Grid Stability in a 100% Renewable Electricity Supply System

Interactions between a High Installed Capacity of Wind Power and the System

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***Abstract*—The research project Kombikraftwerk 2 examined whether and how a reliable and stable electricity supply for Germany with 100% renewable energy sources can be realised in the future. To this end, an assessment of the demand and the provision of ancillary services in such a system with a high share of wind energy was undertaken. Besides presenting an overview of the results of the project, this paper discusses the role of wind energy in the system in particular.**

Grid stability, ancillary services, voltage control, frequency control, control reserve, congestion management, spinning reserve, renewable energy

I. Introduction

Recently the share of renewable energy (RE) in electricity production has grown rapidly in Europe, particularly in Germany. This is an on-going process and will be triggered by the gradual phasing out of nuclear energy. The future electricity system will be based on a mix of renewable power generators, storages and flexible backup plants instead of being dominated by large thermal power plants. The likely development towards high shares of RE in the future raises the question if and how a stable grid can be maintained in such a system at any time.

This paper presents the modelling of a 100 % RE supply system carried out in the course of the 'Kombikraftwerk 2' project and the results of an investigation on how a 100 % RE system in Germany could possibly work in the future, which ancillary services will be required in which quantities and how those can be provided. In this paper, we specifically investigate the role of wind power in the scenario.

II. Model and Simulation

The simulation of the electricity grid is based on the modelling of a future scenario with a high timely and a high spatial resolution. Electricity generators, demands, and storages are covered at the resolution of the extra-high voltage grid (220 kV and 380 kV) for each hour of one model year. Next to a dispatch simulation, it is examined whether and how the RE in the scenario are able to serve the demand for control reserve and reactive power to maintain frequency control and voltage control within the defined ranges [1] and to handle line congestions.

A. Scenario

For the scenario it is assumed that electricity will be generated from wind, sun, biomass, and geothermal and hydro sources in Germany in the future. Electricity generated from fluctuating RE sources that cannot directly be matched with a demand can either be stored in pumped hydro storages and decentral solar batteries, or be converted into renewable methane in power-to-gas plants, respectively. The renewable methane is stored in the national gas grid and

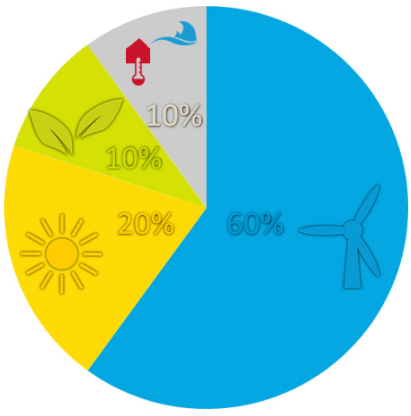


Figure 1: The shares of wind, PV, biomass, geothermal, and hydro energy in the annual electricity production

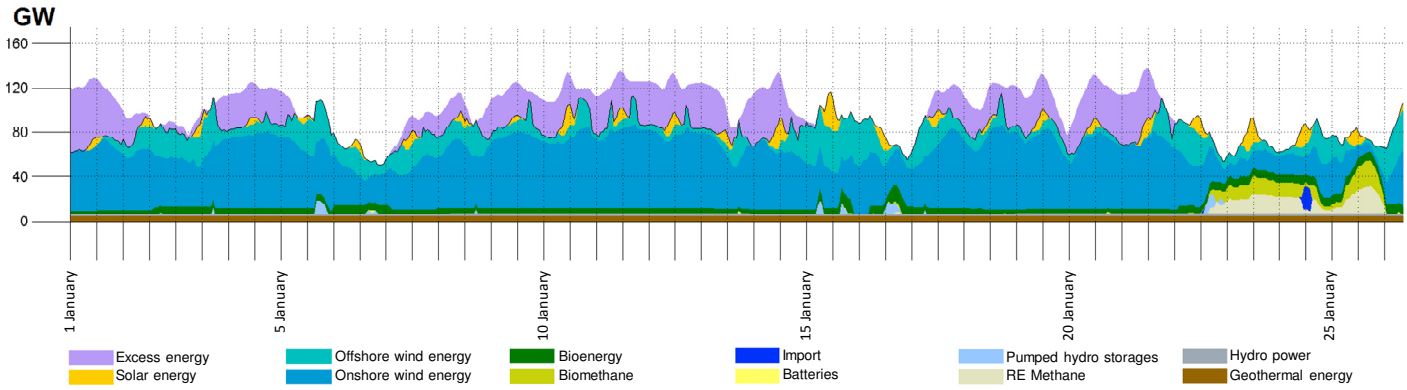


Figure 2: Electricity generation in January

is used in addition to biomethane to fuel flexible backup plants, assumed to be combined cycle gas technology.

Among the renewable sources wind is the most important source, contributing with 60 % to the annual electricity production (Fig.Figure 1). With an installed capacity of 87 GW onshore and 40 GW offshore, the wind power plants generate 380 TWh of electricity (including excess energy) over the scenario year (at a total demand of: 612 TWh).

B. Curtailment of Wind Power Plants

Over the year, certain periods - mainly in winter - occur with extremely high wind feed-in. Once the pumped hydro storages are full, and the power-to-gas plants are running at full capacity, some wind power has to be curtailed. An example of a few very windy weeks in January is shown in Fig. Figure 2. The purple areas show the amount of excess energy, i.e. the amount of energy that gets discarded due to the curtailment of wind turbines. Over the scenario year this amounts to about 57 TWh (15 % of the total possible wind production).

Assuming that the curtailments are selected in a way that ensures the lowest possible grid losses, it is mostly the offshore wind turbines which get cut off. Power from these locations has generally the longest distance to the consumption centres, thus causing the highest losses.

Concerning curtailments, it should be noted that the Kombikraftwerk 2 project focused on the electricity supply system. Future consumers such as heat pumps and e-mobility as well as demand side management measures were taken into account only partially. Other possible consumers, e.g. electrical heaters or the production of methane or hydrogen for mobility, were not considered. Higher shares of heat pumps and electrical cars would be possible, too. A full optimisation of all three sectors and their interactions could probably lead to a higher degree of utilisation of the available renewable energy.

C. Correlation between Wind Feed-in and Line Congestions

An analysis of the statistical correlations of several aspects concerning the feed-in of wind energy in the scenario underlines its impact on the grid. Offshore wind energy must be transported to the mainland at first. Both the offshore and the onshore wind power are aggregated in Northern Germany. The wind power generated there has to be conducted to the consumption centres in the South and West of Germany. This leads to high electricity transports caused by wind power (Fig. Figure 3b) in contrast to photovoltaics (PV) power which is distributed more evenly and also often installed on buildings, i.e. both geographically and electrically closer to the consumption. Moreover, while the generation of PV power has its maximum in the middle of the day when the demand for electricity is high, the feed-in of wind power does not correlate to the demand, as shown in Fig. Figure 3a. Therefore, besides requiring transport capacities, power

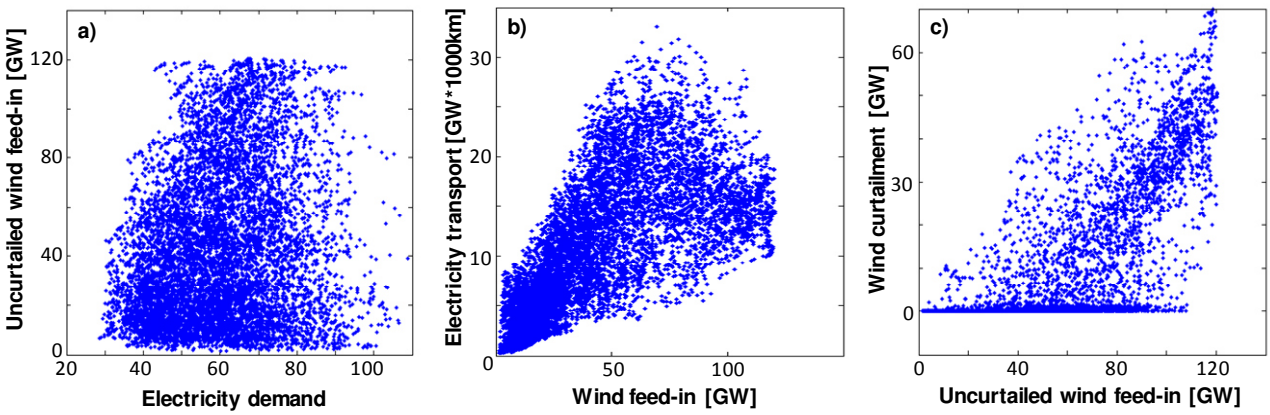


Figure 3: Correlations between a) the nationwide uncurtailed wind feed-in and the electricity demand, b) the electricity transport over the extra-high voltage grid and the wind feed-in, c) the curtailment of wind power plants and the uncurtailed wind feed-in

partially needs to be stored in times of high feed-in (a trade-off that depends on the cost of building power lines vs. storage capacities). Ultimately, in the case of very high wind generation, it is more economical to curtail wind power than to build more storage capacity and power-to-gas facilities to capture every kWh produced (Fig. Figure 3c).

The sites of the power-to-gas plants in the scenario were chosen according to their ability to minimise the load of the grid and thus the need for grid extensions. This resulted in an aggregation of power-to-gas plants in the North of the country. In times of high wind feed-in the grid is often highly loaded already. Transporting wind energy to more Southern storage sites would add additional transport demands that are avoided by this method of allocation.

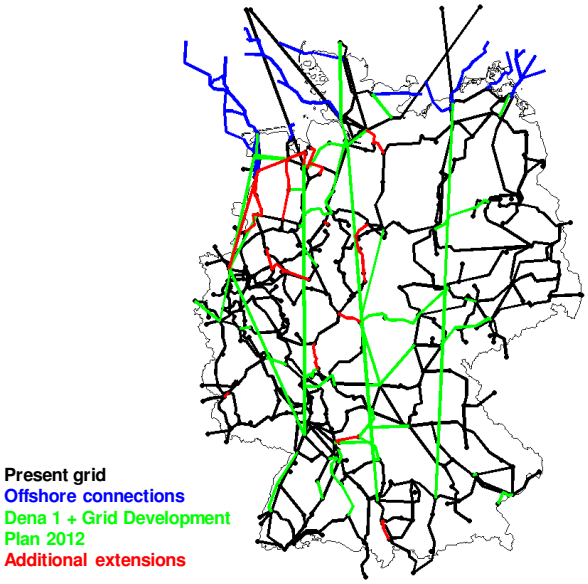


Figure 4: The extra-high voltage grid of the scenario

D. *Scenario Grid*

The extra-high voltage grid of the scenario which stands behind the analysis has been modelled based on the current grid. Planned future extensions according to [3] and [4], connections of the planned offshore wind parks and an additional upgrading of lines which resulted from the simulations of the project formed the modelled grid. The straight green lines (Fig. Figure 4) are HVDC (high voltage direct current) lines which contribute significantly to transporting the electricity generated offshore to the South and are preferred by the project's dispatch planning because of their comparably low transport losses. The lines which were identified in the project as being in need of an additional upgrading add up to 4.800 km.

III. GRID STABILITY

The grid shown in Fig. Figure 4 has the transport capacity to copy with the power flows from generators to consumers in all simulated time steps. Such an assessment of the undisturbed operation is, however, not sufficient to guarantee grid stability. As the frequency must remain within its pre-defined limits [1] at all times, it must be possible to compensate any outage of a plant or a line failure or of unplanned deviations from the forecasted feed-in – in case of the frequency globally via control reserve, whereas the voltage has to be controlled locally with the help of reactive power. Line congestions have to be resolved through redispatch.

A. *Voltage Control and Congestion Management*

The simulations of the project contained calculations on active and reactive power applying a 'distributed slack' strategy (see [2]). The evaluation of the resulting voltage shows that the specified ranges can be maintained in compliance with the provision of reactive power.

In the future scenario, reactive power can be supplied by the backup power plants, some of them connected to the extra-high voltage grid, or by HVDC converters. However, parts of the reactive power may also be provided from the underlying distribution grids where most of the renewable generators (including wind turbines) are connected. The potential provision of reactive power from decentralised power plants has been investigated for exemplary underlying high voltage, medium voltage and low voltage grids at a single node of the extra-high voltage grid. The results reveal restrictions of this potential due to the voltages limits in the underlying voltage levels. A remedy may be tap changing transformers in the distribution grid, but each individual topology of the underlying grid has to be examined in detail. Another important result is that decentralised provision of reactive power for the transmission grid causes additional grid losses.

To ensure operational security regarding the danger of grid outages, simulations were carried out on failures of every single extra-high voltage line and, subsequently, the necessary redispatch. Partially there are redispatch services in the range of several GW required to ensure a secure grid operation. The amount of congestion hours is higher than today as well. The summed up annual energy needed for redispatch, however, is lower than currently. This can occur if there are more, yet less critical, congestions in the scenario than today. Another possibility is that the selected redispatch measures have a positive impact on several congested lines at once.

The demand for redispatch strongly depends on the future grid extension measures. A trade-off between the costs for the grid extensions and the costs for redispatch (i.e. suboptimal power system scheduling) exists. Different choices were simulated in the project, as shown in Fig.

Figure 5.

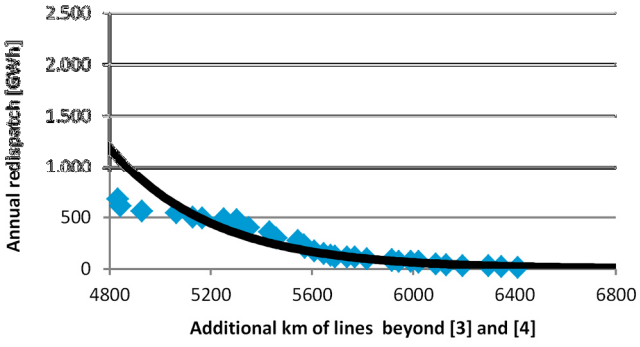


Figure 5: Annual redispatch energy depending on further grid extensions

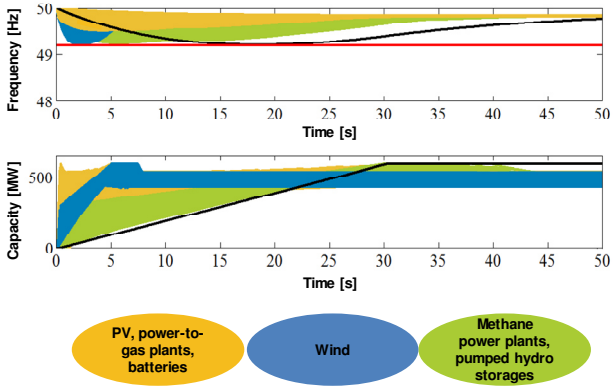


Figure 6: Main providers of primary control reserve with regard to frequency and capacity: converters, wind, spinning reserve

B. Frequency Maintenance

In case of an imbalance of electricity generation and consumption the frequency has to be stabilised with the help of primary control reserve. While nowadays mainly large thermal power plants and pumped hydro storages offer control reserve, in the future a transformed system consisting of renewable generators, storages and flexible backup plants will have to stand in and ensure frequency stability. The renewable generators are technically capable of providing control reserve already today. Compared to large thermal plants they can even react much faster.

Power plants connected to the grid by converters, and not with synchronous generators like conventional power plants, do not deliver spinning reserve into the system. The energy of the spinning reserve is discharged immediately after a power imbalance occurs. This discharging slows down the drop of the frequency in the grid until the control reserve is counteracting against the frequency deviation. In a system with 100 % RE the time constant of the system decreases to about 10 % of today's value at certain times.

To offset the decrease in spinning reserve the project proposes to increase the time requirements for control reserve from RE generators, to e.g. 5 seconds for full activation of control power in the case of wind turbines. With this measure the system remained stable with regard to the dynamic and stationary frequency deviation in simulations of a sudden power imbalance as it is prescribed in [1], see Fig.Figure **6**.

The future demand for control reserve was also determined in the course of the project. While the short-term generation fluctuations will continue to be determined by the failure of large power stations or lines, the somewhat slower fluctuations are significantly affected by fluctuations in the nationwide supply of wind and solar power. In a future 100 % renewable system with almost full electricity generation from wind and solar power at times, the total fluctuations expected will be large. A huge amount of secondary and tertiary control reserve would have to be maintained at high economic costs. In order to counteract this effect, the project studied dynamic reserve capacity dimensioning. By contrast to the current system in which the required control reserve is calculated in advance for a quarter of the year and therefore has to be based on the worst case possible, dynamic control reserve dimensioning determines the daily short-term fluctuations to be expected based on the feed-in forecasts for every hour of the following day. On average, the dynamic control reserve dimensioning resulted in roughly the same demand for secondary and tertiary control reserve as today. If the current method of dimensioning demand were retained, the demand for control reserve would roughly double.

The following technologies were taken into account simulating the provision of control reserve: methane power plants (backup plants), local bioenergy power plants, power-to-gas facilities, decentral batteries, pumped hydro storages, and wind and PV parks. The control reserve distribution was part of the dispatch for the whole system. Minimising the system cost (here, saving as much flexibility for the future as possible, i.e. saving methane) led to the following engagement orders of technologies (high priority first):

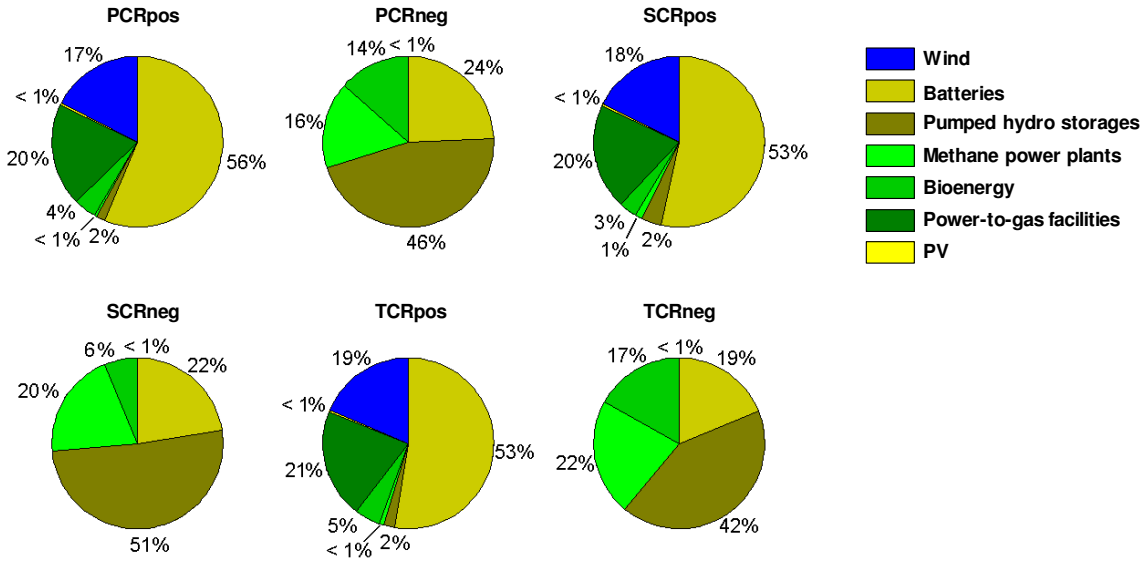


Figure 7: Average shares in the provision of control reserve of the different sources (PCR = primary control reserve, SCR = secondary control reserve, TCR = tertiary control reserve, pos= positive, neg= negative)

- For positive control reserve: wind and PV parks, power-to-gas facilities, batteries, pumped hydro storages, bioenergy plants, methane power plants,
- For negative control reserve: methane power plants, bioenergy plants, pumped hydro storages, batteries, power-to-gas facilities, wind and PV parks.

The calculations of the optimal mixture of control reserve resulted in the shares pictured in Fig. Figure 7. Assuming that decentral batteries will be installed in the future and that they will be allowed to take part in the control reserve market, they would be the main providers of control reserve together with the other storage technologies. Wind would be used for positive but not for negative control reserve. This is because decreasing the load of any thermal plant directly saves fuel and an increase of the feed-in of any storage helps save fuel in the future. In contrast, curtailing wind or PV would not bring any economic gains to the system apart from the momentary power balance. Positive control reserve, on the other hand, can be provided by wind power plants when they had to be regulated down because of very high wind feed-ins already. Wind would thus provide almost a fifth of the amount required for primary, secondary and tertiary positive control reserve. At times when wind energy can still be used to satisfy a demand or fill up storage, it should not be used for positive control reserve. Curtailing wind for holding positive control reserve in this case would lead to definite loss of energy – even when often the full reserve energy is not actually needed.

Under the assumption that batteries are not available for control reserve, the shares of all other generators in the provision of both positive and negative control reserve rise, wind power and PV plants included. Even a few biomass and methane backup plants would have to be activated to meet the demand. The simulated outcomes could change if additional large consumers, such as industrial loads or power-to-heat technologies, were taken into account as well.

IV. Participation in the Control Reserve Market

The calculations described above suggest that a stable frequency can be maintained even in a completely renewable electricity system. A field test revealed that renewable generators are not only faster in their reactions but, pooled in a virtual power plant, able to follow a given signal as it is used for prequalification to the German control reserve market [2]. In order to take advantage from the fluctuating renewables and facilitate their participation in the market, the regulatory framework should be adjusted. Particularly wind power and PV plants are reliant on short term forecasts of a few hours up to a day to reach sufficient accuracy. Shorter bidding periods, product lengths, lead times and auction periods would allow them to offer and provide control reserve. This would also help heat-controlled combined heat and power plants take part in the market.

As of today there is no officially recognised proof method for the provision of control reserve by fluctuating generators. Fraunhofer IWES proposes to calculate the so-called “available active power” [5], i.e. the power a (wind) power plant could produce if it had not been curtailed. The actual provision of control reserve is defined as the difference between the real feed-in and the available active power.

V. Summary and Conclusions

The project showed successfully that a reliable and stable grid operation is technically possible in an electricity system based on 100 % renewable sources, if renewable generation, storage and backup power stations are combined intelligently with renewable methane. The high share of wind energy in the project’s scenario causes a need for huge seasonal storage capacities which can be found in the national gas grid if renewable methane is produced with the help of excess wind energy. To cope with the power flows in this scenario, the extra-high voltage grid would need to be extended beyond the measures according to [3] and [4]. The installed capacity of onshore and offshore wind is aggregated in the North of the country which causes high grid loads. The direct current lines which are planned already are important for an efficient transport of the electricity from the North to the South.

The maintenance of a stable grid operation is mainly dependent on voltage control through reactive power, a successful congestion management through redispatch, and frequency control through control reserve. The reactive power required in the scenario can be provided at any time. The simulations showed that successful redispatch measures are possible as well given the future grid and the positioning of electricity generators and power-to-gas facilities of this scenario. Renewable generators are technically capable of providing control reserve, and the demand in the scenario can be covered. As long as batteries were accepted on the reserve control market, they would be the main players together with pumped hydro storages. Wind would only offer positive control reserve. Otherwise the shares of all other generators would rise. To allow the participation of fluctuating RE, the regulatory framework should be adjusted by shortening bidding periods, product lengths, lead times and auction periods. A high share of wind in the future in Germany is likely due to its high potentials, its high space efficiency and competitive electricity generation costs. The results of the Kombikraftwerk 2 project suggest that even in a system with high shares of renewable generators a reliable and stable grid operation can be maintained, provided an on-going technological development, investments into the electrical infrastructure and adjustments of the regulatory framework.

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