Integration of large-scale renewable energy sources: Challenges to thermal generation in Germany

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Abstract: In Germany up to 100 GW of intermittent wind and solar power feed-in is expected until 2020. The network load probably will be between 45 GW and 85 GW. Therefore the influence of renewable power production especially onto thermal power generation is investigated by this paper in detail.

An adjusted mixed-integer optimization model using the CPLEX solver 11.2 is used to calculate power plant schedules for the thermal generation system with up to 160 single thermal power plants (TPPs). Inter-temporal constraints like minimum up and down times, time depending start-up costs, maximum power transients and a detailed allocation of spinning reserve power for primary and secondary control are considered. The load covered by fossil and nuclear power plants is determined considering the currently projected power from offshore wind farms, solar panels, combined heat and power in combination with the German pumped storage power stations (PSPSs) in 2020. The paper includes several scenarios to illustrate the heavy influence and show the results of the used model and time series.

Keywords: renewable energy sources, power balance, large-scale wind farms, power plant scheduling, mixed integer linear programming, spinning reserve, residual load

NOMENCLATURE

Constants

\( R^{rt}(t) \)  Total reserve of type rt in period t

\( RL(t) \)  Residual load demand in period t

Variables

\( c_{fu}^{su}(t) \)  Production cost of unit u in period t

\( c_{su}^{su}(t) \)  Start-up cost of unit u in period t

\( c_{sd}^{sd}(t) \)  Shut-down cost of unit u in period t

\( p_{u}(t) \)  Power output of unit u in period t

Sets

U  Set of indexes of the generating units
T  Set of indexes of the time periods
RT  Set of indexes of the different reserve types

1. STATUS OF THE GERMAN ELECTRICAL GENERATION STRUCTURE

In Germany the existing electrical power production and distribution systems are going to be essentially influenced due to the continuously increasing influence of renewable energy sources. Because of the massive expansion of the wind turbine capacities within the last years, today wind power plays the most important role concerning the renewable energy sources in Germany. At the end of 2010 the installed capacity of wind turbines amounted 27.2 GW. Besides the photovoltaic capacities are increasing so fast, that the German Transmission System Operators (TSOs) predicted an installed capacity of about 18 GW by the end of 2010. Hereof 17.4 GW were realized. This is an increase of about 80 % compared to 2009.

In regard to a stepwise reduction of legal refunds for photovoltaic power production within the next years nevertheless current predictions yield to about 50 GW of installed capacity for the photovoltaics and an installed wind turbine capacity of more than 51 GW in 2020. This means that there will be more than 100 GW of wind and solar power installed in Germany by the end of the decade facing a peak network load of only 85 GW and an off-peak load of about 45 GW. Hence the share of electrical energy produced by these renewable sources could increase from 8.6 % today up
to 35 % of the German national electrical net energy consumption in 2020.

1.1 Onshore and offshore wind farms in Germany

At the end of 2009, the over-all installed capacity amounted to 25,777 MW. Today there are more than 21,600 wind turbines with more than 27.2 GW in operation. Until 2010 there were no offshore turbines installed in Germany. In 2009 the construction of the first German offshore wind farm called Alpha Ventus was started. In April 2010 the connection to the German transmission line system was finished and the wind farm started its operation. This first offshore wind farm consists of 12 wind turbines each having a rated electrical output of 5 MW. The total offshore capacity installed at the end of 2010 was only 100 MW. Until the end of 2011 an offshore capacity of about 400 MW is predicted by the German Wind Energy Association.

In the moment there are 24 projects already licensed by the local authorities with an overall capacity of about 7,000 MW within the North and Baltic Sea. Most of these new German offshore wind farms will be built 20-60 kilometers away from the coastlines with an average water depth of about 20-40 meters. But there will be single farms that will be more than 100 kilometers away with more than 40 meters of water depth. These long distances and high water depths as well as bad meteorological conditions have caused a lot of problems to observe the construction deadlines in 2009 and 2010. In the early stage of offshore construction it was assumed that offshore technology already known from the oil drilling industry could be used within the offshore wind sector. But these ships and construction equipment appeared to be inappropriate for the new challenges. Thus new equipment had to be designed to install offshore wind turbines with a total mass including the basement of up to 1,000 tons.

The “DENA Grid Study II” predicts an installed offshore wind capacity of up to 14 GW until 2020. The onshore capacities are planned to be expanded up to 41 GW within the next 10 years. So in 2020 there could be a total installed wind turbine capacity of more than 51 GW delivering up to 27.5 % of the German net electricity production assuming a net consumption of about 520 TWh. But these predictions vary in different literal sources.

1.2 Consumption of electrical energy

From 2004 till 2008 the consumption of electrical energy increased from 516 to 542 TWh in Germany. The annual average electrical net power consumption between 2004 and 2009 was about 527 TWh. In 2009 the consumption was notable below the average value with about 511 TWh due to the financial and economical crises. Following today’s predictions for the next ten years the electrical energy demand could decrease by 0.35 % per year to 520 TWh in 2020 if starting in 2010 at 540 TWh. This could be achieved despite the number of electrical devices will increase if the efficiency will be enhanced significantly. Practically this means replacing older devices in millions of households by modern devices which will consume less energy. In contrast to this, the overall demand of electrical energy could increase by an unpredictable amount if electrical cars will be implemented into the market. The predictions for the number of electrical cars in Germany are very uncertain and vary between 500,000 and 2 million until 2020. But in the moment there is still no large-scale marketable car technology available that uses an electrical energy source.

1.3 Renewable power in Germany today

In 2009 all renewable energy sources produced about 18.3 % of the German national electrical energy consumption and covered about 8.9 % of the primary energy demand. In this context wind energy has now advanced to the point that it is the most important renewable energy source in Germany by contributing about 7.4 % towards hydropower with 3.7 %. Solar energy produced by photovoltaic’s provided only 2.3 % in 2010 but following the German Federal Association of Renewable Energy (BEE) it could be expanded up to 7.6 % (about 39.5 TWh) of the predicted electrical energy demand in 2020.

About 6 % is produced by biomass and other renewable sources in the moment.

1.4 Thermal Power Plants (TPP)

In the moment the fossil and nuclear power plants have to follow the intermittent characteristic of wind and solar power production directly in a complementary way to guarantee the balance between power production and power consumption at any time. But with the constantly increasing fraction of non-dispatchable renewable energy within the generation system the number of dispatchable power plants that are online will decrease massively because renewable energy sources have legal priority due to the German Renewable Energies Act.

Today the share of non-renewable energy sources is still more than 80 % of the total electrical energy production. Hereof about 55 % is produced by coal and gas and about 23 % by uranium. Only 18 % is coming from renewable energies until now.
2. MODEL FOR POWER PLANT SCHEDULING AND RESIDUAL LOAD

To analyze these intermittent power sources and to simulate the influence onto thermal power plants several simulation models were created. Some of these models, especially the grid control and power plant models for dynamic simulation of thermodynamic behaviour of different components of a thermal power plant were firstly presented in Ziems et al. (2009) and Gottelt et al. (2009). Therefore in this paper particularly the power plant scheduling model will be presented with more details. This model is used to simulate a power plant scheduling to take care of general technical parameters of thermal power plants like minimum up- and downtimes, minimum power output and ramping rates, reserve capacities and time dependent start-up costs. This model is a Mixed-Integer Linear Programmed (MILP) optimization model that uses IBM CPLEX 11.2 solver to calculate the schedules of the German fossil and nuclear power plants using a variable time resolution usually set to one hour. In this model the spinning reserve for primary, secondary, tertiary control and reserve power for forecast errors are considered. To simulate the existing thermal generation system the power plant parameters were set to realistic values that hold for most of the German power plants. These values were determined with the help of the five biggest power plant operators in Germany and Dong Energy from Denmark as well as the combined cycle power plant (CCPP) operator “Kraftwerke Mainz-Wiesbaden (KWM)” in Mainz (Germany) within the research project “Power plant operation during wind power generation” – the “VGB Powertech” research project No. 333. The “VGB Powertech” is the holding organization for more than 460 companies from the power plant industry in 33 countries.

![Diagram of power reserves](image)

Fig. 2. Classes and types of power reserves in the model.

2.1 General structure of the optimization model

The model includes estimation models for the wind and photovoltaic time series as well as time series to simulate the influence of combined heat and power stations that will have heavy influence onto the remaining must-run power and the resulting residual load that must be covered by dispatchable power stations.

Fig. 1 gives a general overview of the different types of power plants and energy sources within the model. In this diagram two main boundary conditions must be observed at any time. The first is the active power balance (1) between dispatchable generation and the residual load, the second one is the observation of the availability for the different types of reserve power (2).

\[ \sum_{u \in U} p_u(t) = RL(t), \quad \forall t \in T \] (1)

\[ \sum_{u \in U} p_{u^r}(t) = R^{rt}(t), \quad \forall t \in T, \forall rt \in RT \] (2)

In the first stage of the MILP model three binary variables were used for each power station as described in Neise, 2008. One binary was used for the on/off-state, one for the start-up and one for the shut-down cycle. Due to the huge number of flexible units, more than 150 units, and a time horizon of 36 hours the number of overall binaries could be reduced by using a new efficient formulation of the different boundary conditions as stated in Carrion et al. (2006) under consideration of equations from Arroyo et al., (2000). A detailed description of all equations used in this model can be found in these to publications to describe the aforementioned constraints. These equations were adjusted to the assumption described in this paper but the basic structure wasn’t changed.

For similar approaches where MILP structures are used to solve the unit commitment problem under consideration of security constraints and simplified transmission line capacities see Dan Streiffert et al. (2005) and Erik Delarue et al. (2007).

2.2 Types of reserve power within the model

As mentioned before the reserve power is considered as well. Therefore there are different classes and types of reserves for different purposes with different response times. The reserves can be divided into two classes – the spinning and the non-spinning reserves as shown in Fig. 2. Spinning reserves are available in rotating generators that are directly synchronized to the grid. The reserve provided by the accelerating power of the directly synchronized inertia responds immediately to any active power disturbances. The second fastest reserve is called the primary reserve which has to respond not later than 30 seconds after it is requested. It is provided by all power plants in all interconnected countries of the European power grid. The third spinning reserve normally is called the secondary control reserve that has to be observed by every Transmission System Operator (TSO) within its control area. In the past there were four control areas in Germany each having its own reserve capacities. But due to an optimization of secondary control to prevent power plants in different control areas to respond against each other,
these four control areas were pooled to one virtual interconnected control area within the last years. The second class of reserves – the non-spinning reserve – is provided by generators that can be online or offline but ready to start up within 15 minutes. Usually this tertiary or minute reserve is provided by gas turbines or combined cycle power plants. These different types of reserves are necessary to guaranty the stable operation of the transmission network to respond to outages of generation units or changes in the power demand. Unfortunately due to the intermittent character of solar and wind power these energy sources are uncertain and so they are forecasted depending on meteorological measurements and forecasting models. These models always have forecast errors but they were enhanced intensively within the last years. These forecast errors can be divided into two types, the day-ahead or long-term errors and the intra-day or short-term errors. Normally the intra-day errors are noticable smaller than the day-ahead errors because the forecast horizon is much smaller. These average forecast errors are usually characterized by the root-mean-squared-error (RMSE), which in 2009 was between 3.7 and 5.8 % in 2010 for day-ahead and about 2.7 % for average intra-day forecasts in Germany according to information of the German TSOs. Therefore it wouldn’t make sense to provide the whole day-ahead RMSE in spinning reserves. At this point it should be mentioned that there is no forecast error reserve realized in Germany until now. But the massively increasing influence of intermittent feed-in could necessitate such dynamic reserves in the future. Therefore these reserves for the renewable energy were considered within the model as well. The amount of spinning reserve is therefore depending on the forecast and was set to 1.5 % of the day-ahead forecast. Here it was assumed that this is the remaining not betimes detectable short-term (4-6 h) intra-day forecast error that has to be covered by minute reserve or in the worst case by the secondary control. Due to the public unavailability of intra-day forecast time series there couldn’t be made more detailed analyzes until now, but the parameters of spinning and non-spinning reserves are already implemented to the model and were set to a certain amount.

2.3 Objective function

As shown in Fig. 1 the power plants are divided into dispatchable and non-dispatchable generation. Within the model only the power plants that belong to the dispatchable generation are variable. This means their operation point as well as the amount of primary and secondary control reserves are optimized by the CPLEX solver so that the total operation costs are minimized (3). These costs split into fuel costs on the one hand and start-up and shut-down costs on the other hand.

Minimize \[ \sum_{i \in I} \sum_{t \in T} \left( c_{fu}^i(t) + c_{sa}^i(t) + c_{sd}^i(t) \right) \] (3)

This kind of optimization problem is commonly known as the unit commitment problem. For simplification the fuel costs were modelled by a step-wise linear production cost curve for partial loads. In this model the partial production cost curve is divided into maximal three segments. The detailed equations used and adjusted for modelling such step-wise functions as well as equations for start-up and shut-down costs and ramping rates are stated in Carrión et al. (2006), but in addition to the reserve state there the model in this paper considers a detailed allocation of the different types of spinning and non-spinning power reserves, too. This means that the amount of reserve power for primary and secondary control as well as a dynamical reserve for forecast errors is determined for each station that is online. By considering these spinning reserves in each station, the resulting must-run power that can’t be undercut is determined by the optimization process.

The model calculates the global energy balance only. It can’t separate this balance from the regional distribution of power generation and consumption in different distribution networks. A copper-plate one node structure was assumed so no capacities of power transmission lines are considered by the model at the moment.

2.4 Combined Heat and Power (CHP) stations

Within the model the CHP stations do not contribute to the reserve capacities. This assumption is a simplification because in reality a few of these plants contribute to the primary and secondary control in some cases. Due to this simplification the CHP stations were basically assigned to the non-dispatchable generation. The ability of providing reserve power in reality is indicated in Fig. 1 by the dashed link. The feed-in time series for the combined heat and power fraction is simulated by an average temperature time series for Germany and an average power to heat ratio. This is an improvement towards the early stage model where the CHP-fraction was assumed to be a constant value.

2.5 Storage capabilities

Storage of electrical energy will become more important in the future to to integrate the fluctuating renewable sources.
Today there are only pumped storage power stations available to store larger amounts of energy. But compressed air storages or chemical storages like hydrogen or methyl alcohol as well as synthetic natural gas are other opportunities to handle a large amount of electrical energy if the produced electrical power of renewable sources can not be integrated because of transmission line limitations or must-run power limits.

In Germany today there is no indication that there will be new large-scale storage technologies available within the next ten years. Therefore within the optimization model only pumped storage capacities of all German pumped storage power stations were accumulated to a single big storage with about 40 GWh in pump mode and with an accumulated turbine and pump mode where each can have up to 7 GW. The level of efficiency is predefined by the ratio of maximal energy in turbine and pump mode and is set to about 80 %. It was assumed that these storage capabilities are also able to provide a maximum of 2 GW of secondary control reserve in positive and negative direction. Therefore there is an upper and lower limit for the stored energy.

2.6 Wind time series

To simulate the wind power production, measured time series of 2008 published on the internet by the German TSOs were used and scaled according to the predicted installed capacity for the next years. To simulate the more continuous offshore wind power production a certain percentage offset was defined and additionally the onshore time series were layered and cut-off to simulate the maximum simultaneousness power production.

2.7 Time series for the photovoltaics

The time series for the photovoltaic power production are created by a reference time series for solar power production. The time series are scaled by the overall energy production for one year. The value of full load hours for a photovoltaic unit was defined to 1,000 hours per year. Fig. 4 shows the solar power production in Germany at the 10th of October 2010. On this day there hasn’t been cloudiness in wide parts of Germany.

2.8 Water power from run-of-river plants

The water power time series are depending on the seasonal differences due to snowmelt and were created by archived data of a water power plant operator. These data were scaled to the installed capacities in Germany. These time series do not have fundamental influence onto the residual load, because the fraction of water power is relatively low in Germany. See Fig. 3 for a comparison.

2.9 Import & Export

To simulate the influence of imported or exported exchange power with the German neighbour countries a market model will be used in future. At the moment there is no realistic exchange power modelled that depends on market prices in other countries. Therefore as a first assumption a constant import and export energy price was used. But this assumption neglects that in future in other European countries the renewable power production will increase, too. This has to be considered when evaluating the calculated scenarios. In the next step a simplified merit order method will be implemented for the German neighbour countries to determine the market prices in these countries and iterate the resulting power exchange.

2.10 Assumptions for the total network load

In the first optimization model presented in Ziem et al. (2009), the so called vertical loads published by the German TSOs were used to determine the residual load for the thermal generation units. In this improved model the residual load is calculated by subtracting all non-dispatchable generation, set as must-run, from the total network load to determine the residual load. Fig. 3 illustrates an exemplary time period in summer with the different types of non-dispatchable power feed-in.

The national network load assumed within this new model shown in Fig. 6, 7, 8 and 9 was created by time series for the German generation system of 2008 published by the European Network of Transmission System Operators for Electricity (ENTSO-E). These time series were scaled to an assumed total net consumption, for instance 520 TWh for 2020, as described in the introduction. The fraction of industrial power plants was subtracted from the load because these plants do not have a generalizable power production profile and so they were exclude for current investigations.

2.11 Fossil fueled power plants

As shown in Fig. 1 the fossil fueled power plants are separated into four types: Lignite, hard coal, combined cycle power plants and gas turbines. Each type of power plant is characterized by different power plant parameters that can be changed for each station independently or for all plants of one type at once. In various discussions with thermal power plant operators different parameter sets for these types could be determined. Fig. 5 gives an overview for different types concerning minimum load and maximal share of reserve power that hold for a lot of German plants. Here the right type is a future type of modern gas fired plants with very high
The winter scenarios are characterized by a high wind power production and lower solar power feed-in. Therefore the influence of the photovoltaic power production exemplary shown in Fig. 4 is very low in the winter due to more often appearing cloudiness and flatter solar radiation angles. In the summer the influence of wind power is much lower than in the winter period but the typical power production profile according to the solar radiation on sunny days in the summer has heavy influence onto the power plant scheduling. Due to these high solar power peaks around 12:00 PM most of the fossil power plants will shut down in this time and start-up again in the afternoon. So the number of start-up cycles will increase massively due to a massive expansion of the solar capacities in the future.

3.1 Hard- and software used for optimization

The optimization model that was created to simulate the influence of a large-scale wind and solar power production has been improved successfully by reformulating the model equations according to Carrión et al. (2006) and Arroyo et al. (2000). The number of binary variables could be reduced crucially and the efficiency of the model concerning the time for solving could be increased up to 5 times depending on the scenario data. The biggest influence onto the complexity and calculation time seems to have the consideration of reduced levels of efficiency at partial loads. If this is considers the simulation time is extend ten times or more. The absolute gap for the solution accuracy was set to a minimum of 0.5 %. But in some scenarios it was in increased to 2 % to make the model still solvable.

The hardware used to solve the model is a two processor Intel Xeon 64bit server where each has four cores at 2.53 GHz. The system had 24 GB of RAM but it only uses 2 GB due to the limitations of the 32bit CPLEX version. All 8 cores were used in the opportunistic mode.

The calculation times are between several seconds and more than 1 hour for a single 36 hour scenario. It depends on the input time series of the residual load.

To improve the formulation of the model by a more detailed heuristic approach and by using dynamical iteratively approximation steps Antonio Frangioni et al. (2009) gives interesting information for a more efficient solving process. May be this will be adopted by future work for this model, too.

4. CONCLUSION

The residual load that has to be covered by the dispatchable power generation units was improved by modelling the fraction of CHP-plants depending on the average outside temperatures. Further time series for the solar power production was added to the model because the characteristic production profile of this renewable energy source will have a massive influence onto the number of start-up cycles of fossil fuelled power plants.

With the results of this optimization model the number of load changes and the number of start-up cycles can be determined and used within a thermodynamic life-time consumption model that was created within the research project, too.

Fig. 5. Flexibility of different types of fossil power plants

2.12 Nuclear power plants

When the research projected started in 2009 the nuclear phase-out that was commissioned by the former government required that the last nuclear power plant in Germany would be shutdown in 2022. But today a new government extended the nuclear phase-out for probably more than 14 years. Hence there probably will be nuclear power plants in operation after 2022 which means that nuclear power plants will have to follow the renewable energies, too. But despite the public opinion that nuclear power plants are not able to follow the intermittent energy production because they are not flexible enough different studies and technical papers confirm that most of the German nuclear reactors are more flexible than today’s coal fired plants. They were constructed in the 1980’s for the load following operation. But then they were primarily used to cover the base-load. Technical documentations show that these plants were constructed for a very high number of load changes and high ramping rates. All necessary control systems for such a dynamical operation were already available and tested in the past.

Within the model the parameters of these plants are actually very high number of load changes and high ramping rates. All necessary control systems for such a dynamical operation were already available and tested in the past. The parameters can be adapted according to the technical capabilities of single plants for special scenarios.

3. EXEMPLARY SCENARIO CALCULATIONS

To show some results of the power plant scheduling model different scenarios were chosen. The four calculations in Fig. 6, 7, 8 and 9 show typical scenarios for the winter and summer season for the years 2010 and 2020. In these scenarios the nuclear phase-out until 2022 was considered as well as an increase of the CHP-fraction from 12 % in 2010 to about 20 % in 2020. Furthermore there was no import or export capacity assumed within these exemplary scenarios so the German thermal generation has to balance the intermittent feed-in.
As mentioned afore the power exchange depending on market prices can not be simulated with the model until now. Therefore it is planned to add a market model for the German neighbour markets to calculate more plausible time series for the import and export depending on market prices and considering the transmission capacities to the neighbour countries, too.

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