REQUIREMENTS OF THE POWER SYSTEM FOR THE INTEGRATION OF A LARGE SHARE OF RENEWABLE ENERGY SOURCES

Y.-M. Saint-Drenan, R. Spiekermann, S. Bofinger, K. Rohrig

Fraunhofer Institute for Wind Energy and Energy System Technology (IWES), Koenigstor 59, 34119 Kassel, Germany

1. Motivation

The development of renewable energy sources (RES) motivated by the urgent need to reduce CO_2-emissions has been strongly supported during the last years by the German Renewable Energy Act (EEG). To plan the further development of RES, several scenarios were proposed by different institutions. In these scenarios, the impact of RES on the German energy system is usually assessed on the basis of yearly energy production and demand. However, renewable energy sources have a strong impact on the power system due to the weather dependent characteristics of their power production. The influence of a high share of RES on the conventional power plant can thus not be assessed without considering time series analysis.

In 2009, the Fraunhofer IWES evaluated the influence of the renewable energy power production on the conventional power plants for an energy mix with a share of 47% of renewable energy for 2020. This study was made for the German Renewable Energy Association (BEE). The analysis was conducted by implementing the forecast of the scenario in a simulation based on a meteorological year (2007) and analyzing the influence of the RES power on the base, medium and peak energy and capacity needs (Saint-Drenan et al 2009).

With a share of renewable of 47%, RES-power generation is often larger than the medium and peak load demand. The base load need is thus reduced while the medium and peak load capacity demands increase. As a result, it can be observed, that the development of RES has an impact on the type of conventional power plant needed to cover the residual load. Indeed, due to the reduced number of full load hours, small and medium sized power plants with low investment cost and high operational cost will be more economical than large power plants with large investment cost and small operational costs. This study showed that there is a need for a transformation of the current power system to enable an economical integration of a large share of RES.

Assuming that the BEE scenario is to be realized, the observed changes would progressively occur in less than 10 years. In order to get an insight into the expected transformation of the residual load, the path from the current situation to the date of the BEE scenario is simulated and analyzed. On this basis, the development of the base, medium and peak energy demand is assessed and analyzed (Section 4). Last, a fluctuation analysis of the residual load was carried out (Section 5), which allows getting information on the amplitude and time scale of the fluctuations to be balanced. On this basis, the potential role of different compensatory measures (storage, flexible power plant, demand side management…) can be discussed.

2. Scenarios definition

The following analyzes are performed for the years 2010 to 2020, based on the BEE scenario for the year 2020 (Saint-Drenan et al 2009). The BEE scenario expects a share of 47% renewable energy in the electricity generation in 2020 with an installed PV-capacity of 39.5 GWp, an installed onshore and offshore wind capacity of 149 GW, an installed hydro capacity of 32 GW and a biomass capacity of 54 GW. As the analysis was carried out in 2010, the installed RES-capacity at the end of 2009 was used as starting situation. As a result, the large PV development of 2010 is not considered in the path used. Between these two times, the installed capacity of each renewable energy source was linearly interpolated. The assumed development of the different renewable energy sources is shown in Fig.1.

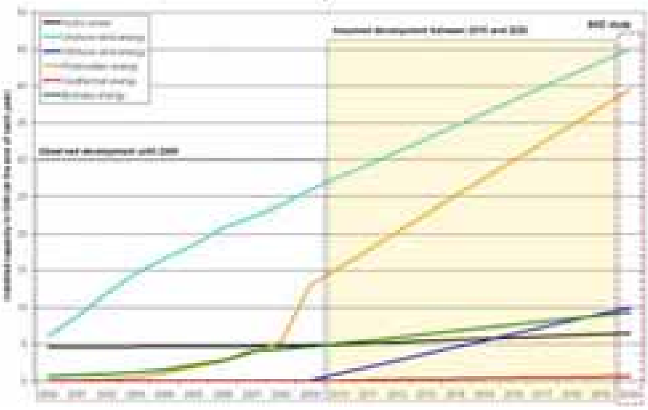

Fig.1: Scenario for the growth of installed capacity of wind and PV power plants

For each year between 2010 and 2020, the hourly time series of the RES-power production and load are simulated. The simulation is made for each cell of a 14x14 km raster and summed up under consideration of geographical distribution of the installed RES capacity. Further detail on the simulation can be found in (Saint-Drenan et al 2009). The different time series are displayed in Fig. 2.

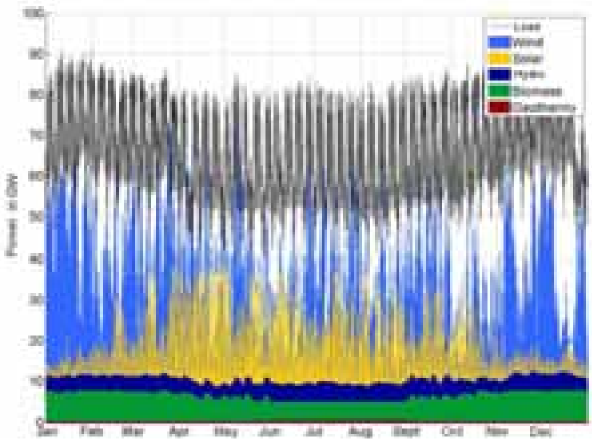

Fig. 2: Scenario for the growth of installed capacity of wind and PV power plants

Two exemplary weeks taken from the simulation made for the BEE study are displayed in Fig.3. As can be observed, import/export and pump-hydro were used to reduce the fluctuation of the residual load. In the present analysis, such balancing technologies are not simulated but investigated through the fluctuation analysis (section 5). In Fig.2 it can be observed that wind and PV power are the main source of fluctuation of the RES portfolio. To simplify the computation and ease the interpretation of the results, only these two energies are considered.

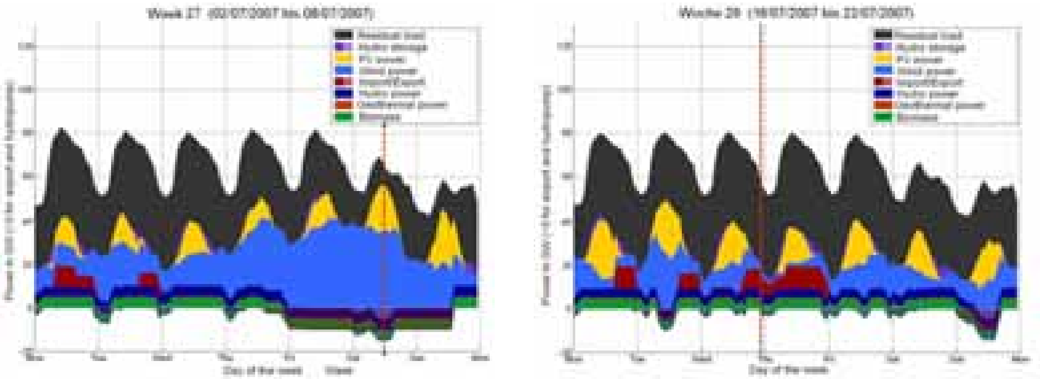

Fig. 3: Simulation of the RES power for two weeks from the BEE study

3. Determination of the base, medium and peak load

Using the time series of the RES power production and the energy demand, the residual load is evaluated. The analysis of the residual load is made by determining the base, medium and peak load demand, which provides a first estimation of the most economical power plant technologies required for balancing the production with the demand.

For the determination of the base, medium and peak load demand, a simple and pragmatic method is chosen. The different types of power plants are characterized by their investment and operational costs. On the one hand small power plants have a low investment cost but high operational cost and on the other hand large power plants have high investment cost but low operational cost. Depending on the number of full load hours (FLH) a power plant is operating in a year, different technology will be more adapted. Small power plants are more economical for a low number of FLH (peak and medium load) whereas large power plants need many FLH to be economical (base load).

A rigorous determination of the optimal set of power plant technology would require exhaustive computations (power plant unit commitment). A simpler approach was preferred, which consists in building an annual duration curve from the load curve and find the values of the power P_1 and P_2 under which the load is 2000 and 7000 h in the year respectively. All values of the load smaller than P_1 are in the base load area. Load values comprised between P_1 and P_2 are in the medium load and values larger than P_2 are in the peak load area.

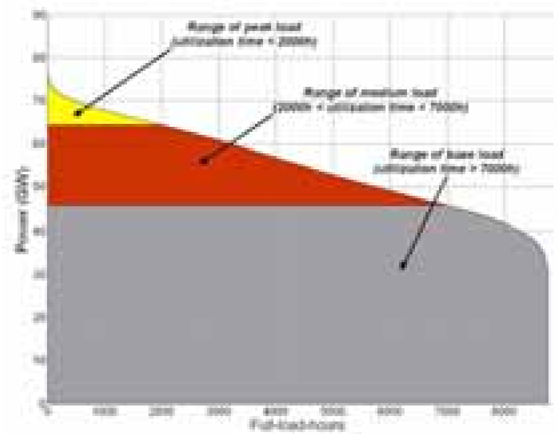

Fig. 4:Annual load duration curve with base, medium and peak load ranges

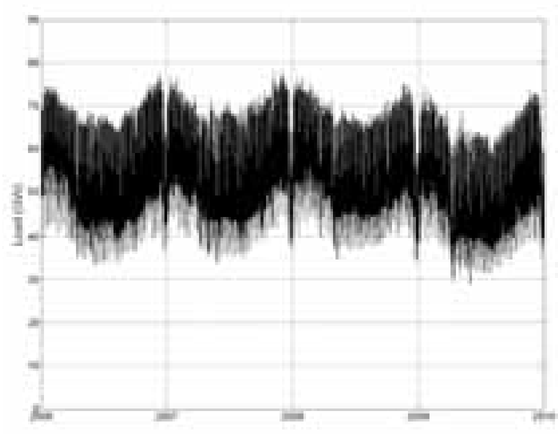

Fig. 5: German electricity load curve from 2007 – 2009

This method is illustrated in Fig.4. The corresponding load curve for 4 years is given in Fig. 5. A small modification was made on the base, medium and peak load determination method to account for the seasonal variation of the base load. For each month, the base load power is calculated as the 10% quantile of the load. It is verified for the entire period whether the annual base load reaches 7 000 hours at full load. If the condition is not met, the quantile is iteratively adjusted until the condition is met.

Should the seasonal fluctuations of the base load were not considered, there would be an overall constant base load demand and a greater medium and peak load demand in winter than in summer. For a realistic evaluation of the influence of the PV power generation to those aspects of the energy supply system, taking into account the fluctuating base-load demand is of crucial importance.

In the next step the base load is subtracted from the total load. The resulting time series is the sum of the medium and peak load. Based on this load profile an annual load duration curve is created and the power at which it falls below 2000 full load hours per year is defined as medium load and everything above as peak load. The described method for determining the base, medium and peak load demand is depicted graphically in Fig. 6.

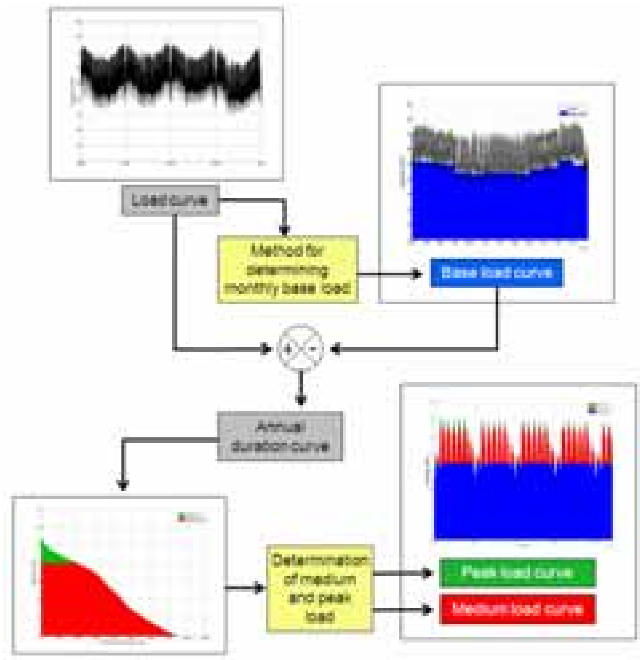

Fig. 6: Schematic depiction of the method for determination of the base, medium and peak load

4. Development of the base, medium and peak load demand until 2020

The evaluation of the simulation results for the years 2010 to 2020 are displayed in Fig.7. The three graphics in the left column show the capacity demand for peak, medium and base load and the three graphics in the right column the energy demand.

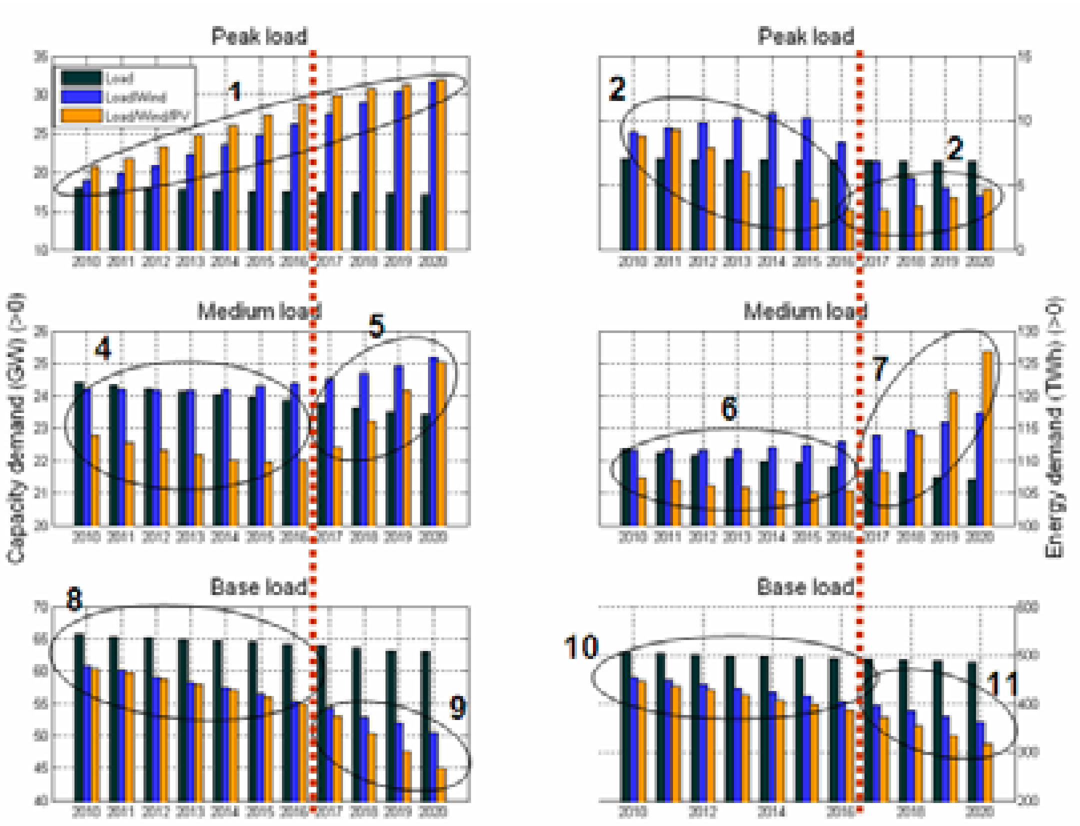

Fig.7: Development of the base, medium and peak load demand until 2020 in accordance with the BEE scenario

In each of the graphics three different values are displayed:

- The black bars represent the development of the peak, medium and base load power and energy demand for the load. This is a reference and includes a reduction of power and energy demand for the three load ranges, according to the energy demand reduction by 2020 as assumed by the BEE.
- The yellow bars show the development of the residual load, which is defined as load minus PV and wind power generation.
- For comparison and to be able to distinguish the influence of the wind- and PV-power generations, the blue bars show the load minus only the wind power generation.

The most important changes of the three load ranges are marked and numbered and shall hereinafter be analyzed and discussed.

Wind power production increases the medium and peak load and reduces the base load (capacity and energy). The influence of the PV-power production on the different classes of load is more complex. Between 2010 and 2016, the PV-power production reduces the medium load ((4) and (6)). After 2016, the medium load tends to increase again due to the PV-power production ((5) and (7)). The cause for this effect is that the PV-power generation occurs mainly during daytime when the medium load demand is high (around noon). As a result, the medium load is reduced by the PV-power production as long as the PV-power is smaller than the amplitude of the load variation. As the installed PV-capacity exceed this limit (30 GW achieved in 2016), the medium load is shifted from daytime to nighttime. At this stage, the increase of the medium load is accompanied by a decrease of the base load ((9) and (11)) while under this limit the influence of the PV-power on the base load is limited ((8) and (10)). This effect is illustrated in Fig.8.

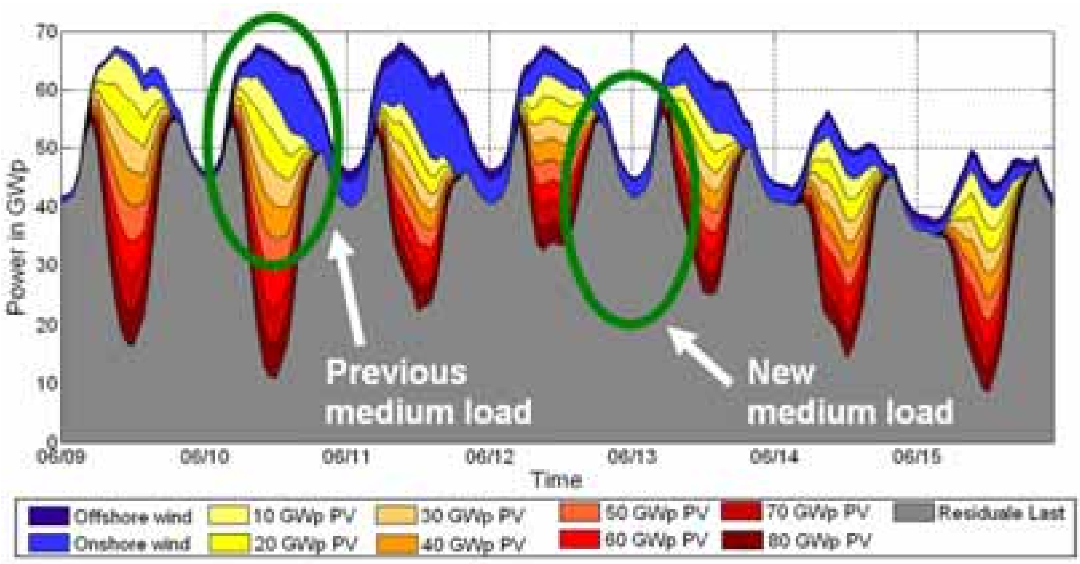

Fig. 8: Load curve and wind and PV power generation curve based on the weather data of a sunny week in 2007

It can be observed in Fig.7 that the PV-power production brings about an increase required peak load capacity (1) and a reduction of the peak load energy (2). The reduction of the peak load energy can easily be explained by the phenomena explained in Fig.8. To understand the increase of the peak load capacity, it is necessary to note that the peak load capacity is the difference between the yearly peak load and the power value corresponding to a number of FLH of 2000. As the maximal demand occurs during the evening of winter month, the maximal load is not affected by the PV-power production. The power value corresponding to the lower peak load limit is reduced with an increasing PV-production (See Fig.9). As a result the required installed capacity for peak load increases.

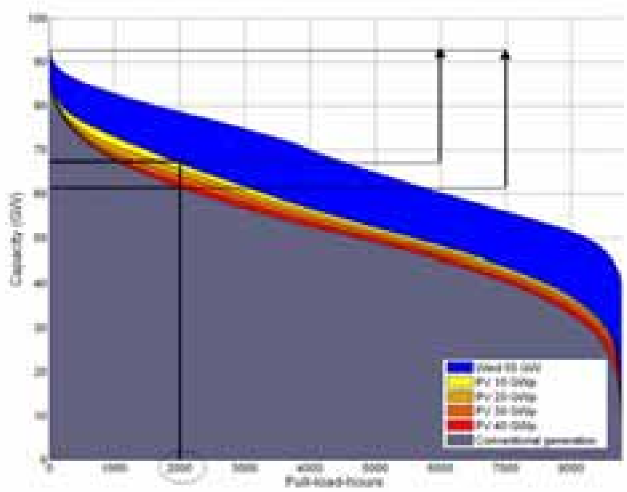

Fig. 9: Annual duration curve for the pure load, the residual load of load minus wind power generation and the residual load of load minus wind and PV power generation

5. Fluctuation analysis and evaluation of measures for the integration of a large share of RES in the German power system

The aim of this section is to analyze the impact of the PV-power generation in conjunction with the wind power generation on the fluctuation of the residual load. In particular, the amplitudes and time scales of the wind, PV and load fluctuations are analyzed separately and in conjunction. The final goal of this fluctuation analysis is to get an insight into the potential of different technological solutions aiming at a better RES-integration (storage, Supergrid, flexible power plants…). For this analysis the time series of 2020 are used.

Different approaches were tested for carrying out the fluctuation analysis of the residual last (Fourier analysis, wavelet…). The results were difficult to analyze due to some computation artifacts. Finally, a more pragmatic approach was preferred. The time series are smoothed using moving averages with a time window of 1 up to 8760 hours. The moving average $\overline{y(t)}^{(T)}$ of a signal y(t) for a time window T is calculated using the following formula:

$$\overline{y(t)}^{(T)} = \frac{1}{T} \int_{\tau = t - T/2}^{t + T/2} y(\tau) \cdot d\tau \qquad \text{(Eq. 1)}$$

The temporal resolution of the original signal is one hour. The calculation of a moving average acts like a low-pass filter, which smoothes the fluctuations within each time window. If the time window is as long as the time series, the moving average is constant and all fluctuations are compensated.

The effect of moving of moving averages with time windows of 12, 24, 168, 744 and 8760 hours is displayed in Fig. 10, 11 and 12 for the time series of PV-, wind power and the load respectively. It is apparent that the amplitudes of the time series are reduced with the increase of the time window. For PV-power, it can be observed that the fluctuations occur within a day and on a seasonal basis. For the wind power, the fluctuations occur within a week and on a seasonal basis. The reduction of the load fluctuations by the moving average is large for each time window considered except between one week and a month.

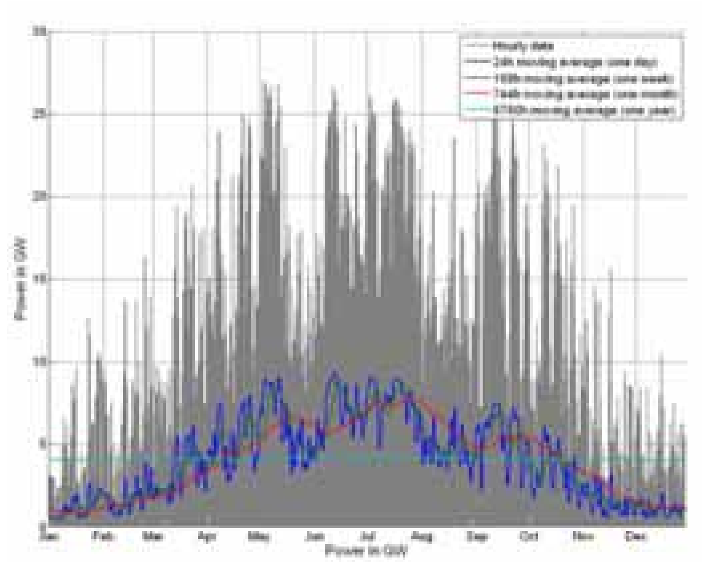

Fig. 10: Effect of the moving average on the PV power time series (year 2007)

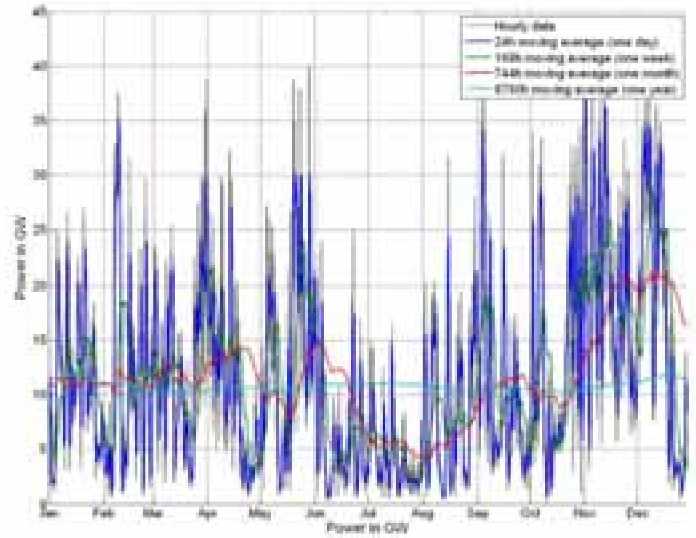

Fig. 11: Effect of the moving average on the wind power time series (year 2007)

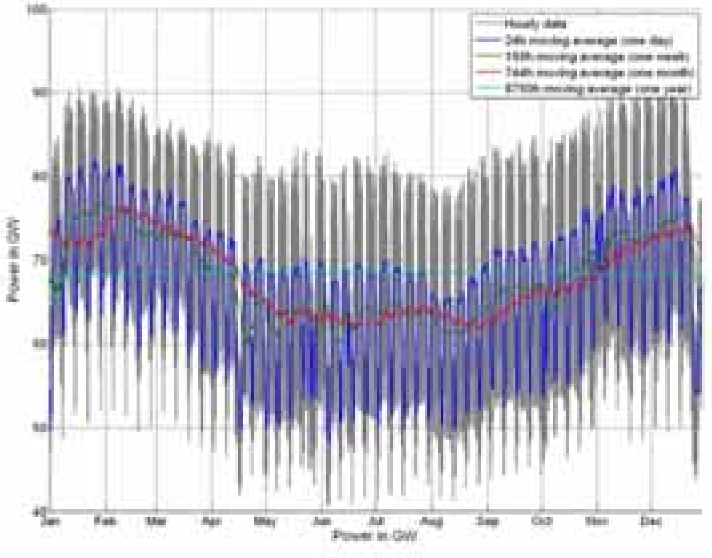

Fig. 12: Effect of the moving average on the load time series (year 2007)

For further analyzes, the moving averages are used to evaluate the amplitude of the fluctuations on different time scales. For this purpose time windows of one hour, one day, one week one month and one year are used. For the analysis it is necessary to separate the fluctuations on different time scale. This is done by considering two time windows T_1 and T_2 and considering the difference between the moving averages made with T_1 and T_2. For example, the fluctuation of the hourly MA within a day is the difference between the original data (T_1=1 hour) and the 24-hour moving averaged data (T_2=24 hours). The type and definition of fluctuations assessed are summarized in Tab. 1. In addition, exemplary technologies potentially adapted to balance the fluctuations are indicated.

Tab. 1: Classes of fluctuations and examples of compensation measures

Time window T_1	Time window T_2	Type of fluctuation	Examples of load fluctuation compensation measures
Hour (1 h)	Day (24 h)	Fluctuation of hourly MA within a day	Pumped storage, CAES, GT, CCGT, load management, E-cars
Day (24 h)	Week (168 h)	Fluctuation of daily MA within a week	CCGT, coal-fired power plant, import/export, load management
Week (168 h)	Month (744 h)	Fluctuation of weekly MA within a month	Hydrogen, coal-fired power plant, maintenance of brown coal-fired power plants, import/export
Month (744 h)	Year (8760 h)	Fluctuation of monthly MA within a year	Hydrogen, maintenance of coal-fired power plants, import/export

For each fluctuation type, the amplitude of the difference between the moving averaged data with a time window of T_1 and T_2 time is assessed. At this step a correction for the phase shift occurring with the moving average is implemented to reduce computation artifacts.

The maximum amplitude is used as an indicator of the importance of the fluctuation. Since the maximum amplitude of each time series occurs in only a few or only one period, the 99%-quantiles and the 95%-quantiles of the maximum amplitudes are also determined, to show how the capacity demands changes by using those quantiles.

The analysis of the compensation capacity demand is performed for the following four load and residual load time series and the results are presented in:

- Load
- Load minus wind power generation
- Load minus PV power generation
- Load minus wind and PV power generation

This allows assessing the influence of wind and PV-power independently and in conjunction on the residual load. The results of the fluctuation analysis are given in Fig. 13 for the three different quantiles and the four time series considered. To ease the interpretation of the results, the influence of the wind, PV and wind/PV on the load is shown in Fig.14.

The observations observed in Fig. 10 to 12 are confirmed. The PV-power reduces the fluctuations of the last within a day and increases the seasonal fluctuations. The wind power increases the fluctuation from day to day within a week and week to week within a month. These effects can also be observed when wind and PV are considered together (Last minus wind power minus PV power).

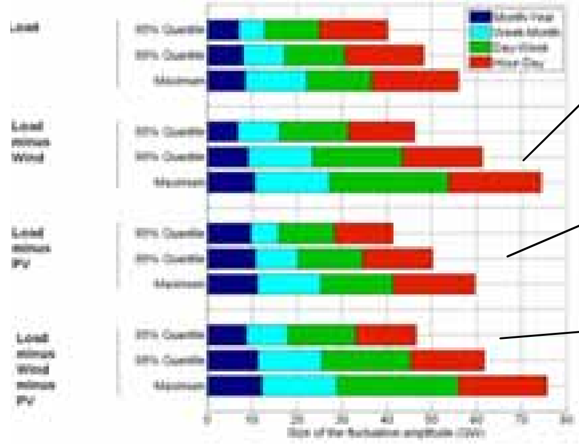

Fig. 13: Results of the fluctuation analysis of the load and different residual loads for 2020 (BEE scenario)

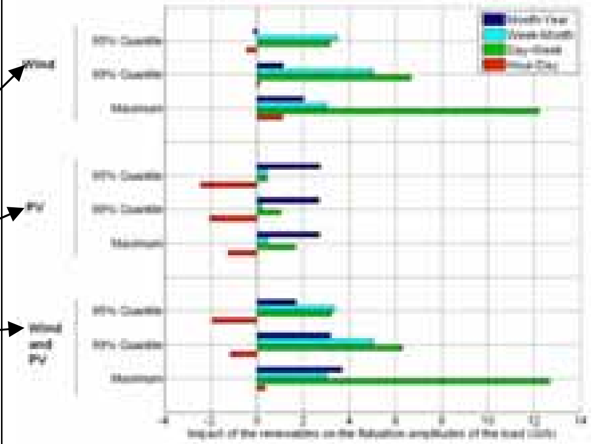

Fig. 14: Change of the load fluctuation owing to the power generation of RES in 2020 (BEE scenario)

This analysis shows the importance of considering the interaction of the RES together and with the load. Indeed, it is observed that one of the major fluctuations of the PV power is taking place within the day. Considering the PV-power and the load together, it appears that the PV-fluctuation reduces the load fluctuations, making it useless to shave them.

The PV-power production increases the seasonal fluctuations of the load, due to the fact that the PV generation is high when the load is low (summer) and low when the highest demand occur (winter). For wind it is the opposite: the seasonal pattern of the wind production is well correlated with the demand curve, so that the seasonal fluctuations of the load are reduced with the wind generation. The combination of the wind and PV generation reduces the negative impact of the PV generation. However, an increase of the seasonal fluctuation remains since the seasonal variations of the PV power are more important as the seasonal wind variations.

The fluctuation of the residual load will increase with the development of the RES for each time scale except between 1 and 24 hours, due to the daily profile of the PV-power production. Balancing measures are needed thus for each of the time scales considered. The most important increase will appear in the fluctuation from day to week and week to month. Flexible gas turbine and import export should thus gain in importance in the next years. In the longer term, should hydrogen-based storage system be economical and reliable, they would play an important role for shaving the expected increase of the load fluctuations.

6. Conclusion

The scenario of the BEE study (RES share of 47%) was used for a path simulation between 2009 and 2020. A detailed simulation of the RES time series and the load was carried out to assess the development of the base, medium and peak load capacity and energy needs. The RES increase the peak and medium load and reduce the base load, which raises the importance of adapting the power system for coping with a large RES penetration.

To further assess the impact of the RES on the power system a fluctuation analysis of the residual load was carried out. This analysis shows that the PV reduces the fluctuations of the load within a day but increases the seasonal variations. The increase of the seasonal variation brought about by the PV-power is reduced by the wind power but remains. The wind power brings about a very important fluctuation from day to day and from week to week. As a result, the fluctuations of the residual last increase for each time scale except within a day. To cope with these fluctuations flexible gas turbine and import export will gain in importance with the development of the RES capacity. Storage system may also be a key technology for this issue.

7. References

BEE (2009): Strom-Ausbauprognose der Erneuerbare-Energien-Branche: Stromversorgung 2020 – Wege in eine moderne Energiewirtschaft. BEE - Bundesverband Erneuerbare Energien. Berlin.

Saint-Drenan, Y.M., Sterner M., von Oehsen A., Gerhardt, N. Bofinger, S., Rohrig, K, 2009, Dynamische Simulation der Stromversorgung in Deutschland nach dem Ausbauszenatio der Erneuerbaren-Energien-Branche