About the Need of Combining Power Market and Power Grid Model Results for Future Energy System Scenarios

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Abstract. The European power grid infrastructure faces various challenges due to the expansion of renewable energy sources (RES). To conduct investigations on interactions between power generation and the power grid, models for the power market as well as for the power grid are necessary. This paper describes the basic functionalities and working principles of both types of models as well as steps to couple power market results and the power grid model. The combination of these models is beneficial in terms of gaining realistic power flow scenarios in the grid model and of being able to pass back results of the power flow and restrictions to the market model. Focus is laid on the power grid model and possible application examples like algorithms in grid analysis, operation and dynamic equipment modelling.

1. Introduction
The expansion of renewable energy sources (RES) and the liberalisation of the energy markets in Germany and other European countries pose various challenges on the power grid infrastructure as power grid expansion is not keeping pace with increased transmission needs. The future energy system will even be based more on distributed RES generators instead of large conventional power plants. Additionally, sector coupling technologies (e.g. electric vehicles, heat pumps, power to gas) will have a big impact on the future power grid. For investigations on the interaction of electric power generation, grid and consumption, models for the power market as well as the power grid are necessary. At Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) models for the power market and the transmission grid have been developed separately from each other. Now they are coupled by exchanging data and simulation results to better and fully address these challenges [1].

In literature, there are several approaches to model power generation and power grid as well as their interaction. Most market models assume that there are no technical restrictions or limits in transmission capacity within the grid. Exchange capacities are only taken into account between single countries or market regions. In contrast, detailed power grid models spend special focus on grid restrictions and bottlenecks addressing research questions like grid planning, price zone tailoring, exchange capacities or optimal power plant operation in terms of the status of the power grid itself and grid operator requirements. In order to take future developments of the power plant fleet and the respective degree of capacity utilisation of single power plants into account, it is necessary to analyse the interaction between power market and power grid. For example, an integrated power market and power grid model is used to calculate an optimal market area tailoring in central Europe [2]. In contrast, a power grid model only covering Germany is used to investigate the feasibility of regional ener-
gy autarky [3]. Additionally, power grid modelling can pursue different approaches by using the more complex alternating current (AC) load flow as most of the above mentioned models do, or a simplified, so called direct current (DC) load flow approach, as e. g. presented in [4]. A broad overview of respective literature, models and their implementation is given in [1].

This paper is organised as follows: In the second and third chapter the IWES power market model and the power grid model will be introduced before the model combination is described in chapter 4. Chapter 5 gives an outlook especially on future applications of the power grid model and chapter 6 summarises the paper and gives an outlook on further works.

2. Power Market Model

The model family “SCOPE” developed at IWES encompasses fundamental energy system models for generation expansion planning as well as for power plant dispatch. The basic model was developed and is explained in more detail in [5]-[6]. The capacity expansion model part is used to determine newly installed capacities of power plants, RES, storages, transfer capacities as well as heat technologies as linear optimisation problem (see Figure 1). These results are passed to the detailed dispatch model part considering the demand for balancing power as well as the heat demand and the transportation sector requirements in more detail (mixed-integer optimization). The power market model considers any desired period (usually one year) in hourly time steps. Regarding the electricity, heat and transportation sector as well as the coupling of them, SCOPE covers Europe. The heat sector encompasses the demand for space heating, domestic hot water and process heat. The transport sector covers an hourly representation of the (within certain limits) flexible power demand of electric vehicles (battery electric, plug-in hybrid, range extender and eHighway trucks). Thereby, power plant fleet specific input data with a high spatial resolution is used, whereas restrictions in transmission are just incorporated as transfer capacities between countries or market areas in this step. As a result, the power market model calculates unit-wise power plant schedules. For more detailed descriptions see [5]-[8].

An example of a future power generation scenario for the year 2025 was designed to consider sector coupling as follows ([9], compare also [1]): The installed capacities of RES and thermal power plants are mainly based on scenarios used by transmission system operators for their grid expansion planning [10]-[11]. Therefore, they describe realistic assumptions concerning the future development of the energy system. For the investigations, the data of the scenario “B” of [10] was linearly interpolated for the year 2025. Fossil-thermal power plants are assumed to be decommissioned according to their technical life time while combined heat and power plants (CHP) are replaced by new gas-fired CHP plants. Power generation profiles of wind and solar power plants are derived by own models. The power consumption of Europe was taken from the scenario “EU 2020” of [12] also describing a realistic forecast of the European transmission system operators. Figure 2 shows the power generation of renewable and conventional energy sources for two illustrative weeks in August 2025. The situation is characterised by high peaks of photovoltaic (PV) generation (upper part of the figure). Additionally, there is high wind power generation in the second week. While the power generation of RES is below the power demand in the first week, RES generation exceeds the demand in the following week. Dur-

![Figure 1. Overview of the model SCOPE for investment and dispatch optimisation across energy sectors (colours of the technology boxes refer to the associated markets).](image-url)
ing this time the power generation of thermal power plants is decreased considerably (lower part of the figure). During the highest RES generation only lignite power plants are still running because of the provision of system services. Additionally, pump-storage hydro power plants are dispatched to store the excess power on a daily scale. The power export of Germany is quite high during times with low residual load. In the middle part of the figure, the power consumption of the transportation sector is depicted. While the demand of eHighway (trolley) trucks is relatively inflexible, the charging profile of passenger cars can follow the RES-generation using residual load dependent charging schemes. From the model results it can be seen that lignite substitutes the base load of former nuclear power plants while other fossil-thermal power plants need to produce power more flexibly. Accordingly, the power flows in the power grid will change depending on the RES in-feed situation.

3. Power Grid Model
The current version of the power grid model, as introduced in [1], which was originally gathered at the Institute of Electric Power Systems of Leibniz University Hanover, uses publicly available data of the European power system as given in respective ENTSO-E grid maps on the extra high voltage levels 220 and 400 kV [13]-[14]. At IWES, this power grid data, as developed in [13]-[14], is available for the continental part of the ENTSO-E region and with higher level of detail for the German part of the grid (see Figure 3). Since accurate power grid modelling especially is an issue of data availability and quality, the major problem in the past (compare [15]), validation and enhancements of the current data is important. Based on an increasing availability of such data due to open source mapping services such as [16]-[17] and initiatives to extract and interpret this data [15], the access to real electrical grid data in general has improved.
The commercial software package DlgSILENT PowerFactory was chosen for the modelling in order to utilise the graphical representation of the grid topology as well as its implemented analysis functionalities. In order to be able to generate different grid scenarios (e. g. diverse future years or various scenarios for the same year), an automated approach to generate the model in PowerFactory was developed. Therefore, a data pre-processing using MATLAB was realised, in which grid scenarios, equipment data and generation units as well as load information are gathered and the actual modelling is prepared. The grid itself is modelled using the respective information about the grid’s elements and topology as given in [13]-[14]. The transmission system consists of lines and nodes with typical equipment types. The nodes of the transmission system are modelled considering their geographical position (see “Lines” in Figure 3). Within the model, transformers connect the voltage levels 220 and 400 kV of the transmission grid. All nodes were equipped with loads that represent the underlying network structures. Conventional power plant data was implemented using the list of power plants of the Federal Network Agency [18]. The power plants were distributed and connected to nodes using information about their locations as shown in the part “Locations” of Figure 3. Following, the grid is parameterised and assumptions are set for the load flow (or other) calculations. These steps as well as the actual load flow calculation are automated using the DlgSILENT Programming Language (DPL). Finally, the calculation results are post-processed using MATLAB to generate respective figures and diagrams. The whole process is illustrated in Figure 4.

A typical application example using the power grid model is the redispatch analysis, which was performed and presented in [19]-[20]. A quantitative/technically optimal (“tech”) as well as cost-effective (“eco”) solution of an optimisation problem for the redispatch of power plants is presented. Furthermore, process enhancements allowing a reasonable trade-off between the solutions of quantity $P_{tech}$ and cost effectiveness $C_{eco}$ are developed. This was realised by normalisation (“norm”) of the results of the previous optimizations ($P_{tech}$ and $C_{eco}$) in order to find the minimal deviation from the ideal point $(C_{eco}, P_{tech})$ of redispatched power and costs (for further explanation on the normalization process, see [19]). For the analysis, power plant dispatch as well as load was simply evenly distributed among the power plants. Slight changes in the load distribution and dispatch lead to a congestion presenting a typical situation in the German grid [21]. Costs were assumed for dispatch changes of the power plants as variable and as fixed costs.

Relating the different optimisation targets “tech”, “eco” and “norm”, the results are shown in Figure 5 (see also [20]). Therein, “before” and “after” show the line loading according to colours from green (0 % loading) to red (100 % loaded) while the figures in the middle show the locations and volumes of the redispatched power according to the circle sizes given in orange (decrease of generation) and blue (increase in generation). All three variants lead to a grid without congestion (see “after”). While the “eco” optimisation leads to the lowest costs, the amount of redispatched power is higher compared to the “tech” case which on the other hand leads to much higher costs as the “eco” approach. In comparison, “norm” leads to only slightly higher costs than the “eco” case and only a marginal increased amount of redispatch power compared to the “tech” approach.

![Figure 5](image-url) Results of the application example congestion management using redispatch of power plants with different optimisation targets (for further information see [20]).
4. Combination of Models

For research questions it is essential to simulate future scenarios of the power market and grid. In order to be able to simulate realistic scenarios and to analyse the behaviour of market mechanisms and technical challenges, a combination of the models is necessary. The current implementations follow a sequential approach, which represents today’s procedure in reality. This allows the analysis of realistic power plant and renewable feed-in and therefore occurring technical challenges in the grid. Additionally, resulting constraints which are detected via the grid calculation(s) can be used as feedback for the market model, especially in terms of price zones, transfer capacities or further technical restrictions.

Up to now, the market result of the power plant dispatch is transferred to the power grid model providing set points for each single power plant. In order to realise realistic power flows within the grid model, also loads and renewable energy generation has to be distributed among the nodes of the transmission grid which currently is in progress. The market model generates hourly values for any desired time range (e. g. one year). Since market model and power grid model interact by exchanging simulation results, but generally are working on their own, there is just a soft-link between them.

One first application showing the combination of the developed power market and grid model combination is a contingency analysis. For this purpose, market model results for power plant in-feeds for the historical year 2011 were implemented in the power grid model (see also [1]). The market results represent a precise power plant dispatch on an hourly basis for the whole year. For the analysis, the residual load – as a further result of the market model – was simply evenly distributed to the network nodes neglecting regional differences in RES in-feed and power demand. Power exchange to neighbouring market areas or countries were considered in the market model, but not explicitly modelled in the grid. For the power flow calculation all generators were set to voltage control, while typical active and reactive power limits of the elements were deployed. The set point for the voltage control was set to 1.03 per unit (p.u.).

The results of the contingency analysis are presented in Figure 6, in which part a) shows the power generation of dispatchable plants and the residual load. The map in b-1) shows the average loading of the lines represented by width and colouring showing the percentage of overloaded time during the simulated year. Depicted are the average loading of the lines (line width – green) and the congested time (loading above rated/threshold value) ranging from no overloading (0% – yellow) to congested throughout the year (100% – red). Part b-2) gives the average node voltages as percentage from nominal voltage (100%). Typically a voltage range of +/-10% around nominal voltage is acceptable and also occurring in this example. Therefore the scale is given from 90 to 110% (of nominal voltage). Since the results represent a unit-wise dispatch for the conventional power plants while the residual load (load minus renewable power generation) is just evenly distributed among the nodes, the presented results do not show typical overloadings as observed and reported in the recent years (see e.g. [21]). Nevertheless, underlying methods and algorithms are developed and subsequently can be used with more realistic assumptions. Also, a realistic distribution of load as well as RES is in development.

Figure 6. a) Power plant dispatch and residual load as result of the market model. b-1) Average line loading (line width) and congestion as percentage of time of the year (coloured from yellow to red). b-2) Average node voltages as percentage of nominal voltage for a years’ power plant dispatch.
5. Further applications
Within the following, further typical applications in the categories grid analysis & operation and dynamic modelling are presented. Most of these applications are developed in small test systems or for grids with just a few nodes showing the respective behaviour. In order to generate statements concerning the future behaviour in the German and European power system, these algorithms and control schemes have to be implemented in or at least scaled to the introduced models of the power system. Since system responsibility is an issue of transmission system operators (TSO), questions of grid analysis and operation, dynamic behaviour of active grid components and also system restoration have to be modelled and investigated on transmission system level.

Questions of market mechanisms on the one hand and technical boundaries and dependencies on the other hand need respective modelling. Being able to investigate questions on either and especially on both sides calls for models that are able to represent the whole picture. Analysis of power grid challenges can only be addressed adequately, if the power flow scenario – which directly is defined through generation and load distribution – is realistic or describes a certain situation. Therefore investigations on power grid side require the results of the power market. On the other hand, the liberalized power market is constrained by technical boundaries such as transfer capacities, which only can be included correctly, if an adequate power grid model allows to determine these demands correctly. In the following, several application examples are given, which take market as well as technical modelling into account.

5.1. Power system analysis & operation
Active as well as reactive power management for the transmission grid, especially in the context of changing supply structures and decentralised generation in the transmission connected distribution grids, is a field of research with large impact on system security and efficiency. Addressing this issue, optimisation algorithms for reactive power management in transmission and distribution grids are possible solutions. In [22] a control concept is proposed using reactive power capabilities of wind farms and tap-changer positions of transformers to improve distribution grid operation. Control signals, namely tap-changer positions and reactive power set-points, are smoothed over the forecast horizon using the implemented algorithms. Further possible optimisation objectives are power loss reduction, voltage profile smoothing and complying with reactive power exchange limits with the transmission grid. Being able to number the improvements needs correct scenarios (derived out of market models) as well as correct technical representations (on grid model side).

Driven by the liberalisation of the electricity market as well as cross border energy trade and the large-scale integration of renewable energy sources, electrical grids are subject to power flows, for which they are not planned and yet prepared. Since implementation of grid enforcement plans take long time, coordinated methods and management of congestion must be developed. Especially in future scenarios the installation of new wind farms on- and especially offshore leads to further challenges. Furthermore, the impact of voltage source converters in high voltage direct current (HVDC) transmission systems on economically optimal redispatch scenarios is a field of research for which powerful models of realistic scenarios derived from market structures and the modelling of respective technical equipment on power grid side are necessary.

Additional works incorporating HVDC systems consider offshore networks, their long term planning and layout taking optimal market as well as power grid integration into account. Balancing and congestion management on- and offshore requires respective models of the considered areas and applications.

5.2. Power system dynamics
Frequency control in interconnected electrical power systems is nowadays realised using the networks’ conventional thermal power plants. Up to now a contribution of renewable sources to primary frequency control is not realised in interconnected power systems. Possibilities to support the frequency of power systems using wind turbines with enhanced active power functionalities such as primary
frequency control and synthetic inertia are presented e.g. in [23]. In future works, these investigations could be implemented in models of real power systems using generation patterns derived from the market model incorporating weather data for RES.

In todays and future power systems, HVDC is to be used in electrical power systems to increase transmission capacity, contributing to enhance the system stability, security and controllability. Thus, HVDC is applied to transfer bulky power over long distances. One of the application areas in this sense is the consideration of HVDC systems and their flexible controllability in the event of power system restoration. Operating HVDC systems in these scenarios, developing methods and algorithms to generate set points and control structures needs input of realistic boundary conditions in power systems and therefore respective models.

Today’s dynamic models for stability simulations mainly focus on the electrical part of the generator of conventional power plants. Compared to this, active power dynamics during medium time events (in the range of a couple of seconds to a few minutes) is mainly influenced by the steam turbine. Usually the upstream steam process and the pressure control system are not modelled. In many cases it is simply assumed that steam power is available. To conduct dynamic simulations in applications with small or islanded systems on a time scale not only including a few seconds after a disturbance, consideration of energy storages within the system is important. These storages have to be considered, since they provide the power to support the frequency after load connections. In combination with grid models, the investigation of the dynamic behaviour also in ranges of several minutes becomes possible.

6. Summary & further work
After a brief introduction of models for power market and power grid simulation developed at IWES, the combination of these two models and occurring tasks and challenges are presented. Typical applications of the single models, as well as a first analysis of the combination of market and power system model are shown. Using the models it is possible to simulate the (future) energy system starting from a power markets’ perspective up to typical questions in grid operation and planning. Especially the integrated approach of power, heat and transportation allows analysing future energy scenarios.

Further possible applications are presented in the fields of grid operation and dynamic modelling. In the field of grid operation the modelling of real power systems is important to develop, test and validate algorithms and optimisation schemes to be used in grid operation and analysis. Furthermore, possible applications of dynamic models of network equipment have to be combined with grid structures in order to analyse the dynamic behaviour in small time ranges (seconds) as well as over times going up to several minutes and hours.

Further applications and research especially cover system studies on the implementation of future energy scenarios, the impact of new technologies as well as technical and algorithmic aspects on transmission grid level. Furthermore, especially system restoration is not an issue of daily work and cannot be trained in real systems, powerful simulation tools and respective models are important to ensure and validate grid restoration plans and to enable training for operators.

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