Chances and barriers for Germany's low carbon transition - Quantifying uncertainties in key influential factors

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Abstract

With the energy sector being one of the largest sources of global greenhouse-gas emissions, a swift change in the ways of energy generation and consumption is needed for a fulfilment of climate goals. But while the existence of global warming and the resulting need for action are widely agreed upon, there is a lot of discussion around the concrete measures and their timeline. A major cause of this discussion is that of uncertainty, both with regard to possible outcomes, as well as to a multitude of factors such as future technology innovation (concerning both availability and costs), and final energy demands, but also socio-economic factors such as employment or sufficiency. This paper aims to give valuable insights into this uncertainty by applying the method of exploratory sensitivity analysis to an application of the Global Energy System Model (GENeSYS-MOD) for the German energy system. By computing over 1500 sensitivities across 11 core parameters, the key influential factors for the German *Energiewende* can be quantified, and possible chances, such as so-called no-regret options, as well as potentials barriers (if assumptions are not met) can be distilled. Results show that final energy demand developments, renewable potentials and costs, as well as carbon pricing are among the main drivers of the analyzed energy pathways. It would thus be highly beneficial for policy makers to focus on these key issues to ensure a timely transformation of the energy system and reach set climate targets.

Keywords: Energy Systems Modeling, Decarbonization, Energy Policy, Energy Transition, Uncertainty, Long-Term Energy Pathways, GENeSYS-MOD

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1. Introduction

To combat the adverse effects of climate change, a large-scale transformation of the ways we generate and consume energy has to be undergone. These widely agreed upon measures are needed in order to limit global warming to below 2 degrees Celsius, the threshold set in the historic Paris Agreement. Germany, as the largest economy of Europe, has portrayed itself as very committed to climate issues, with the German *Energiewende* being a major factor in German politics for the last decade.[1]

However, while the existence of global warming, its adverse effects on the environment, and general measures of greenhouse gas emission reductions are widely accepted, the concrete steps on the pathway towards these goals is heavily debated, both in policy, and academia [3, 4]. A major part of this discussion is that of uncertainty, both with regard to possible outcomes, as well as to a multitude of factors such as future technology innovation (concerning both availability and costs), and final energy demands, but also socio-economic factors such as employment or sufficiency. While quantitative models can give meaningful insights into future developments, an actual realistic prediction of the future is impossible. As George Box [5] famously put it: *"All models are wrong, but some are useful"*. It is thus the job of quantitative modeling to inform decision makers about possible outcomes and necessary steps to reach set goals, especially considering factors such as path dependencies. Only with well-informed decisions, the extremely ambitious goals to limit global warming can reasonably be achieved, since they require immediate action, focused on long-term goals instead of short-term near-future gains. To achieve this, modelers spend an extensive amount of time researching historic parameter values, and constructing future scenarios using assumptions on the development of said parameters. One can therefore reasonably assume that model results themselves carry a large portion of uncertainty, albeit often being portrayed as singular, infallible results.

This paper aims to give valuable insights into this uncertainty by applying the method of exploratory sensitivity analysis to an application of the Global Energy System Model (GENeSYS-MOD) for the German energy system. By computing over 1500 sensitivities across 11 core parameters, the key influential factors for the German *Energiewende* can be quantified, and possible chances, such as so-called no-regret options, as well as potentials barriers (if assumptions are not met) can be distilled. While this paper presents an application specific to the German case, the general methodology and model changes can be universally

[1] *Energiewende* describes the German term for energy transition and is widely used within research, policy, and media, also outside of German-speaking countries [1]. The term has been used since the 1970s and got well-known for Germanys early pushes towards renewable energies [2].

applied to other regions as well. Also, with Germany being the largest economy in Europe and the fifth-largest in the world (both in terms of gross-domestic product (GDP)), the German *Energiewende* has been followed closely across the globe. Germany therefore has a great responsibility to ensure that global climate goals are met. Also, seeing as this paper also highlights the main drivers of cost-optimizing energy system models, many of the generated insights can be translated to other model applications as well.

1.1. Literature review

In general, the transformation of an energy system towards renewable energy sources has been analyzed in various studies for differing regional scopes. Hereby, quantitative energy system models have been used in a variety of ways to generate implications of transformation pathways for policy- and decision makers. Overall, several studies are available looking at possible transformation pathways for the global energy system [6, 7, 8, 9]. In this regard, the importance of swift and consequent actions, combined with long-term planning taking potential effects of sector coupling, are highlighted. Similarly, a plethora of studies are analyzing the region of Europe specifically. Primarily, the future need for renewable energies in a low carbon transformation of Europe is analyzed, with the possibility of 100% renewable power generation or a complete decarbonization of the whole energy system until 2040/2050 set as a focus for some case-studies [10, 11, 12, 13]. In this regard, the necessities and implications of European wide grid-extension for a low-carbon energy system transformation is being discussed frequently [14, 15]. Furthermore, Gerbaulet et al. [16] and Löffler et al. [17] asses and discuss the problem of stranding assets in the fossil fueled power generation when moving away from conventional power generation. This stranded assets problem might lead to substantial economical loss of wealth, if not considered in long-term planning. While many studies often only analyze the power sector, Connolly et al. [18] and Hainsch et al. [12] promote the importance of sector-coupling and its positive effects of the transformation of the European energy system.

Similarly, sector-coupling is also deemed an important factor for the energy transition in Germany, as especially coupling the transportation and heating sectors with the power sector results in different implications for energy system transformation pathways [19, 20, 21]. As sector-coupling largely increases the power demand for future energy systems and often outpaces energy efficiency gains and demand reduction, large investments into renewable energy sources are necessary to comply to ambitious climate targets, as presented by Bartholdsen et al. [22]. For Germany, power generation from offshore wind farms is projected to become a crucial part of the future power system as large cost decreases are projected and offshore wind power generally has high load-factors for a variable renewable energy source [23, 24, 25]. As such, it is able to substitute medium-load fossil fueled power plants [26]. With increasing shares of variable renewable energy sources, the importance of large-scale energy storage deployment needed for a successful energy transition in Germany is also assessed by certain case-studies [27, 28, 29]. Also the topic of net-zero emissions and the transition towards 100% renewables is discussed for Germany in various studies [30, 31, 32]. For reaching the German climate targets, a decline of fossil fueled power generation is required, the economic, social, and ecological and implications of phasing out the existing coal-based power generation is being discussed by Heinrichs and Markewitz [33] and Oei et al. [34].

In general, the complexity of energy system models is currently rising due to the inclusion of higher temporal and regional detail, sector-coupling, and adding further techno-economic detail [35]. The challenge of complexity is often handled by creating more flexible models in terms of spatial and temporal resolution [36]. However, even with the previously rising complexity, uncertainty in energy system planning is often neglected in energy system models, although it is widely accepted that uncertainty is a key issue for energy models [37, 38]. In this regard, several methods of analysing uncertain elements in energy system planning could be used: stochastic programming, Monte-Carlo simulations, or robust programming. A further way of handling uncertainty is a systematic sensitivity analysis, as mentioned by Iyengar and Greenhouse [39] and Ferretti et al. [40]. By reducing the complexity of the original problem it is possible to perform rigorous uncertainty and sensitivity analyses [41]. This allows for probing the decision space and to generate valuable insights for policy- and decision-makers about energy system transformation pathways [42].

Overall, all of the previously mentioned studies tackling the German energy transition neglect the importance of uncertainty for energy system planning. Furthermore, no other research is available that investigates the barriers and opportunities for the German energy transition with a systematic sensitivity analysis. Moreover, the impact of sector coupling is often neglected in studies only assessing the power sector. In this regards, we propose the application of a systematic sensitivity analysis to evaluate possible chances and barriers for Germany's low-carbon energy transition using the multi-sectoral Global Energy System Model (GENeSYS-MOD).

The remainder of the paper is structured as follows: the upcoming section gives an overview over the status quo of the German energy system. Section 2 will briefly describe the utilized model before introducing the methodology and chosen sensitivities. The results of the explorative sensitivity analysis are showcased in Section 3, and Section 4 presents the conclusions and recommendations.

1.2. Status quo of Germany's Energiewende

Germany's efforts to achieving climate protection and efficiency have a long-running record, as it is committed to several multilateral and unilateral goals [43, 44, 45, 46]. Especially the climate protection law enacted in 2019 (*Klimaschutzgesetz*) is meant to be one of the cornerstones of climate protection ambitions, being the first instance of a law which defines sectoral climate goals with greenhouse gas (GHG) reduction targets for the sectors transportation, energy, industry, buildings, agriculture, and waste. This includes the goal to reduce GHGs until 2030 by at least 55% compared to 1990 [46] and to reach climate neutrality by 2050 [47]. Measures to reach these targets include phasing out electricity production from coal power plants by 2035-2038 [48] as well as the introduction of an additional Carbon dioxide (CO_2) price for the heating and transportation sectors which are not yet included in the EU Emissions Trading System (ETS) [49].

With respect to the progress of the German energy transition (*Energiewende*), the early achievements of rapid deployment of wind and solar energy have slowed down over the last years. In the case of wind energy, between 2014 and 2017 a new annual capacity of 4609 GW could be observed on average, while the two succeeding years don't reach that number combined [50]. Solar PV on the other hand had its peak in new installations around the years 2012-2013 with a heavy dip afterwards, but the numbers are increasing again since 2017 at a steady rate [51]. Yet, despite these developments, renewable energy sources accounted for more than 50% of the total electricity production in 2020 [52] and even though this is partially caused by the global COVID-19 pandemic and resulting demand reductions, it can be seen as an encouraging step towards a decarbonized electricity system.

As for the other sectors, the picture is less encouraging. According to the Federal Ministry for Economic Affairs and Energy [53], space heating and warm water made up for almost one third of the total energy consumption in 2017, yet since 2012 the share of renewable energies for space heating application only increased by 2% with most of the energy coming from biomass [54]. In the industry sector, energy consumption increased between 2008 and 2017, with no notable change of the share of renewable energies [53]. Lastly, the transportation sector shows increasing energy consumption since 2009 [53], while at the same time emitting 22% more emissions than in 1995 [55].

Taking into account all sectors, overall GHG emissions were reduced by 34.3% between 1990 and 2019 [56]. In the last year, 2020, emissions could even be reduced by as much as 45% according to estimates of the *Agora Energiewende* thinktank [57], a reduction that would mean the 2020 intermediate target of a 40% reduction compared to 1990 would be achieved. However, the authors point out that this reduction can mainly be attributed to the effects of the global pandemic on energy demand and consumption, since otherwise it would have been reasonable to assume that the climate target would have been missed.

The aforementioned developments highlight two aspects of the German energy transition: First, targets such as the one aimed at climate neutrality by 2050 still have to be transformed into binding laws and efforts have to be expanded in order to reach the defined climate targets since the current trajectory is not sufficient. Second, a high degree of uncertainty is predominant in the future development of the energy system, not only caused by disruptive events like the pandemic but also driven by technology development, regulations, and societal attitude. Therefore, in this work we aim to illustrate and highlight how changes in these projections can affect the configuration of the energy system and which no-regret options policy makers can focus on.

2. Materials and methods

2.1. Model description

The model used for this analysis is the Global Energy System Model (GENeSYS-MOD) an open-source linear optimization model, encompassing the electricity, buildings, industry and transportation sectors of the energy system, which is an extension of the Open-Source Energy Modeling System (OSeMOSYS) [58].[2] It was successfully applied in multiple case studies [7, 17, 59, 60, 13, 12], including possible pathways of the German energy system transformation [22]. A stylized representation of the model is illustrated in Figure 1.

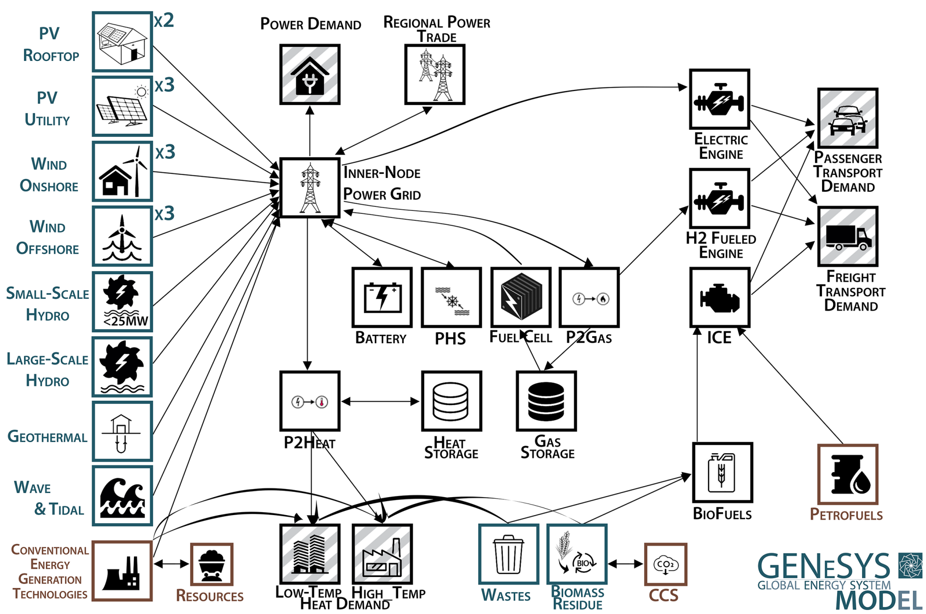

Figure 1: Structure of Global Energy System Model (GENeSYS-MOD) including its main technologies and the respective connections. Own depiction.

For each time step, the model has to satisfy the exogenously defined demands for the different energy services (electricity, industry, buildings, and transportation) while also ensuring that sufficient generation capacities are provided. To achieve this, the model can choose to invest into capacity expansion of a plethora of available technologies across the sectors. This dispatch and capacity expansion optimization is carried out under perfect foresight and from a central planner perspective, meaning full information, also about future years, is available at all times. As the objective function, the model aims to minimize total system costs,

[2]For more information and access, the reader is referred to: https://git.tu-berlin.de/genesysmod/genesys-mod-public

encompassing both capacity expansion, energy generation, trade, storage, and conversion costs. All fiscal units are discounted towards the base year.

2.2. Exploring uncertainty via sensitivity analysis

The purpose of this paper is to give insights into the uncertainty that inherently comes when trying to model and quantify any aspects of the future. While the existence and general danger of global warming are widely accepted within academia and politics, the actual process and necessary degree of the low-carbon transition are still heavily debated [3, 4, 61]. As perfect predictions of the future are impossible, the role of models should rather be to generate insights and thus useful information to improve short-term plans to be more aligned with long-term goals (e.g. in order to avoid path dependencies and/or unnecessary stranded assets [17]).

There are various ways to tackle uncertainty in quantitative modeling, such as adding stochastic elements to the model formulation [62], changing the amount of foresight applied in the model [16, 17], or modifying (uncertain) input assumptions to observe the model's behavior [41, 42]. This last approach is commonly known as sensitivity analysis and mostly used as a tool to validate the model workings, as it can easily point towards inconsistencies in the model results. In this study, however, a much more widespread technique is being applied - that of *exploratory sensitivity analysis*, a technique that is frequently used in various scientific fields [39, 40].

Compared to this exploratory sensitivity analysis approach, robust or stochastic programming usually provide a singular solution instead of a range of sensitivities. Although this singular solution considers uncertainty and can be used for extensive risk assessments, robust and stochastic programming both usually result in substantially increased problem sizes, making the variation of input parameters difficult without deployment of additional decomposition techniques. Monte-Carlo simulations present a further method for analyzing uncertainty. These simulations are used to generate probabilistic results based on uncertain/random input parameters. In general, Monte-Carlo simulations are used to model the probability of different outcomes in a process that cannot easily be predicted due to the intervention of random variables. However, as the input parameters are considered random variables, each model run generates a different outcome. Instead, the advantage of a large-scale (deterministic) *exploratory sensitivity analysis* as being applied in this research is the ability to always generate the same outcomes according to the changes in the input parameters. As a downside, uncertainty is not inherently included in the model setup but has to be assessed ex-post. However, due to the setup of an *exploratory sensitivity analysis*, a large variety of input parameters can be analyzed without the need for an adjusted model setup or adding artificial randomness to the variables.

As such, a wide amount of key parameters to the model are changed iteratively, yielding a total of 1591 separate sensitivities that have been considered in this study. The chosen sensitivity parameters and their value ranges are presented in Section 2.4. All of these sensitivity results are then cross-compared with each other, as well as with a defined reference scenario, or *base case*. We analyze each sensitivity *ceteris paribus*, thus with all other values remaining unchanged. This allows for a proper separation of effects for each sensitivity.

GENeSYS-MOD was expanded with a new module that enables this exploratory sensitivity analysis, adding the functionality to vary key input parameters via automated scripts that can then be used to run a multitude of sensitivities in parallel. In addition to the exploratory sensitivity computations, the module also introduces new automated methods for result aggregation and dissemination in GENeSYS-MOD.

2.3. Chosen base case scenario

To provide a reference point for the sensitivity analysis, a base case was defined and computed. Building upon the work in Bartholdsen et al. [22], the German application of GENeSYS-MOD has been updated to the newest version of the model, including the improved time-series reduction method presented in Burandt et al. [59].

The model depicts Germany at a federal state level, thus consisting of 16 nodes total. The years 2015 to 2050 are modeled, with 2015 being taken as a base year, and 2017 as an intermediate step between 2015 and 2020. After 2020, the model is set up in 5-year steps. This setup for modeled years has been chosen to remain comparable to the results of Bartholdsen et al. [22] (which starts with the year 2015), while better reflecting real-world developments towards 2020 at the same time. 2017 has been chosen as an intermediate step between 2015 and 2020 since it was the most recent year where detailed data on all sectors was available. The sectors electricity, buildings, transport, and industry are included in the analysis, with a strong focus on sector-coupling options. For this analysis, no carbon budget has been implemented. Instead, the base case serves as more of a 'current policy' scenario, including a CO_2 price that has been passed as part of the "Climate Action Plan 2030" in Germany [63], setting the minimum CO_2 price to 55€ after 2026, expected to rise at least 85€ per ton of CO_2 in 2050. 2038 is set as an exit date for coal in the electricity sector, and nuclear power is shut down as soon as 2022. All relevant input data can be found in the accompanying supplementary material at the Zenodo repository.

2.4. Sensitivities analyzed in this study

In this study, a total of 1591 sensitivities, spread across 11 different parameters, have been analyzed. These parameters have carefully been selected for being part of the most influential parameters of the model, or facing the most discussion in science, media, and policy. As these sensitivities highlight the effects of changes to the base case without altering the other parameters (*ceteris paribus*), the results provide decision and policy makers with the opportunity to see how effective policies targeting a specific area would be. Therefore, the ranges of the sensitivities are not limited by what can be found in the current literature or political debate, to paint a bigger picture and possibly highlight effects which might be overlooked otherwise. With the sensitivities being computed *ceteris* *paribus*, no combinations of different sensitivity parameters is made in the scope of this study. Table 1 lists all sensitivities, as well as their value ranges.

Final energy demands. Being one of the main drivers of GENeSYS-MOD, as well as a highly uncertain factor, final energy demands are of major importance in the future development of the energy system. As their future predictions often rely on qualitative scenario assumptions, they are exposed to extreme uncertainty and heavily reliant on expert assessment. Additionally, aspects of sufficiency, which see an increased representation in recent literature [64, 65], are difficult to include in typical energy system modeling and usually have to be considered through exogenous assumption (such as reducing energy demands). In this study, energy demands are varied per sector, relative to the base case.

Costs of breakthrough technologies. Breakthrough technologies, especially related to hydrogen, and future energy storage concepts, are often hailed as being a cornerstone of the low-carbon transition. Especially when extremely high levels of decarbonization are targeted, many studies heavily rely on these future technologies to reduce emissions. As such, their projected costs are not only highly uncertain, but also of great importance. They are varied per technology in relation to the base case assumptions.

Growth rate of renewables. Another uncertainty is that of the maximum possible introduction of renewables into the electricity grid per year. It is often argued that there is a maximum that can reasonably be introduced without causing issues with grid stability.

Rate of transmission grid expansion. In German media and politics, there is an extensive and ongoing debate about the necessity of transmission grid expansions when incorporating more renewables into the grid. Since most renewable potentials (notably offshore wind) are located in Northern Germany, but much of the (industrial) energy demand is in the south, many argue for the expansion of these north-south transmission lines.

Renewable potentials. Even though studies show that the potential for renewable energies in Germany is much higher than required for a complete decarbonization of the energy system [66], local preferences and matters of acceptance can have a major impact in the final configuration of the electricity sector. Moreover, some determinants of renewable potentials are in an ongoing discussion (e.g.: minimum distance from wind turbines to settlements) or rely on societal participation (e.g.: solar power on residential buildings). Therefore, in this case study a varying potential for onshore, offshore and solar photovoltaic simulates these uncertainties, as the exact potential for renewable energies is difficult to assess, yet the effects of increasing or decreasing said potential can be of significant importance.

Carbon price. There exists a multitude of different possible climate policies (varying from more market driven to regulatory instruments). The implementation of a carbon price for the sectors energy, industry, buildings, and transportation is hereby taken as proxy for the level of climate stringency. Yet, there are frequent differences in the magnitude of proposed carbon prices, as well as compared to already implemented ones. In this sensitivity, we significantly alter the carbon price to highlight its effects, specifically onto the different sectors. The currently agreed on carbon price trajectory for Germany consists of a price per ton of CO_2 of 25€ in 2021, increasing to 55€ per ton of CO_2 in 2025. This price corridor is already an updated version of an earlier one, which was heavily criticized as being too low, with prominent research institutes arguing for prices as high as 180€ per ton CO_2 in 2030 [67, 68]. Therefore, the chosen sensitivities range from 350 €/ton CO_2 in 2050 (assuming a carbon price of 180 €/ton CO_2 in 2030 with a similar development afterwards) to 20 €/ton CO_2 in 2050, assuming a decreasing development after 2025.

Building renovation rate. The building renovation rate is one of the cornerstones of reducing GHG emissions in the buildings sector, since improved insulation has a significant effect onto the energy required for space heating. In Germany, however, only about 1% of the buildings is renovated each year, far less then recommended by most studies to achieve any meaningful climate target [31]. Therefore, in this sensitivity we analyse the effects of an increased or decreased renovation rate and the resulting effects on residential energy demand. Hence, the chosen sensitivity range assumes 1.5% as the baseline which is considered to be the minimum rate required if moderate climate targets were to be achieved [69], which is then drastically altered towards both ends to simulate stagnating or very progressive policies.

Hydrogen import price. As already mentioned above, hydrogen is often viewed as a key component in the low-carbon energy transition. Apart from producing it locally from renewable energy sources, importing hydrogen would be another, yet possibly controversial, option of covering the demand. While in our base case the option for importing hydrogen is not enabled, we implement this feature in this sensitivity with the values ranging from 33.1 €/MWh to 254 €/MWh.

Modal split. The choice of vehicle to satisfy transportation demand depends on behavioural aspects and is difficult to replicate with a purely cost-minimizing approach but still can have huge implications for the energy system. Trains are generally speaking more cost and fuel efficient when it comes to produce passenger or ton kilometer, however road transportation remains (and probably will remain) the most important mode of transportation. In GENeSYS-MOD, the modal choice is very limited due to the linear nature of the model and the otherwise extreme results which would be produced. However, this sensitivity explores the potential effects of a more energy efficient modal split by allowing higher amount of transport demand being shifted towards other modes of transportation (e.g., from road-based to rail-based transportation).

Costs of renewables. With GENeSYS-MOD being a linear cost-optimization problem, costs are always one of the most influential factors. Since a large-scale introduction of renewables will be inevitable to achieve set climate goals, their costs and learning rates - being higly understimated in the past [70] - are highly relevant to the model results. They are varied per technology relative to the base case.

Biomass availability. Biomass usage is another often critical factor in decarbonization studies. However, one has to distinguish between actually renewable biomass (such as waste and other bi-products), and 1st generation biofuels such as fuel crops. With biomass being both a highly valuable and scarce resource (e.g. for the decarbonization of the transport or industrial sectors), its availability is an extremely important uncertainty to be analyzed.

Table 1: Analyzed sensitivities in this study, including quantity and value ranges for each chosen parameter.

		#	Min value	Default value	Max value	Step size
Demands	per sector	231	70%	100%	150%	2.5%
Costs of breakthrough techs	per technology	243	50%	100%	250%	2.5%
RES integration	max increase/year	131	3.5%	5%	10%	.05%
Grid expansion	max increase/year	121	0%	3%	6%	.05%
RES potentials	per technology	264	70%	100%	150%	2.5%
Carbon price	[€/tCO_2]	133	20 €	85 €	350 €	2.5€
Renovation rate	max share/year	77	0.5%	1.50%	7.5%	.125%
Hydrogen import price	[€/kg H_2]	88	1.2 €	N/A	10 €	.1€/ kg H_2
Modal shift		77	80%	100%	120%	0.5%
RES costs	for solar & wind	145	80%	100%	150%	2.5%
Biomass availability		81	50%	100%	150%	.125%
Total		1591				

The step size for each sensitivity has been chosen to keep the distribution of sensitivities as even as possible. In some cases, (e.g., for energy demands), the sensitivities are applied for a number of sectors or technologies, both separate, as well as in combinations (e.g., demand developments in only the industry sector versus demand changes across both industry and transport). This leads to a higher total number of runs, while the step size remains the same.

3. Results

This section will present some general findings from the range of model runs, with some meta analysis across noteworthy sensitivities. Subsequently, the four most commonly and widely discussed potential barriers and opportunities will be analyzed and put into context of our modeling results.

3.1. General findings

The general results across all 1591 computed sensitivities show a clear trend for the German energy transition. Emissions heavily decline across all sensitivities, albeit with varying intensity. While the base case manages to achieve the German policy goal of 85 to 95% with a reduction of 88.4% compared to 1990 values, some sensitivities only achieve 75% emission reductions (see Figure 2).

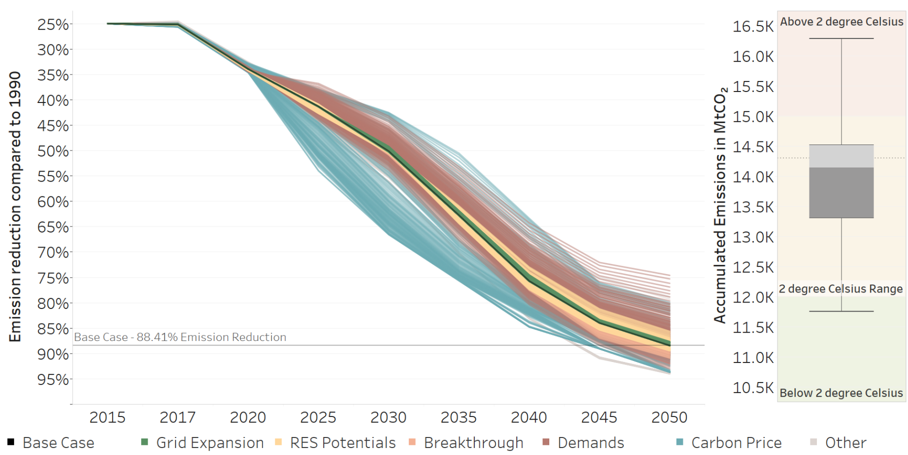

Figure 2: Spread of emission reductions compared to 1990 across all tested sensitivities (left) and spread of accumulated emissions in 2050 across all sensitivities. The range for the emission budgets is derived from the IPCC SR1.5 with a share for Germany based on its population.

While most sensitivities (including the base case) therefore fall in the 2° C range for global warming, some outliers above and below 2° C can be observed. However, these outliers are noticeably skewed towards the upper end, signaling an increased risk of failure to uphold the 2° C target within the computed sensitivities. The same shift towards renewable-based and thus emission-free technologies can also be observed in the electricity sector, with a drastic increase in RES-based electricity generation, as shown in Figure 3. The base case achieves a value of 95.9% renewables in electricity generation, with sensitivities ranging in between 100% and 78% renewable electricity. As with the emission reductions, the largest spread can be seen in the demand and emission price sensitivities.

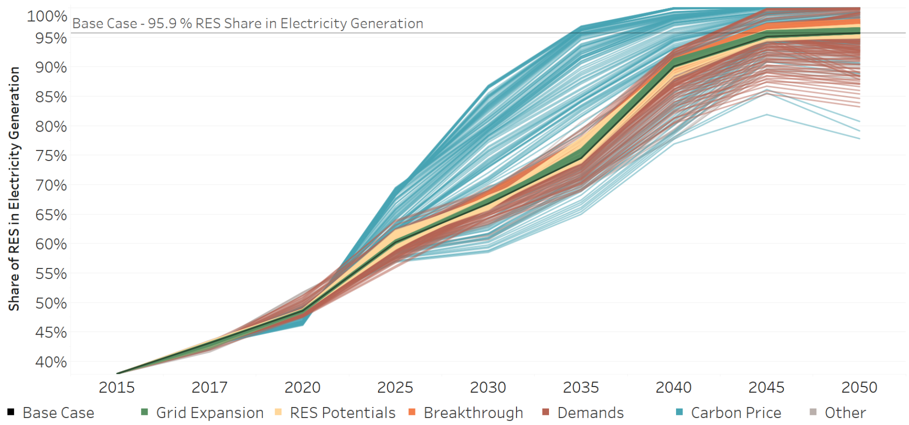

Figure 3: Spread of the share of renewables in electricity generation across all tested sensitivities.

The development of power generation costs, however, shows less of an influence of demands and emission price, and instead a strong reliance on exploitable renewable potentials and costs of renewable technologies (Figure 4). The emission price sensitivity is mostly noticeable in the intermediate future, and, contrary to popular opinion, we find only a marginal change in power generation costs when limiting the expansion of the electricity transmission grid. Looking at the state level, significant differences between German federal states can be observed in 2050. While some states only experience minor spreads of generation costs across all sensitivities, some states, such as Baden-Württemberg, Saarland, North-Rhine-Westfalia, and the city states Hamburg and Berlin experience a major spread in resulting electricity generation costs. Generation costs in Baden-Württemberg, for example, range between 25 and 78 € per MWh in 2050, leaving a threefold increase between lowest and highest sensitivity results. Except for the worst sensitivities regarding renewable technology costs, the generation costs for electricity experience a decline over time, with the base case reaching costs of 32€ per MWh in 2050, down from 52.5€ per MWh in 2015.[3] On a positive note, the results indicate that even in the 'worst case' sensitivity, generation costs remain at 2015 levels, contradicting a commonly found fallacy that a large-scale introduction of renewables comes at an increase in electricity costs.

[3]Please note that these only represent the pure generation costs of electricity. Transmission, storage and infrastructure costs are not included in these numbers.

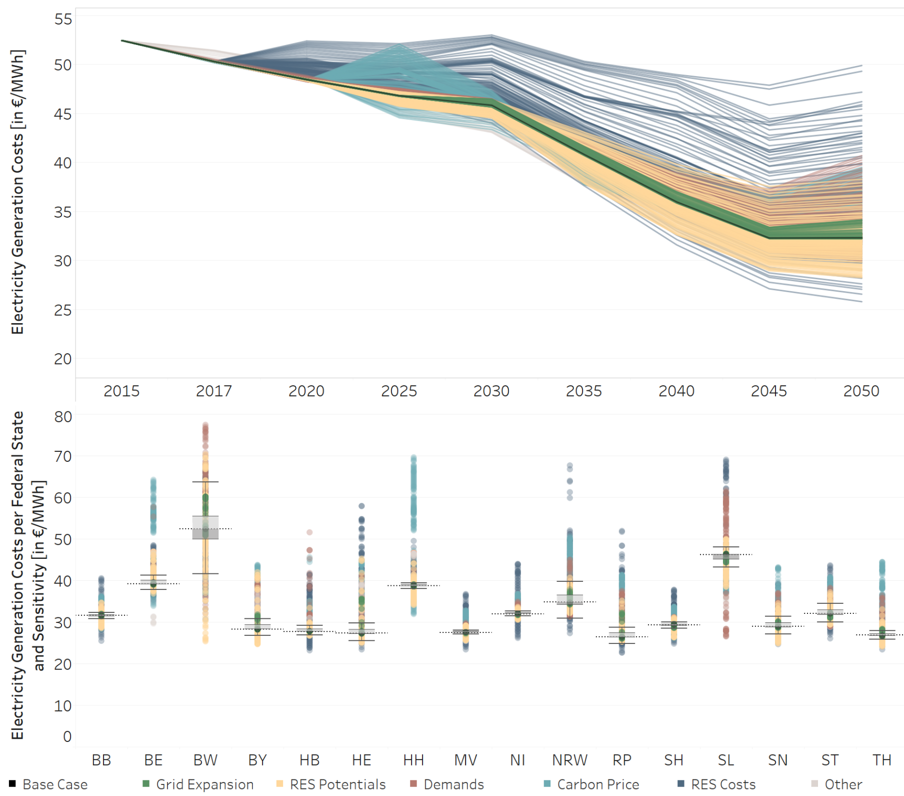

Figure 4: Average generation costs for electricity across all tested sensitivities. The top graph shows the development over time for Germany as a whole, the bottom graph shows the spread of electricity generation costs in 2050 per federal state.[4] The costs are displayed in € per MWh and do not factor in infrastructure costs.

3.2. Demands

One of the key drivers of the transformation of the energy system is the overall energy demand. This is especially true in a post-COVID world, dominated by economic recovery and green investments [71]. As outlined by Zaharia et al. [72], primary and final energy consumption are affected by a multitude of factors and for some of them conflicting results are found in the literature, which in turn highlights the importance of including energy demand in this sensitivity analysis.

Across all sensitivities, altering the various demands of the sectors proved to have one of the most significant effects with respect to various key indicators. On the one hand, increasing (or decreasing) the input demand consequently comes with and increase (or decrease) of final energy consumption in the respective

[4]The list of acronyms for the German federal states can be found in the Appendix.

sectors. On the other hand, the sectors react differently with respect to the share of energy provided by electricity based technologies. This effect is illustrated in Figure 5, where the range of results is shown for the case where only the electricity demand is being analysed (top) and the case where all sector demands are considered (bottom).

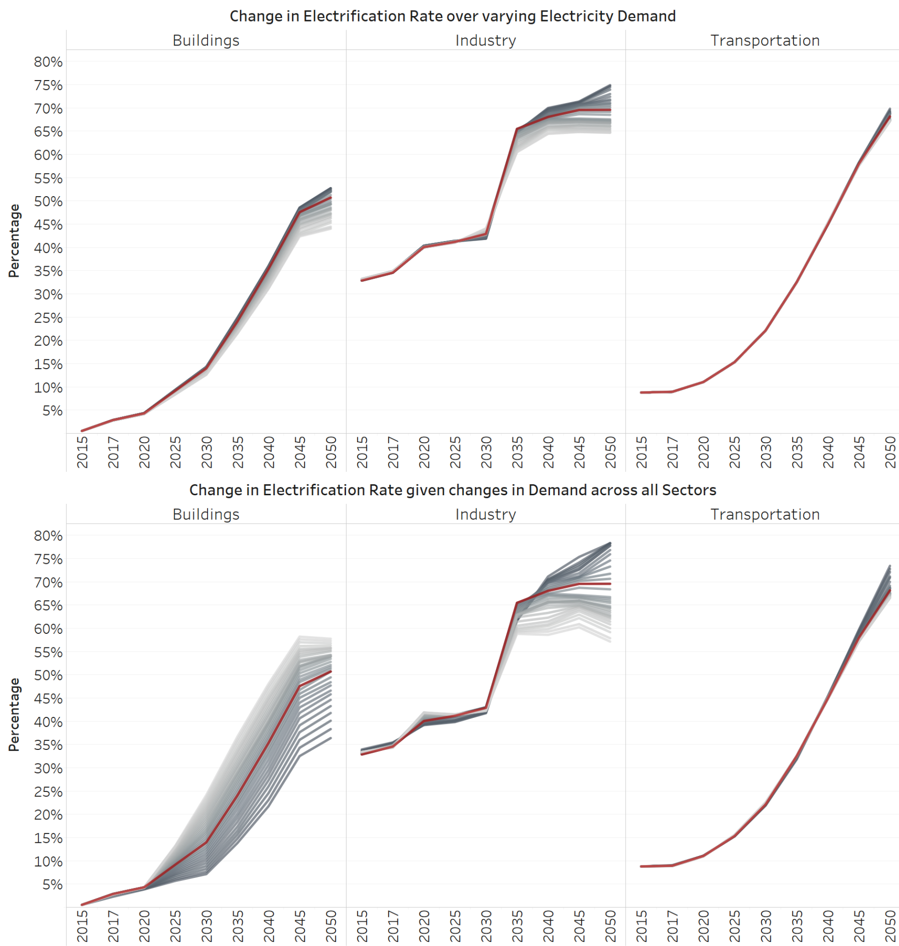

Figure 5: Changes in electrification rates by varying electricity demand in building, industry and transport sector (figure above). Changes in electrification rates by varying total energy demand in building, industry and transport sector (figure below).

The top half of the figure shows the industry sector being the one most affected by a change in the electricity demand. Less electricity demand means more electricity which can be used in other sectors and the industry sector seems to be the one where, despite the overall high level of the electrification rate, this effect is the strongest. In contrast, the other two sectors, transportation and buildings, show less variability in their electrification rate. This observation implies two aspects: First, the industry sector is the most difficult (or expensive in model terms) to electrify, as a reduction in available electricity leads to the reduction of electrification rate in the industry sector instead of the other two. Second, the sectors buildings and transportation seem to have reached a very stable state in the base case. Another observation is that the effect on the industry sector in 2050 is more or less symmetrical around our base case, while the buildings sector reacts stronger to an increase of electricity demand (reflected in the reduced electrification rate in the buildings sector) and the transportation sector is more affected, although only slightly, by decreasing electricity demand. These tendencies are amplified when analyzing the bottom half of Figure 5, where the range of results widens in general. The electrification rate in the transportation sector still seems to be less affected by varying demands than for the other two sectors. The buildings sector, on the flip side, now shows effects as early as 2025 which is caused by the installation of heat pumps at a rapid rate, regardless of the overall demand development.

Another indicator with significant results for the demand sensitivity is the amount of electricity production. In fact, out of all sensitivities, demands had the strongest effect on this indicator. As explained in the previous paragraph, all sectors experience significant rates of electrification and, therefore, electricity generation is strongly affected by demand changes across all sectors, as the overall electricity production is determined endogenous and consists electricity consumption for heating and transportation purposes as well as the residual power demand which is used for lighting, appliances, etc. The effects can be seen in Figure 6, which shows a wide range of outcomes where in 2050 the results range from 650 TWh to almost 1,200 TWh. An interesting development can be seen in the years 2020 - 2030 showing decreasing electricity production for the sensitivities with lower demand (darker shades). This can be explained by a slow uptake of electricity-based technologies across the sectors until 2030, such that the demand reduction dominates the additional power demand. In the later periods though, electricity becomes substantial in all sectors, overcompensating the demand reductions even in the most ambitious sensitivities.

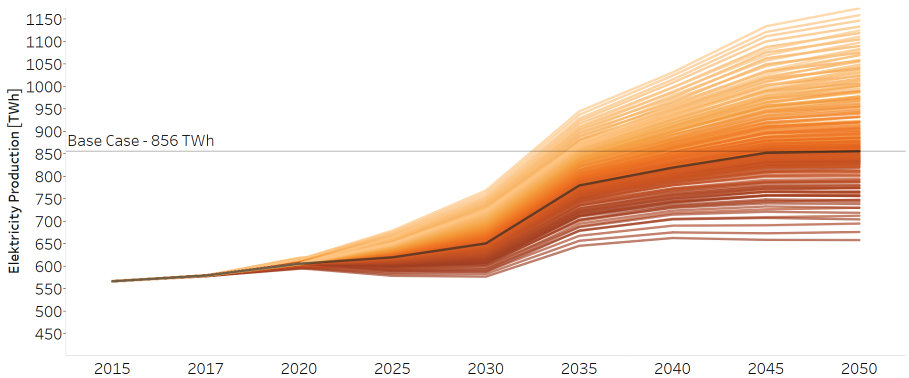

Figure 6: Effects of demand development sensitivities on electricity generation (in TWh).

3.3. Carbon price

As already outlined in Section 1.2, the discussion about a successful transformation of the German energy system sparked a debate about the dimension of an appropriate carbon price. Starting in 2021, Germany put in place a CO_2 price of 25 €/ton for the sectors heating and transportation (excluding aviation) which will increase up to 55 €/ton in 2025. After this 5-year period, a cap and trade system is planned with the amount of certificates being determined by agreed on climate targets. While leading research institutes in Germany deemed the general structure of the law to be a suitable tool in facilitating the *Energiewende*, the carbon price in particular was criticised in being too low to have a meaningful effect [68, 73]. This debate raises the need for a more in-depth analysis of the impacts of a carbon price on the German energy system transformation and through the sensitivity analysis on said instrument (as described in Section 2.4) light is shed on its effects on the different energy sectors.

To analyze the effects of a carbon price, the changes in the electrification rate of the different sectors will be analyzed again. For this modeling exercise, a uniform carbon price is assumed across all sectors disregarding possible slight differences between the German carbon price and the EU-ETS. Similar to the demand sensitivity, the transportation sector remains unaffected by a change in carbon price compared to a higher susceptibility observed in the buildings and especially the industry sector (Figure 7). This hints at higher difficulties for the decarbonization of certain parts of transportation, especially in freight transportation. While in the later years of the modeling period the effects in the industry sector are nearly symmetrical, a higher carbon price also shows effects in the earlier years, showing a massive uptake in electrification (and therefore mostly carbon free energy) caused by high carbon prices. Vice versa, a low carbon price leads to fossil fuels staying in the industry mix with only a small percentage being phased out until 2050. Overall, the results in the industrial sector in 2050 range from 55% to almost 80%. The buildings sector seems to be less affected which suggests that renovation rates (as in the demand sensitivity in Section 3.2) are more effective in electrifying the sector than a carbon price.

Moreover, a carbon price has less of an impact in the buildings sector in the long term since the potential of heat pumps is already exhausted to a high degree in the base case.

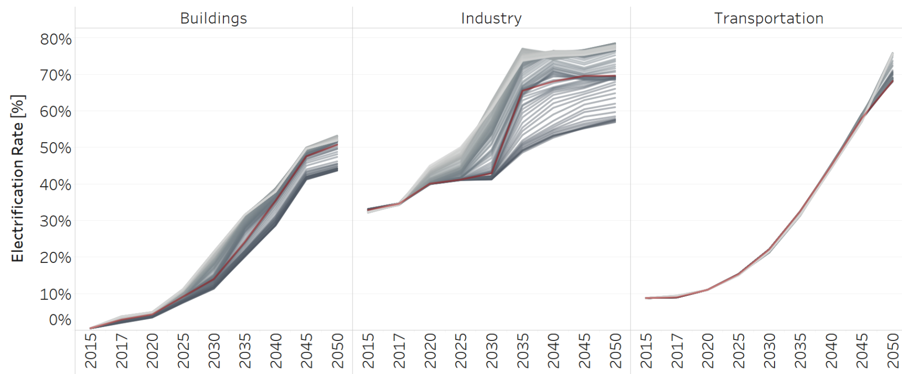

Figure 7: Effects of emission price sensitivities on the electrification rate across different sectors.

3.4. Hydrogen

Figure 8: Usage of hydrogen per sector (top) and usage of hydrogen per federal state in 2050 (bottom) by varying costs for breakthrough technologies.

Hydrogen offers a great potential for the decarbonization of the energy system, from being a storage medium in the electricity sector to replacing processes in industry, which are difficult to electrify, or powering vehicles, especially heavy-duty ones. The potential and effects of hydrogen and subsequently sector coupling where analyzed extensively by Ausfelder et al. [74]. In recent years, national and EU-wide hydrogen strategies were developed across the continent, with Germany labeling it a "key element in the transformation of the energy system" [75]. Therefore, in this paper the usage of hydrogen in the different sectors as well as the regional distribution of hydrogen consumption are discussed.

In general, a greatly varied hydrogen consumption can be observed, changing various input parameters. The hydrogen consumption in the transportation sector is particularly sensitive to varying costs for breakthrough technologies, as depicted by Figure 8. With highly reduced costs for hydrogen generating technologies, the consumption of hydrogen in the transportation sector nearly doubles, whereas the consumption in the industrial and buildings sectors stay close to base-case levels. In particular, significant cost reduction of fuel cell electric vehicles could lead to these vehicles being the dominant technologies for passenger cars, a field otherwise dominated by BEVs in the calculations. Freight transportation, on the other hand, is less sensitive and already in the base case relying heavily on hydrogen for road transportation.

With increased production of hydrogen and consequently its consumption, additional storage capacities for hydrogen are needed, as hydrogen is preferably produced in hours with excess renewable energy sources. Due to the late commercial availability of hydrogen transportation technologies, significant effects of changed breakthrough costs arise from 2035 on-wars, with 2025 and 2030 staying close to base-case levels for all sensitivities. With overall increased costs for breakthrough technologies, the overall consumption of hydrogen in all sectors decreases. However, even with the highest increase of breakthrough costs, small amounts of hydrogen are still used in the transportation sector, as for certain use-cases hydrogen poses a valid alternative for direct electrified transportation technologies or biofuels.

With the transportation sector being the main driver of hydrogen consumption, a correlation between population of the federal states and the respective hydrogen demand can be observed. The four most populated federal states (North Rhine-Westphalia, Bavaria, Baden-Wuerttemberg, and Lower Saxony) show both the highest over all demand as well as the highest sensitivity towards changing input parameters. Since these states are also the largest ones in terms of land-area, the potential for local production, storage, and consumption of hydrogen generated through renewable energies is substantial.

3.5. Renewable energy sources

Renewable energy sources are also a widely discussed topic regarding the low-carbon transition. While consensus has been reached that they are an important cornerstone to reduce emissions, there is widespread discussion about their optimal share in the energy mix, as well as about effects on e.g. power generation costs, energy security, or socio-economic factors such as jobs [76, 34, 77]. In this paper, two main uncertainties are discussed, the costs of renewables, and their potentials.

3.5.1. Costs of renewables

As already highlighted in section 3.1, the costs of renewable technologies largely influence future electricity generation costs. With a global political push away from fossil fuels towards renewables to fulfil set carbon reduction goals, RES are the only option for decarbonization apart from negative emission technologies (which themselves face huge uncertainties and risks [78, 79]). Therefore, their costs inevitably have a strong influence on overall costs and, therefore, cost-optimized model results. It can be observed that given an increase in solar and wind costs of the 'worst-case' scenario, electricity generation costs would almost stagnate at 2015 levels. An increase of wind costs influences results quite more significantly than that of solar, as shown in the upper part of Figure 9, which is in line with similar research in the field [11, 26]. The costs of wind turbines also significantly influence the amount of electricity trade within Germany, highlighting that solar energy potential is more evenly distributed across the regions compared to wing potential. While in the base case, the state of Lower Saxony proves to be a large net exporter of electricity (especially to the densely populated state of North-Rhine-Westfalia), an increase of wind costs leads to a more even distribution of electricity generation across Germany, but at a noticeably higher cost. Offshore wind plays a large role here, as Lower Saxony has abundant wind-rich coastal areas. However, even in a worse case characterized by RES costs higher than the ones assumed, although not declining, generation costs would not see an increase when compared to 2015 levels, which is a strong argument for RES as a no-regret option concerning future energy supply.

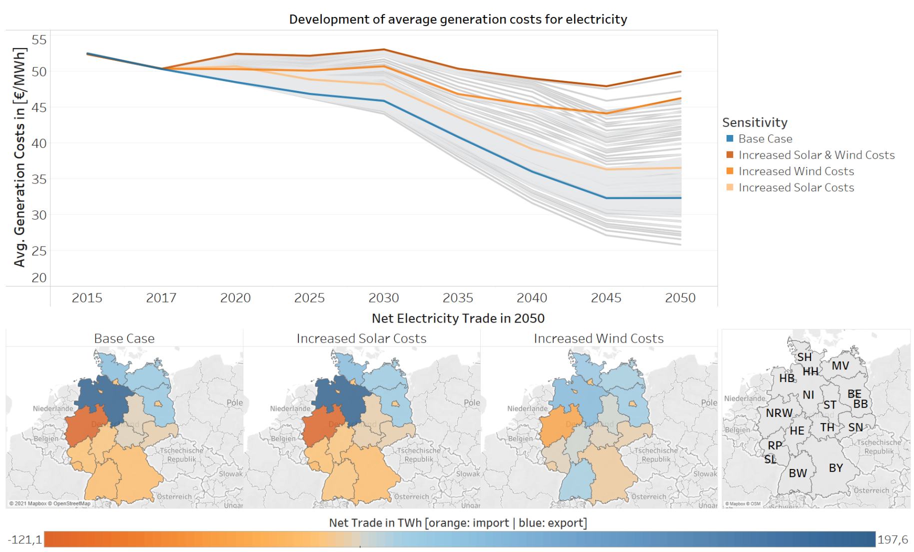

Figure 9: Development of average generation costs for electricity (top) and net trade of electricity in 2050 (bottom). Electricity generation costs in € per MWh, net trade in TWh.

3.5.2. Renewable energy potentials

Another commonly discussed topic is that of renewable potential. While the technical potential is usually quite abundant, economic viability and political barriers often significantly reduce these potentials. Policies such as the 10H rule as e.g. applied in Bavaria[5] shrink the available surface area for renewable installations. Especially wind turbines often face public acceptance issues, frequently related to the not-in-my-backyard phenomenon [80]. The sensitivity runs underline that importance, especially regarding the resulting cost-optimal technology mix and the distribution of installed capacities across Germany. Figure 10 shows the change in installed capacity for offshore and onshore wind, as well as solar, for each federal state. Overall, it can be observed that especially an increase in usable solar potential leads to more spread out PV installations and less offshore expansion in the three northern federal states. A similar effect can be noticed when onshore potentials are increased, albeit to a lesser extent, where offshore wind is reduced, mainly in Lower Saxony, in favor for onshore wind turbines across most parts of northern Germany. This hints at the role of wind onshore and solar gaining in importance and eliminating the need for baseload production offered by offshore if potentials were to increase, be it due to technological or regulatory developments.

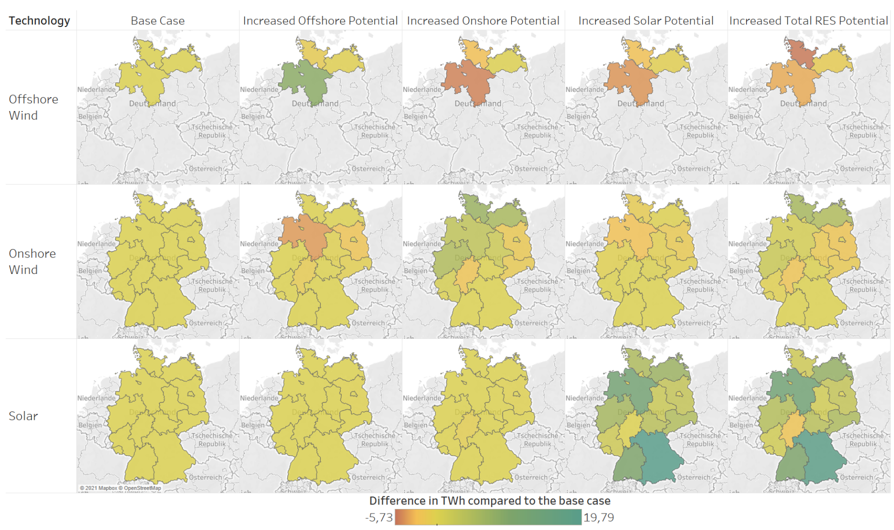

Figure 10: Electricity generation per federal state for offshore, onshore, and solar relative to the base case. Red color indicates less production than in the base case, yellow indicates no change, and green indicates an increase in generation.

[5]The 10H rule states that a wind turbine needs to be at least 10 times it's height from any populated area.

Increasing all renewable potentials simultaneously results in the similar picture as only increasing solar PV potentials. This highlights that PV potentials seem to be a binding constraint in a number of federal states. Cross-referencing the results of said sensitivity shows a more decentralized German electricity system relying more heavily on solar and onshore wind, instead of large-scale offshore facilities in the Northern Sea. This also drastically reduces the need for new transmission capacities. Combined with an increase in the usable PV potential, if at all possible, a chance for a more distributed low-carbon transition across the country can be seen.

4. Conclusion

This paper uses the open-source energy system model GENeSYS-MOD to provide insights into key uncertain factors of the German low-carbon transition. For this, the newest version of GENeSYS-MOD has been used and adapted to Germany at a federal state level. A base case was defined as a reference for the exploratory sensitivity analysis. In total, 1591 sensitivities across 11 key influential factors have been computed. This allows for not only one singular pathway to be obtained, but a whole *scenario corridor*, highlighting the change in results with underlying changes of input assumptions. Therefore, it is possible to identify the most influential factors on the German *Energiewende* and how this translates to possible chances and potential barriers, depending on how the underlying parameters actually develop in the future. With such an exploratory sensitivity analysis, a wide view on possible pathways for the future of the German energy system can be obtained.

Results show that especially demand reduction plays a tremendous role in the process of reaching climate targets. Across all analyzed result values, changes in final energy demand heavily impacted the model results to achieve ambitious reduction targets by 2050, with an especially pronounced effect in the buildings sector. Also, the costs and available potentials of RES have a significant impact on generation costs, necessity of grid expansion, and the distribution of generation capacity across Germany. The choice of a price on emissions has a noticeable effect in the near to intermediate future, heavily reducing cumulative emissions since action is taken sooner, especially in the industrial sector. The costs of hydrogen are another noteworthy finding of this study: While usually mostly seen as a use-case in long-distance freight transportation and aviation, decreasing costs of hydrogen might open up usage across large parts of the transportation sector, including fuel-cell electric vehicles in passenger transport.

In general, it can be seen that an increase in energy efficiency, along with consumer-level demand behavior changes (e.g. in transport), could drastically help with the fulfilment of climate goals. However, further reductions of demands and an increase in sufficiency might be helpful to reach climate goals. Furthermore, a carbon price proves to be an efficient tool to reduce emissions in the buildings and industrial sectors. In these sectors a higher carbon price drastically improves overall electrification rates. Hence, the establishment of higher carbon prices in the near term could significantly reduce emissions and boost investment into renewable technologies. Nevertheless, the carbon price in this model can also be seen as a proxy for other climate policies that prove to be efficient in reducing emissions as well. As shown in our analysis, hydrogen and increased power trade capacities have also substantial potentials in decreasing emissions, although both show less effects on emission reduction than a decrease in demand. Overall, large-scale investments into renewable energies and storages are a no-regret-option for climate targets and often prove to be minimum requirements for other technologies.

Summing up, given the large amount of uncertainty in the results of energy system models, an extensive exploratory sensitivity analysis can produce meaningful insights. The spread in general results, as well as in effects for each parameter variation can be analyzed, giving an overview of key influential factors. For the analyzed German case study a reduction of 88% by 2050 (compared to 1990) was calculated, clearly missing the German (and European) target of climate neutrality. The obtained sensitivity pathways (changing always just one parameter) reach reduction values of 75 - 95% - showing that additional efforts in more than one domain are needed to allow for a faster decarbonization pathway. Thus, one can only underline the importance of immediate action that needs to undergo for the low-carbon transition to succeed. However, since many of the uncertain factors such as technological innovation, resource availability, and international trade (e.g. for hydrogen) go beyond the scope of a country-level analysis, further research should also look at implications on a global scale. Additionally, an expansion of the scope of the analysis, e.g. by broadening the range of analyzed sensitivities to also include socio-economic factors (such as behavioral aspects) would be beneficial. This would allow for a more holistic view over possible challenges, especially from a non-technical viewpoint. A further analysis could also inspect possible interdependencies and interactions between the different key factors, since this paper only focuses on the factors *ceteris paribus*. Finally, a combination and comparison of exploratory sensitivity analyses with Monte-Carlo simulation methods could provide additional insights on both effect on obtained results, but also on topics such as computational and model requirements.

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Appendix A: 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 targets, integration of renewables, and sector-coupling. The model minimizes the objective function, which comprises total system costs (encompassing all costs occurring over the modeled time period) [7, 58].

The GENeSYS-MOD framework consists of multiple blocks of functionality, that ultimately originate from the OSeMOSYS framework. Figure 11 shows the underlying block structure of GENeSYS-MOD v2.9, with the additions made in the current model version (namely the option to compute variable years instead of the fixed 5-year periods, as well as an employment analysis module, in addition to the regional data set and the inclusion of axis-tracking PV).

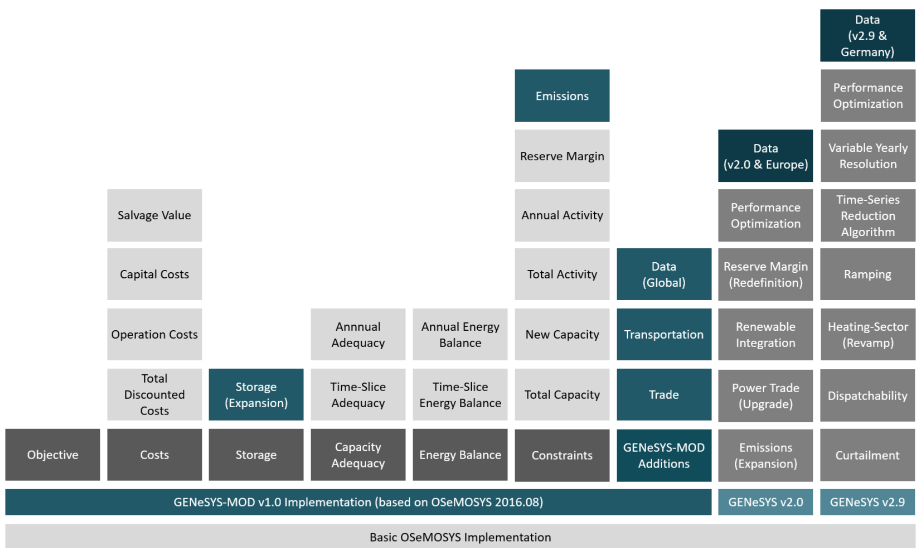

Figure 11: Model structure of the GENeSYS-MOD implementation used in this study.

(Final) Energy demands and weather time series 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.[6] Additional demands through sector-coupling are derived endogenously. Constraints, such as 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), emission budgets (given either yearly or as a total budget over the modeled

[6] GENeSYS-MOD offers various storage options: Lithium-ion and redox-flow batteries, pumped hydro storages, compressed air electricity storages, gas (hydrogen and methane) storages, and heat storages.

horizon) are given to ensure proper functionality of the model and yield realistic results.

The GENeSYS-MOD v2.9 model version used in this paper uses the time clustering algorithm described in Gerbaulet and Lorenz [81] and Burandt et al. [59], with every 73$^{\mathrm{rd}}$ hour chosen, resulting in 120 time steps per year, representing 6 days with full hourly resolution and yearly characteristics. The years 2017-2050 are modeled in the following sequence: 2017, 2022, 2025, 2030, 2035, 2040, 2045, 2050. All input data is consistent with this time resolution, with all demand and feed-in data being given as full hourly time series. Since GENeSYS-MOD does not feature any stochastic features, all modeled time steps are known to the model at all times. There is no uncertainty about e.g. RES feed-in.

The model allows for investment into all technologies and acts purely economical when computing the resulting pathways (while staying true to the given constraints). It usually 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).

For more information on the mathematical side of the model, as well as all changes between model versions, please consult [58, 7, 82, 59].

Appendix B: Selected input data

This section of the Appendix displays the key financial and technical assumptions that have been used for this study. Fore a more detailed description of all relevant input data, please refer to Burandt et al. [82].

Regional potentials for utility-scale solar PV, onshore wind, and offshore wind in GW.

Region	**Solar PV**	**Wind Offshore**	**Wind Onshore**	**Total**
BB	27.66	0.00	13.00	40.66
BE	4.08	0.00	0.30	4.38
BW	49.89	0.00	23.00	72.89
BY	81.27	0.00	41.00	122.27
HB	1.27	0.00	0.20	1.47
HE	27.34	0.00	14.00	41.34
HH	2.89	0.00	0.30	3.19
MV	20.05	6.55	11.00	37.60
NI	57.22	49.81	26.00	133.03
NRW	61.44	0.00	20.00	81.44
RP	23.83	0.00	12.00	35.83
SH	19.01	28.64	9.00	56.64
SL	4.36	0.00	2.40	6.76
SN	20.62	0.00	10.00	30.62
ST	19.71	0.00	7.40	27.11
TH	15.77	0.00	7.50	23.27
Total	**436.40**	**85.00**	**197.10**	**718.50**

Source: Bartholdsen et al. [22]

Capital cost of power generation and transformation technologies in €/kW.

	2015	2020	2025	2030	2035	2040	2045	2050
Renewables								
PV Utility	1000	580	466	390	337	300	270	246
PV Rooftop [commercial]	1360	907	737	623	542	484	437	397
PV Rooftop [residential]	1360	1169	966	826	725	650	589	537
CSP	3514	3188	2964	2740	2506	2374	2145	2028
Onshore Wind	1250	1150	1060	1000	965	940	915	900
Offshore Wind [shallow]	3080	2580	2580	2580	2330	2080	1935	1790
Offshore Wind [transitional]	3470	2880	2730	2580	2480	2380	2330	2280
Offshore Wind [deep]	4760	4720	4345	3970	3720	3470	3370	3270
Hydro [large]	2200	2200	2200	2200	2200	2200	2200	2200
Hydro [small]	4400	4480	4490	4500	4500	4500	4500	4500
Biomass Power Plant	2890	2620	2495	2370	2260	2150	2050	1950
Biomass CHP	3670	3300	3145	2990	2870	2750	2645	2540
Biomass Power Plant + CCTS	4335	3930	3742	3555	3390	3225	3075	2925
Biomass CHP + CCTS	5505	4950	4717	4485	4305	4125	3967	3810
Geothermal	5250	4970	4720	4470	4245	4020	3815	3610
Ocean	9890	5095	4443	3790	3083	2375	2238	2100
Conventional Power Generation								
Gas Power Plant (CCGT)	650	636	621	607	593	579	564	550
Gas CHP (CCGT)	977	977	977	977	977	977	977	977
Oil Power Plant (CCGT)	650	627	604	581	558	535	512	490
Hard coal Power Plant	1600	1600	1600	1600	1600	1600	1600	1600
Hard coal CHP	2030	2030	2030	2030	2030	2030	2030	2030
Lignite Power Plant	1900	1900	1900	1900	1900	1900	1900	1900
Lignite CHP	2030	2030	2030	2030	2030	2030	2030	2030
Nuclear Power Plant	6000	6000	6000	6000	6000	6000	6000	6000
Transformation & Storage								
Electrolyzer	800	685	500	380	340	310	280	260
Methanizer	492	421	310	234	208	190	172	160
Fuel Cell	3570	2680	2380	2080	1975	1870	1805	1740
Li-Ion Battery	490	170	155	140	140	140	140	140
Redox-Flow Battery	1240	810	770	730	520	310	310	310
Compressed-Air Energy Storage	600	600	565	530	520	510	480	450

Source: Carlsson et al. [83], Gerbaulet and Lorenz [81], and Ram et al. [9].

Variable costs for transformation and storage technologies, in M€/PJ.

	2015	2020	2025	2030	2035	2040	2045	2050
Electrolyzer	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Methanizer [synthetic gas]	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Methanizer [biogas]	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28
Fuel Cell	11.11	6.94	6.67	6.39	5.42	4.44	4.44	4.44
Li-Ion Battery	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
Redox-Flow Battery	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Compressed-Air Energy Storage	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33

Source: Carlsson et al. [83].

Input fuel efficiency for common conventional power plants.

	2015	2020	2025	2030	2035	2040	2045	2050
CCGT (Natural Gas)	58%	60%	61%	62%	62%	62%	63%	63%
CCGT (Oil)	38%	38%	39%	39%	40%	40%	41%	41%
Hard coal	45%	46%	47%	48%	48%	48%	48%	48%
Lignite	42%	45%	46%	47%	47%	47%	47%	47%
Nuclear	37%	37%	38%	38%	40%	42%	42%	42%

Source: Carlsson et al. [83].

Fuel prices of fossil fuels in M€/PJ.

	2015	2020	2025	2030	2035	2040	2045	2050
World Prices								
Hard Coal	1.83	2.02	2.00	1.87	1.83	1.79	1.75	1.71
Lignite	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36
Natural Gas	5.97	6.11	6.25	6.45	7.00	7.54	8.09	8.74
Uranium	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82
Oil	6.99	4.82	7.26	9.64	9.64	9.64	9.64	9.64

Source: World Bank Commodity Price Forecasts 2020.

Appendix C: German federal states

Table 2: Acronyms for German federal states.

GENeSYS-MOD	ISO 3166-2:DE	German Federal State
BW	DE-BW	Baden-Württemberg
BY	DE-BY	Bavaria
BE	DE-BE	Berlin
BB	DE-BB	Brandenburg
HB	DE-HB	Bremen
HH	DE-HH	Hamburg
HE	DE-HE	Hesse
MV	DE-MV	Mecklenburg-Vorpommern
NI	DE-NI	Lower Saxony
NRW	DE-NW	North-Rhine-Westfalia
RP	DE-RP	Rhineland-Palatinate
SL	DE-SL	Saarland
SN	DE-SN	Saxony
ST	DE-ST	Saxony-Anhalt
SH	DE-SH	Schleswig-Holstein
TH	DE-TH	Thuringia

Appendix D: Base case results

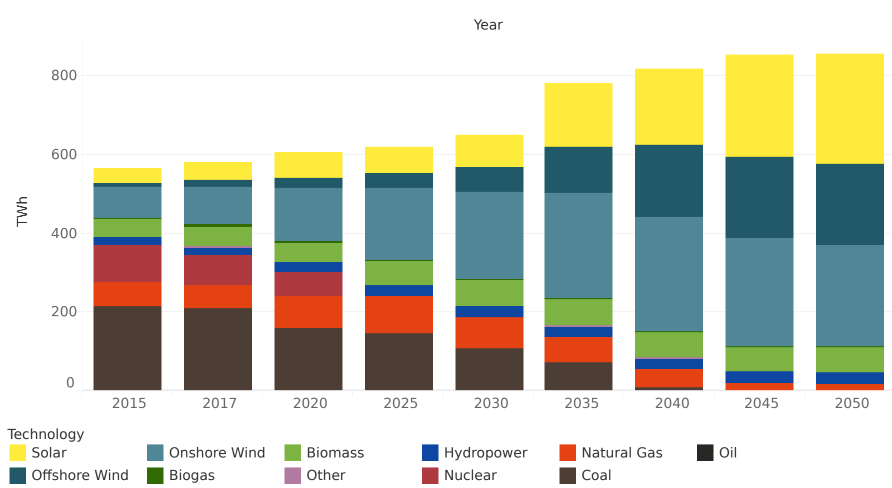

Figure 12: Power generation per year and technology in the base-case.

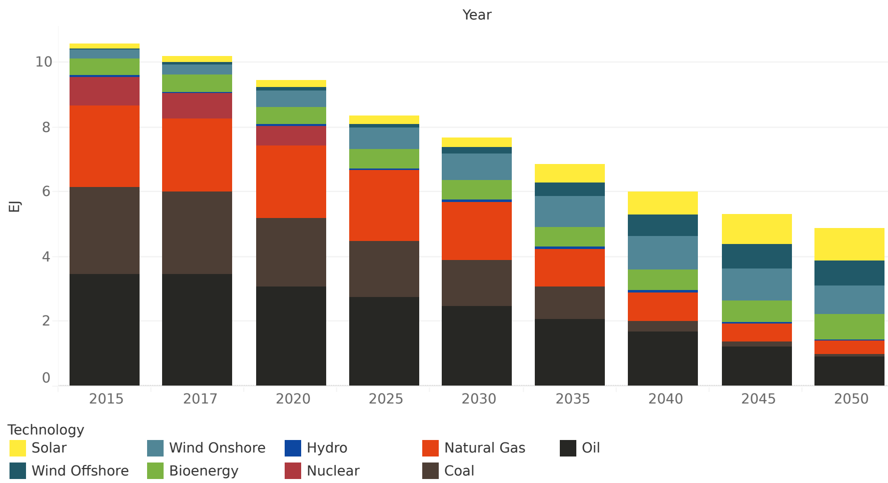

Figure 13: Primary energy demand per year and fuel in the base-case.

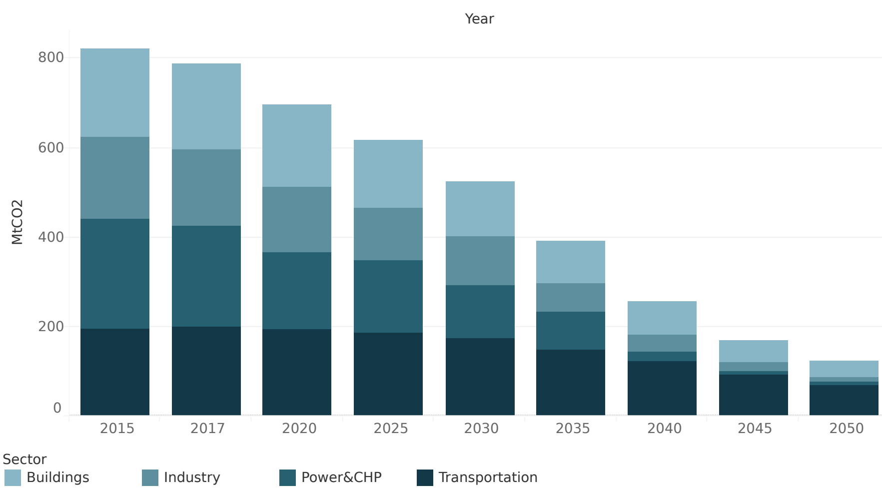

Figure 14: Emissions per sector and year in the base-case.

Appendix E: Supplementary material

The supplementary material to this paper, including input data tables and additional results can be found at the Zenodo repository 'GENeSYS-MOD Germany: Technology, demand, and renewable data' [84].