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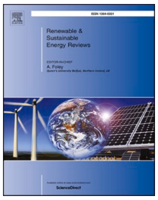

Comparing open source power system models - A case study focusing on fundamental modeling parameters for the German energy transition

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ABSTRACT

Recent European and German climate targets call for a faster power system transition towards variable renewable energy sources. With the increasing importance of Open Science, several Open Source models have been developed in recent years. However, only a few studies exist that compare their performance against each other. Therefore, this study performs a comprehensive model comparison of five mature Open Source power sector models. For this purpose, we apply eight fully harmonized and simplified one-year scenarios for the German power sector, to analyze deviations in model results. First, an in-depth analysis of two base scenarios for 2016 and 2030 reveals that linear programming-based models differ substantially from models with pre-implemented dispatch orders. Other deviations occur across all models and are mainly caused by the indifferent use of flexibility options such as storage and transmission. Second, variations of parameters and characteristics with a political significance are individually applied to the 2030 base scenario to identify their impact on model results. This includes CO_2 emission budgets, increased demands by sector coupling, coal exit strategies, and renewable generation shares. The results prove that some models are far more sensitive to these parameters than others, and renewable generation shares alone are not sufficient to reach desired effects in emission reductions. Finally, a comprehensive scenario for 2030 combines all measures to evaluate general trends that result from the most recent updates in German energy policy. Model results indicate that the new targets require substantially increased investments into renewable generation capacities, storage, and transmission.

1. Introduction

The European Climate Law as part of the European Green Deal paves the path to climate neutrality by 2050. A central target is the reduction of greenhouse gas (GHG) emissions of at least 55% until 2030 compared to 1990 levels [1]. To meet these European targets, Germany as a European Union (EU) member state is constantly adjusting its climate action plans. A 2021 study by an influential think tank in Germany proposed to even go beyond EU regulations to reach climate neutrality five years earlier by 2045 [2]. The German government has adopted this target shortly after its publication, including a reduction of GHG emissions of at least 65% until 2030 [3].

To reach the necessary emission reductions, the German energy system needs to transition from fossil fuels towards renewable energy sources. However, in 2019 only a small share of 17.4% of the German gross energy consumption was covered by renewable energy sources [4]. This picture changes when focusing solely on the power sector. The

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List of abbreviations

API	application programming interface
C2D	charge-to-discharge
CC	combined cycle
CHP	combined heat power
E2P	energy-to-power
EU	European Union
GENESYS-2	Genetic Optimization of a European Energy Supply System
GENeSYS-MOD	Global Energy System Model
GHG	greenhouse gas
HVDC	high voltage direct current
LOPF	linear optimal power flow
LP	linear programming
MILP	mixed-integer linear programming
oedatamodel	Open Energy Data Model
oedb	Open Energy Database
oemof	Open Energy Modeling Framework
OEP	Open Energy Platform
OS	Open Source
OSC	Open Source community
OSPSM	Open Source power system models
OSS	Open Source software
PV	photovoltaics
TREQ	transparency, reproducibility, and quality
VRE	variable renewable energy

renewable share of gross electricity generation reached 42% in 2018 [4]. Despite this achievement, the power sector only accounted for 20.6% of the total energy consumption in 2018 [5]. For the decarbonization of all sectors, the power sector will become more and more important. Its share of the total energy consumption is expected to rise in the coming decades with the emergence of sector coupling through electrification options in the other energy sectors. For a scenario reaching 100% renewable energy supply, it is estimated that the current yearly electricity demand will almost double to over 1000 TWh [2]. Decarbonizing the power sector primarily demands an extensive expansion of variable renewable energy (VRE) generation capacities. The main renewable energy sources available in Germany are solar photovoltaics (PV), wind onshore, and wind offshore. In recent scenario calculations from several studies, their assumed potential varies between 99-550 GW, 83–180 GW, and 20–70 GW, respectively [2,6,7]. To bring demand and supply from these VRE sources into balance, additional flexible technologies are required. Storage systems can serve this purpose by shifting energy in time. A study estimates that the storage capacity demand for Germany needs to be substantially increased in systems with high shares of renewable generation [8]. In addition to temporal flexibility, the power system requires spatial flexibility. The efficient distribution of local generation from VRE demands a substantial expansion of electricity grids. On a European level, the expansion of transmission capacities between countries plays an important role. However, for Germany, already substantial transmission capacities exist to neighboring countries and therefore they only need to be expanded by small margins towards 2050 [9]. On a local level within Germany, however, transmission capacities have to be greatly expanded to balance geographically distributed generation from VRE sources [10].

1.1. Towards EU and German climate policy goals

The Paris climate agreement from 2015 sets ambitious goals regarding the reduction of GHG emissions for countries around the world [11]. Consequently, the EU is in charge to ensure that all its member states take the appropriate actions to achieve the agreed targets. As a major cornerstone of European climate politics, the European Green Deal aims at transforming the EU towards, among others, climate neutrality in 2050 [12].

To address this pledge towards climate protection and neutrality, the German government adopted the climate protection act in 2020 [13]. Among others, the government planned to reduce primary energy consumption by 50% compared to 2008 levels, aiming for 65% and 80% renewable shares in gross electricity production by 2030 and 2050, respectively [14]. Regarding GHG emissions, targets were set to reduce emissions by 55% until 2030 and achieve 80–95% reduction or even carbon neutrality by 2050 compared to 1990 levels [13]. In April 2021, however, the 2020 climate protection act was partly deemed to be unconstitutional by the federal constitutional court as it infringes Basic Law [15]. The act lacked clarity on measures of how the goals should be achieved beyond 2030 and disproportionately put the burden of emission reduction on future generations [15]. Consequently, an update was enacted that raised the GHG reduction targets for 2030 and 2040 to 65% and 88%, respectively, and aimed for carbon neutrality by 2045 [16]. Additionally, GHG reduction targets for the different sectors (energy, industry, transport, buildings, agriculture, and others) until 2030 were redefined, especially increasing the pressure on the energy sector.

Still, some of the German climate targets, such as the share of renewable generation in gross electricity production, were ranked as 'highly insufficient' to achieve the Paris Agreement goal to limit global warming to well below 2 °C by 2050, according to [17]. Several studies already highlight the viability of an energy system based on 100% renewable energy, focusing on the rapid expansion of renewable power generation capacities and sector coupling [18–20]. As a consequence, the newly appointed government, which was elected in December 2021, agreed on much more ambitious climate targets for the year 2030, like increasing the share of renewable energy in gross electricity production to 80%, aiming for a phase-out of all coal power plants, and increasing the number of electric vehicles to 15 million [21]. While the new government aims to put Germany on a pathway compatible with a 1.5 °C climate target [21], various experts and institutes already pointed out the insufficiency of the agreed measures [22,23].

1.2. Challenges in power system modeling

Power system models, which are a subset of energy system models, have proven to be useful tools in helping decision-makers to take concrete steps to, among others, define renewable and emission reduction targets. Therefore, it is expected that they can deliver reliable and robust results of the highest quality. Despite most models being capable of answering a wide range of policy questions, there are many obstacles in complexity, transparency, and standardization [24] that still need to be addressed. Consequently, a strong movement within the research community has emerged that can be summarized as Open Science practices. Open Science practices contribute to increasing transparency, reproducibility, and quality (TREQ) of software-based research [25]. Open Source software (OSS) is a prerequisite of Open Science and has led to the development of a large number of Open Source power system models (OSPSM) within recent years. The Open Source (OS) approach aims to accelerate the availability of the latest modeling approaches and to guarantee high-quality results. Another important aspect of OS is that it encourages greater collaboration between modelers with different backgrounds [26], thus improving the quality of the power system models through the re-use of data and source code. The potential for greater transparency and availability achieved through OS is increasingly recognized as a fundamental aspect of funded science.

Consequently, funding agencies such as the EU Commission or the German Federal Ministry for Economic Affairs and Energy have increasingly promoted Open Science practices in recent years.

Since power systems and their future concepts become more and more complex, new diverse modeling approaches aim to improve performance and results [24]. At the same time, it becomes increasingly difficult to keep up with the latest model developments from a policy perspective. For this reason, several studies compare different power system models [24,27–34] most of which are not Open Source. They can be grouped into two main categories. The first group of studies [24, 27–32] exclusively focuses on differences in modeling approaches of power system models from a theoretical point of view. This includes mathematical formulations, spatial and temporal resolutions, applicability, and others. Groissböck [30] especially focuses on OS versus commercial models, confirming the maturity of Open Source. The second, smaller group of studies [33,34] performs a scenario analysis to compare the results of different power system models. While Siala et al. [34] compare model features like type (optimization, simulation) and resolution (temporal, spatial) in a European decarbonization pathway scenario towards 2050, Gils et al. [33] analyze model load balancing and sector coupling with single year scenarios for 2050 in Germany. In both groups, only the minority of the models used are Open Source. More information about the studies' main findings is summarized in Table 1. We conclude that in literature, a comprehensive Open Source comparison of solely OSPSM with a detailed scenario set-up and fully harmonized input data set does not exist to the best of our knowledge.

1.3. Contributions

With our work, we aim for a profound comparison of five OSPSM by modeling the transition of the German power system with eight single-year scenarios. The selection of contributing models is characterized by a variety of modeling approaches that allow for well-founded model comparison. However, our scenario set-up is chosen to go beyond a simple comparison. With the variation of key modeling parameters and characteristics, that are relevant to model policy-relevant targets, we aim to evaluate their influence on optimal system configurations for all participating models. Furthermore, the proposed policy targets for 2030 by the new German coalition, which was elected in December 2021, are applied in all models to show overall trends that may arise for the optimal system. However, it is important to note, that with our scenario scope and analysis we do not intend to evaluate any of the political measures and targets in-depth, since simplifications of our models in terms of the harmonization process are inevitable. To address the challenge of data harmonization, we use a novel OS data model connected to the Open Energy Platform (OEP) database [35], which serves as a central repository for accessing the scenario data and uploading the results. Scenario data, modeling results, as well as the connectors between the participating OSPSM and the OEP, are made publicly available to emphasize the Open Science characteristics of this study.

2. Scenario definition and methodology

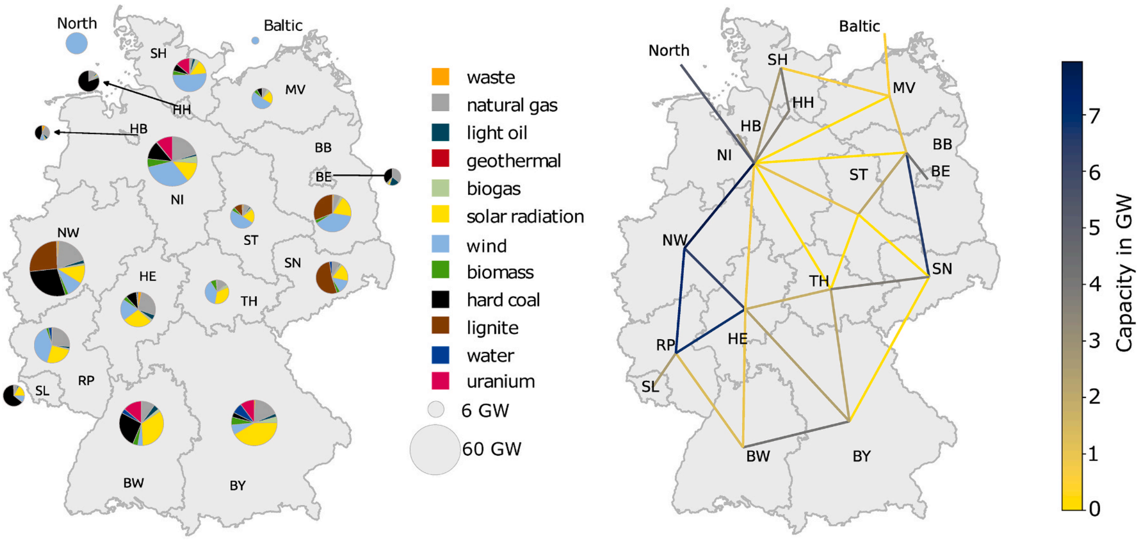
In our model comparison, we focus on the transition of the German power system by applying eight one-year scenarios to five selected OSPSM. Subsection 2.1 presents the definition of the scenarios and highlights modeling choices. The contributing OSPSM and their respective model configurations are described in Subsection 2.2. In Subsection 2.3 we explain our model and data harmonization procedure in detail.

2.1. Scenario definitions

The geographical scope of all scenarios in this study is Germany, which is made up of 16 federal states. The historical generation capacities for each federal state in 2016, obtained from MaStR [36], build the foundation for all scenarios (brownfield approach). Fig. 1a illustrates the generation capacities in each state categorized into primary input energy. In addition to generation capacities, the data set consists of basic techno-economic power plant characteristics, which include efficiencies, costs, and lifetimes. The federal states are further interconnected with AC-transmission lines. Their capacities are calculated using historical data from SciGrid [37] and Platts [38] (Fig. 1b). Moreover, we define a transmission line to offshore wind farms in the North Sea (North-link) and offshore wind farms in the Baltic Sea

Table 1
Overview of scientific publications that compare OS energy system models.

Group I	Ref.	Total models in study	Of which are OS
Cebulla et al. investigate the influence of LP and MILP power plant modeling on storage deployment and expansion in an energy system with a high share of renewables. They find that LP modeling leads to a lower storage expansion and utilization compared to MILP and that MILP modeling is superior in considering storage realistically.	[27]	1	0
Ringkjøb et al. review 75 modeling tools to provide an updated overview of their theoretical potentials and differences using a category system. They identify future challenges amongst others openness and transparency.	[28]	75	24
Gacitua et al. theoretically review planning models for power generation expansion and their suitability for energy policy analysis. They highlight methodological differences and modeling challenges.	[29]	21	4
Groissböck reviews OS energy system optimization tools on 81 functions for their maturity. He concludes that OS tools have a high quality, but just like commercial programs, they need to constantly adapt to the challenges of new energy systems.	[30]	31	26
Savvidis et al. examine model comparison schemes and propose a set of comparison criteria to cluster energy policy questions to quantify the gap between model capabilities and policy questions. They identify lagging model features and set priorities for future energy system modeling funding.	[24]	41	14
Ridha et al. review 145 energy system models regarding their complexity and cluster them on their purpose and underlying research questions.	[31]	145	n/a
Klemm et al. evaluate existing energy system modeling tools and identify typical model characteristics to optimize city-level systems. They introduce a category system and conclude that only a fraction of the models are suitable for energy system optimization at the city level.	[32]	13	5
Group II			
Gils et al. present a systematic model experiment on a German case study. In addition to theoretical model differences, they strive to link result differences to model differences and quantify their impact. Due to the nature of their experimental design, this is difficult to do and future modeling decisions are deduced to enable this.	[33]	4	1
Siala et al. conduct a model experiment to assess the impact of four major model features on the results. The impact of each feature is analyzed in an isolated experiment and a high level of data harmonization is applied.	[34]	5	1



a) generation capacities b) transmission capacities

Fig. 1. Historical generation and transmission capacities in 2016 that are the basis of all scenarios. The federal states are: Brandenburg (BB), Berlin (BE), Baden Wurttemberg (BW), Bavaria (BY), Bremen (HB), Hessen (HE), Hamburg (HH), Mecklenburg West Pomerania (MV), Lower Saxony (NI), North Rhine Westphalia (NW), Rhineland Palatinate (RP), Schleswig-Holstein (SH), Saarland (SL), Saxony (SN), Saxony Anhalt (ST), and Thuringia (TH).

(Baltic-link). Transmission interconnections with neighboring countries are not considered in the scenario set-up. However, exogenous historical and future hourly export and import trades with neighboring countries are taken from the European power system model calculated in [39] and are added to (or subtracted from) the demand of adjacent federal states. Existing capacities for batteries and pumped hydro storage in 2016 are included in the base set-up of all scenarios. Fig. 1 summarizes the base set-up while Table 2 gives an overview of the modeled technology portfolio. Access to the full input data set and data sources are provided in the data availability section of this manuscript.

By adding additional constraints to the base set-up, we create specific scenarios for the model comparison for the years 2016 and 2030 (Fig. 2). In all scenarios, hourly electricity demands are taken from [40,41]. For 2030, this includes future exogenous demands from the (partial) electrification of the industry, buildings, and transportation sectors (Fig. 3). Expansion potentials for solar PV and onshore wind are calculated by using the pyGRETA tool [34] by aggregating high-resolution spatial data for each German federal state. This calculation is based on MERRA-2 Reanalysis weather data from 2017 and it uses geospatial data for the land use (cropland, settlement, marsh, etc.), topography, slope, and distances to urban regions. For the offshore wind expansion, a limit of 50 GW is set, which is a conservative assumption and slightly lower than the limit given in [7]. We assume that all those renewable potentials can be fully exploited by 2030 and do not consider any limiting factors. For CO_2 prices, in a conservative assumption already adopted political targets in Germany are linearly extrapolated, which corresponds to a CO_2 price of 70 €/t for all 2030 scenarios. Additionally, we implement overall CO_2 budgets for each year as stated in the recent climate law of the German federal government (Subsection 1.1) with a budget of 98 Mt CO_2 in 2030. Furthermore, for 2030 we include three currently planned and already partly built high voltage direct current (HVDC)-transmission lines [42–44]. These grid interconnections are built from Lower Saxony (NI) to North Rhine Westphalia (NW), from Schleswig Holstein (SH) to Baden-Wurttemberg (BW), and from Saxony Anhalt (ST) to Bavaria (BY) with a capacity of 2 GW, 4 GW, and 2 GW, respectively.

Table 2
Overview of the modeled technology portfolio.

Energy conversion		Storage	Transmission
hard coal steam power plant	nuclear power plant	battery storage (Li-Ion)	HVAC transmission
hard coal steam CHP plant	waste steam power plant	pumped hydro storage	DC transmission
lignite steam power plant	waste CHP power plant	hydrogen cavern storage	
lignite steam CHP plant	biogas combustion engine plant	hydrogen gas power plant	
gas power plant	biomass steam power plant	alkaline electrolyzer	
combined cycle gas plant	wind turbine onshore		
combustion engine gas plant	wind turbine offshore		
gas CHP power plant	photovoltaic rooftop		
combined cycle CHP gas plant	photovoltaic utility		
combustion engine CHP gas plant	geothermal power plant		
light oil power plant	run-of-river power plant		
light oil CHP power plant			

CHP - combined heat and power; HVAC - high voltage alternating current; DC - direct current.

Furthermore, the politically set phase-out plans for power plants are included in the modeling. On the one hand, as nuclear power plants are phased out until 2022, no capacities are remaining in all 2030 scenarios. On the other hand, the coal exit plan, as decided by the coal commission appointed for this purpose, is also implemented in the scenarios [45]. For all other power plants, the same brownfield generation capacities as in 2016 (Fig. 1a) are pre-installed in 2030 with the option of expanding the capacities to a defined upper limit. Concerning the inner-yearly temporal resolution, electricity demand and renewable time series are provided in an hourly resolution. All models are capable to model the required degree of detail, except for *GENeSYS-MOD* which uses a time-series aggregation algorithm based on [46]. The hourly granularity of time series used for this model comparison exclusively allows for the analysis of aggregated energy flows and is not detailed enough to analyze stability issues within the power system, that may arise from high shares of VRE generation capacities.

The scenario set-up of all eight scenarios and corresponding assumptions and parameters is summarized in Fig. 2. With the base set-up in Fig. 1, we define two base scenarios for the years 2016 and 2030 (*Base*

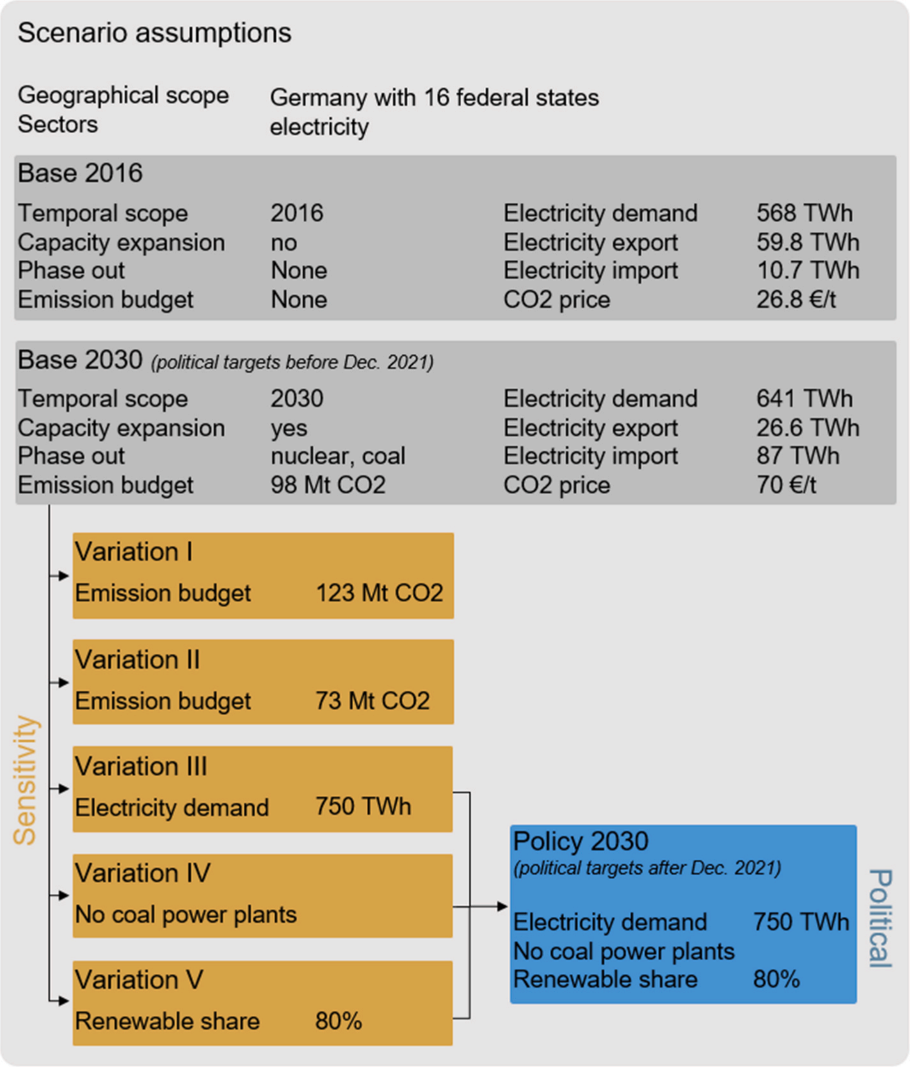


Fig. 2. Overview of scenario set-up and corresponding assumption, as well as important characteristics.

2016 and *Base 2030*). They serve as a basis for fundamental model comparison. The base scenario for 2030 is then further used to derive five sensitivity scenarios, which include variations of single policy-relevant parameters and characteristics. In a final scenario referred to as *Policy 2030*, variations III to V are combined to replicate the most relevant policy targets by the new German coalition, which was elected in December 2021. However, this scenario is not intended to compete with the most accurate modeling existing in literature, since simplifications of our models in terms of the harmonization process are inevitable. Simplifications include inflexible demands for sector coupling as well as inflexible imports and exports to neighboring countries. The main purpose of the *Policy 2030* scenario is to identify general trends in all contributing models that result from updated policy targets.

2.2. Contributing power system models

With *Balmorel*, *GENESYS-2*, *GENeSYS-MOD*, *oemof*, and *urbs*, five OSPSM contribute to this model comparison. Each of these models in turn represents only one possible configuration of its underlying and eponymous OS energy system modeling framework. All contributing models can be characterized as Open Source, techno-economic optimization models that are mainly applied for capacity expansion planning and dispatch optimization. An overview of a criteria-based methodological comparison is presented in Table 3. The contributing models are developed in one of the main programming languages GAMS, Python, or C++, and published under an OS license. All of the five models are based on a bottom-up analytical approach. However, in contrast to all other linear programming (LP)-based models, the *Genetic Optimization of a European Energy Supply System (GENESYS-2)*-model uses a rule-based dispatch algorithm and heuristics to define and solve the optimization problem. For this reason, it can also be used as a simulation tool and is particularly suitable for the analysis and optimization of long-duration seasonal storage. Although the remaining LP-based models have a very similar basic approach, each model has its special features. *Balmorel* for instance features add-ons for enabling couplings between the power, district heating, gas, and hydrogen sector. Furthermore, it also can include social welfare maximization in the objective function. The *Global Energy System Model (GENeSYS-MOD)* is mostly used for long-term energy system scenarios at various regional levels. Furthermore, it provides several demand time series models and has integrated time series aggregation functionalities. The *Open Energy Modeling Framework (oemof)* and *urbs* show the greatest variability of frequently used or existing approaches related to temporal scope, regional scope, and grid model. Furthermore, *oemof* and *urbs* provide linear optimal power flow (LOPF) functionalities. In contrast to *GENESYS-2* and *GENeSYS-MOD*, *Balmorel*, *oemof*, and *urbs* also allow for mixed-integer linear programming (MILP).

Table 4 depicts an overview of individual modeling choices, which

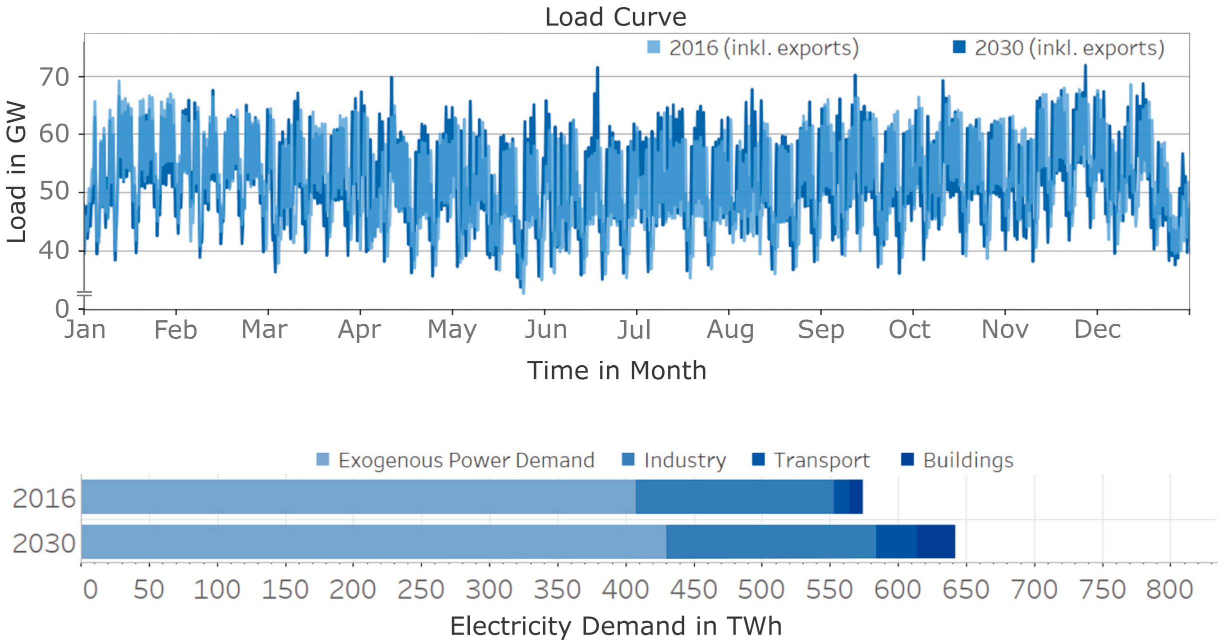


Fig. 3. Input assumptions on electricity demand data. The top side depicts the load curve, whereas the bottom half displays the electricity demands per sector. Load curve data are taken from [40], while sector-specific demands are taken from computations with the Global Energy System Model (GENeSYS-MOD) for Germany [41].

Table 3
Overview of contributing models to the model comparison.

Classification	Balmorel	GENESYS-2	GENeSYS-MOD	oemof	urbs
Programming language	GAMS	C++	GAMS	Python (Pyomo)	Python (Pyomo)
Licence	ISC	LGPL	APL 2.0	MIT	GPLv3.0
Documentation	[47,48]	[49,50]	[51]	[52]	[53]
Analytical approach	bottom-up	bottom-up	bottom-up	bottom-up	bottom-up
Mathematical approach	(MI)LP	rule-based dispatch, heuristics	LP	(MI)LP	(MI)LP
Temporal scope (mainly used)	short term, mid term, long term	long term	long term	short term, long term	short term, mid term, long term
Variable time steps	++	–	++	++	++
Regional scope (mainly used)	local, regional, national, multinational	local, regional, national, multinational	regional, national, multinational	local, regional, national, multinational	single projects, local, regional, national, multinational
Grid model	single-node, transshipment	single-node, transshipment	single-node, transshipment	single-node, transshipment, LOPF	single-node, transshipment, LOPF

Table 4
Overview of individual modeling choices, which are model specific and not predefined in the scenario input data set. They are a result of the modeling process and do not necessarily represent the full capability of the models.

	Balmorel	GENESYS-2	GENeSYS-MOD	oemof	urbs
Storage					
E2P ratio (short)	fixed	optimized	fixed	fixed	fixed
E2P ratio (long)	fixed	optimized	fixed	optimized	fixed
C2D power ratio (short)	1	1	1	1	1
C2D power ratio (long)	1	optimized	1	optimized	1
Initial storage level	optimized	0	0	0	optimized
Final storage level	fixed to initial	optimized	fixed to initial	fixed to initial	fixed to initial
Transmission					
Grid model	transshipment	transshipment	transshipment	transshipment	transshipment
Lines between nodes	2	1	2	2	2
Other					
Investment model	annuity	annuity	per-period capital investment	annuity	annuity
VRE share	not implemented	not implemented	capacity limit	capacity limit	not implemented

are model specific and not predefined in the scenario input data set. Two types of storage are distinguished: short duration-storage (referenced as “short”) and long-duration storage (referenced as “long”). Under short-duration storage, we include batteries and pumped hydro storage whose energy-to-power (E2P) ratio (E2P ratio (short)) has been fixed in all models. On the contrary, we classify hydrogen cavern storage as long-duration storage whose E2P ratio (long) is fixed for *Balmorel*, *GENeSYS-MOD*, and *urbs*, yet it is optimized in *GENESYS-2* and *oemof*. The ratio of rated charge-to-discharge (C2D) power can either have a fixed ratio or is part of the optimization. For short-duration storage, the C2D power ratio of all models is fixed and equals 1. For long-duration storage, this also applies, except for *GENESYS-2* and *oemof* in which the C2D ratio is optimized. The model configurations also differ concerning the state of charge in the first time step (initial storage level), which is either set to 0 or is an optimization variable. The state of charge in the last time step of the optimization (final storage level) is either set equal to the initial storage level or optimized, depending on the model. Looking at transmission, all models apply the transshipment model [54] in which the grid is represented by multiple nodes that can exchange power. For each node, an upper threshold limits the useable net transfer capacity, hence no physical characteristics of power flows are considered. The number of lines between nodes, however, is not equal between contributing models. Whereas in all LP-based models a back and forth connection between two nodes is modeled, in GENESYS-2 only unidirectional flow via one line is possible. Furthermore, differences occur in terms of the investment model applied and the implementation of VRE shares is only an available feature in some of the contributing models.

2.3. Model and data harmonization

A comprehensive model comparison requires sufficient harmonization of the model configuration and the input data. Above all, it is essential to harmonize the definition of total system costs as the contributing models partly feature different interpretations of cost calculations [55]. This needs to be considered in the model-specific interface (connector) to the input database. To avoid misinterpretations, the definition of total system costs in (1) is used throughout this model comparison. Total system costs (TSC), also referred to as objective value, consist of investment costs (IC), fixed costs (FC), and variable costs (VC). For investment costs, we exclusively consider expanded capacities while existing capacities are considered depreciated. On the contrary, fixed costs are included as a technology-specific percentage of all existing and expanded capacities. The operational expenditures are represented by variable costs that consist of fuel costs and CO_2 emission costs. It is important to note that costs for unintended load shedding (unsupplied load) are not displayed in the definition of total system costs. They are nevertheless part of the objective value that is minimized in all models. We harmonize costs for unsupplied load and ensure the feasibility of all models by modeling a slack variable that can only generate electricity with very high variable costs. On the contrary, possible surplus from VRE sources is defined as curtailment.

$$TSC = IC + FC + VC \tag{1}$$

The input data harmonization process follows a formalized procedure. All participating OSPSM follow this procedure to ensure input data harmonization across all OSPSM and thus model comparability (Fig. 4). The data harmonization is intended to achieve a uniform and partially automated parameterization of the models. The procedure aims to avoid errors when transferring technology data into the models and changing scenario data through central data curation and partially automated deployment. Additionally, it leads to time savings, especially with many scenarios runs. The input scenario data is stored and maintained in a database on the OEP by utilizing a subtype of the Open Energy Data Model (oedatamodel) format that is referred to as oedatamodel-normalization format. The oedatamodel [56] was specifically designed for the comparison of energy system models that examine scenarios with a high level of detail. It consists of three tables to distinguish between scenario-specific data (scenario table), scalars data (scalars table), and time-series data (time-series table). The scenario table holds basic information like name, year, and region, among others, of the scenario and works as a reference to related scalar and time series entries. Both the scalars and time-series table hold the techno-economic data of the scenario and technologies. Data is deployed to models through so-called connectors, which convert data from the efficient oedatamodel-normalization database format to the more user-friendly oedatamodel-concrete tabular format or other model-specific input data formats. The data management procedure is depicted in Fig. 4. Customized tabular input data can be downloaded directly from the OEP via the oedatamodel API as either CSV or JSON files. After model parameterization and optimization, the results from each model require a backward conversion. Therefore, model-specific output connectors linked to the oedatamodel application programming interface (API) convert model output data back to the oedatamodel-normalization format, which is then equally structured as the input data format. Thus, output data of all models can be easily fed back into the OEP database and compared with a connected dashboard [57].

3. Result comparison and analysis

3.1. Base scenario results

Applying harmonized scenarios in a model comparison helps to understand fundamental correlations between model differences and result variations. Therefore, we compare the base scenario results for the years 2016 and 2030 of all contributing models. One of the most important indicators of result differences is total system costs (definition in (1)) which are minimized in all models. Fig. 5 illustrates the model-specific results for total system costs, which in turn consist of fixed, investment, and variable costs. The results highlight that in 2016 all models reach a very similar cost level, *GENESYS-2* being the only exception showing about 40% higher costs accumulating to almost 35 billion euros. The difference in *GENESYS-2* is mainly driven by increased variable costs. The pre-defined dispatch order in *GENESYS-2* eliminates foresight and reduces the flexibility of generating, storing, and transmitting energy. In addition, the structure favors the local use of energy and limits transmission via grid into more distant regions. These limitations lead to the less cost-effective use of technologies in *GENESYS-2* and increased overall system costs in comparison with the other LP models that find a more optimal dispatch.

For 2030, the variable costs for all models decrease in comparison

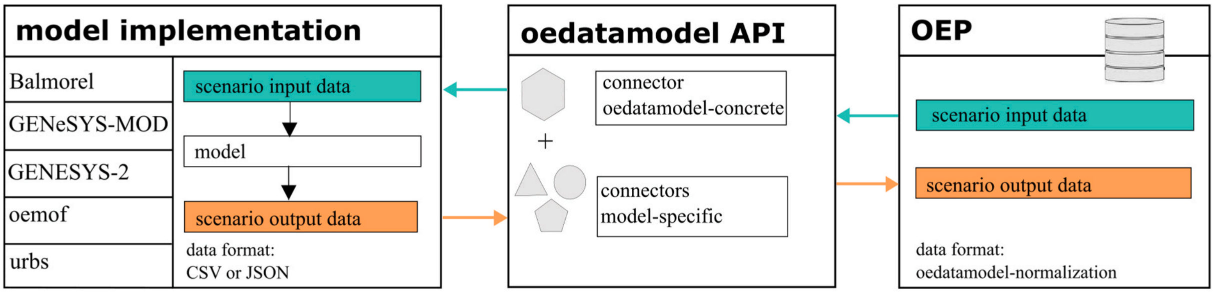


Fig. 4. Data management workflow for the model comparison with five OSPSM.

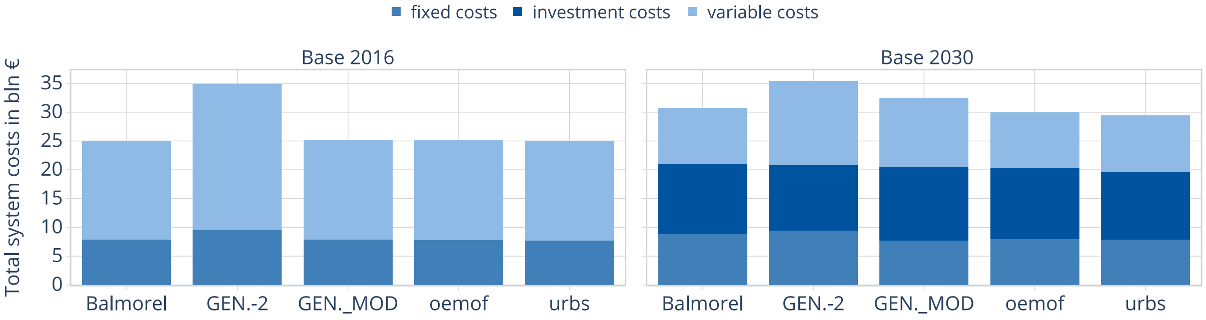


Fig. 5. Total system costs (TSC) for base scenarios 2016 and 2030, for all contributing models.

with 2016, since the implementation of a GHG-reduction target coupled with a CO_2 price leads to an expansion of VRE generation capacities that are characterized by low variable expenditures. However, this adds a large share of investment costs due to increased generation capacities and causes a slight increase in fixed costs in all models. However, in *GENESYS-2* those effects are less pronounced which indicates that thermal power plants are still used to a great extent. This is supported by the slightly higher variable expenditures in comparison with the other models. Similar investment costs for *Balmorel*, *GENeSYS-MOD*, *oemof* and *urbs* indicate that they derive at similar optimal system configurations. Nevertheless, it can be observed that small differences occur between the remaining models. They are partly caused by different investment decisions into flexibility technologies like storage and transmission capacities. Overall, the results in 2030 highlight that with a substantially different approach, like the dispatch hierarchy in *GENESYS-2*, OSPSM can derive very different optimal solutions.

To further understand the observed differences in total system costs, we compare the results for the optimal generation (dispatch) calculated by all contributing models (Fig. 6). The reference value (REFERENCE) displays the historical values for the year 2016 from the German Federal Ministry for Economic Affairs and Energy (BMWi) [58]. The results show that the dispatch for all models, besides *GENESYS-2*, is almost identical. Around two-thirds of total electricity is generated by lignite and hard coal-fired power plants (about 58%), followed by nuclear power plants (about 14%), wind power plants (about 10%), and solar PV (about 7%). Oil, gas, hydro, biogas, and biomass power plants only contribute shares of 3% or below. This solution represents sort of an optimal dispatch of the power system that could be reached if it was operated in the most cost-efficient way possible, with perfect foresight considered. However, the comparison with historical net generation values (REFERENCE) reveals that the dispatch of the actual power system looks considerably different. Above all, generation from gas-fired power plants and oil power plants is more pronounced in comparison with the LP-model results. This more diverse technology portfolio is a consequence of market mechanisms and structure, which determine the actual allocation of generation capacities. This also proves that the real-world system is usually not operated most cost-effectively and efficiently. In the contributing LP models, however, a market structure is not implemented, and therefore, technologies with lower marginal cost, like lignite-fired power plants, are used more extensively across the system. On the contrary to the LP models, the dispatch obtained in *GENESYS-2* almost entirely follows the dispatch displayed by the historical values. This is caused by the dispatch order in *GENESYS-2*, which sets a fixed rule-based hierarchy including a merit order list for generation plants on a local scale and thus can better reflect the historic German market behavior of 2016, within the boundaries of this specific scenario set-up. Cheap, large, and centralized power plant units like lignite power plants are used less, while distributed, small, and more expensive power units like gas power plants are used more often (see Fig. 6). This effect is also amplified by the GENESYS-2 structure considering local generation before importing from other regions, which leads to less lignite generation that is concentrated in only few regions in Germany. Generally, this proves that models with rule-based dispatch structures can be very useful tools to provide accurate results for current power system structures and can be a trade-off between an optimal and plausible solution. However, the digitization of the power system is a paradigm shift that might lead to different future market structures that will most likely require dispatch-based models to adapt.

For 2030, results indicate that total generation only increases by small margins compared to 2016, despite the increased demand from 568 TWh to 641 TWh. This is caused by a shift from exports towards imports. While in 2016 the export-import balance to neighboring European countries was positive with about 49 TWh of exports, the assumption for 2030 is a balance shift towards imports with a balance of about −60 TWh as shown in Fig. 2. Furthermore, the optimal dispatch of all contributing models reveals a substantial shift towards renewable generation, with renewable shares ranging from 67.8% in *GENESYS-2* to 80.5% in *Balmorel*. Moreover, the dispatch results for *oemof* and *urbs* are almost identical. This is expected, since both models feature a very similar approach [55], and proves the reliability these models can provide. Nevertheless, small differences, like an increased generation from wind offshore and decreased generation from solar PV in *oemof*

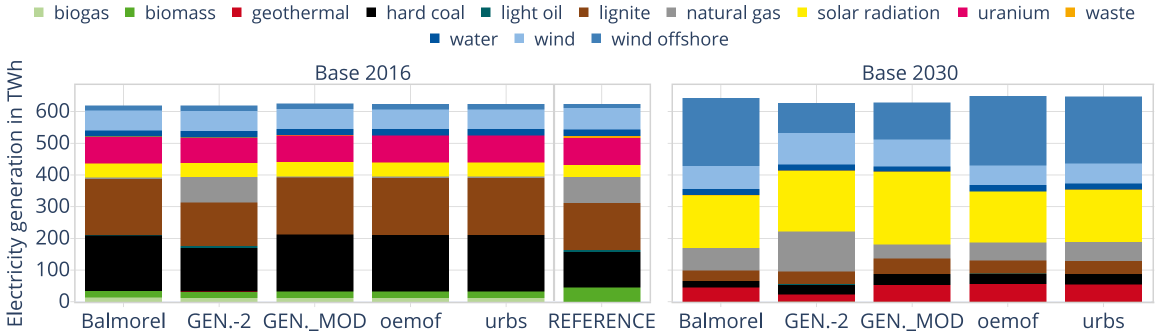


Fig. 6. Optimal dispatch for all power plants considered in base scenarios 2016 and 2030, for all contributing models.

compared to *urbs*, also occur. This is partly caused by different levels of technology modeling detail and divergent modeling choices (Table 4). Considering the other models, the dispatch results of *Balmorel* are closest to *oemof* and *urbs*. However, in *Balmorel* slightly higher shares of distributed solar PV and onshore wind are found in the optimal solution together with slightly more electricity being transmitted. A similar, but more pronounced effect can be seen in the *GENeSYS-MOD* dispatch, which shows about 40% higher generation from solar PV in comparison with *oemof* and *urbs*. *GENeSYS-MOD* favors a system based on solar PV and short-duration storage like batteries. One major difference between *GENeSYS-MOD* and the other models is the way how investment costs are being accounted for since for the former all costs occur in the year where the capacities are built (and are subsequently refunded at the end of the modeling period) while the other models use an annuity calculation for their capital expenditures. As a result, *GENeSYS-MOD* favors a solution with less variable and more investment costs, which in this case consists of a system composed of solar PV and storage. In contrast to all other models, the dispatch results in *GENESYS-2* show a higher share of fossil fuel-based thermal power plants, with a strong tendency towards gas-fired power plants. Since the dispatch model reduces flexibility, renewable generation cannot be utilized and distributed as effectively as in LP-based models. Therefore, thermal power plants preferably cover gaps in supply.

Apart from minimizing total system costs one of the other major policy requirements of OSPSM is to accurately model or determine CO_2 reduction targets. For all models, the CO_2 emission results for the 2016 base scenario are clearly below the reference value (REFERENCE) of 327 Mt, which is provided by the German Federal Ministry for Economic Affairs and Energy (BMWi) [5] (Fig. 7). This is partly caused by inefficient fuel usage in real-world generation units due to part load behavior and different accounting methods of emissions from CHP plants. Between all models, except for *GENESYS-2*, there are only small differences for 2016 emissions, as the dispatch obtained for fossil fuel thermal power plants in *Balmorel*, *oemof*, *GENeSYS-MOD*, and *urbs* is almost identical (Fig. 6). In *GENESYS-2*, however, the pre-defined dispatch order forces increased generation from gas-fired power plants, which mainly substitutes generation from lignite- or hard coal-fired power plants. Therefore, overall emissions in *GENESYS-2* are lower than in all other models (see Fig. 6), caused by lower specific emissions from gas-fired power plants, in comparison with lignite and hard coal-fired power plants.

The 2030 emission results highlight that almost all models find an optimal solution substantially below the permitted CO_2 emission budget of 98 Mt implemented in this scenario. This means that investing in new VRE capacities is more beneficial than using existing fossil fuel thermal power plant capacities with the considered assumptions for techno-economic parameters and CO_2 prices. Furthermore, the variations between all LP-based models are only minor and range from 70 Mt in *Balmorel* to 74 Mt in *GENeSYS-MOD*. The only clear result outlier is *GENESYS-2*, which fully exploits the implemented budget, with a high share of gas-fired generation (Fig. 7). However, the dispatch for 2016 (Fig. 6) has shown, that dispatch models like *GENESYS-2* can be closer to the actual system operation. Therefore, it is possible in LP-based models to underestimate the true emission compared to a real-world system, considering that market structures in 2030 are still similar to 2016.

To further evaluate and strengthen the findings, we compare all base scenario results of contributing models for existing and added capacities of generation, storage, and transmission units (Fig. 8). In 2016, no capacity expansion for generation, storage, and transmission is allowed, thus all reported capacities are identical between the models. On the one hand, the 2016 results act as proof that all model maintainers have modeled the scenarios correctly. On the other hand, they act as a benchmark to clarify the differences. When focusing on the expanded generation capacities for 2030, we primarily notice the high expansion of solar PV in all contributing models. The highest capacity expansion for solar PV with 180 GW is detected in the capacity portfolio of *GENeSYS-MOD*, which also shows the highest generation from solar PV (Fig. 6). For wind generation capacity expansion, a very diverse picture occurs between the models. While *Balmorel*, *oemof*, and *urbs* only invest in wind offshore, with similar values ranging between 39 GW and 42 GW, *GENESYS-2* and *GENeSYS-MOD* expand less capacity in total but have an additional share of wind onshore. This is mainly caused by different grid representations that substantially influence the distribution of generation from offshore wind. For *Balmorel*, *oemof*, and *urbs*, it is beneficial to strongly invest in grid infrastructure to distribute high generation shares from offshore wind from the north to the south. For *GENESYS-2* high investments into grid infrastructure can be seen as well, however, due to the dispatch model, energy can be distributed less efficiently, and local generation is preferred. In *GENeSYS-MOD* fewer investments into grid infrastructure are reported, since local solar PV generation coupled with batteries is preferred over wind capacities and hydrogen cavern storage. On the contrary, *GENeSYS-MOD* builds higher capacities of storage to store generation from solar PV. Due to the fixed E2P ratios for both short- and long-duration storage, mainly battery storage is built (Table 4). Apart from *GENeSYS-MOD*, only *oemof* reports noticeable investments in storage capacities. It mainly invests in long-duration hydrogen storage since in contrast to the other models the E2P ratio is considered flexible for this technology and can be optimized. This makes them more suitable than battery storage to store large amounts of energy for a longer time period.

More insights into model differences can be gained from different investment behavior regarding thermal power plants. In *GENeSYS-MOD* fewer investments can be obtained, whereas all other models invest substantially into new gas-fired power plants. Since gas-fired power plants have comparably high variable costs, the earlier mentioned preference for investment costs leads to only a few new plants being built in *GENeSYS-MOD*. For *GENESYS-2*, the dispatch structure favors local use of energy. Therefore, geothermal generation is only expanded by small margins, and few local light oil-based power plants are built to cover peak loads. The other models, however, almost fully exploit the available geothermal potential of 6.4 GW, since they can flexibly use its generation across the grid. Moreover, with geothermal power plants, it is at the same time possible to reduce emissions without losing flexibility in generation. Moreover, geothermal power plants are also clearly preferred before zero-emission biomass and biogas power plants, resulting from lower marginal operation costs.

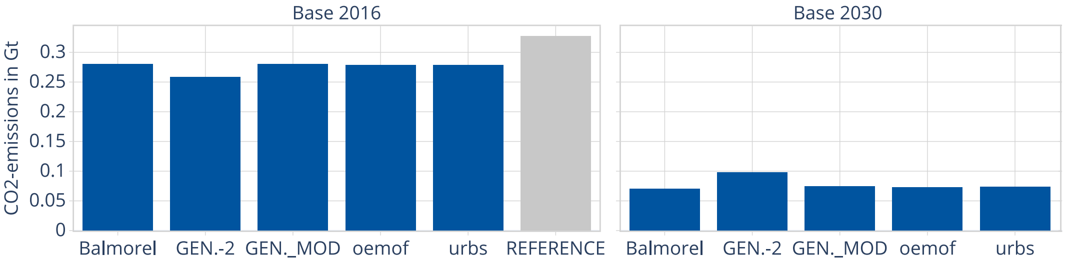


Fig. 7. CO_2 emissions for base scenarios 2016 and 2030, for all contributing models.

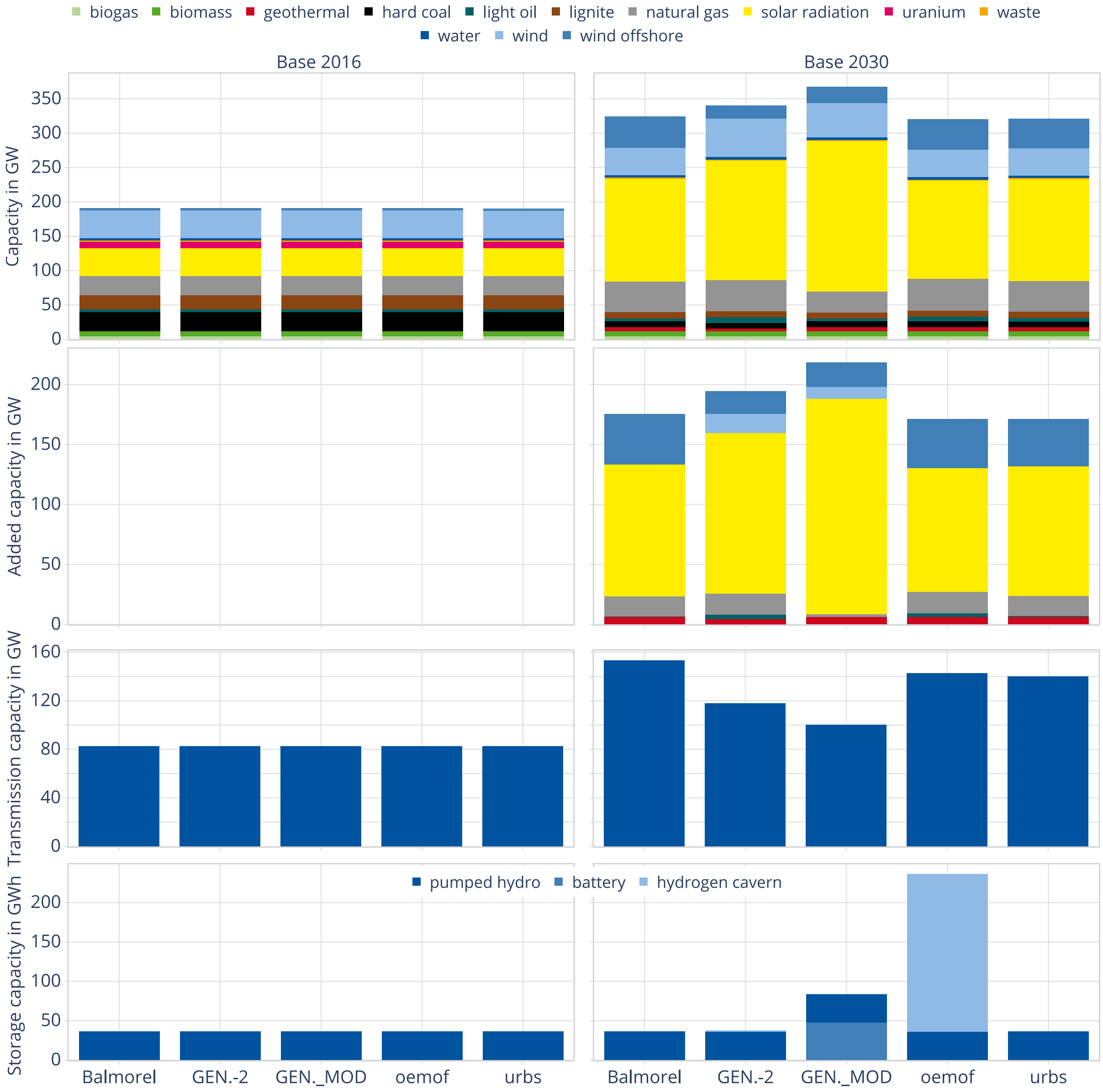


Fig. 8. Capacity and added capacity for all generation, storage, and transmission technologies included in the 2016 and 2030 base scenarios, for all contributing models.

A holistic consideration of all interactions in the base scenario requires investigating the use of flexibility technologies. Fig. 9 shows the curtailed energy from VRE generation, the uncovered load (slack), the storage discharge, and the transmitted energy, for base scenarios 2016 and 2030, as well as for all contributing models. The results indicate that overall the curtailed energy increases from 2016 to 2030. As renewable generation capacity expands largely in 2030 (Fig. 8), the surplus of VRE generation increases simultaneously. With the increasing surplus, it becomes less economical to store or transmit the energy, such that curtailment remains the last option for the models to ensure a feasible energy balance. Between the models, there are significant deviations in curtailed energy. For 2016, *GENESYS-2* reports a higher value compared to all other models, which proves that the implemented dispatch hierarchy effectively reduces the flexibility to make use of VRE generation. On the contrary, in 2030, the lowest value for curtailment is shown in *GENeSYS-MOD*. The reason can be found in the storage discharge results. Of all models, *GENeSYS-MOD* has the highest storage throughput with 23 TWh (mainly battery storage), of which a high share can be allocated to shifting its high solar PV generation (Fig. 6) in time. In *oemof,* a slightly lower storage throughput of 17 TWh that mainly comes from hydrogen cavern storage is reported. In comparison with *urbs*, which utilizes less storage and transmission, *oemof* is less efficient in energy distribution and therefore has slightly higher total system costs (Fig. 5), despite a very similar dispatch (Fig. 6). Small differences in individual modeling choices like inflexible storage levels in *oemof* (Table 4) are a potential reason for this behavior. For *Balmorel*, transmitted energy is even higher than in *oemof* as it has the highest share of generation from VRE of all models, which needs to be distributed across regions. In contrast to all other models, *GENESYS-2* avoids grid transmissions as much as possible. This is especially pronounced in 2016 when all other models have similar values for transmitted energy, but *GENESYS-2* is only reporting about 20% of this amount.

The occurrence of uncovered load is only possible in 2016 since no capacity expansion is allowed. In 2030, the existing electricity generation would consistently be increased to meet the demand, since the uncovered load is penalized with high costs. The results show small

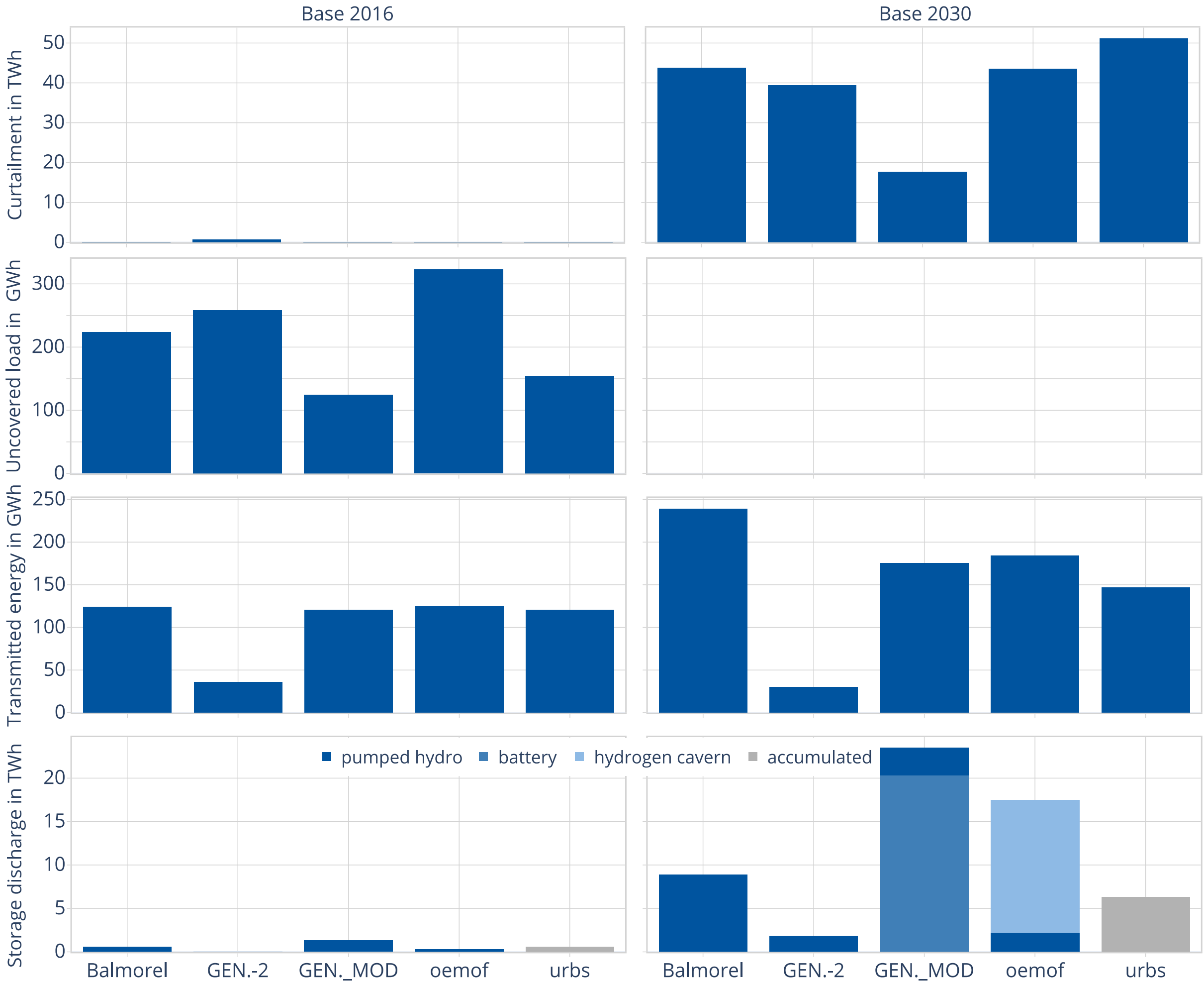


Fig. 9. Use of model flexibilities separated into curtailed energy from VRE sources, storage discharge, and transmission usage, for base scenarios 2016 and 2030 and all contributing models.

values (of less than 0.1% of total demand) of uncovered load in 2016 for all models. This is a result of the scenario set-up as the entire uncovered load occurs in the federal state of Saarland (SL). The geographical overview in Fig. 1 highlights that only one transmission connection from SL to other states is modeled since it is located at the outer German border. Additionally, imports from neighboring European countries are modeled as fixed time series. However, both assumptions are based on different sources. Therefore, the combination of location and reduced flexibility of the transmission imports is the main driver for the increased uncovered load. This also shows that simplifications in modeling, which result from different sources, should be used carefully to avoid such unwanted effects.

3.2. Influence of key modeling parameters

The identified effects in the base scenario analysis have to be further validated on a broader data foundation. Therefore, to strengthen the model comparison, we perform scenario variations with selected, politically relevant parameters of the base scenario for 2030. Key parameters include the CO_2 emission budget, the sum of total demand, generation capacity restrictions, and the renewable share. With this selection, it is possible to analyze the effects of different model approaches and technology modeling and to evaluate the impacts of single political measures on overall model results.

For the first two scenario variations, the emission budget of the base scenarios (98 Mt) is increased by 25 Mt (to 123 Mt) in Variation I and lowered by 25 Mt (to 73 Mt) in Variation II. Those variations are sensitivities chosen exclusively for this model experiment and do not reflect any political targets. Fig. 10 shows the deviations for generation, costs, and emissions, compared with the results of the 2030 base scenario. While all LP-based models show the same results for all variations of the emission budget, the optimal solution in *GENESYS-2* highly depends on that parameter. For all variations, *GENESYS-2* fully exploits the emission budget. Therefore, a higher budget of 123 Mt in Variation I leads to increased generation from fossil fuel-based power plants, especially for gas-fired technologies. Moreover, with decreasing emission budget, costs increase in *GENESYS-2*. This concludes that investments into VRE generation capacities are generally less economically viable for the range of the considered emission budget. For all the other models, solutions below the 78 Mt threshold are optimal so that a change of the emission budget does not affect results.

For future scenarios in energy system modeling, the total electricity demand is a factor with high uncertainty. With the emergence of sector coupling applications, the demand for 2030 can only be an estimate. Therefore, in Variation III, we increase total electricity demand from 641 TWh in the 2030 base scenario to 750 TWh, which is in line with the estimates of the new German government [21]. For all models, higher demand results in increased emissions and costs, which is an expected pattern (Fig. 10). However, the amount of generation and the correlation between the models changes compared to the *Base 2030* scenario. In *urbs*, the generation and costs increase to a greater extent than in all other LP-based models. This shows that in *urbs* it becomes increasingly

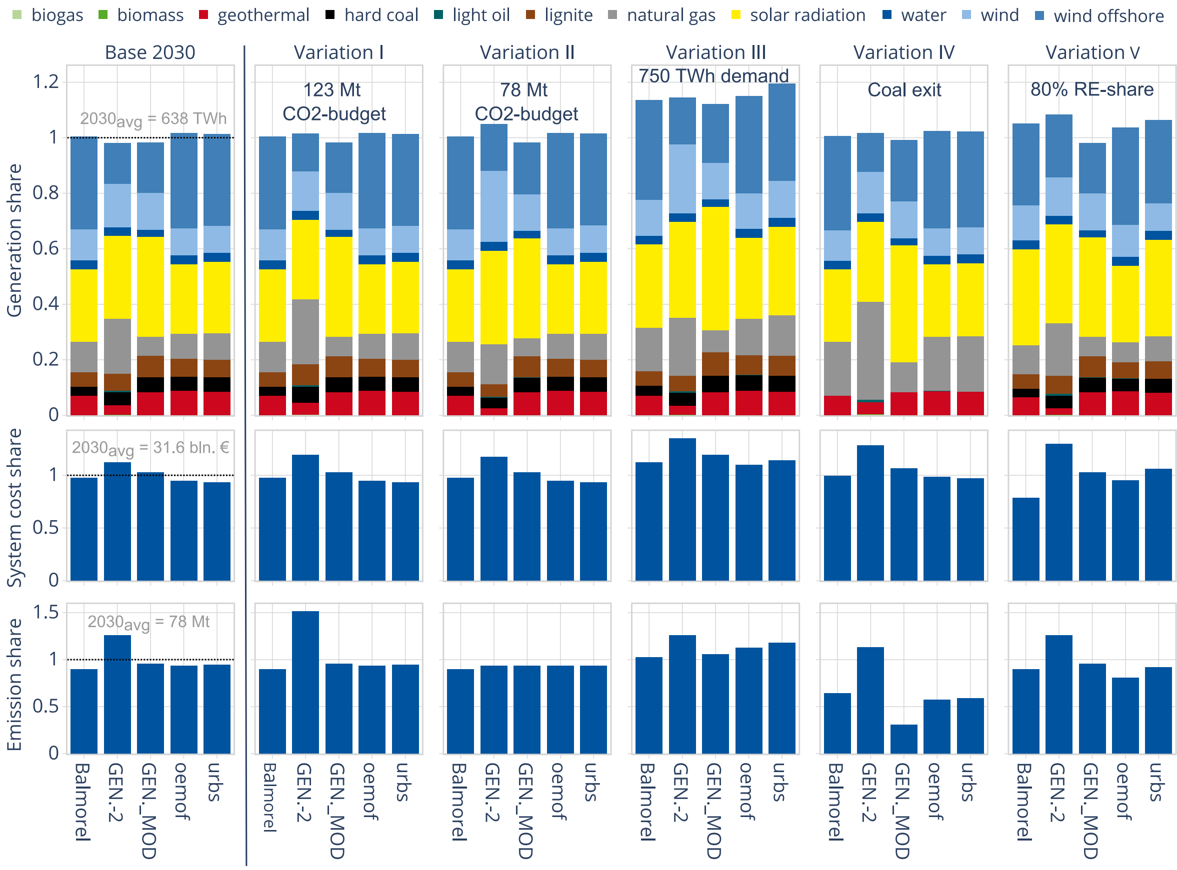


Fig. 10. Sensitivity of generation, costs, and emission results towards key modeling and policy parameters, normalized to the average of the 2030 base scenario results.

expensive to distribute energy generation with higher generation shares from VRE. Although less pronounced, the same effect is illustrated by increased generation of *GENESYS-2* compared to *GENeSYS-MOD*. The underlying dispatch model of *GENESYS-2* is less efficient than LP-based models and therefore higher generation is required.

One key topic that has shaped the energy transition debate in Germany is the coal exit (see Section 1.1). Therefore, Variation IV does not allow for any generation from lignite- or hard coal-fired power plants. One general effect illustrated by the results is that the generation pattern between the models, except for *GENESYS-2*, stays rather constant (Fig. 10). This indicates that without generation from coal power plants, the system does not entirely change. Instead, the generation is mainly substituted by generation from gas-fired power plants. Consequently, the overall system costs increase slightly, but emissions are substantially reduced. In *GENESYS-2* the shift towards gas is even more pronounced as it makes higher use of the CO_2 budget. Nevertheless, in comparison with the *Base 2030* scenario, it does not fully exploit the budget. Despite this, the renewable share in *GENESYS-2* drops to a minimum of 67.3%. The coal exit thus does not guarantee that the 80% renewable target is met. It nevertheless effectively reduces emissions by 12 Mt (*GENESYS-2*) to 50 Mt (*GENeSYS-MOD*), depending on the model.

Another possible parameter to set reduction targets is the renewable share in generation. The new German government, which was elected in December 2021, has raised the target for this share to be at least 80% in 2030. In Variation V, all capable models apply this share. However, in the versions of *GENESYS-2* and *urbs* used in this analysis, it is not possible to model this target. Therefore, we include additional constraints for minimum capacities that have been proposed by the new policy agenda. This includes a minimum of 200 GW of solar PV and 30 GW of wind offshore generation capacity. The results of Variation V in Fig. 10 highlight that a renewable share as implemented in *GENeSYS-MOD* and *oemof* has only minor effects in comparison with the *Base 2030* findings. While emissions are reduced by small margins for all models except *GENESYS-2*, the reduction is substantially more pronounced in *oemof* and *urbs*. Nevertheless, the emission results prove that the renewable share alone is ineffective in reducing emissions and needs to be combined with other measures like the coal exit. With the results from models without the ability to model a renewable share (*Balmorel*, *GENESYS-2,* and *urbs*), it further is possible to evaluate if the proposed minimum VRE capacities are sufficient to reach the 80% renewable target as well. The results indicate that this might be possible as *urbs* reports a renewable share of 80.8%. However, in a less efficient system representation, like in *GENESYS-2*, this is not the case as the renewable share is only at 71.4%.

4. Policy implications of model comparisons

The analysis in Section 3.1 and 3.2 supports that model comparisons provide a solid basis to discuss general trends that arise in an energy transition process. This is why the insights can also be valuable for the political debate. The variety of approaches and assumptions used by the contributing models of this comparison allows us to analyze the new climate policy goals of the new German government from different angles. The regulation proposals by the new German coalition, which was elected in December 2021, show more ambitious targets for CO_2 emission reductions compared to the status quo of the previous government. However, implications for the required transformation of the power system partly remain unclear and need to be evaluated. Therefore, we adjust the *Base 2030* set-up, which represents the targets of the previous government, with the new targets, and model it with all contributing models. The adjustments include a minimum capacity of 200 GW of solar PV and 30 GW of wind offshore, a renewable share of 80%, the exit from coal generation, and higher annual demand of 750 TWh by increased sector coupling (for more details refer to Section 1.1). Fig. 11 shows the optimal dispatch and curtailment detected by all contributing models for the *Policy 2030* scenario. The scenario can be classified as "ambitious", as it considers the option for high investments into wind offshore and geothermal power plants. Whether available potentials for VRE capacities can be realistically exploited until 2030 is not further analyzed in this manuscript.

The optimal dispatch reveals that not all models reach the required CO_2 reductions to meet the required 80% renewable share. In the used versions of *GENESYS-2* (67.3% renewable share) and *urbs* (78.5% renewable share), the implementation of this constraint does not exist. Therefore, only minimum capacities could be applied. This implies, that the intended minimum capacities of 200 GW of solar PV and 30 GW of wind offshore of the new German coalition do not guarantee that emission reduction targets are met. Additionally, all other models that meet the 80% renewable share propose higher shares of wind offshore, ranging from 36 GW to 54 GW. This represents an ideal system configuration and does not consider if it is realistic from an installation point of view to reach such high shares until 2030. Nevertheless, this trend supports, that investments in wind offshore capacity are beneficial and should be increased to the maximum extent possible. For models with lower shares of offshore wind, the generation is mainly substituted by wind onshore, which has lower capacity factors and therefore is not prioritized as the first solution. Another important factor to notice is that the scenario set-up allows for high investments into geothermal power plants. As they provide a maximum of flexibility, their full potential of about 6.4 GW is built in all models, except for *GENESYS-2*, which applies the less flexible dispatch approach. At the same time, the generation in *GENESYS-2* is highest which also leads to the largest curtailment value of 115 TWh. For the other models, it still ranges from 25 TWh in *GENeSYS-MOD* to about 71 TWh in *urbs*. This emphasizes, that the energy system in 2030 has a very high potential to increase energy efficiency, which can be achieved with flexible loads by utilizing concepts like smart charging for electric vehicles [59].

To evaluate the measures taken by the new government, the measures of the old government as shown in the *Base 2030* results (Section 3.1) are taken as a benchmark. Fig. 12 shows necessary capacity expansion rates per technology, that are required to reach the updated targets in comparison with the old targets. The benchmark between the models is very different so growth rates for some technologies vary by large margins. Nevertheless, general trends can be observed that are similar across the models. Results clearly show that substantial additional investments into solar PV are required to reach the updated targets. The values between the models range from 21% to 43%. The same applies to investments in wind power capacities. However, depending on the configuration for the old targets, the investments are either more pronounced for wind offshore (up to 58% additional capacity), or wind onshore (up to 28% additional capacity). Apart from generation capacities, a major shift is detected for storage and transmission capacities. For storage, up to 500% of additional capacity is required, considering the rather low capacities with the old targets (Fig. 8). For transmission, up to 15% of new capacity is needed, despite the already high investments in the *Base 2030* scenario (Fig. 8). This emphasizes, that a renewable share of 80% (or higher) represents a certain threshold for which substantial investments into storage and/or transmission become inevitable. For all models, the results predict no noticeable further investments into biogas and biomass power plants, for the updated policy agenda under the given scenario conditions.

5. Summary and conclusion

In a comprehensive model comparison, we compare five OSPSM by using harmonized scenarios for the German power sector. The geographical granularity of the scenario set-up consists of the 16 federal states of Germany that are interconnected with a transmission grid. The technological scope covers all relevant technologies that are available for the power sector. We exclusively conduct single-year optimizations, to find the optimal system configuration. Two base scenarios for the years 2016 and 2030 are the foundation for a detailed model comparison. For the 2016 base scenario, the results are very similar between models as no capacity expansion is allowed and capacities are endogenously fixed in the scenario set-up. Nevertheless, substantial differences occur between LP-based models and models with a pre-defined dispatch structure, that show about 40% higher total system costs for the base scenario 2016. The comparison of generation patterns proves that models with a dispatch order can be closer to the real system dispatch than LP models. The reason for this is that they more accurately simulate the current market behavior, that among others relies on a merit order list for generating units. Therefore, we conclude, that models with a defined dispatch order can be a tradeoff between the plausible and optimal solution, while LP-based models show the best possible system. However, this does not imply that one or the other is better suited since in future systems there are higher uncertainties regarding the overall system design and efficient use of energy. Applying both approaches to future scenarios, however, can help to estimate a possible range to cover this uncertainty.

For the 2030 base scenario, the deviations between models substantially increase as capacity expansion is now allowed. With the implemented CO_2 emission budget of 98 Mt, high investments into VRE capacities are required in all models. However, this leads to very different renewable generation shares ranging from 67.8% to 80.5%.

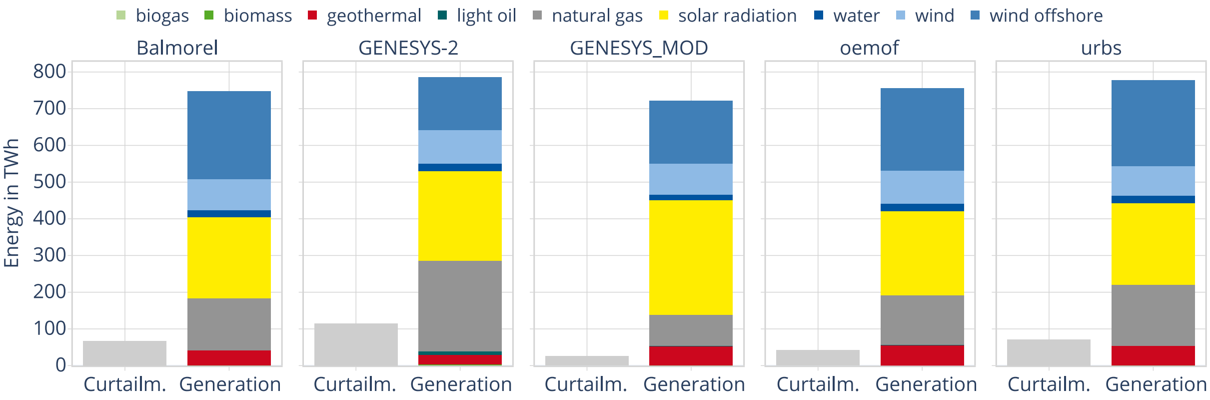


Fig. 11. Electricity generation and curtailment of contributing models for the *Policy 2030* scenario, including the proposed policy targets of the newly elected German coalition.

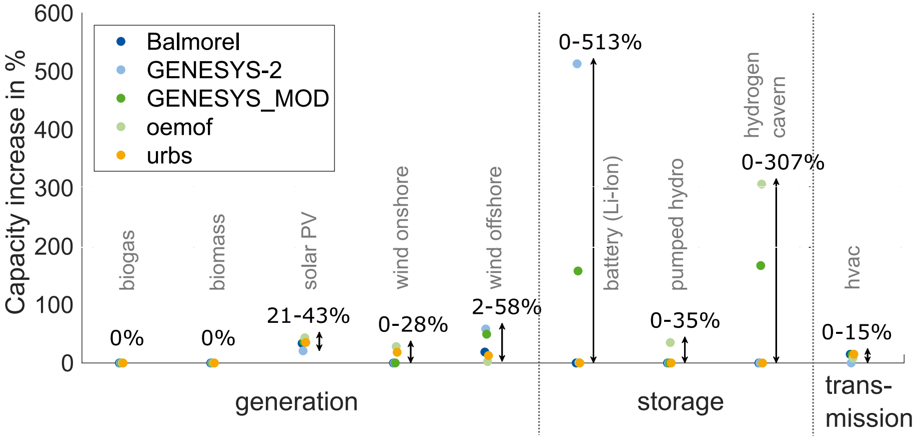


Fig. 12. Capacity increase that is required for the new political agenda, compared to the old political targets, divided into technology groups. For generation capacities, the unit is in GW. For storage capacities, the unit is in GWh.

While models with a dispatch order fully exploit the emission budget and rather try to make use of existing thermal power plants, LP-based models find an optimal solution that leads to substantially fewer emissions as they more efficiently can distribute generation from VRE sources. Between LP-based models, variations especially occur from different use of flexibilities, like storage and transmission. For some models, it is beneficial to highly expand wind offshore capacities, as their grid representation enables them to efficiently distribute energy from North to South. In other models, investments into wind offshore are lower and the transmission grid is used less. Instead, they highly invest in solar PV capacities that are more evenly distributed across the federal states. This leads to an increased overall demand for storage and increased energy throughput. The choice of storage technology, however, turns out to be different across the models. This is mainly caused by the implementation of E2P ratios. For some models, this ratio is optimized while others consider it as fixed. The effect is especially pronounced for long-duration storage, like hydrogen cavern storage, since the investment costs for charging (electrolyzer), discharging (hydrogen gas power plants), and storage unit (salt caverns) substantially deviate. Therefore, we generally recommend optimizing the E2P ratio for storage.

Since single modeling parameters and policy requirements can have a major impact on the optimal system design, we conduct a sensitivity analysis with modifications to the 2030 base scenario. The selection of modifications includes variations for CO_2 emission budgets, the total sum of demand, and the renewable share. Furthermore, a coal exit strategy is implemented. To isolate the effects the modifications are applied individually and the effect on the results are compared between all models. The variation of CO_2 budgets highlights that for LP-based models results do not change when the optimal solution lies below the implemented threshold. While this is expected, models based on a dispatch structure tend to have a high sensitivity to this parameter, as they are less efficient in energy usage and distribution. For this reason, existing fossil fuel-based thermal power plants are the obvious choice before investments into new VRE generation capacities. In another variation, the total electricity demand required is increased to 750 TWh, which reflects current political assumptions for a higher sector coupling in 2030. Apart from the expected increase in costs and CO_2 emissions, the results between the models indicate that this has substantially different effects on investment decisions. This implies that the gradient of the correlation between total system costs and renewable generation share is more or less steep, depending on the model. Therefore, with higher renewable shares also the deviations between model results tend to increase.

Another topic that has shaped the energy transition debate in Germany is the coal exit plan. Applying a coal exit by 2030 has several effects that are very similar across models. Despite substantially lower emissions in all models, total system costs increase with the more extensive generation from gas-fired power plants that are characterized by high marginal costs. Thus, they mainly substitute the phased-out generation from lignite- or hard coal-fired power plants. The optimal system configuration, however, remains largely the same. Only in models with a dispatch order, this leads to lower renewable shares as gas-fired power plants can be used extensively without violating existing emission budgets. In the last variation, we evaluate the effectiveness and implications coming from renewable shares as a model constraint. Our analysis proves, that the implementation of the politically agreed renewable share of 80% in 2030 does not guarantee substantial emission reductions as generation shifts from gas-to lignite and hard coal-fired power plants. Therefore, this parameter should always be implemented in combination with other CO_2 reduction measures.

In the last step, we apply all relevant policy decisions from the new German government, which was elected in December 2021, and analyze the overall trends that can be observed for the optimal system configuration. One main insight is that the proposed minimum capacities of 200 GW for PV and 30 GW for wind offshore might not guarantee that a renewable share of 80% is reached. Moreover, a comparison of the new policy targets with previous targets reveals that higher investments are required for most technologies. The additional required capacity varies between models and ranges from 21% to 43% for solar PV, between 0% to 28% for wind onshore, and from 0% to58% for wind offshore. In addition, substantially increased investments into flexibility technologies, such as storage and transmission, are necessary. The new policy decisions correlate with higher uncertainty in energy system modeling, as deviations between models increase.

It should be emphasized, that the scenarios conducted in this study have been simplified to ensure data harmonization. The main simplifications include inflexible demands and inflexible imports. The results of our comparison prove that most models are robust in the sense that they show similar results for different scenario variations. Nevertheless, significant differences occur that pose the question of how reliable models are for answering pressing political questions. Our analysis shows that to answer specific questions, the choice of the model plays a very important role. Choosing the right model, however, depends strongly on the purpose behind the question that is supposed to be answered. All models have their philosophy and idea of how to approach the optimal solution. This implies basic assumptions that certainly have a major impact on the outcome. If the purpose is to find the most optimal energy system possible, LP-based models are the obvious choice. However, capturing some system operation patterns that follow historical decisions, models with pre-defined dispatch orders can be a trade-off between the optimal and plausible solution. Additional constraints in LP models are one possibility to fill the gap between those two extremes, as future system design is of high uncertainty. One example is the definition of investment costs that can lead to solar PV generally being favored over other renewable sources. The depth of technology modeling, especially for transmission, can also make a substantial difference.

The used approach for this model comparison exclusively focuses on the power sector, including the other sectors through exogenous assumptions. Modeling an integrated energy system where sector-coupling effects are endogenously accounted for would provide better insights into the inter-dependencies within the energy system. The same applies to the modeling of flexible transmission lines to neighboring countries. If considered, they could potentially increase flexibility and reduce generation and storage demand. However, especially for future scenarios, this is very challenging due to the unavailability of Open Source data. Stronger collaboration and exchange of data between scientists could substantially improve future model comparisons. For the 2030 scenarios, however, we expect that despite the simplifications our results hold as still a significant amount of thermal power plants provide flexibility. Nevertheless, we propose to use this approach and adapt it to cover sector coupling technologies and other flexibilities including transmission exchange and demand response among others.

Credit author statement

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Data availability

The data template that contains all input data for the utilized scenarios is available on: https://zenodo.org/record/5854410.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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