of the model period. Internal combustion engines are the predominant technology used. Only in some years, petrofuels are being utilized. Beginning in 2030, a network of streets with overhead power supply is being set up. This rather expensive way to decarbonize the freight transport becomes an important factor in 2040 with increasing shares of up to 30% in 2050. Heavy-duty freight vehicles with only batteries will not penetrate the market extensively but have a small but constant share. Internal combustion engines and petrofuels will be dominant over the whole model period.

Passenger Transport Unlike freight transport, passenger transport will have a stagnating volume over the years, with an increasing share of traffic handled by rail. In absolute numbers, the volume of passenger kilometers handled by rail increases from 87.2 billion person-kilometers (GPkm) per year to 291.5 GPkm. Road based traffic will be handled mainly by BEVs. The market penetration will increase from 15% in 2025 to 62% in 2050. Plug-In Hybrid Electric Vehicles (PHEVs) will stay in a niche with a share of only 0.11 % until 2040. Even after that, this technology is only used as an intermediate solution or bridging technology. Biofuels are not an alternative in the long term but being used in the years 2020 and 2050, as an intermediate solution to achieve the reduction targets.

3.6. Emissions

Figure 8 compares the various developments in annual emissions and total CO_2 emissions and puts them into relation with carbon budgets. The left y-axis and the clomumns represent the annual CO_2 emissions. Here, the main differences in the scenarios are visible: GD shows a drastic decline in annual emissions on account of drastic policy measures, namely the phase out of coal in the power sector early on. Together with a quick electrification of the other sectors and steeply increasing costs of CO_2, the emissions can be more than halved in between 2020 and 2035. These measures also lead to very high rates of emission reduction in 2050, even though a net zero, as German chancellor Angela Merkel announced in May 2019, to be an objective for 2050 is not feasible under the model’s and scenario’s assumptions (www.tagesschau.de/inland/merkel-klima-111.html Last accessed: 25 June 2019). EI follows the same pattern, however, less strict reduction targets and policy measures, as well as later coal phase outs will result in higher annual emissions for the entire modeling period. This throws a rather negative picture on the current climate efforts of the Federal Government, considering that this scenario is largely in line with the decisions of the Coal Commission, as far as the phase out of coal from the electricity sector is concerned (see also Section 1.2). SOTF resembles future developments of annual emission when all mitigation action is mainly driven by the market powers of resource prices, demands and technology development and costs. As Figure 8 clearly shows, the emission reduction is not sufficient enough and is more than twice as high as the emission from EI. Unlike both other scenarios the pathway is not characterized by a period of high reduction rates, instead it constantly declines by decreasing demand and assumed increasing fuel costs.

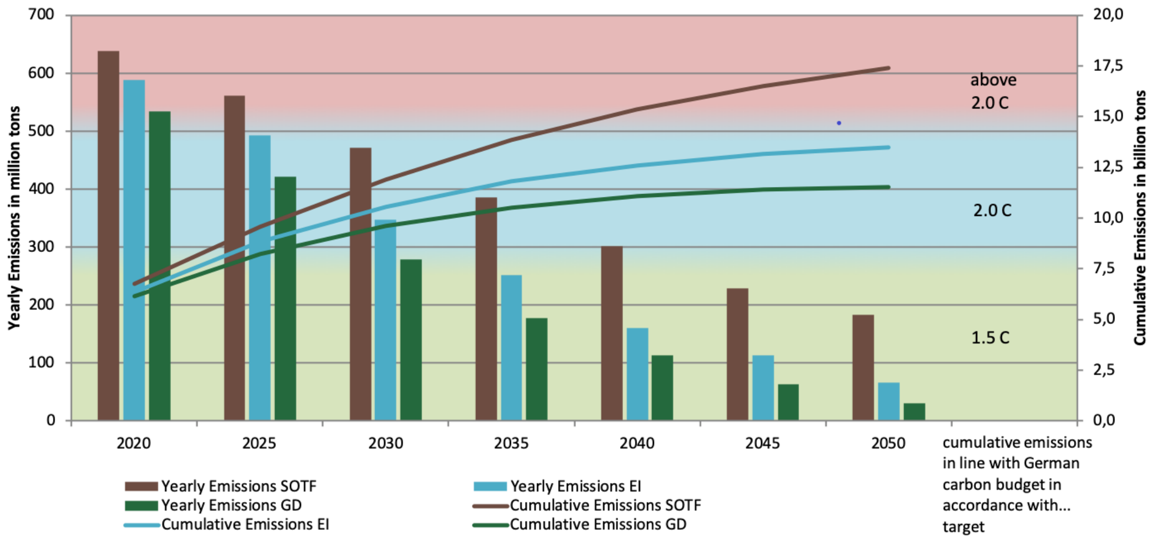

Figure 8. Development of yearly and cumulative CO_2 emissions per scenario. CO_2 emissions from material conversions in industry processes, meat production, and land use, land use change and forestry (LULUCF) land use, land use change and forestry (LULUCF) are not taken into account. The green area marks being calculated in the model and thus excluded from the German carbon budget for 1.5 °C if the global carbon budget was shared according to the countries' population. The blue marks the same share for the 2.0 °C target, the red area marks the the remaining German carbon budget for 1.5 °C target if it was shared according to the countries' GDP. Calculations is L based on 2015. The global carbon budget according to Rogelj et al. [1] was taken and counted back to 2015. Share the share of Germany's population in the world in 2015: 1.12%.

The right *y*-axis of Figure 8 represents the over the model period accumulated emissions of all three scenarios in comparison to certain carbon budgets. The global carbon budget according to climateactiontracker.org (climateactiontracker.org is a cumulative project by the NGOs Climate Analysis, NewClimate Institute, Ecofys and the Potsdam Institute for Climate Impact Research and is funded by the ClimateWorks Foundateion and the German BMU via the International Climate Initiative.) was taken, split up by the German share of the global population and calculated for 2015. All carbon budgets are calculated until the year 2100, while this study's time horizon ends in 2050. Especially the SOTF and EI scenarios, therefore, have to undergoo further decarbonization action after 2050 to stay within budget limits. Most strikingly, this figure shows, that not even GD will stay within the Paris Agreement's target to limit the global warming below 2 °C and aiming at 1.5 °C (see also Section 1 and 1.1. Nevertheless, by comparing the development of the three scenarios' cumulative emissions, one can see that early, drastic measures are helping a lot to decrease overall emissions: The final cumulative emissions will differ by 33% between GD and SOTF.

3.7. Model Limitation and Further Research

The model was set up using available data for technology costs and potentials as well as demands for power, heat, as well as personal and freight transport. The model was calibrated with data for the base year of 2015. Installed power plant capacity, as well as demands for power and heat, kilometers travelled, and freight moved can be found in different governmental statistics agencies.

However, GENeSYS-MOD lacks some features macro-economical models might provide, thus exogeneously defined demand projections had to be included. This also includes assumptions concerning efficiency gains and progress of technological progress. This forces the model into a corridor of boundaries which are set up under somewhat different assumptions than the scenarios' narratives. Nevertheless, under- or overestimations of technologies and their impact on developments are inevitable. Hence, the approach to use three different story lines is an attempt to mitigate this bias.

Another characterization of the model is its linearity: As soon as one technology is marginally cheaper than an alternative, the model will choose this one until there is a constraint. This usually leads to jumps in the utilization of technologies and drastic technology swaps. To circumvent this, smoothing factors where included, which, on the one hand pose as restrictions on the model's freedom, while on the other hand also pose as a tool to calibrate the model to fit into realistic predictions.

Furthermore, GENeSYS-MOD uses relatively large time steps of five years with 16 annual time slices. Each year is separated into four seasons and four time slices of different length, each to represent a typical demand curve over the day (night, morning, midday, afternoon) of each season (for the length of each time-slice refer to Burandt et al. [15]). Compared to load curves in energy economics with a resolution of 15 min time steps, the possible loss of information seems quite high. Still, the deviation is small, as [77] found out comparing an enhanced OSeMOSYS implementation with 16 time slices to a full hourly dispatch model. Nevertheless, a more granular model would be optimal and might be subject to further research.

The lack of integration and calculation of other GHG emissions apart from CO_2 is another limiting point of the model and its results. Primarily methane, although it has a shorter residence time in the atmosphere, has a strong GHG effect and is therefore not irrelevant for Germany's climate balance. The same also applies to the conversion of substances in industry, which sometimes emit large quantities. All of this is not further illustrated in this model, but represent about 10 to 20 percent of total German emissions [78]. An integration of emissions outside of the energy market and emissions of other GHG are also subject to further research.

4. Conclusions

This study analyzes three possible scenarios for the German energy transformation in the light of climate change and global resource scarcity. The scenarios, namely European Island (EI), Green Democracy (GD), and Survival of the Fittest (SOTF), outline possible pathways in the period between 2015 and 2050, including different phase-out policies, carbon- and resource price developments, and efficiency improvements. Therefore, the sector coupling model Global Energy System Model was applied. Irrespective of a scenario-specific consideration, the expansion of wind energy and PV play a major role in the cost-optimized development of the German energy system, especially in the electricity sector (see Section 3.2). The expansion of renewable energies for power generation is a key element on the development path to combine low costs with low emissions. A discernible trend towards increasing electricity demand corresponds to the gradual electrification of the individual sectors and the utilization of electrolysis to provide hydrogen and methane as alternative fuels (see Section 3.3). Nuclear energy thereby is neither required in the long term nor as a bridging technology. The use of power-operated heatpumps plays an important role in the provision of residential space heating and is gradually replacing fossil fuels such as oil and fossil gas. In the industrial sector, emission reductions in high-temperature heat generation exclusively require electrification, whereas for medium- and especially low-industrial heat generation, biomass can be a vital part of possible decarbonization pathways (see Section 3.4). In the transport sector, battery-powered passenger vehicles and electric overhead freight trucks are gradually replacing conventional combustion engines. The transport sector electrification is also reflected in the expansion of electric rail transport (see Section 3.5).

In EI and GD, the model calculated the cost optimal energy system given the desired emission reduction pathway based on Germany's climate protection targets [22]. As a result of the ambitious restrictions of the GD scenario already in the 2020's, the associated early emission reductions demonstrate that the time is a decisive determinant for achieving the lowest possible cumulative emissions. However, in the SOTF scenario, neither emissions constraints nor fossil phase-outs were applied. Even without any given emissions reduction pathway, Germany still reduces its yearly emissions by 85% based on 1990 level. This represents the lower boundary of the targets Germany has defined for 2050. However, the measures are not sufficient to reach the 1.5- nor 2-degree limit and therefore not in line with the climate targets of the Paris agreement. The decisive factor for the remaining emissions in SOTF is the high-temperature heat sector powered by hard coal. This underlines that the phase-out from coal as an energy carrier is a major key for a successful renewable energy transition. This transformation is highly needed to start taking action to face the real threats of climate change. A net decarbonization in Germany by 2050 is needed to comply with internationally agreed on-climate targets.

More general, these results show, that a country with a relatively high energy consumption per inhabitant or per ground area is able to decarbonize its energy system by large fractions within a given timeframe. Being an early adopter, Germany was able to push first decarbonization methods early on and also gain experience in the deployment and application of renewable technologies. Nevertheless, the current system and industries surrounding it are relucant to undergo big changes, as hesitancies among industry association, local politics and even the society shows. On the other hand, decarbonization and deep intergration of all sectors also offer chances in flexibilization of energy supplies and demands, offer jobs even in rather underdeveloped areas and help decrease accumulation of power and influence on few stakeholders or regions in Europe as wind and solar irradiance are rather omnipresent sources of energy. Even though, the cross boarder trade of electricity decreases with a decentralization of the power generation landscape, there is a demand for grid expansions in between regions of supply and demand. While the regions of demand remain unchanged, the regions of supply may differ in future decades. Other countries, that are also trying to decarbonize their energy system can take some valuable insights: (A) Many countries have a lower power demand by ground area while even having a higher energy supply, due to better wind or solar exposition. This means, the endeavours Germany has to take to decarbonize its system might not be as high for another country. (B) Deployment of solar farms and wind farms is necessary, even in regions where the relative power demand is quite low. This might not be accepted by the people affected by it, therefore it is important to start a discussion early on and find concepts of participation to counteract movements lead by the "not in my backyard" (NIMBY)-principle. The same NIMBY-thinking applies for needed grid expansions measures and thus needs to be addressed early on. (C) Conflicts of distribution will rather increase than decrease, since technologies from all sectors will have to compete for resources. This can be examplified in the case of biomass: Being the cheapest way to decarbonize several processes and applications, each sector would like to use as much of it as possible. Nevertheless, in some applications biomass might be worthier than in others. Therefore, in the planning of future generation technologies and demands, it is indispensable to always look at the energy system as a whole and then to decide on means of distribution.

The results presented in this paper pose as a first successful elaboration and implementation on the complete decarbonized German energy system on a federal level. Further next steps include a more detailed representation of the largest branches of industry in Germany and their decarbonization options. This could more accurately resolve and endogenously calculate the requirements for process heat, which have so far only been considered superficially, instead of prescribing exogenously.

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Abbreviations

The following abbreviations are used in this manuscript:

BDEW	German Association of Energy and Water Industries
BDI	Federation of German Industries
BEE	German Renewable Energy Federation
BEV	Battery-Electric Vehicle
BMBF	German Ministry for Education and Research
BMU	German Ministry of the Environment, Nature Conservation,and Nuclear Safety
BMWi	Germany Ministry for Economic Affairs and Energy
CHP	combined heat and power
COP	Conference of the Parties
CSU	Christian Social Union in Bavaria
DSO	Distribution System Operator
DUH	Deutsche Umwelthilfe e.V.
dynELMOD	Dynamic, Investment and Dispatch, Model, for the Future European Electricity Market
EEG	German Renewable Green Energy Act
EI	European Island
EJ	Exajoule
EnWG	Energy Industry Act
ETS	Emission Trading System
EU	European Union
GD	Green Democracy
GDP	Gross Domestic Product
GENeSYS-MOD	Global Energy System Model
GHG	Greenhouse Gas
GPkm	billion person-kilometers
GW	Gigawatt
IGBCE	Labour Union of the Mining, Chemical and Energy Industries
IPCC	Intergovernmental Panel on Climate Change
km	kilometer
LCOE	Levelized Costs of Electricty
LULUCF	Land Use, Land Use Change and Forestry
NDC	Nationally Determined Contribution
NIMBY	"Not in my Backyard"
OSeMOSYS	Open Source Energy Modelling System
PHEV	Plug-In Hybrid Electric Vehicle
PJ	Petajoule
ppm	parts per million
PV	Photovoltaics
SOTF	Survival of the Fittest
TSO	Transmission Grid Operator
TW	Terawatt
TWh	Terawatt Hour
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
V2G	Vehicle to Grid
VDA	German Association of the Automotive Industry
VDMA	Mechanical Engineering Industry Association
WACC	Weighted Average Cost of Capital

Appendix A. Stakeholder of the German Energiewende

Germany has a federal system with the fundamental principle of subsidiary. Therefore, decisions should only be made on a higher level if the lower level is not able to, or the consequences would impact the higher level [79]. Due to the decentralized character of the low-carbon transformation, the federal states have a great opportunity to influence the implementation. In general, all states have adopted own climate targets, which differ greatly in their ambitions. Geographical circumstances, the structure of the local economy, and the respective state governments are important factors influencing this. While on the one side, a state-driven approach can lead to more fitting and localized solutions (Biomass is mostly promoted in rural areas, observable in the CSU-governed state Bavaria [80]), on the other side however, state governments tend to concentrate more on their own voters which might lead to decisions made by the "not in my backyard" (NIMBY)-principle [81]. A prime example is the so-called H10 regulation in Bavaria, which requires that the distance between wind power plants and settlements must be ten times higher than the total height of the windmills [82]. This halves the effective area for wind power plants [83]. The phenomenon of federal governments being tempted to support local interests rather than the "greater" plan of nationwide goals is also visible in the different resorts of the government (See also Section 1.1): In §1 of the Energy Industry Act (EnWG), the objective to provide a safe, low-cost, consumer-friendly, efficient, and environmentally compatible energy system was announced [32]. This set of objectives illustrates the basic conflict potential between the Ministry of the Environment, Nature Conservation, and Nuclear Safety (BMU) and the Ministry for Economic Affairs and Energy (BMWi) [84]—a confrontation of environment against economy [85]. The focus of the BMWi concerning decarbonization is set on using the energy transformation as a "success story for Germany" [86]. For this purpose, the ministry created a ten point agenda to merge loose initiatives into a structured energy roadmap in 2014 [87]. Furthermore, the BMWi integrated the energy department so that it has the overall control over most of the energy reforms within Germany's policy, such as the EEG or the EnWG [88]. This ensemble should combine the economic and environmental responsibility into one ministry to ensure a more efficient problem-solving [89]. The BMU, on the other hand, operates in the field of frugal handling with resources and the preservation of habitat, for instance in the Emission Control Act. Thus, this remit positions the BMU on the side of advocates for environment and climate protection and initiatives [90]. In general, the German government is influenced by a range of different entities and serves as a hub for different interest groups. While there are top-down targets given by international agreements or EU-wide guidelines, there are also influences through established industry and demands by the public that need to be brought in line. Within the political system of Germany, the separation of power and the federal system leads to a discourse between many different departments which are entangled in multi-level governance. The discrepancy between pro-environment interests and pro-economic interests of the ministries can be transferred onto the economy itself: most of the economic spectrum can be divided into two camps. Those industries that tend to appear as "polluters" or "emitters" are more in favor of a slow transformation and no regulations, and those industries that benefit from the energy transformation are clear proponents of stronger incentives and clear government targets [90].

Influencing policy is usually done through lobbying by industry associations. Here, it can be clearly observed that associations tied to large and heavy industry, such as the Federation of German Industries (BDI) (The so-called Federation of German Industries (BDI) has 100,000 members with a total of 8 million employees: https://english.bdi.eu/bdi/about-us/#/article/news/the-federation-of-german-industries-bdi/), have an influence on draft laws. For instance, the BDI was working on an exemption from the EEG levy for energy-intensive companies in the amount of 5 billion Euros in 2014, designed in a way that does not violate European state aid law [89]. However, due to heterogeneity of its members, the BDI also supports a low carbon transformation. In contrast, branch associations with more homogenous members tend to have stricter positions: among others, the German Association of Energy and Water Industriess (BDEW) and the German Association of the Automotive Industry (VDA), argue that a fast decarbonization would harm the industry due to higher energy prices and lower reliability, risk jobs due to changing production lines (Süddeutsche Zeitung. 2018. "Elektromobilität gefährdet 75,000 Jobs in der deutschen Autoindustrie." https://www.sueddeutsche.de/wirtschaft/studie-zu-e-autos-elektromobilitaet-gefaehrdet-jobs-in-der-deutschen-autoindustrie-1.4002449), and decrease attractiveness of Germany as an industrial standpoint. The argument that the transformation is endangering a multitude of jobs, especially in so-called structurally weak regions, is also supported by trade unions: the Labour Union for the Mining Chemical and Energy Industries (IGBCE) in particular is working side by side with the major energy suppliers for the continuation of lignite power generation, arguing that with a phase-put of coal, 20,000 directly and numerous indirectly affected jobs could be lost (Most of them in structurally weak (former industrially shaped) regions like the Lusatia (8500 workers) in former East Germany or the Rhineland (9903 workers). This number is repeatedly confirmed, it originates from DEBRIV (federal German association of all lignite producing companies and their affiliated organizations) (Statistik der Kohlenwirtschaft e.V. 2018) but could be a little lower in reality.).

On the other side, associations supporting the benefitting sectors like the German Renewable Energy Federation (BEE) argue that the transformation would provide numerous jobs and the renewable energies sector itself is already an important factor on public wealth and development. Among others, the Mechanical Engineering Industry Association (VDMA) is one of the largest associations in the engineering sector, and, unlike the BDI, represents the German medium-sized companies (VDMA. Maschinenbau in Zahl und Bild. 2018. https://www.vdma.org/documents/105628/20243678/MbauinZuB2018_1524470187749.pdf/14e4650e-bb39-37de-92f1-cf43902e05e5 Last accessed: 18 June 2018). Aligned with the general arguments of the benefitting sectors, the VDMA focuses on export possibilities and global competitiveness. According to the association, a policy regime of incentives (e.g., the expansion of the ETS) and clear regulations lead to innovation and investments in the areas of energy infrastructure and production, sector coupling, and transformation technologies [91]. Furthermore, there are several state-funded or private research institutes and think tanks, as well as environmental organizations which are rather supportive of the energy transformation and also have an influence on the public opinion. With the instrument of the so-called "right of collective action", environmental associations recognized by the Federal Environmental Agency [92] are able to make sure environmental directives are enforced. Most prominently, this tool is used by the Deutsche Umwelthilfe e.V. (DUH) to force cities to comply with emission values and driving bans.

At last, the public opinion plays a major role of the success of energy transformation: Unlike the industrial sector, the vast majority of people are supporting the transformation: Representative polls reveal a positive public agreement of up to 95% (AEE. 2017. "Repräsentative Umfrage: 95 Prozent der Deutschen wollen mehr Erneuerbare Energien." https://www.unendlich-viel-energie.de/akzeptanzumfrage2017.). However, some surveys record a negative tendency in the past years [93]. Especially on a municipal level—in areas where onshore wind turbines are installed—projects are confronted with criticism and skepticism that might lead to heavy protests and the foundation of a countermovement which could significantly hamper the energy transformation [94–97]. The motivation of energy transformation opponents goes beyond the NIMBY pattern which is often used to hastily explain countermovement [93,98]. NIMBY arguments (e.g., potential negative consequences for health or any decreasing value of the own property) are among the motives, but are accompanied by other concerns such as protection of the environment, aesthetic reasons concerning the landscape, or a general critique of the present energy policy.

Appendix B. Model Description

GENeSYS-MOD is a cost-optimizing linear program, focusing on long-term pathways for the different sectors of the energy system, specifically targeting emission constraints, the integration of renewables, and sector-coupling. The model minizes the objective function, which comprises total system costs (encompassing all costs occuring over the modeled time period) [14,71].

(Final) Energy demands are given exogenously for each modeled time slice, with the model computing the optimal flows of energy, and resulting needs for capacity additions and storages. Additional demands through sector-coupling are derived endogenously. Constraints, including energy balances (ensuring all demand is met), maximum capacity additions (e.g., to limit the usable potential of renewables), RES feed-in (e.g., to ensure grid stability), and emission budgets (given either yearly or as a total budget over the modeled horizon) are given to ensure proper functionality of the model and yield realistic results. Figure A1 shows a graphical representation of the functional units of GENeSYS-MOD, as well as additions and changes between model versions.

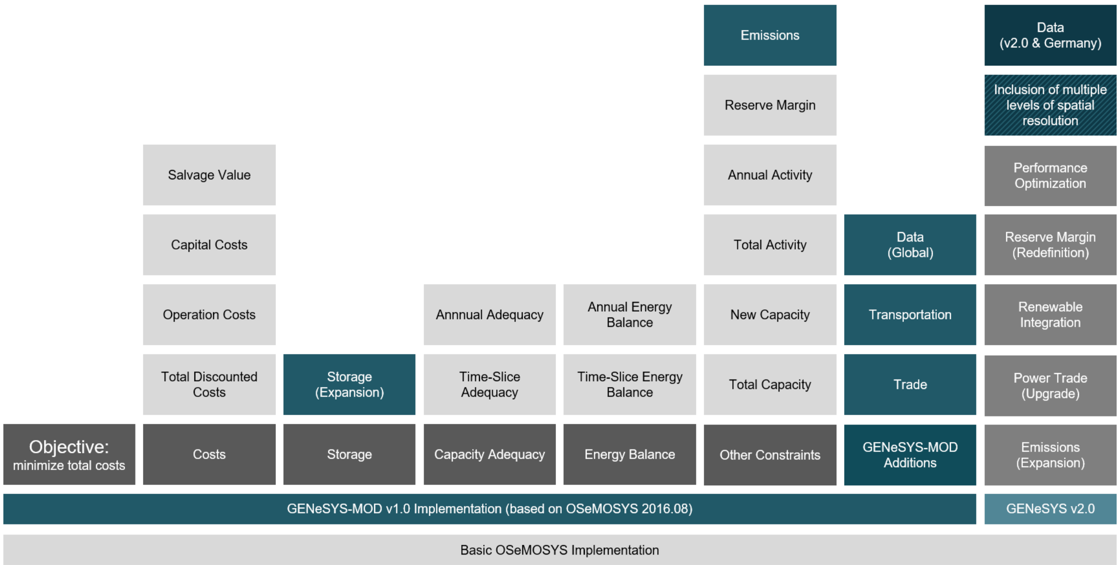

Figure A1. Model blocks of GENeSYS-MOD, including objective function, constraints, and version changes.

The model allows for investment into all technologies (Except when given fixed, predetermined phase-out dates, such as for nuclear power in Germany.) and acts purely economical when computing the resulting pathways (while staying true to the given constraints). It assumes the role of a social planner with perfect foresight, optimizing the total welfare through cost minimization. All fiscal units are handled in 2015 terms (with amounts in other years being discounted towards the base year). The effects of myopic/limited foresight, as well as the analysis of different discount rate models are planned for further reasearch and might yield even more insight in the possible developments of the energy system.

Fore more information on the mathematical side of the model, as well as all changes between model versions, please consult Howells et al. [71], Löffler et al. [14], and Burandt et al. [15].

Appendix C. Relevant Input Data

Appendix C.1. Technology Costs

Table A1. Capital Costs of main electricity generating technologies in M€/GW.

	2015	2020	2025	2030	2035	2040	2045	2050
Utility PV	1000	580	466	390	337	300	270	246
Onshore Wind	1250	1150	1060	1000	965	940	915	900
Offshore Wind Deep								
Offshore Wind Shallow								
Offshore Wind Transitional	3500	2637	2200	1936	1800	1710	1642	1592
Geothermal	5250	4970	4720	4470	4245	4020	3815	3610
Coal-Fired Thermal Plant	1600	1600	1600	1600	1600	1600	1600	1600
Gas-Fired Thermal Plant	650	636	621	607	593	579	564	550
Oil-Fired Thermal Plant	650	627	604	581	559	536	513	490
Coal-Fired CHP	2030	2030	2030	2030	2030	2030	2030	2030
Gas-Fired CHP	977	977	977	977	977	977	977	977

Appendix C.2. Fuel Costs

Table A2. Fossil Fuel Cost Assumptions in M€/PJ.

		2015	2020	2025	2030	2035	2040	2045	2050
Oil [Import]	EI/GD	7.12	10.18	11.02	11.86	11.37	10.88	10.39	9.91
	SOTF	7.12	10.91	12.60	14.40	14.62	14.77	14.85	14.86
Coal [Import]	EI/GD	1.52	1.54	1.53	1.52	1.44	1.36	1.28	1.20
	SOTF	1.52	1.65	1.75	1.84	1.85	1.84	1.82	1.80
Fossil Gas [Import]	EI/GD	6.63	6.54	7.72	8.91	9.15	9.38	9.62	9.86
	SOTF	6.63	7.01	8.83	10.82	11.76	12.73	13.74	14.79
Lignite [Domestic]	EI/GD	1.09	1.11	1.14	1.17	1.13	0.99	0.72	0.42
	SOTF	1.09	1.19	1.39	1.73	2.17	2.56	2.68	2.33

Appendix C.3. Renewable Potentials

Table A3. Renewable Potentials in GW installed capacity per region.

	Onshore Wind	Offshore Wind	Utility PV
DE_BB [Brandenburg]	13	0	19.2
DE_BE [Berlin]	0.3	0	0.6
DE_BW [Baden-Württemberg]	23	0	23.1
DE_BY [Bavaria]	41	0	45.6
DE_HB [Bremen]	0.2	0	0.3
DE_HE [Hesse]	14	0	13.6
DE_HH [Hamburg]	0.3	0	0.5
DE_MV [Mecklenburg-Western Pomerania]	11	6.6	15
DE_NI [Lower Saxony]	26	49.8	30.8
DE_NRW [North Rhine-Westphalia]	20	0	22
DE_RP [Rhineland-Palatinate]	12	0	12.8
DE_SH [Schleswig-Holstein]	9	28.6	10.2
DE_SL [Saarland]	2.4	0	1.7
DE_SN [Saxony]	10	0	11.9
DE_ST [Saxony-Anhalt]	7.4	0	13.2
DE_TH [Thuringia]	7.5	0	10.5

Appendix D. Additional Result Graphs

Appendix D.1. Transport

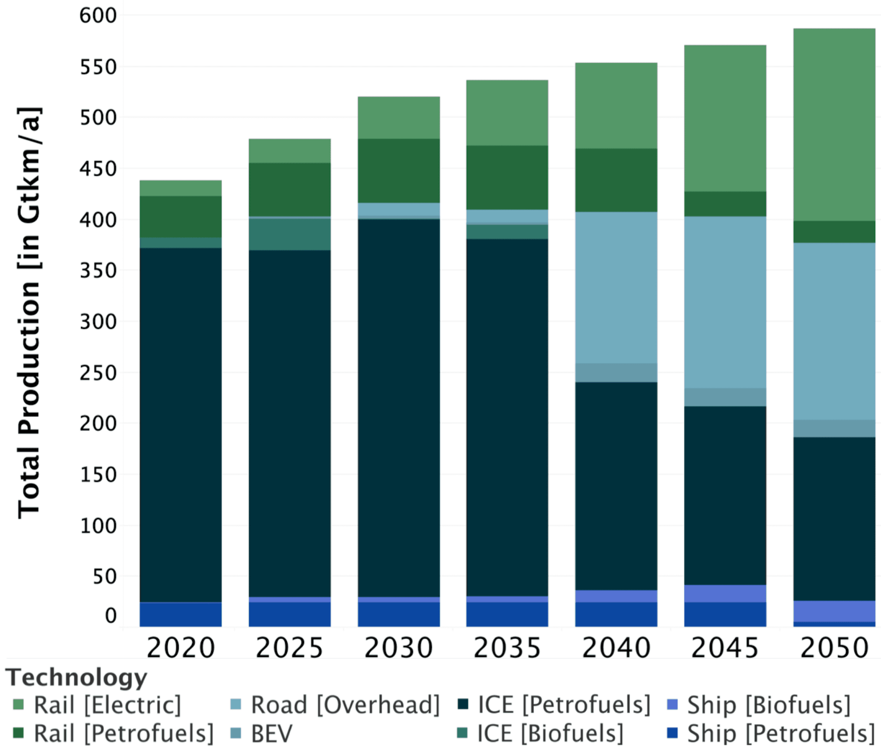

Figure A2. Development of freight transportation for the Green Democracy scenario.

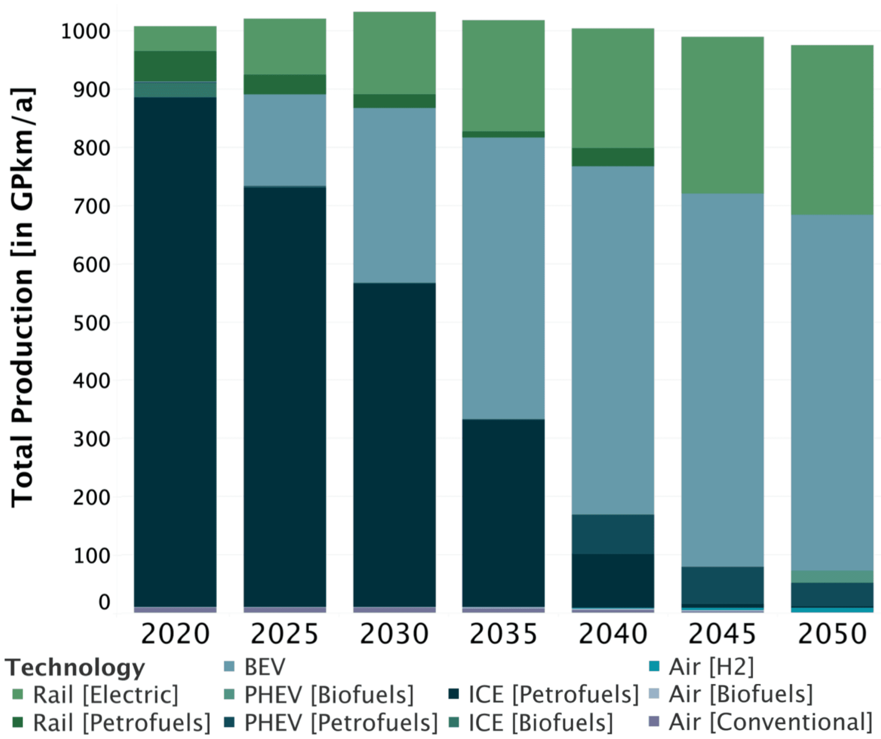

Figure A3. Development of passenger transportation for the Green Democracy scenario.

Appendix D.2. Regional Power Development for the EI and SOTF Scenarios

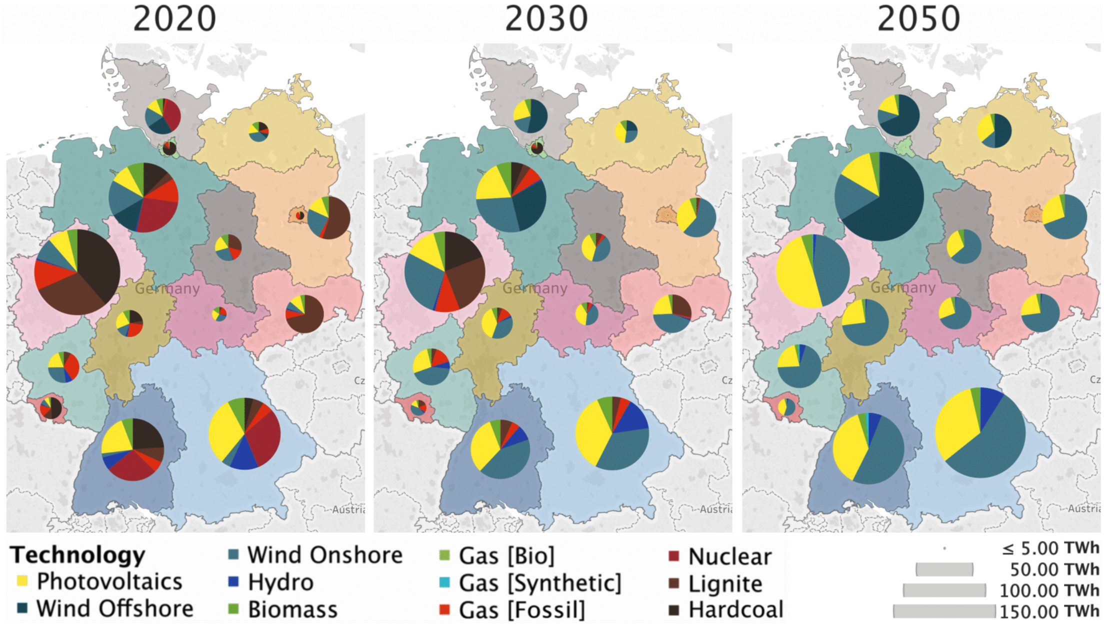

Figure A4. Regional development of Germany's power production for the scenario.

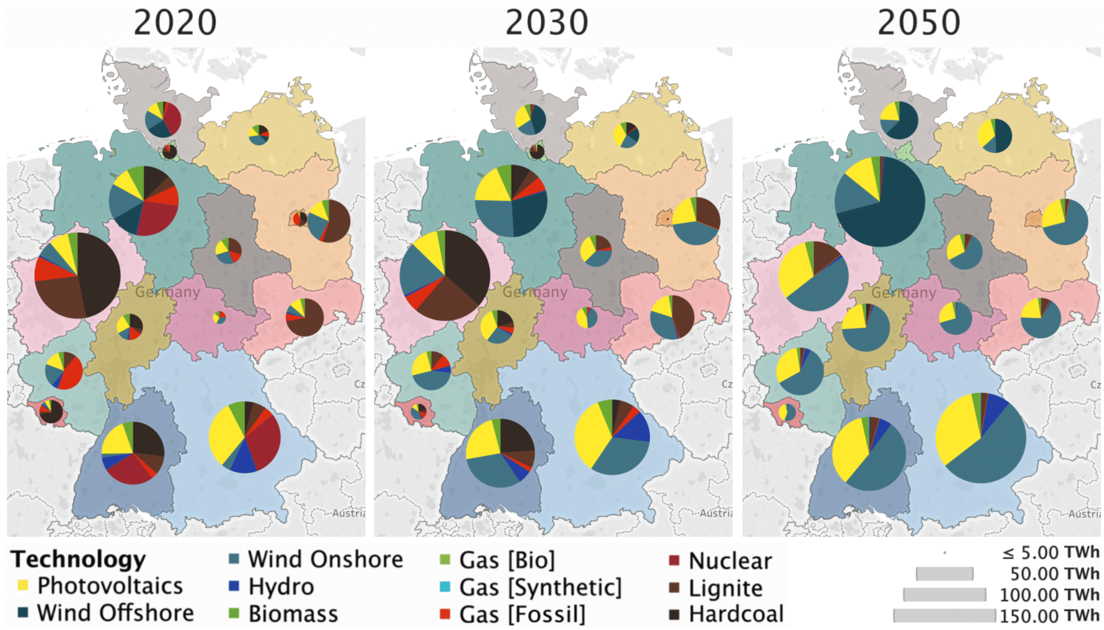

Figure A5. Regional development of Germany's power production for the Survival of the Fittest scenario.

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