Renewable and Sustainable Energy Reviews 159 (2022) 112055

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Development of an open framework for a qualitative and quantitative comparison of power system and electricity grid models for Europe

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ARTICLE INFO

Keywords:
European transmission grid
Power system simulation
Model comparison
Python
Open energy platform

ABSTRACT

The ongoing needs to develop power systems towards more environmentally friendly technologies with respect to climate change in conjunction with the continuous evolution of the respective market conditions is leading to a transition away from the traditional system operation. The upcoming challenges have motivated the development of an increasing number of models for transmission grids. Nevertheless, the high complexity of such models renders it exceedingly difficult to compare their results as well as any corresponding conclusions.

In this paper, we develop an open framework to compare a variety of pan-European transmission grid models with a strong focus on the German power system. The comparison is performed in both a qualitative and quantitative manner, depending on the investigated modeling aspect including input data, methods, system boundaries and results. The quantitative model comparison is done by performing harmonized model experiments, one for 2016 as back testing and one for 2030 for analyzing the future system.

Core elements of our comparison framework are:

We proved that our comparison framework is suitable to make similarities and differences between the different model results visible, e.g. using quadratic heat maps. To ensure transparency and to support the open modeling community, the fact sheets with the model specifications and the database with selected model results are uploaded on the open energy platform.

- Factsheets
- Harmonized input data and model experiments
- Selected key figures for model results
- Public available database for two scenarios (2016, 2030)
- Methodologies to compare model results

1. Introduction

A significant increase in the desire for analyzing the European power system has been observed over the past decade, resulting in a variety of modeling approaches that have been developed by scientists in order to accurately represent its properties and behavior [1]. One of the most important drivers for this trend includes the commitment of the European Union to decarbonize its economy, and the power sector constitutes one of the highest emitters [2], which will require the use of a variety of novel generation, transmission and storage technologies. Such technologies may substantially alter and pose challenges to the traditional way of power system operation, control and security [3], while also questions regarding cost-efficient transition can become difficult to ask. Another significant driver consists of the economic transformation of the European power market, where the goal is to accelerate the integration of a single market and facilitate a variety of system flexibilities within a liberalized environment.

Power systems constitute a field with a long history of analysis, however the new challenges introduced by the system transition typically require a variety of novel methods, increased computational resources as well as a greater scope [4]. For instance, the increasingly decentralized and inflexible power supply needs to be accurately described in both spatial and temporal dimensions in order to capture the most important dynamics. In the presence of such challenges, a variety of new modeling efforts have been conducted in order to answer

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https://doi.org/10.1016/j.rser.2021.112055
Received 31 August 2021; Received in revised form 12 November 2021; Accepted 29 December 2021
Available online 3 February 2022

Abbreviations

AC	alternating current
API	Application Programming Interface
CCGT	combined cycle gas turbine
CHP	combined heat and power
DC	direct current
DLR	Dynamic Line Rating
DTW	Dynamic Time Wrapping
ENTSO-E	European association for the cooperation of transmission system operators for electricity
EU	European Union
FLH	full load hours
GDP	gross domestic product
HVDC	high voltage direct current
ISO	Independent System Operators
JRC	Joint Research Centre
LAU	Local Administrative Unit
NDP	Network Development Plan
NTC	Net Transmission Capacity
NUTS	Nomenclature des unités territoriales statistiques
OEP	Open Energy Platform
OPF	Optimal Power Flow
PDF	probability density function
PST	Phase Shifting Transformers
PTDF	Power Transfer Distribution Factor
RES	renewable energy sources
SOC	state of charge
TSO	transmission system operator
TYNDP	Ten Year Network Development Plan
VRES	variable renewable energy sources

the relevant research questions [5]. The goal of this paper is to supply a framework that can provide insight on the differences of such models and their inner workings. In this way researchers will be able to more easily identify the most important areas for further development and it can further increase the trust as well as limitations of such approaches. Following the history of the broader energy modeling community, the relatively recent increase in power system models requires a deeper investigation and comparison of such models as well. In particular, the comparison should focus on the recently developed models which concentrate on this new technology landscape as well as the economic and operational effects. Moreover, such models should incorporate the complete and realistic depiction of both the system conditions and operation, for example the consideration of the existing grid infrastructure or load curves at each bus, and not merely an aspect of those or synthetic conditions.

As with energy system modeling in general, power system models describe complex problems with different approaches and many different models may produce contrasting results while trying to represent the same real world system. Therefore, it has always been interesting to compare such models with each other and explore the inner workings, which among others can provide crucial understanding of the system itself as well as benefit the understanding and improvement of each individual model and the modeling process in general [6]. A more comprehensive review of the existing model comparison techniques is presented in section 2, where it is observed that such a comparison is rarely conducted for power systems. Especially transmission expansion planning's main steps, namely: regionalization of generation and demand, power market simulation, transmission grid and congestion management simulation have not been analyzed in a structured model comparison yet. In contrast to existing attempts, the proposed framework aspires to address issues that are specific to power systems and provide a model-agnostic approach that does not require substantial knowledge of the involved models a priori.

The goal of this paper is to describe the various challenges and aspects of model comparisons for power systems as well as to provide a framework on how to approach such a task. Besides input data related to generation and demand as well as the grid infrastructure, various methodologies and assumptions regarding the spatial distribution of generation and demand (regionalization), the operation of conventional power plants (market simulation), the operational concept of power flow controlling devices (grid simulation) as well as the sequence of costly and non-costly remedial actions (congestion management simulation) are compared, since these are expected to play a vital role in the overall behavior of each model. The framework includes comparison methods and tools for all aspects of power system modeling within the specific context such as formulating the system conditions, congestion management methods or market output. Although the scope of the paper is to present a complete comparison framework, quantitative comparison includes only the market output, whereas the remaining areas of comparing the regionalization methods and the congestion management output are discussed in separate publications. Moreover, specific models are used to better illustrate these approaches and provide further insight; however, a complete comparison of models is beyond the scope of this paper, which focuses primarily on developing and discussing the comparison framework itself.

2. State of the art

Model comparisons aim to compare existing approaches in terms of methodology including model structures and data. The aim is to gain a better understanding of the respective approaches and to identify opportunities for further development. Furthermore, a model comparison offers an ideal platform for in-depth discussion for model developers [7].

Model comparisons have been an effective means of achieving these goals for many years. At the international level, the Stanford Energy Modeling Forum (EMF) should be mentioned here, which was introduced in the 1970s and has been continued ever since [8]. On the EU level, the Energy Modelling Platform for Europe (EMP-E) [9], the project ACROPOLIS (Assessing Climate Response Options: Policy Simulations - Insights from using national and international models) [10] and CASCADE-MINTS (Case Study Comparisons And Development of Energy Models for Integrated Technology Systems) should be mentioned [11]. Between 1997 and 2007, a total of five model experiments were carried out by the German Federal Ministry of Education and Research (BMBF) and the German Federal Ministry for Economic Affairs and Energy (BMWi) within the framework of the FORUM for Models [12]. Model comparisons were carried out on the example of selected problems, which included models of different categories as well as the coupling of models. Recently running research projects in Germany are RegMex [13,14], 4NEMO - Research Network for the Development of New Methods in Energy system Modeling [15] and BEAM-ME [16,17]. These model comparisons performed on power generation models with a specific focus on flexibility (RegMex), economic and social dynamics (4NEMO) or calculation algorithm and acceleration strategies (BEAM-ME).

Transmission grid models are often used to analyze the impact of integrating high shares of renewables into the power system. In this case, the analysis is usually coupled with power plant dispatch and the regionalization of generation and demand to grid node level [18]. Depending on the focus set, the underlying models can differ, among other things, in the type of load flow modeling and control, in the level of detail modelling individual grid components, in the geographic scope that is covered in detail, and in the consideration of network expansion and congestion management in general.

Regarding the power-flow calculation in transmission grid models, a distinction can be made mainly between Power Transfer Distribution Factor (PTDF)-based, Direct Current (DC) and Alternating Current (AC) approaches as well as Net Transmission Capacity (NTC) approaches [19]. Depending on the applied power-flow calculation method, the required computational effort allows different degrees of detail of the system representation [20,21]. This is one of the reasons why there are fewer AC approaches, which are used in particular for detailed technical analyses. For similar reasons, network reduction methods are becoming increasingly important [19]. In contrast to AC approaches, the other approaches (DC, PTDF, NTC) have a much lower computational cost allowing the consideration of more extensive systems at the expense of a lower accuracy of the results [22]. Hence, the range of existing approaches for modeling transmission grid has its justification. Furthermore, the approaches mentioned above can complement each other [20,21]. The same applies to various operational concepts of power-flow controlling equipment such as Phase Shifting Transformers (PST) or High-Voltage Direct Current (HVDC) links, which will be increasingly integrated into the AC grid in the future [23,24].

A detailed comparison of large-scale European transmission grid models (including regionalization, dispatch, power-flow and congestion management methods) has not been performed yet. One reason for this is that all input data and model results have to be available in high spatial (several thousand grid nodes in continental Europe) and temporal resolution (hourly). In contrast to other model comparisons covering large geographic areas from an economic or regulatory perspective, a detailed comparison of infrastructure models becomes disproportionately complex by significantly extending the geographic area under assessment. Furthermore, modelling the relevant electrical and technical restrictions make the applied methodological approaches complex. Hence, the concept of accuracy or the level of detail must be understood and considered on several levels by modelling the electrical transmission grid. The first level is the width of the modeling in the sense of the geographical area of the real grid topology and in particular the modeling of the edge area. The second level is formed by the different voltage levels of the power system. This horizontal dimension of the grid infrastructure has to be represented in the transmission grid model by an appropriate modeling depth with suitable grid equivalents. The last level represents the system-specific abstraction level. Taking into account the diversity and heterogeneity of the grid's components (like busbars and breakers) in substations and switching stations, an exact component-specific modeling of the continental European transmission system is highly complex. For this reason, parts of the electrical systems or groups of components are typically merged and aggregated in power system models in order to be able to subsequently transfer them into a so-called bus-branch model [25]. For this purpose, a number of simplifying assumptions have to be made, which have a significant influence on possible results and their informative value. In particular, the way in which switchgear, breakers and individual busbars are represented in the network model has an influence on the number of nodes and links. At this point, the situation is aggravated by the fact that transmission grid data is only publicly accessible to a limited extent, which makes validation virtually impossible, even though there are increasingly publicly accessible but unconfirmed data sources [26].

However, in recent years a trend towards open source modeling and more and more also open data begun and is further increasing. In the meantime, there are a whole range of open modeling and open data platforms, such as e.g. GitHub or Zenodo. The open energy platform specifically targeted towards modelling of energy systems [27]. Furthermore, an open source python package has just been released that provides software tools and methods for comparison and visualization of model results [28].

3. Development of a comparison framework and definition of model experiments

This paper presents a newly developed framework to compare grid models and supporting the open modelling and open data community by using the open energy platform as a basis. The framework can provide useful information to researchers and decision makers. On the one hand, the framework can provide orientation on the question, which parts of the power system should be modeled on which level of detail for different research questions or fields of application. On the other hand, the developed framework provides a platform for the modeling community. The published reference datasets enable other researchers to compare their models against other models. This chapter describes the comparison framework. The MODEX-Net research project team developed and used the framework to analyze various power system models. The comparison framework consist of two consecutive workflows (Fig. 1).

3.1. Workflow of the comparison framework

As a starting point, the framework analyzes the model's inputs and methods in a qualitative manner. Therefore, the initial workflow collects basic information about the models. To do so it makes use of factsheets to gather information on the basic data sources and methods. The developed factsheets are available as supplementary material as well as at https://www.energiesystem-forschung.de/forschen/projekte/modex-net. The comparison framework considers the model's inputs for the regionalization of generation and demand as well as for existing power grid infrastructure in the field of data sources. With regard to the models inner workings, the comparison framework analyzes the methods applied for spatial disaggregation as well as time series generation, for unit commitment and dispatch optimization, for power flow calculations and for congestion management optimization. Based on the comparison of the models main inputs and processed data sources as well as applied methods across all models, the comparison framework identifies each model's key characteristics and highlights major differences and similarities.

In a second workflow, the comparison framework determines harmonization potentials as a basis for the quantitative comparison. Taking into account the model's key characteristics as well as major differences and similarities, the workflow identifies inputs and methods that can easily be harmonized, e.g., by using publicly available data that is already used by some models. Furthermore the workflow proposes a harmonization of participating model's individual features, such as methods on the consideration of power flow controlling devices or modelling the (n-1)-criterion in explicit or indirectly by a simplified security margin. To put it concisely, the qualitative comparison builds the foundation to parametrize the participating models in a way that input data and applied methods across all participating models represents the lowest common denominator that can be reached without models having to implement new features in advance.

Against the background of performing a quantitative comparison of power system model's results especially with a focus on transmission grid utilization, it needs further steps to carry out detailed analysis in a structured procedure. After harmonizing the most relevant input data and methods of the models, the harmonization of the model experiment itself becomes crucial. Especially when real transmission grid infrastructure instead of test systems, like IEEE 118 Bus, are considered, the point in time of the study is important. On the one hand there are so called back testing studies that try to replicate the historic systems behavior as good as possible. On the other hand, there are system studies dedicated to forecast the future power system. The latter are heavily dependent on and driven by assumptions with regard to different components of the future energy systems. A key factor by analyzing future scenarios is the transmission grid infrastructure that is assumed to be built in the meantime (today until year of future scenario, e.g., 2030)

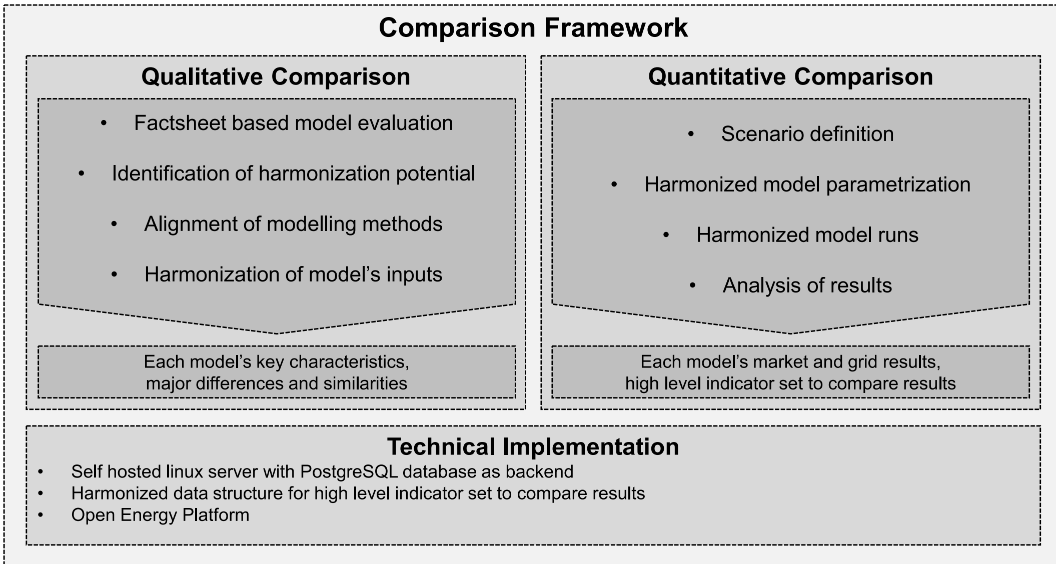

Fig. 1. Workflow of the comparison framework.

forming the system studies reference grid. Hence, the (future) market and grid scenarios have to be defined in detail to serve as an adequate reference in a model comparison. The scenario definition workflow specifies the energy-economical framework in terms of installed generation capacities and electricity demand. Furthermore, the workflow defines the reference transmission grid by providing a list of already known grids expansion and reinforcement measures that are assumed to be realized until the point in time under assessment.

Based on the detailed market and grid scenarios as well as the harmonized data sources and methods so called model experiments (MODEX) are carried out. Each model experiments includes the parametrization of all participating models with the harmonized data and methods, whereby each model makes use of its own transmission grid data and grid modelling methods, the execution of a model run including a simulation of the power market, the transmission grid's utilization and congestion management measures, the upload of each simulation's results to the OEP clone, the automated analysis of all provided model results with a newly developed python framework and finally a discussion of possible adjustments that were tracked in an issue list.

3.2. *Definition of model experiments*

As mentioned before, the point in time (the scenario year) of a system study is essential, if real transmission grid infrastructure is analyzed. Hence, the model experiments in the MODEX-Net research project were designed in a way to incorporate the two most relevant types of system studies. The first model experiment will be a back testing study for the year 2016. The back testing considers the year 2016, as sufficient historical data is available from qualified sources. The second model

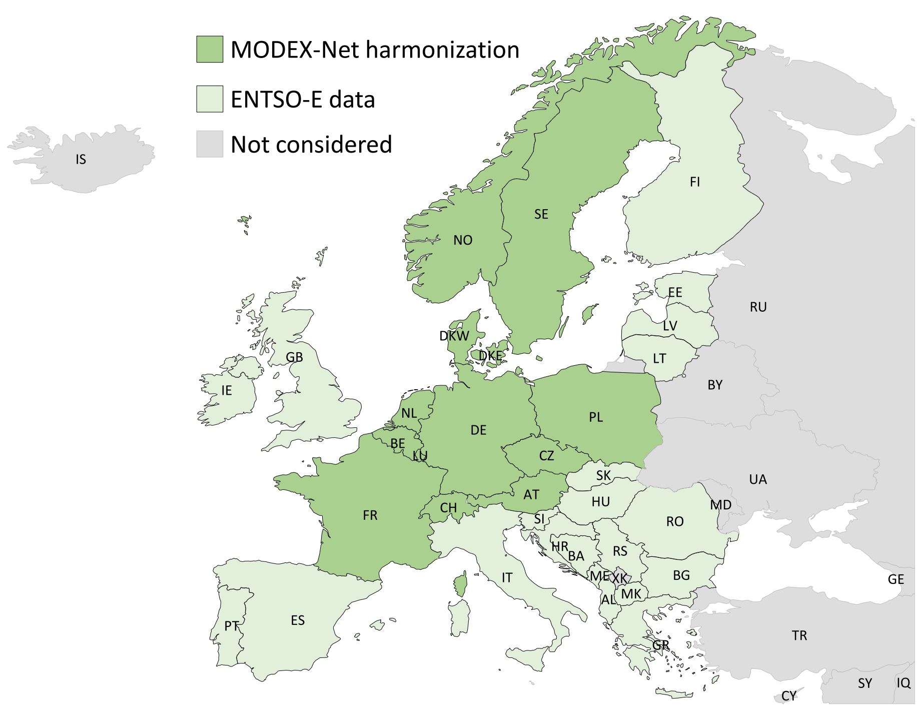

Fig. 2. Geographical scope of data harmonization and maximum spatial extent of individual models.

experiment will analyze a future energy system for the year 2030 based on assumptions from the German national grid development plan with regard to the system's development [23]. The reference data sets for 2016 and 2030 used the model experiments are publicly available at https://www.energiesystem-forschung.de/forschen/projekte/modex-net. In both model experiments Germany and its neighboring countries are considered as main focus region of the study. However, the complete area under assessment includes further countries the so-called satellite regions.

Fig. 2 shows the countries that were considered in the model experiments. Germany's neighboring countries as well as Norway and Sweden, which are linked via sea cables to the German transmission grid, are considered in all models. Therefore we harmonized the input data for these countries. The maximum spatial extent of individual models covers all ENTSO-E countries, excluding Cyprus and Iceland.

Both model experiments include the simulation of the European power market, the simulation of the transmission grid's utilization as well relevant congestion management measures to resolve congestions in Germany by conventional redispatch and curtailment of renewable energy sources. The power plants dispatch, the power flows in the transmission grid as well as the congestion management measures are determined on an hourly basis for a complete year, resulting in 8760 consecutive snapshots of the system providing the raw input data for the comparison framework.

3.3. Technical implementation of the comparison framework

The comparison framework is implemented at a cloud server, which is a self hosted linux server with a postgresql database as backend.

The database consists of several predefined tables and views, which take into account the spatial and time resolution (e.g. country code, region code and timestamp) of the selected key figures (e.g. hourly electricity price, CO_2-emissions, power imports and exports as well as load/vRES curtailment per country respectively) from the quantitative model results. The selected key figures are defined within a given data structure including foreign key constraints for dimensions to enforce integrity. The tables use fixed naming conventions for each parameter and model. All key figures shown in Fig. 3 refer to market results (dispatch).

Grid related key figures need further spatial resolution per line and per node:

- per line: congestion work, amount of congestion and maximum overload
- per node: positive and negative redispatch of conventional power plants, curtailment of variable renewable energy sources

For the upload procedure we developed a python client for communicating with the API as well as additional helper functions to parse csv files into proper data structures. Following this, each model maintainer uploads their own model data into their designated tables as defined by the naming convention.

The linkage to the open data community is given by using a clone of the open energy platform (https://github.com/OpenEnergyPlatform/oeplatform) as middleware stack (django) with public API for data upload and download. The final model results are publicly available under an open data license at the open energy platform (https://openenergy-platform.org/), while the relevant input data can be found at the project's website (https://www.energiesystem-forschung.de/forschen/projekte/modex-net). Other models can add their own model results and compare them with our results. The chosen comparing methods are described in section 5.

4. Qualitative model comparison

Designing the proper model experiments requires the identification of the key modeling aspects and differences among the various models. Moreover, such a process becomes essential for determining the harmonization potential of the modeling components, which may also play a significant role in designing the experiments and the final comparison of the models as well. Therefore, a systematic investigation of their properties and parameters is deemed necessary. Such a task can be typically accomplished by designing and filling appropriate factsheets, where all the necessary information can be conveniently consolidated, hence providing a way to more easily compare the models and gain further insight about their most critical discrepancies.

The process of transmission grid planning typically consists of the following methodological steps:

- Definition of **Scenarios,**
- **Regionalization** of generation and demand,
- Generation of **time series** of inflexible loads and variable renewable energy sources,
- Power **Market Simulation** for unit commitment and economic dispatch as well as commercial exchanges in Europe,
- **Power Flow studies** to calculate the grid's utilization (considering power flow controlling devices) and identify congestions,
- **Congestion Management Simulations** to preventively avoid potential overload situations.

4.1. Comparison of input data

As each of the steps mentioned before make use of individual

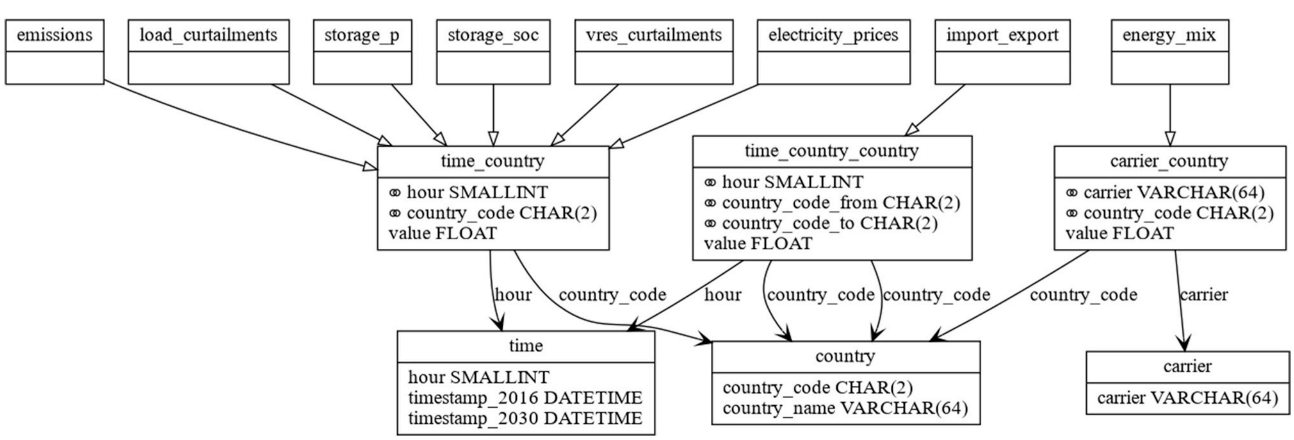

Fig. 3. Predefined tables and views of the database for market results.

specialized input data and methods, the comparison framework clearly differentiates between data and methods. Furthermore, the comparison framework's factsheets consider the input data and methods of each step separately. Tables 1 provides an overview on the most important model's characteristics considered to compare input data and data sources. The factsheets consider the methodological steps of simulating the transmission grid's utilization before and after the application of congestion management measures in an aggregated manner, as the main data sources are typically identical in these steps.

As the methodological steps of regionalization and time series generation is covered in detail in Ref. [18], this paper sets the focus on modelling power generation in the step of the market simulation. At first, all models are compared with regard to the inclusion or neglect of fuel types and generation technologies. It is found that the corresponding agreement among the models is high, hence this aspect may be disregarded as a source of discrepancy. Further invariant subcategories include the spatial resolution of power plants, where these are modeled as single power plants or units and are usually connected to the nearest substation. The operational parameters of hydro and VRES power plants, as well as the spatial distribution of the electricity demand which follows the nearest substation principle as well. Therefore, although these aspects may strongly influence the modeling outputs, this influence cannot be examined by this study, since there is no discrepancy among the models. Furthermore, it is worth noticing that although all models include the same operational parameters for hydro and VRES generation or the same principle for connecting the demand or the power plants to the grid, these aspects cannot be subject to harmonization, since they constitute core modeling elements whose differences are under investigation (e.g., the variable capacity factors of wind generation).

Despite the partial agreement on several sub-categories of generation data, the models show significant discrepancies with respect to primary data sources, the spatial distribution of VRES as well as the operational parameters of conventional power plants. The data of the primary sources may contain information regarding the geographical locations, parameters like the commissioning year or the year of the latest retrofitting, fuel type, technology or even more technical ones like overall efficiency. Due to their significant role in the model, these data are also not suitable for harmonization. Nevertheless, a further quantitative description is deemed necessary. Similar conclusions apply for the spatial distribution of the VRES as well, which is discussed further in Ref. [18] in order to identify the key differences between the models with the corresponding methodologies considered unsuitable for harmonization.

On the contrary, the operational parameters of conventional power plants provide one of the highest potentials for harmonization among the various models. It can be observed, that besides the parameters related to the combined heat and power (CHP) plants operation, the ones related to unit commitment formulation as well as the part-load efficiencies, all other parameters are shared by the majority of the models. Therefore, for the cases where these parameters can be harmonized (e.g., CO_2 costs), a respective harmonization of them can render them invariant among all models. In addition, this finding highlights the necessity of each parameter with regard to modeling power systems as well as the diversity in modeling the flexibility of thermal power plants.

In contrast to generation, comparing the modeling of the transmission grid requires fewer sub-categories, namely topology data and grid data. However, despite the lower number of sub-categories, more differences can be identified among the models. Similarly, to the comparison of the primary data sources for power plants, little information can be extracted with respect to the grid topology data from the factsheets alone, while also a corresponding harmonization is considered undesirable for the purposes of this study as well. Nevertheless, it can be noticed from the factsheets that most of the models consider ENTSO-E and the German Network Development Plans as data sources. Moreover, it can be observed that almost all models apply special considerations to Germany in contrast to the rest of Europe.

Regarding the grid data, it can be observed that most models consider typical line parameters for the European grid outside Germany. Although not all models share the same assumptions, many of them do not include any modeling of transformers. On the other hand, the line parameters for Germany show a higher diversity among the models and thus an increased difficulty for harmonization. Finally, modeling the connections to offshore wind generation shows discrepancies that cannot be easily evaluated by the factsheets alone, therefore further comparison is deemed necessary [18].

Tables
1: Exemplary data points (excerpt) considered to compare input data and sources of each model.

Methodological step	Exemplary data points considered in comparison of input data
Scenario definition	• External scenario data, e.g., NDP or TYNDP, as an input
Regionalization	• Current fleet/assets/portfolio in models' base year • Land cover/usage data for RES potential areas • Social and structural data, like GDP or population density
Time-series generation	• Profiles vs. weather data and historic full load hours (FLH) • Solar and wind power plant model to transform weather data • Social & structural data, like GDP, for sectoral demand forecasts
Market simulation	• Power plant data base, load profiles, NTC-Values • Commodity prices, outages & availabilities
Grid simulation and congestion management simulation	• Basic grid topology and its electrical parameters • Grid expansion and reinforcement projects

4.2. Comparison of methods

Aside from input data, models may also differ significantly with regard to their methodologies. Tables 2 provides an overview on the most important model's characteristics considered to compare the applied data processing techniques and simulation methods.

Regarding the regionalization methods used to simulate the spatial distribution of VRES and demand the basic working principle of the models looks quite similar. On the one hand, there are models that make use of top-down approaches using distribution factors to break down

Tables
2: Exemplary data points (excerpt) considered to compare data processing and simulation methods of each model.

Methodological step	Exemplary data points considered in comparison of methods
Scenario definition	• External scenario data, e.g., NDP or TYNDP, as an input
Regionalization	• Top-down vs. bottom-up • Dis-/Aggregation methods from/to grid nodes
Time-series generation	• Weather data vs. profiles
Market simulation	• Regional scope • Nodal pricing (OPF) vs. zonal NTC energy only
Grid simulation	• AC vs. DC vs. PTDF • Consideration of grid losses • Dynamic line rating • (N-1)-criterion vs. security margins • Power flow controlling devices: PST, HVDC
Congestion management simulation	• Consecutive steps (real world) vs. integrated OPF (academic) • Power flow controlling devices: HVDC, PST • Consideration of time coupling

national capacities to smaller regions, e.g., NUTS or LAU regions. On the other hand, some models make use of bottom-up approaches by explicitly considering land usage and land cover data to simulate the spatial distribution of installed VRES capacities. Furthermore, this observation can be extended to data processing and simulation methods in the field of time series generation. Models applying top-downs regionalization approaches typically scale historical generation profiles to simulate the hourly VRES feed-in, whereas models that apply a bottom-up regionalization approach tend to use numerical weather models to simulate the hourly feed-in of VRES. However, all models consider historical load profiles to simulate the inflexible demand that is extended by additional load profiles of flexible consumers. Further details on the topic of regionalization and time series generation can be found in Ref. [18].

With regard to the market simulation methods applied to optimize the operation of conventional power plants and storages as well as commercial exchanges between the European bidding zones, it can be observed that the models cover different regions but all have a strong focus on Germany. All models consider Germany and its neighboring countries in the market simulation, but some models do not consider the countries behind the direct neighbors, e.g., Italy, Great Britain or Spain. Besides the regional scope of the models the basic working principle of the market or dispatch simulation shows some discrepancies between the models. On the one hand, there are models following a consecutive approach starting with a zonal market simulation that considers each bidding zone as a copper plate having no transmission constraints. Hence, the grid's transmission capacities are considered in a very simplified way (typically by bilateral NTC values) in the market simulation. This represents today's consecutive market and system operation processes. On the other hand, there are models that apply an integrated market and grid simulation by considering grid's transmission capacities directly inside their dispatch optimization. Such kind of approaches are often used in academics or non-European system studies where Independent System Operators (ISO) typically perform Optimal Power Flow (OPF) simulations.

The methods used to simulate transmission grid's utilization are quite different in the models. At first, it has to be noted that the electrical power flow can be described in different ways going along with different levels of complexity. The full AC power flow equations are non-linear making it challenging to integrate them in optimization problems. Thus, linearization techniques and iterative methods to solve the non-linear equations are typically used to formulate and solve optimization problems in the field of power system analysis.

Regarding the modeling methods for the transmission grid, it can be observed that the discrepancy is high. It is worth mentioning that for redispatch a more elaborate comparison is required since the various approaches cannot be easily consolidated in the form of simplified factsheets. Due to the high diversity in transmission methodologies, further analysis is considered necessary to understand the differences between the various models and can be found in Ref. [29].

The detailed comparison of the different models with the assistance of the factsheets has provided significant insight into the various modeling aspects and the corresponding discrepancies. Nevertheless, further conclusions may be extracted out of this analysis. Such conclusions may include the identification of the most crucial modeling aspects that can form the guidelines for designing the scenario frameworks, upon which the individual model experiments can be carried out.

The aim of the qualitative comparison consists of identifying and interpreting the differences between the various models and more specifically the influence of the different modeling methodologies. Therefore, the model experiments are designed in such a way that the impact of the most critical aspects can be adequately isolated and hence be better estimated and quantified as well as interpreted with respect to the model behaviors. To this end, the modeling aspects that constitute the primary candidates for the potential discrepancies in the models' behavior and outputs are collected and classified by the application of a quantitative model comparison making use of different key performance indicators and means of visualization (cf. section 5).

4.3. Identified harmonization potentials and applied harmonization

Based on the qualitative model comparison using the presented factsheets the relevant input parameters that should be harmonized to generate a unified data basis were identified. The objective here is to harmonize the model's input parameters only to a certain degree, so that the methodological differences applied by each model regarding the regionalization and the modelling of the transmission grid can continue to take effect. For these reasons, the input data for electricity grid parameters were not harmonized at all and electricity demand, energy carrier-specific generation capacities and storage capacities were only harmonized at country level (NUTS-0). The further topics concerning regionalization of input data [18] as well as grid simulation and redispatch calculation [29] are discussed in two associated papers of this project.

The selected input data used for harmonizationinclude installed generation capacities by fuel type, storage capacities, technical availabilities of conventional generators, full load hours of renewable energy generators, annual total demand and NTC values for the capacities of commercial exchanges. A comparison of model data with a variety of literature sources showed similar trends in terms of agreement in generation capacity values. The most challenging generation type was found to be hydropower, where significant discrepancies were observed both within the models as well as the literature, while also the distinction to the different types of hydropower may differ or be ignored. This differentiation, however, was deemed significant for the harmonization, where the three types were distinguished based on the individual flexibilities, namely run of river, reservoir and pumped hydro storages. The harmonized values for the selected input data were decided to be independent of any models and only based on the literature survey, where it was attempted to use as few sources as possible and mostly official sources, such that consistent scenarios could be maintained. The main data sources for these input parameters for the reference scenario 2016 and 2030 are:

Reference scenario 2016.

- ENTSO-E Statistical fact sheet [30].
- Joint Research Centre (JRC) Hydro-power database [31].
- List of power plant from the German Federal Network Agency [32].
- NTC as maxima of forecasted year ahead transfer capacities from ENTSO-E Transparency Platform [33].

Reference scenario 2030.

- TYNDP 2018, scenario "Sustainable transition" [34].
- Network development plan for Germany 2030 (version 2019), scenario "B 2030" [35].
- Mid-term adequacy forecast 2019 from ENTSO-E [36].

Imprecise information was collected in an issue list in order to finally develop a common understanding and use a uniform definition of the data. Whenever necessary, additional literature sources were included, such as historical data for technical availabilities of thermal power plants or the JRC data base for hydro power plants. For pumped storage power plants, we have made the assumption that the pumping capacity is equal to the turbine capacity and the storage capacity is eight times the turbine capacity.

In addition, harmonized default values were also provided for individual input parameters from the MODEX thematic network. These include energy carrier-specific CO_2 emission factors, fuel and CO_2 prices as well as country-specific standardized profiles for load and variable renewable energies for the weather year 2016 [37].

Besides the identification of input parameters that should be harmonized for the model comparison, the qualitative model comparison shows harmonization potentials in the field of the applied methods. As the developed framework has a strong focus on comparing the transmission grids utilization as well as overloads and congestions management volumes needed to remove the overloads, the following methodological steps were harmonized to ensure a better comparability of the model's results. As not all participating models were able to consider Dynamic Line Rating (DLR) in their power-flow studies it was decided that no models will consider it. However, it has to be noted that DLR significantly increases transmission capacities and therefore can reduce redispatch and VRES curtailment drastically. Most of the participating models were not able to consider the effects of PST in their power-flow or congestion management simulations, as a consequence no model will consider PST. Only two models have methods implemented to explicitly simulate outages and to perform power-flow studies in the (n-1)-case. The other models typically apply static security margins by reducing the maximum power-flow of all lines. Therefore, the method to model the (n-1)-criterion was harmonized in all models by applying a static security margin of 70%.

5. Quantitative model comparison

5.1. Definition of key performance indicators

Comparing methodologies and input data provides significant understanding of similarities and differences among models, nevertheless, the comparison of their outputs can provide additional useful insight to their inner workings. Using both sources of information can provide a better understanding of the differences between models. However, comparing results only also carries its own merit. Since different models may generate a variety of different types of output data, a process similar to input data harmonization can be applied, where all models should be able to provide the selected output in comparable format. Moreover, this selection should incorporate sufficient complexity for analyzing the models, while also be simple enough, such that the data are intuitive to interpret as well as easier to be linked to the differences in input and methods. To that end, appropriate visualization methods should be designed as well as key performance indicators be derived. It is important to notice that the use of the proposed indicator depend on the comparison context and the interests of the researchers, as well as the involved models, as described in the introduction. Despite the narrow context of this paper, power systems can be modeled in a variety of ways, hence the output selected for comparison should be generic enough that almost all models should be able to produce, regardless of their inner structure. To that end, it is selected to follow the existing paradigm of operating the European power system in a relatively coarse manner and providing data for two levels: the results of a day ahead market level and of a grid level where the whole transmission grid is taken into account for redispatch calculation. For each of these two levels a collection of minimal output can be selected as shown in Tables 3.

Tables
3: Minimal model results for comparison framework at market level and grid level. Results marked in red are not shared, instead secondary results are used.

Market level	Grid level
Time series	Time series
• Generation per unit/timestep [MW]	• Upwards redispatch per node/ timestep [MW]
• Electricity price per zone/timestep [€/MWh]	• Downwards redispatch per node/ timestep [MW]
• Cross-border power flow per interconnection/timestep [MW]	• VRES curtailments per node/ timestep [MW]
• VRES curtailments per zone/timestep [MW]	• Congestion work per line/ timestep [MW]
• CO_2 emissions per country/timestep [Gtons]	• Amount of congestion per line/ timestep [h]
• Charging/discharging per zone/timestep [MW]	• Overload per line/timestep [%]
• State of charge per zone/timestep [GWh]	
• Load curtailments per zone/timestep [MW]	
Secondary results	Secondary results
• Energy mix per zone [TWh]	• Upwards redispatch per node [TWh]
• Net balances per zone [TWh]	• Downwards redispatch per node [TWh]
• Price convergence per region [%]	• VRES curtailments per node [TWh]
• Price convergence per interconnection [€/MWh]	• Congestion work per line [TWh]
	• Amount of congestion per line [h]
	• Maximum overload per line [%]

5.2. Comparison of market results

In this paper the focus lies more on the discussion of the market level, since the comparison of grid model formulations and corresponding conclusions (see Ref. [29]) requires a more detailed discussion that goes beyond the mere description of a comparison framework. Regarding the market results, the results of the corresponding list in Tables 3 can used for the model comparison. As it can be observed, besides the options in the *secondary results* list, all other results constitute time series data, thus resulting in comparing two-dimensional data for each model, e.g., a temporal and a spatial dimension for electricity prices. Therefore, the main goal of the comparison of models' output consists of deriving meaningful values for the differences of these data.

Extracting information from the market level results can be achieved by calculating indicators that reduce the dimensions of the original data such that they provide insight on their properties and ultimately reveal properties of the models as well. In this framework, four main ways are suggested for achieving this goal, accompanied with additional visualizations for better comprehension:

- Reduction of each time series independently by deriving additional results.
- Reduction of each time series independently based on an operator.
- Reduction of pairs of time series based on a distance metric.
- Elimination of the spatial dimension by focusing on a single region of interest.

The application of each method and its interpretation depends on the original result including its properties and its significance analyzing the model's behavior. Similarly, the selection of the specific operators and distance metrics depends on each case and the corresponding usefulness. Fig. 4 summarizes the reduction methods of the time series results suggested by the existing framework. The depicted operators and metrics merely constitute a, far from exhaustive, collection of the most popular alternatives that are typically found in the literature and their application will be discussed later in the paper. The recommendations stem primarily from the applicability as well as their usefulness to interpreting model behavior. In fact, in many cases comparing the full time series is not necessarily more useful than comparing the respective averages. In addition, some of the results are more important for model comparison than others that may be more sensitive or too complicated to interpret.

The *percentile converter* operator can be understood as an alternative to the kurtosis of the respective probability density function (PDF) that can provide a value with more direct interpretation for energy systems. It can be essentially viewed as a metric of the curvature of the corresponding duration curve and measures the area for a given percentile as shown in Fig. 5. For the case of VRES curtailments this would indicate whether the corresponding energy is concentrated over a few incidents with high volume or are more uniformly distributed over time.

Regarding the indicators that measure the distance of time series, two different categories can be distinguished: distance metrics applied on the original time series data (time series metrics) and metrics applied

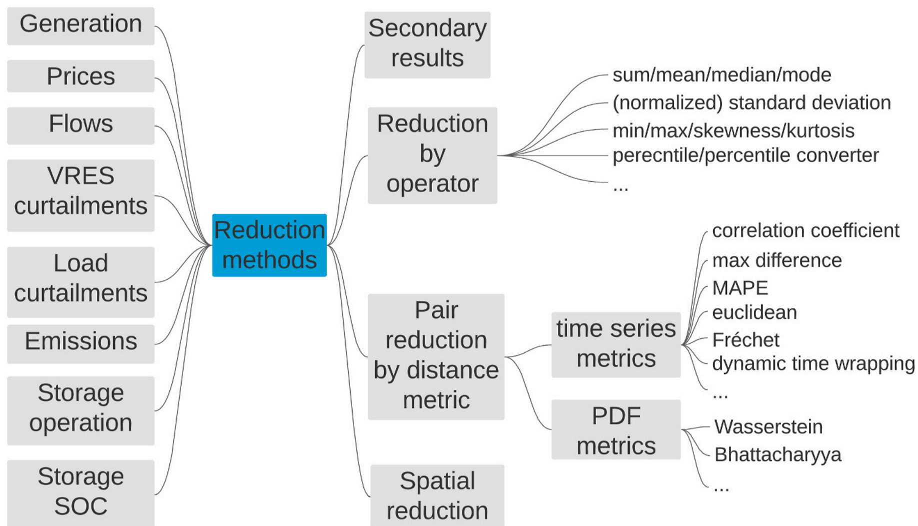

Fig. 4. Sketch for possible reduction methods of primary market results in order to derive suitable comparison indicators.

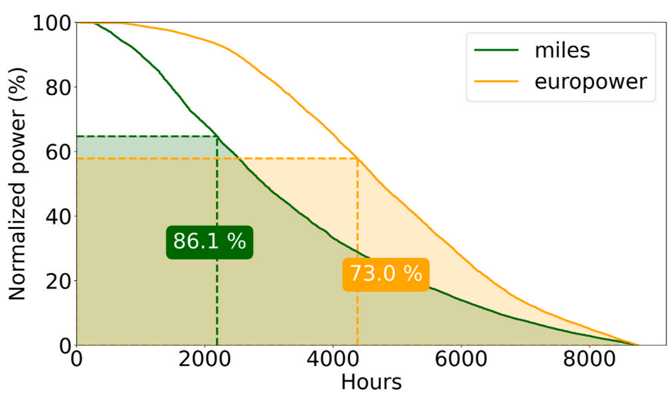

Fig. 5. Exemplary illustration of different *percentile converter* indicators for different duration curves and percentiles. The data corresponds to the wind offshore profiles of Germany for the models miles and europower.

on the derived probability density function (PDF metrics). Both categories can provide different information that may be useful depending on the measured result. For instance, the correlation coefficient may show how similarly two time series fluctuate over time, while measuring the similarity of the shapes of the corresponding PDF can show whether the two data sets exhibit similar distributions in a more averaged manner. A better understanding is given in Tables 4, where they are also applied to exemplary results.

A better understanding of the suggested indicators and metrics can be achieved via a discussion over data produced by market simulations rather than random time series. In this way the indicators can be viewed within the respective context, hence illustrating their usefulness and potential limitations for power system comparison. Moreover, the analysis will only focus on the generation output and electricity prices results, since, compared to the other results, these are observed to be the most relevant for model comparison and can also sufficiently illustrate the relevance for most of the afore-mentioned operators and metrics. This is not entirely unexpected, since the information of how much energy each unit will produce and each time and what price it will receive constitutes the primary result of every dispatch model. Nevertheless, it also appears that these results are the most useful for model comparison, since model behavior can be more easily tracked via them, while also patterns in how similarly models behave become easier to identify.

5.3. Generation

Generation output constitutes an extensive set of data that is both very difficult and not useful to compare in its primary form. Since models do not use the same input data or methods for generation units, it becomes more advantageous to aggregate them in both time and space. The most popular and useful way to accomplish that consist of the energy mix, where power units are grouped based on their fuel or

Tables
4: Exemplary distance metrics and their values when comparing isaar and europower to powerflex for the electricity prices in Germany. The green color indicates the lowest distance and the red color indicates that the numbers may be misleading.

	Metric	Original		Normalized		Comments
		ISAaR	Europower	ISAaR	Europower	
	Mean difference	−0.36	−4.63	0	0	Distance between the mean values
Time series	Correlation coefficient	0.16	0.83	0.16	0.83	Highest score shows the highest correlation
	Max difference	35.6	17.2	35.2	12.6	Maximum difference at any timestep
	MAPE	0.17	0.17	6.1	1.1	Linear error, small values can disproportionately skew the result
	Euclidean	610.3	482.3	609.3	212.2	
	Fréchet	35.4	15.9	35	12.6	Similarity accounting for location and ordering of points [38]
	Dynamic Time Wrapping (DTW)	42,360	42,076	42,108	12,386	A technique to find an optimal alignment between two given sequences [39]
Probability density function	Wasserstein	0.01	0.01	0.01	0.01	Measures the minimal effort required to reconfigure the probability mass of one distribution in order to recover the other distribution [40]
	Bhattacharyya	0.08	0.58	0.08	0.09	Based on the Bhattacharyya coefficient that measures the overlap of two samples [41]

technology type, e.g., onshore wind or natural gas CCGT. The corresponding classification depends on the context of the desired information and one obvious selection can be the classification of the harmonization process, nevertheless, the number of generation types can be further reduced for better visualization purposes.

Fig. 6 shows the annual energy mix for all investigated models and their common countries including the respective data from ENTSO-E [30] for the year 2016 in both absolute and relative values. It is considered the most important indicator regarding a model's performance with respect to the market behavior since it is comprehensive enough as well as easily comprehensible to use for interpretation and comparison. For instance, it can become relatively easy to observe whether models may collectively exhibit similar behaviors such as high nuclear production in France that may be due to overestimation of the available capacity during the harmonization or if there are outliers because of specific modeling aspects.

Nevertheless, a more quantitative indicator regarding the energy mix can also be derived in order to better distinguish the differences between the models and identify similarities. This can be achieved by measuring the average difference of the energy mix, weighted over all countries and generation types such that differences in small categories, e.g., oil in Denmark, do not skew the results. Fig. 7 shows a heatmap of this indicator, where it can become more apparent which models behave more similar than others.

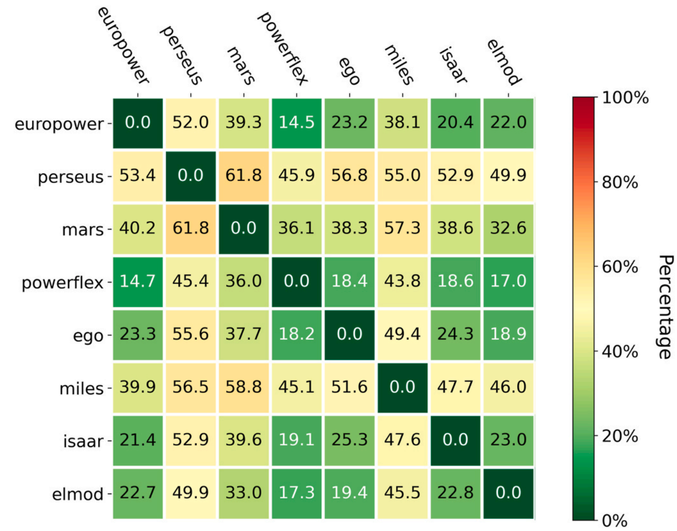

Fig. 7. Heat map of the average difference of the energy mix, weighted over all countries and generation types.

5.4. Electricity prices

Electricity prices constitute the second most important result since it also includes comprehensive information about a model's behavior, while also it is relatively easy to compare since each biding zone only has one time series. Using electricity prices, we can also demonstrate some of the main aspects of time series comparison in power system modeling as well as evaluating the various types of results for model comparison. Covering all indicators on all results in Tables 3 and their respective

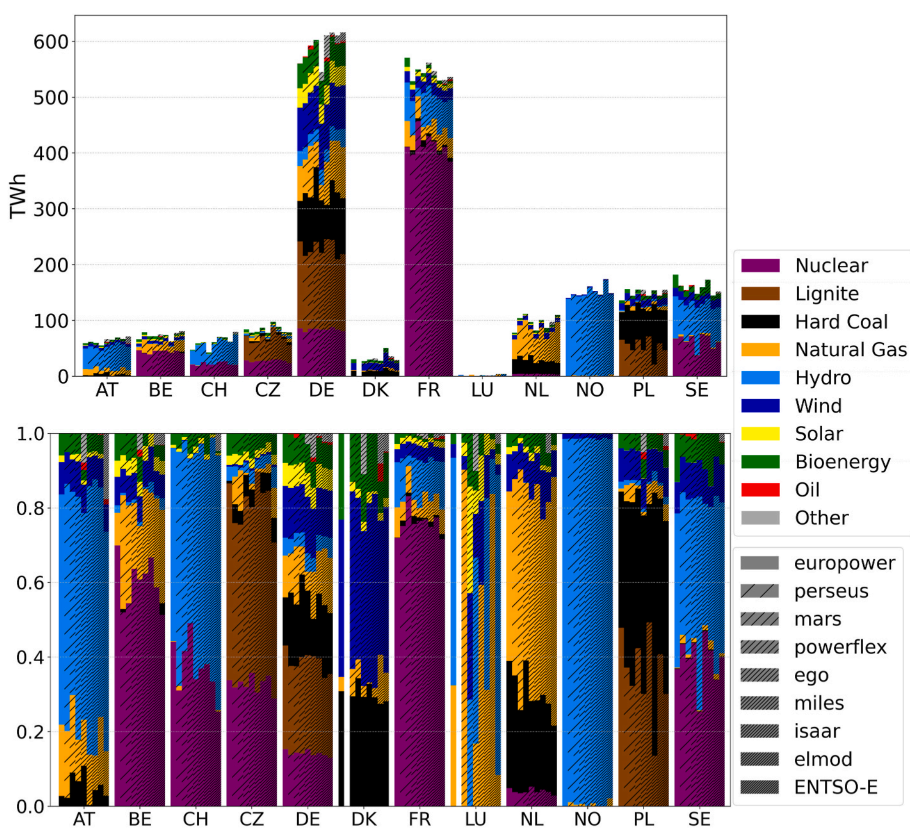

Fig. 6. Annual energy mix for all investigated models and their common countries including the respective data from ENTSO-E for the year 2016 in both absolute and relative values.

interpretation would go beyond the description of a comparison framework, while also the corresponding prioritization may depend on the results themselves as well as the context of the comparison. Therefore, the primary aspects of time series comparison can be illustrated via electricity prices, where the main conclusions can be then extended to the other types of results as well.

5.4.1. Time series reduction by descriptive statistics

The most direct approach to comparing time series consists of the independent reduction into a single value via descriptive statistics or derivation of secondary results. Besides the 'sum' or the 'percentile converter' operators that do not generate any useful value, all other operators can provide values that can be used for comparing electricity prices. Some of the most directly comprehensible operators for electricity prices consist of the first two moments that can measure the average behavior and spread over the mean value correspondingly. An additional advantage of this type of time series reduction consists of the ability to use hierarchical clustering in order to identify clusters of models with respect to that operator and measure a respective distance between the clusters. After reduction, a single vector with the various countries as coordinates corresponds to each model. These data can then be clustered using hierarchical clustering for a given distance metric, such as Euclidean, and a linkage criterion, such as minimization of the cluster variance.

Fig. 8 shows the mean and standard deviation of electricity prices for all models and the harmonized countries, including data from ENTSO-E [33]. Since models tend to behave similarly, it becomes easier to extract conclusion from these visualizations. For instance, it can be observed that, for the mean value, most models have small variations among the countries and similar to each other as well as ENTSO-E. However, for the standard deviation value, it can be seen that models tend to have significantly less spread in comparison to the ENTSO-E values, which may be an indicator that models do not sufficiently capture all the temporal dynamics involved as well as strategic behavior. The dendrogram produced for the 'mean' operator further shows which models are closer to each other over all countries.

5.4.2. Time series comparison in pairs by distance metrics

The third way of comparing model results consists of the comparison of pairs of time series. As discussed earlier, there are two main categories for computing distance or similarity indicators, one applied directly on the original time series and the second applied on the respective PDF. In order to better understand the nuances behind each approach and the respective metric, we consider the electricity price results for Germany using the model PowerFlex as reference and compare to the corresponding results from the models ISAaR and Europower. The reason for this selection is illustrated in Tables 4, where it can be seen that different indicators can show different, even opposite, results with respect to the distance (closer marked with green) to the two models.

There exist a variety of metrics to measure the similarity of time series and they have been in a variety of contexts. Such metrics for instance may focus on measuring the correlation, error or apply geometric or more complex approaches. Tables 4 includes a non-exhaustive selection of such metrics for both time series and their PDF. Except for

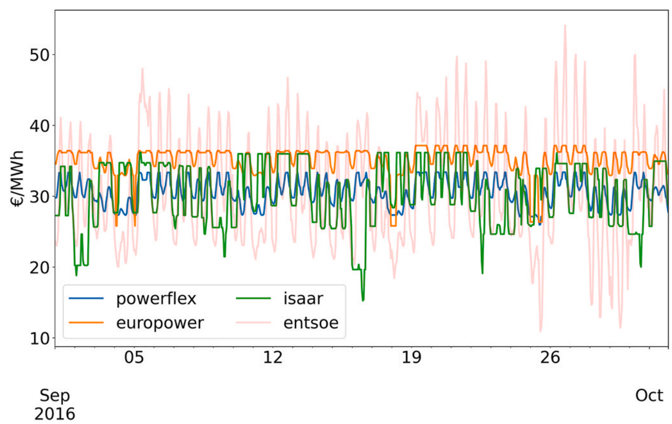

Fig. 9. Electricity prices for Germany in September for the models PowerFlex, ISAaR and Europower as well as ENTSO-E.

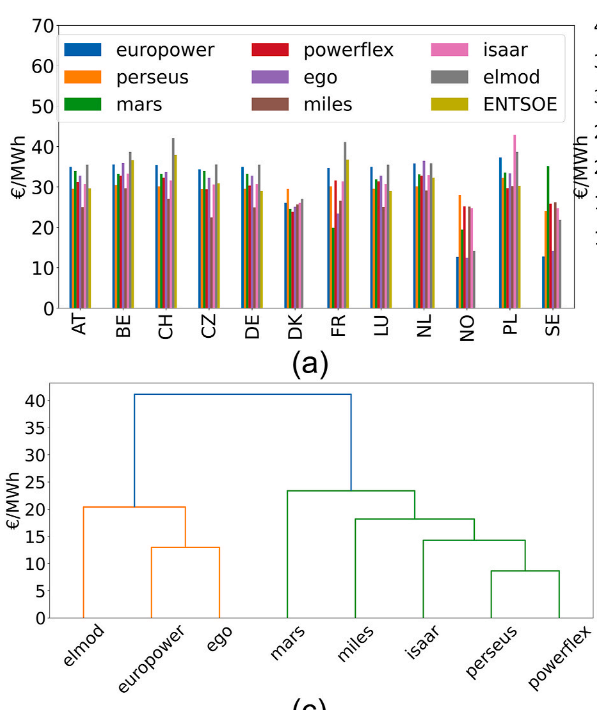

Fig. 8. Mean (a) and standard deviation (b) of electricity prices for all models and the harmonized countries as well as dendrogram (c) for the electricity prices reduced by the mean operator.

the Wasserstein metric that appears to show insignificant differences and hence is not deemed useful for model comparison in this context, the remaining metrics show a similar behavior. That behavior consists of the expected dependency on the difference between the mean values. Fig. 9 shows all three time series for the month September. It can be observed that Europower correlates to PowerFlex better than ISAaR, nevertheless with a clear positive offset, while ISAaR remains in the similar range but with significantly less correlation.

It follows that two main indicators can be extracted that are mostly useful for model comparison. The first indicator consists of the difference of the mean values of the two time series and the second indicator consists of one or more metrics that measure the distance of the normalized time series (i.e., centered around their mean values). The first indicator measures the average distance and can be connected to the input data such as the bidding prices of generators. The second indicators can also be related to the input data, e.g., the distribution of bids, however, it also reveals additional information about the behavior of the model, assuming a harmonized residual load. For instance, high correlation and high shape similarity of the time series and the corresponding PDF may indicate a higher similarity of the model methodologies. Apart from error scores which are not particularly useful, since a close match is not expected, all other metrics exhibit the same trend, i.e., exhibit shorter distances for more similar shapes. However, it is not straightforward to compare the results of different metrics since they can be interpreted differently and have different "units". For that reason, it is recommended to use the most intuitive ones for the specific context. For instance, the "max difference" metric is easier to interpret, whereas Frechet and DTW distances are less intuitive for power system modeling and more difficult to compute.

Comparing PDFs instead of the time series directly, additionally holds the advantage of capturing a more average behavior that can be more robust to rare but high differences in the time series or to the modeling of VRES production. As it was shown earlier using reduction operators, even average results can differ substantially and may pose difficulties in comparing models. Hence, analyzing in higher detail is unlikely to provide useful information for the models. Comparing PDFs constitutes a recommended compromise of analyzing time series in detail and usefulness for understanding. Fig. 10 shows the PDFs of the three selected time series as well as ENTSO-E. It can be observed here as well, that PowerFlex and ISAaR are closer on average, however PowerFlex and Europower have a more similar shape. One of the most intuitive methods to quantify that consists of the Bhattacharyya distance applied on the normalized curves, a metric which is based on measuring the curves overlap.

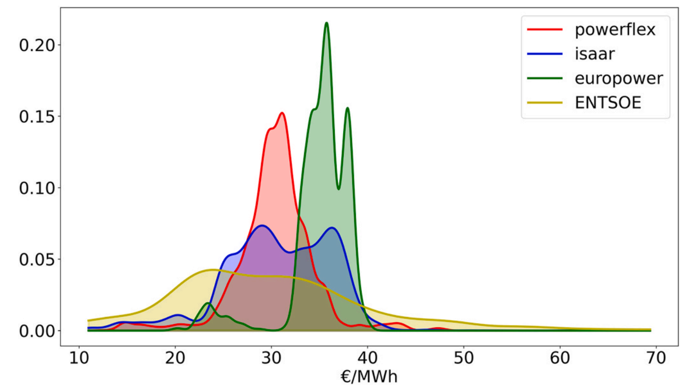

Fig. 10. Probability density function for the electricity prices of Germany for the models PowerFlex, ISAaR and Europower as well ENTSO-E.

5.5. Discussion of grid model formulations and their impacts

Besides market results, an important aspect of comparing power system models also consists of comparing results from grid simulation and redispatch calculation. Such results may include line loadings, congestion work or amount and cost of redispatch and curtailments. A similar approach is also recommended for this case, where the focus is primarily on average values and visualizations, since the various models may have different grid data, regionalization methodologies, market results as well as congestion management methods. However, a more detailed discussion is necessary, which lies beyond the scope of this paper. Hence, different model formulations and its impact on grid results are presented in further detail in Ref. [29]. Furthermore, the learnings of grid modelers in the process of model development concerning the validity of network congestion management results are also discussed in Ref. [29].

6. Discussion and conclusions

Although different models attempt to describe the same real world system, the variety of the different methods and input data (cf. section 3) for the different modeling contexts may result in significant differences in model output. Moreover, model output consists of a variety of results that also not necessarily coincide. Therefore, a detailed quantitative comparison such as deriving a single distance or error-like value between two models becomes impractical. To that end, a novel framework is introduced to systematically compare power system models including tools for both qualitative and quantitative comparisons.

The proposed framework takes into account that the various models have been developed within different contexts, while also acknowledges that the intended comparison may also depend on various comparison contexts, where different aspects and levels of investigation may be desired. For instance, whether prices or curtailments are considered more important. However, even in such cases, a detailed comparison and interpretation of any discrepancies may still not be straightforward due to significant modeling differences. Such differences may be alleviated by a harmonization process as described by the framework, nevertheless, a complete alignment is neither practical nor desirable, since it may alter the original function of the involved models and obscure their differences.

Because of the afore-mentioned challenges, the proposed framework consists of a flexible workflow and a variety of tools (cf. section 5) instead of a rigorous algorithm. Regarding the part of results comparison, it is similarly recommended to concentrate on average behavior and on the results that are easier to interpret, for example prioritize the energy mix and electricity prices, instead of the cross-border exchanges. It may be possible to also compare time series, rather than only averages; nevertheless, it is also recommended to use metrics that only measure the average distance and the shape similarity of either the original time series or the respective PDF, instead of quantifying the differences via measuring an error metric. The various indicators that are proposed are demonstrated for a specific context and only discussed for electricity prices as well as merely recommended, since each individual comparison may be applied in a different context and the necessary tools to reach useful conclusions may depend on the results themselves. This implies that a significant amount of freedom is left to the researcher, nevertheless, this framework can provide a specific structure on how to approach such a task as well as valuable lessons learned and a catalog of tools that are discussed and may be considered useful. This may pose some limitations on the use of the framework depending on the comparison context and the involved models, hence the generated conclusion also fall in the responsibility of the researcher.

Finally, it can be concluded that the developed model comparison framework is able to deliver insights in the inner working principles of the considered models as well as in the interactions of different modelling techniques and results. Hence, the presented framework to compare power system models can be considered as a proof of concept. Furthermore, the framework is based on the open energy platform to ensure future interoperability. By using the OEP as a basis the developed framework ensures transparency in the total workflow and supports the idea of openness in power system modelling.

Credit author statement

Chloi Syranidou: Conceptualization, Methodology, Software, Data curation, Investigation, writing, Project administration **Matthias Koch**: Conceptualization, Methodology, Investigation, Data curation, writing **Björn Matthes**: Conceptualization, Methodology, Investigation, Data curation, writing **Christian Winger**: Investigation, Software, Data curation, writing **Jochen Linßen**: Conceptualization, Supervision, Project administration Christian Rehtanz: Supervision **Detlef Stolten**: Supervision.

Funding

This research was funded by the Federal Ministry for Economic Affairs and Energy in the 6. Energy research funding program, grant number 03ET4074.

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.

Acknowledgements

We would like to thank all partners and project members for their contributions regarding model descriptions and input data harmonization as well as dispatch and redisptach modeling results, especially.

- German Aerospace Center (DLR), Institute of Networked Energy Systems: Oriol Raventós, Chinonso Unaichi, Julian Bartels, Jan Buschmann, Wided Medjroubi
- Forschungsstelle für Energiewirtschaft (FfE): Andreas Bruckmeier, Timo Kern, Felix Böing, Tobias Schmid, Christoph Pellinger
- Karlsruhe Institute of Technology (KIT), Institute for Industrial Production (IIP): Thomas Dengiz, Rafael Finck, Armin Ardone, Katrin Seddig, Manuel Ruppert
- Öko-Institut e.V., Energy & Climate Division: Franziska Flachsbarth, Sebastian Palacios and Susanne Krieger
- RWTH Aachen University, High Voltage Equipment and Grids, Digitalization and Energy Economics (IAEW): Jonas Mehlem, Lukas Weber, Annika Klette, Levin Skiba, Alexander Fehler
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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2021.112055.

Appendix

Description of the models included

The models under study belong to the partners involved in the MODEX-NET project. From all the information contained in each of the models, MODEX-NET focuses on the transmission grid in Germany. The transmission grids as implemented in the different models are considered in a status quo scenario for 2016 and a future scenario for 2030.

ELMOD

The model ELMOD uses optimal power flow calculations to analyze the interaction between generation and the transmission system regarding the operation of the grid and investment decisions [42–44]. The model was developed at the chair of energy economics of Technische Universität Dresden – Chair of Energy Economics – and has been used for several energy system studies. The European transmission system and the corresponding generation infrastructure is modeled in a great detail at a level of transmission grid nodes. The load flow calculations are approximated by a direct current approach. In its basic version the main aim of ELMOD is to analyze effects of renewable energy integration on the European transmission system. This includes various aspects regarding market design, congestion management, and future developments of the electricity sector. Moreover, latest research conducted with ELMOD involve studying flow-based market coupling.

Fig. 11 shows the topology of the German transmission grid 2016 (left) and 2030 (right) as implemented in the ELMOD model. The 2016 model includes 609 nodes and 975 lines (966 AC and 9 DC). The 2030 model includes 646 nodes and 1077 lines (1020 AC and 57 DC).

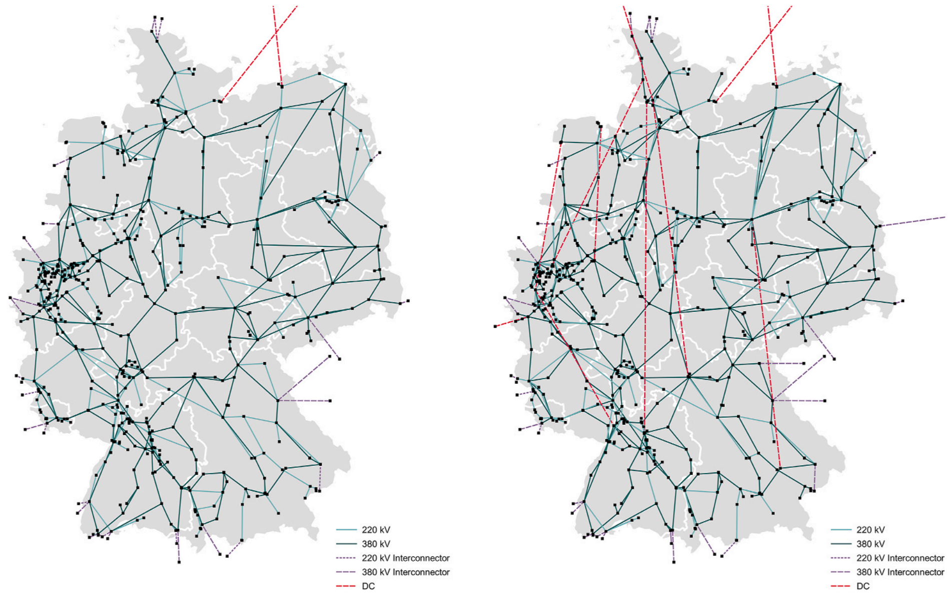

Fig. 11. Topology of the German transmission grid 2016 (left) and 2030 (right) as implemented in the ELMOD model

eTraGo

The model eTraGo model co-developed by the German Aerospace Center (DLR) – Institute of Networked Energy Systems – is a planning tool for the German electricity grid comprising the different grid levels [26,45,46]. The model was developed by several institutions in the context of the openeGo project [46]. eTraGo uses PyPSA [47] for DC load flow calculations to determine the cost-optimized dispatch of power plants and optimal storage capacities. The German transmission grid is modeled together with the 110 kV grid level with a total of about 11,300 grid notes and neighboring countries are represented by a single grid node. The model calculates weather-dependent generation data and uses standardized load profiles to derive demand data. The share of renewable energy sources varies in three scenarios for the years 2016, 2035 and 2050. In addition to the optimized costs for the transmission grid, eTraGo also calculates the hourly time series of the active power for each grid node (from 110 kV to 380 kV).

Fig. 12 shows the topology of the German transmission grid 2016 (left) and 2030 (right) as implemented in the eTraGo model.

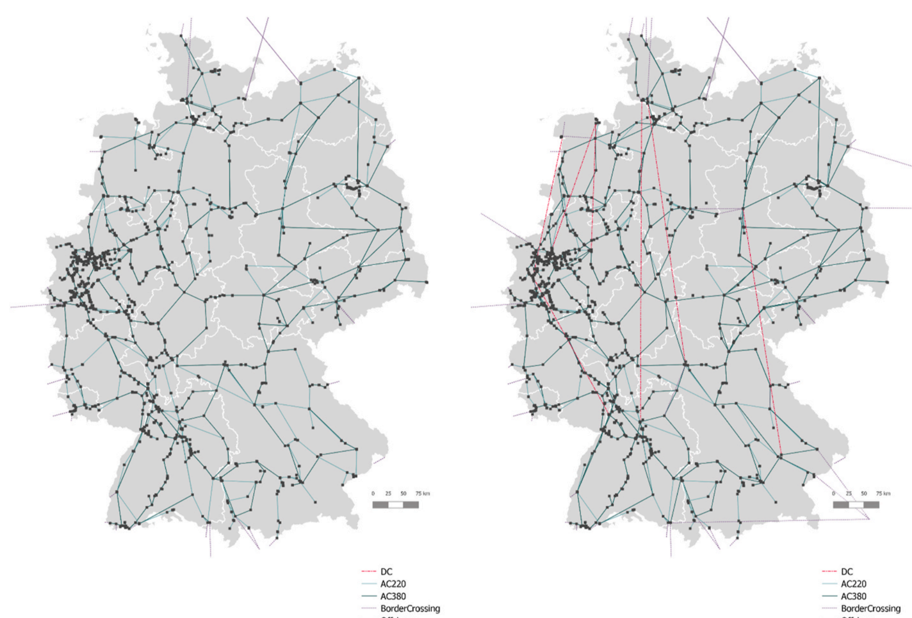

Fig. 12. Topology of the German transmission grid 2016 (left) and 2030 (right) as implemented in the eTraGo model

Europower

Europower from the Jülich Research Center – Institute of Technoeconomic Systems Analysis (IEK-3) – is a linear dispatch and grid model for Europe based on PyPSA [48–51]. It models the European electricity system in high temporal and spatial resolution, with approximately 4000 grid nodes, and includes constraints on thermal, hydro and RES generation as well as load shifting. The model consists of a set of linear optimization problems where the total cost of the system's operation is minimized considering grid constraints, where the DC approximation is used for modeling the power flows. For future scenarios, an upgraded European grid can be used, as well as future electricity consumers like battery electric vehicles and heat pumps.

Fig. 13 shows the topology of the German transmission grid 2016 (left) and 2030 (right) as implemented in the Europower model.

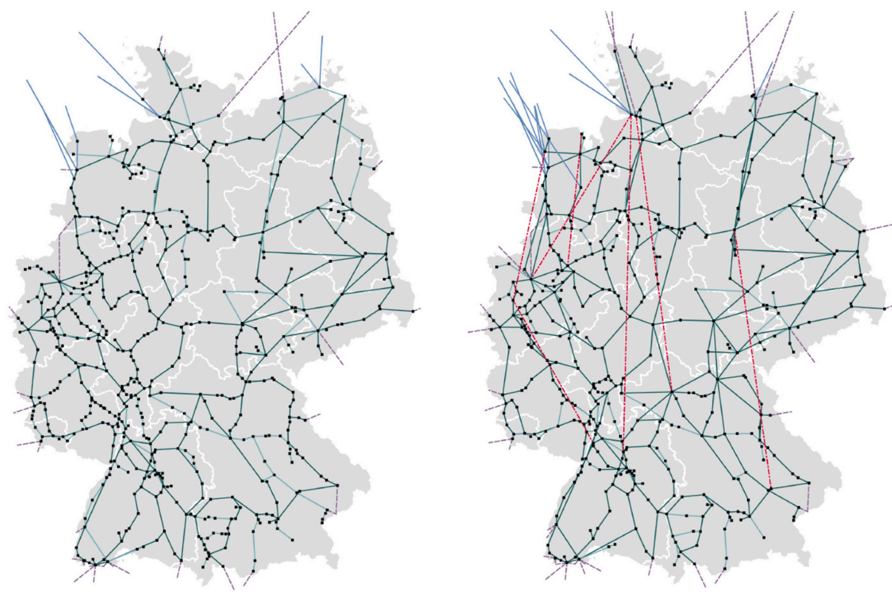

Fig. 13. Topology of the German transmission grid 2016 (left) and 2030 (right) as implemented in the Europower model

ISAaR

The ISAaR model developed at the Forschungsstelle für Energiewirtschaft (FfE) is an energy system model which uses linear optimization for modelling the generation, the demand and the storage systems in the electricity, heat and gas sectors [52–54]. The regional coupling of the electricity sector is considered by using an European transmission grid model with about 1500 grid nodes and a linearized load flow calculation. ISAaR uses grid data from German transmission grid operators, from a tool based on Open-Street-Map and from network developing plans for Germany and Europe. The model determines the optimal dispatch of power plants, flexible consumers and storage systems. Next to a market simulation, a grid and a redispatch simulation can be carried out considering the transmission grid.

The German part of the transmission grid model comprises HVDC lines, the 220 kV- and 380 kV voltage level as well as the 110 kV voltage level in regions where the distribution grid takes a relevant part on energy transmission. Around 460 grid nodes are connected with about 1100 transmission lines in the German part of the grid model.

Fig. 14 shows the topology of the German transmission grid 2016 (left) and 2030 (right) as implemented in the ISAaR model.

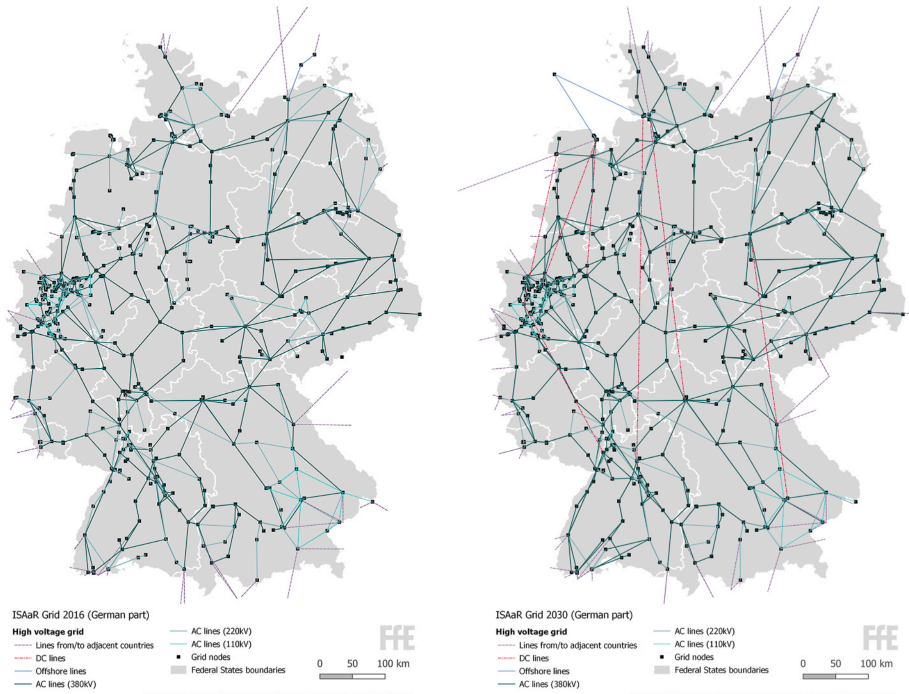

Fig. 14. Topology of the German transmission grid 2016 (left) and 2030 (right) as implemented in the ISAaR model

MarS/ZKNOT

The model MarS from the RWTH Aachen University – Institute for High Voltage Equipment and Grids, Digitalization and Energy Economics – determines the optimal dispatch of hydrothermal power plants in the ENTSO-E region under the consideration of flexibility options [55–57]. To this end, it uses the results of a regionalization approach for determining the generation of renewable energy sources and the electricity demand [58]. Using this information for all grid nodes the operation of the transmission grid is simulated by the model ZKNOT [59]. The model uses AC load flow calculations to determine the use of the network capacity both in conventional operation scenarios and in the (N-1) scenario. Thus, ZKNOT can identify technical constraint violations. ZKNOT uses optimization to control network elements like phase shifters with variable modulation degrees and high-voltage direct-current power lines. Moreover, power plants and facilities for generating renewable energy are controlled such that they are capable to compensate for the constraint violations with minimal costs and a minimal number of interventions.

Fig. 15 shows the topology of the German transmission grid 2016 (left) and 2030 (right) as implemented in the MarS/ZKNOT model.

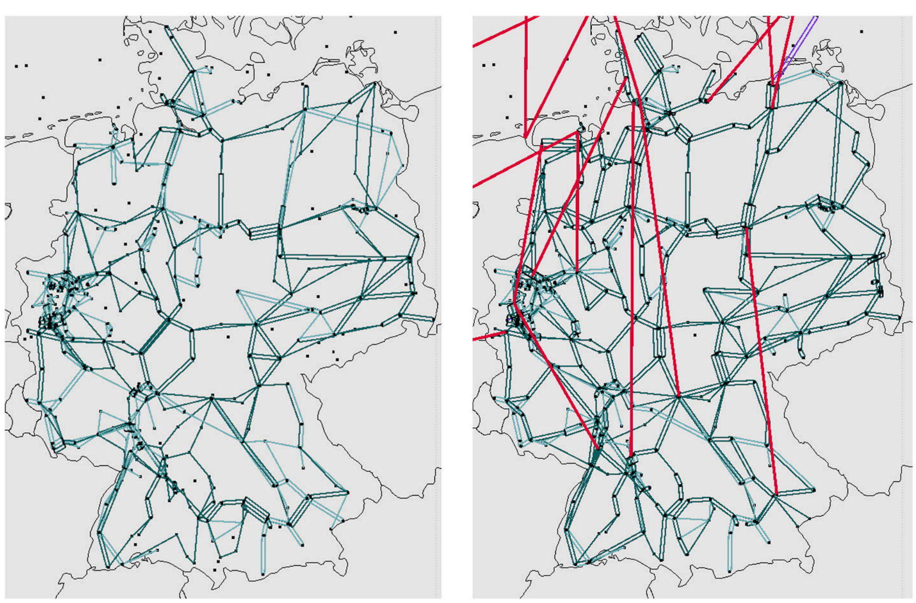

Fig. 15. Topology of the German transmission grid 2016 (left) and 2030 (right) as implemented in the MarS/ZKNOT model

MILES

The model MILES from TU Dortmund University – Institute of Energy Systems, Energy Efficiency and Energy Economics (ie3) – is a tool for simulating the European electricity market and transmission grid to answer technoeconomical questions regarding the energy system [60–62]. The modules of MILES cover the whole process chain of the strategical network development planing. For this purpose the tool determines the electricity demand and the decentralized generation on an hourly basis considering sector coupling with new electrical consumers. Further, MILES calculated the cost optimal dispatch of conventional power plant to serve the residual load and the result of electricity trading based on the dispatch decisions. MILES uses a detailed model of the transmission grid to consider technical restrictions of the grid by determining the status of grid elements. To this end, the model uses load flow calculations. Thus, it is possible to identify necessary congestion management actions for resolving bottlenecks in the transmission grid.

Fig. 16 shows the topology of the German transmission grid 2016 (left) and 2030 (right) as implemented in the MLES simulation framework. The German transmission grid 2016 consist of 414 AC lines at 380 kV level, 378 AC lines at 220 kV level and 10 HVDC lines (wind offshore and cross-border connections). In 2030, the German transmission grid consist 583 AC lines at 380 kV level, 174 AC lines at 220 kV level as well as 36 HVDC lines (wind offshore connections, cross-border connections and internal HVDC lines in Germany).

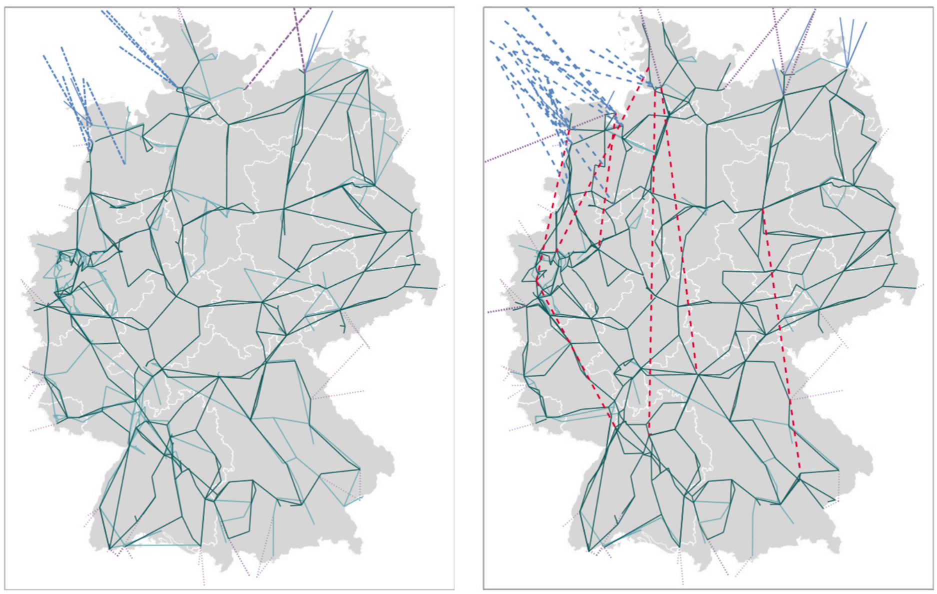

Fig. 16. Topology of the German transmission grid 2016 (left) and 2030 (right) as implemented in the MILES model

PERSEUS

The model family PERSEUS from Karlsruhe Institute of Technology (KIT) – Institute for Industrial Production (IIP) – is based on a bottom-up energy system model that minimizes system costs [63–65]. It comprises the EU28 countries and it can determine the power plant expansions until the year 2050. It has different modules that can be classified based on applications they are used for and applied methodologies. Based on the strategic research question, PERSEUS determines optimal energy balances and flows. It models the individual nodes of the German transmission grid (220 kV/380 kV) and the cross-border transmission lines to the neighboring countries. The grid model is coupled to a NTC based 1-node transport problem of the European electricity trading. Under the consideration of grid constraints (DC approach) and cross-border power line capacities, PERSEUS determines the optimal power plant dispatch. The TANGO grid model is used to simulate the transmission grid operation [20]. It includes the expansion path for the transmission grid (220/380 kV) of the Core Capacity Calculation Region (core CCR) from 2016 until 2035. The model uses AC optimal power flow to determine feasible operation points and necessary measures for congestion management. Countries outside the Core region are modeled with a single node per country and coupled through the interconnectors with each other and to the grid region.

Fig. 17 shows the topology of the German transmission grid 2016 (left) and 2030 (right) as implemented in the PERSEUS/TANGO simulation framework. The German transmission grid 2016 consist of 939 nodes at 505 substations, 602 AC lines at 380 kV level, 495 AC lines at 220 kV level and 15 HVDC lines (wind offshore and cross-border connections). In 2030, the German transmission grid consist of 1050 nodes at 561 substations, 884 AC lines at 380 kV level, 346 AC lines at 220 kV level as well as 48 HVDC lines (wind offshore connections, cross-border connections and internal HVDC lines in Germany).

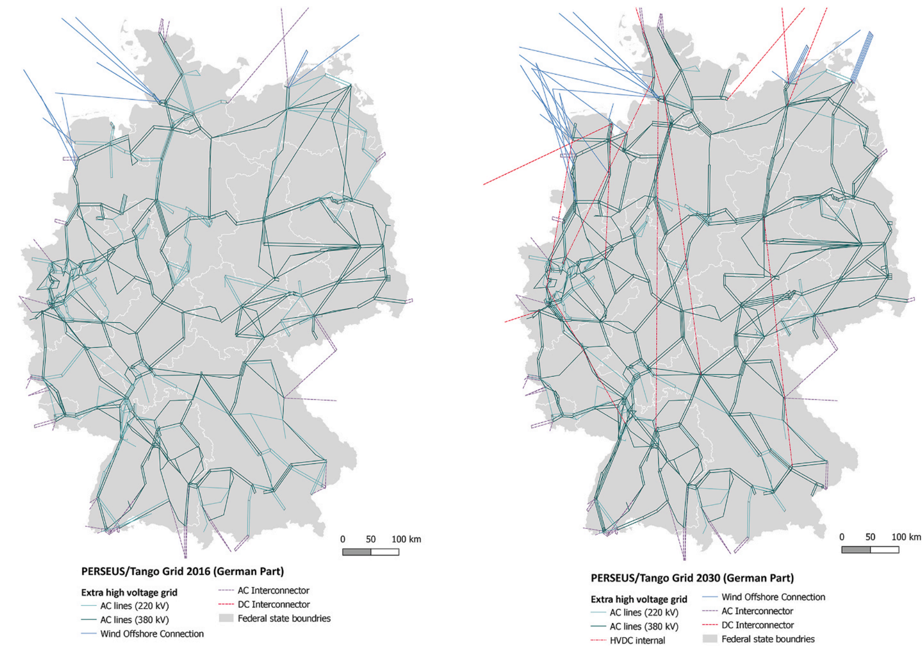

Fig. 17. Topology of the German transmission grid 2016 (left) and 2030 (right) as implemented in the PERSEUS/Tango model

PowerFlex

The model PowerFlex from Öko-Institut e.V. – Energy & Climate Division – is a European electricity market model that determines an optimal dispatch of the power plants and the optimal operation of storage systems and flexibility options minimizing generation costs in order to serve the electricity demand and the need for balancing power [66–69]. It models the transmission grid of Germany with about 320 grid nodes and, depending on the scenario framework, it includes also the planed high-voltage direct current lines. The load flows in the German grid are approximated using a linear DC-approach and a PTDF-matrix. The required redispatch is determined using an optimization model for minimizing line congestion at the lowest possible cost. The specific costs for line congestion are determined as part of a sensitivity analysis. For pumped storage power plants, intertemporal constraints are considered. PowerFlex represents the single ENTSO-E countries by using one grid node. The countries are coupled through interconnection point (transport-model approach).

Fig. 18 shows the topology of the German transmission grid 2016 (left) and 2030 (right) as implemented in the PowerFlex model. The German transmission grid 2016 consist of 310 nodes, 350 AC lines at 380 kV level, 118 AC lines at 220 kV level and 6 wind offshore connections. In 2030, the German transmission grid consist of 316 nodes, 413 AC lines at 380 kV level, 82 AC lines at 220 kV level, 7 DC lines and 6 wind offshore connections.

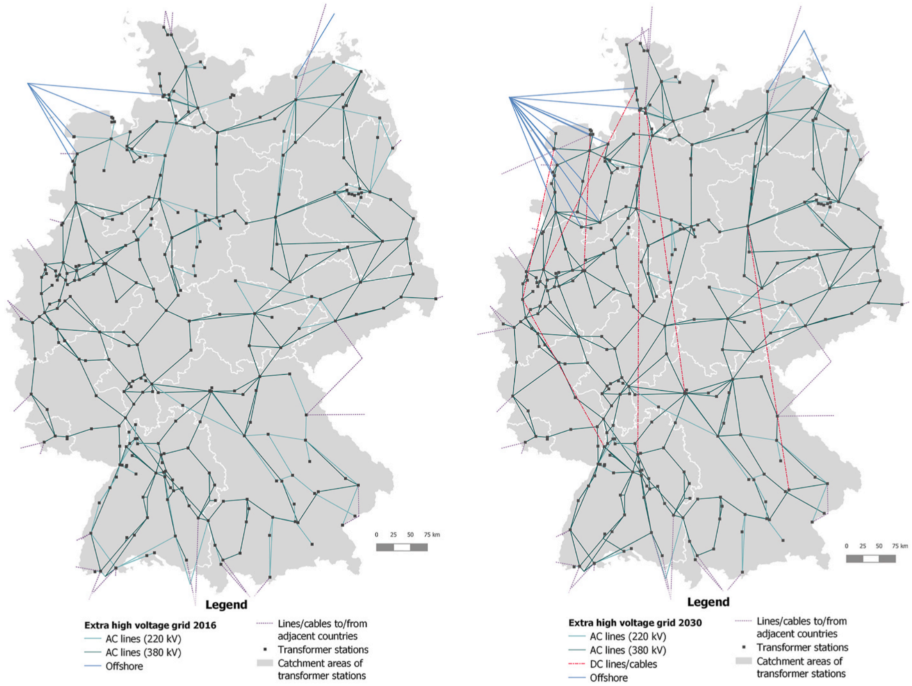

Fig. 18. Topology of the German transmission grid 2016 (left) and 2030 (right) as implemented in the PowerFlex model

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