IPP-Report

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# Eigenschaften einer Stromversorgung mit variabler Einspeisung

# Feature of an electricity supply system based on variable input

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**Zusammenfassung**

In dieser Arbeit analysieren wir die wesentlichen Merkmale und Eigenschaften einer Stromversorgung, die hauptsächlich auf den variablen Quellen onshore und offshore Wind und Photovoltaik beruht. Verwendet werden gemessene Leistungsdaten über Verbrauch und Erzeugung in Deutschland im Jahr 2010. Die Erzeugungskapazitäten werden in dieser Arbeit zu höheren installierten Leistungen skaliert. Der Hauptzweck dieser Arbeit ist es, die charakteristischen Merkmale und die weitgehend systemorientierten Konsequenzen einer Versorgung mit fluktuierenden Quellen hoher Leistung aufzuzeigen.

Die wesentlichen Ergebnisse sind:

- Die Nutzung von erneuerbaren Energien (EE) verlangt die Installation von zusätzlichen Versorgungskapazitäten, welche die der gegenwärtig installierten thermischen Kraftwerke deutlich übersteigen.

- Die Nutzung von EE ersetzten konventionelle Kraftwerke in geringem Umfang (< 10%).

- Die direkt nutzbare Einspeisung von EE ins Netz saturiert deutlich unterhalb der Verbrauchslinie.

- Bei einem starken Ausbau von EE werden große Mengen an Überschussenergie erzeugt, die nicht ohne weiteres exportiert werden können, weil sie an die Kapazitätsgrenzen potenzieller Empfänger stoßen.

- Es gibt eine optimale Zusammensetzung von Wind und PV Erzeugungskapazitäten, welche die Nutzung eines thermischen Versorgungssystems zur Deckung der Residuallast minimalisiert.

- Wegen der Schwankungen von EE werden alle Komponenten des Versorgungssystems mit niedrigen Lastfaktoren betrieben, was einen ökonomischen Betrieb gefährdet.

- Dies gilt auch für ein Speichersystem, wenn der einzige Zweck die Speicherung von Überschussenergie darstellt. Unabhängig von der gewählten Speichertechnologie kann ein derartiger Speicher kaum unter ökonomischen Bedingungen betrieben werden.

- Das Residuallastsystem hat auf häufige Leistungsänderungen großer Amplituden zu reagieren. Dieser Umstand reduziert die Betriebseffizienz und erhöht die Gefahr der Materialermüdung.

- Nur unter großen technischen und finanziellen Anstrengungen lassen sich die niedrigen spezifischen $CO_2$ Emissionswerte erreichen, die in der Kombination von Wasserkraft und Kernenergie in Europa bereits realisiert sind.

- Da die Überschussleistung maximal ist wenn auch der Verbrauch am höchsten ist (ungünstige Phasenlage), ist das Konzept des Nachfrage-Managements von eingeschränktem Wert. Der effizienteste Weg, Überschussstrom zu nutzen und die Residuallast zu reduzieren, ist, die wirtschaftlichen Aktivitäten auf die Perioden mit niedrigem Verbrauch auszudehnen etwa auf die Wochenenden.

- Innerhalb der Annahmen dieser Studie finden wir, dass die Konsequenzen überschaubar bleiben, wenn der Beitrag der erneuerbaren Energien auf einem Anteil von 40% des Jahresstrombedarfs begrenzt wird.

Diese Studie wurde im Rahmen folgender Annahmen durchgeführt:

- Der jährliche Strombedarf bleibt konstant.

- Außer Abfall wird keine Biomasse für die Stromproduktion verwendet.

- Stromimport und nukleare Erzeugung werden nicht betrachtet.

- Transport- und Prozessverluste werden vernachlässigt.

Die Berechtigung für diese Annahmen wird diskutiert.

**Abstract**

In this paper we analyse and present the major features of electricity production being based predominantly on variable wind onshore and offshore and on photovoltaic (PV) generation. Actual data are taken from the German demand and supply situation in 2010. On this basis, the generation capacities are scaled to higher installed powers. The main purpose of the paper is to show characteristic trends and the mostly system oriented consequences of large-scale wind and PV use with fluctuating input.

The major findings are:

- The use of renewable energies (RE) requires the installation of additional power capacity, which surpasses the present one of conventional thermal power systems.

- RE do not displace thermal power; the capacity saving is < 10%.

- The directly used RE shows the tendency of saturation substantially below complete coverage of the demand.

- Large amounts of surplus energies are produced by RE at a power level where export may not be possible any longer because of capacity limitations of potential receptors.

- There is an optimal mix between wind and PV generation, which minimises the use of a back-up system based on thermal power plants to cover the residual demand.

- Because of the variable nature of RE all components of the supply system operate under low capacity factors jeopardizing their economic basis.

- This applies also to a storage system set up for the sole purpose to store and integrate the surplus energy. Irrespective of the technology, such a storage can hardly be operated under economic conditions.

- The back-up system has to respond to frequent and large power changes. This will reduce the efficiency and cause material fatigue.

- The specific low reference $CO_2$ emissions, which are already realised in the combination of hydro- and nuclear power in Europe, can be reached with RE only with a tremendous technical and financial effort.

- As the surplus power is maximal at the maximal demand (and not out of phase to it) demand-side management will be of limited use. The most efficient way to utilise surplus energy and reduce thus back-up energy is the avoidance of low-load periods by moving electricity consuming activities into the weekends.

- Within the boundaries of this study, we find that RE can be integrated up to a share of about 40% of the annual demand with manageable consequences.

This study is based on the following assumptions:

- the annual electricity demand stays constant;

- apart from waste no bio-energy is used for electricity production;

- electricity import and nuclear power are not considered;

- transport and process losses are not considered.

The justification of these assumptions will be discussed.

## 1. Introduction

The need and desire for energy will further grow because the Earth population will further grow and the per-capita energy use will continue increasing: A saturation of the population can only occur over decades; the increase in per-capita energy is driven by the large global differences in the individual availability of primary energy from tens of kW to a few 100 W in terms of power. The success with new energy technologies will decide about the avoidance of societal frictions in possible periods of deficit and energy paucity and the prevention of the ongoing environmental damages by the replacement of fossil fuels.

There are only three paths to a sustainable energy supply system – fission on the basis of breeders, fusion, and RE in their different forms of occurrence [1]. In this paper we analyse the major characteristics of an electricity supply system being predominantly based on RE. We do this with the example of Germany because of the rapid deployment of renewable energies. Germany will soon demonstrate the pros and cons of a rapid technology change for an essential commodity like electricity and it provides an attractive basis for a forward-looking analysis.

## 2. Construction of the data set

Modelling of characteristics of the electricity supply system for Germany with increasing contributions of the RE forms wind (on and offshore, $W_{on}$ and $W_{off}$) and photovoltaic (PV) power has been studied on the basis of available data of 2010.

The following source data were used.

The electricity demand (load) was obtained from Tennet [2] with 15 min resolution and from ENTSO-E [3] with 1 h resolution. The more representative ENTSO-E data were taken. The ENTSO-E data were scaled to deliver the net electricity production of 588 TWh in 2010 (see Table 1) [4]. Thus, the demands both from the high-voltage and the lower-voltage grids are included.

| **Source** | **TWh** | **%** |
|---|---|---|
| Coal | 105,8 | 18 |
| Lignite | 135,2 | 23 |
| Nuclear | 135,2 | 23 |
| Gas | 82,3 | 14 |
| Wind onshore | 35,3 | 6 |
| Photovoltaic | 11,8 | 2 |
| Bio-mass | 29,4 | 5 |
| Hydro electricity | 17,6 | 3 |
| Oil, pump storage, others | 29,4 | 5 |
| waste | 5,9 | 1 |

***Table 1:*** *Electricity sources in Germany in 2010 [4].*

The onshore wind data are obtained from 50Hertz [5] with 15 min resolution. In order to represent the total wind electricity in 2010, the data were scaled to the totally harvested wind electricity of Germany of 35.3 TWh [4]. In order to check whether this spatial extrapolation is justified the 50Hertz onshore wind data are correlated with data obtained from TransnetBW [6] representing the wind pattern over Baden-Württemberg. The correlation coefficient R=0.48. The correlation function has a distinct maximum with a delay of 2h.

Offshore wind is not yet available in Germany to the extent that one could apply the same procedure as for onshore wind. The offshore data used were constructed from wind velocity data $v_w$ obtained from FINO3 [7]. Data were taken from the sensor at 100 m height pointing in 345° direction[1]. The offshore wind power is given by the cubic relation: $P = \alpha\, v_w^3$. In order to get verified power values the data from the first successful operation of the north-sea test-field Alpha Ventus wind park [8] were used. The 2×6 wind turbines with a nominal power of 5 MW each worked from October 2010 to June 2011 without interruption and produced 190 GWh. For the determination of $\alpha$ the wind velocity data were matched to the operational conditions of the wind turbines. The power was set to 0 for wind velocities $v_w < 3.5$ m/s (cut-in velocity) or $v_w > 30$ m/s (which was not reached in the considered data sample); P was assumed to scale according to the above cubic relation between 3.5 m/s and 14.5 m/s and to be constant at the maximal power (5 MW) for 14.5 (rated velocity) < $v_w$ < 30 m/s (cut-out velocity). It is problematic to take point data as representatives for a turbulent field where specifically the peaks average out to a certain extent. In case of offshore wind, the peaks are removed by the maximal power setting of the turbines. Therefore, this way of constructing the data seems justified.

Again, as a means of control, the FINO3 velocity data and the onshore wind power values were correlated ($v_w^3$ with $P_{on}$). The correlation coefficient R = 0.46 indicating a weak but distinct relationship of the data as can be expected facing the long-range nature of the wind pattern over Germany (50Hertz region) and the German Bay region. The correlation is between a point value (FINO3 velocity) and a field average value ($P_{on}$). The correlation function has a maximum and decreases for larger time displacements between the data. For comparison, the offshore wind data were also correlated to the PV data. Of course, no correlation is expected. The correlation coefficient is found to be R = 0.09.

The photovoltaic data were obtained from 50Hertz in 15 min increments [5]. Like in the other cases, they were scaled to the photovoltaic energy harvested in 2010 of 11.8 TWh. A further correction was necessary because of the strong development of PV systems in Germany in 2010 growing from 9.9 GW installed power at the end of 2009 to 16.8 GW (up to 17.3 GW can be found in the literature) a year later. As we assume constant installed PV power for the scenarios to be analysed in this study, the 2010 data were corrected assuming a linear growth of installed power in 2010 (which differs from the actual growth curve, which is ignored). The corrected PV data set would have delivered 13.4 TWh at a constant installed power of 16.8

[1] A few gaps in the data were filled with data from the sensor at 106 m height. The missing data of the 1st week in January 2010 were replaced by data from January 2011 of the same week. The velocity data are provided in 10 min increments. For a synchronized data base ordered in quarter-hour steps, the data at the full and the half hour could directly be used. The data at 15 min and 45 min were obtained by interpolation.

GW.

In this manner, a data base for the load, $W_{on}$, $W_{off}$ and PV power is obtained for 35040 time points with a resolution of 15 min. The ENTSO-E load data with 1 h time steps are kept constant over the 15 min time grid. The comparison with the regionally limited Tennet load data with 15 min resolution shows that no significant error is introduced by smoothing the load. Anyway, the major dynamics in the data base is introduced by the RE supply forms. For the temporal response studies of Chapt. 5, however, the better time resolved Tennet data were used.

In 2010, the net electricity production in Germany of 588 TWh originates from the different sources according to table 1.

The fossil fuel fraction is about 55%. The 35,3 TWh from onshore wind were produced by 27,2 GW installed wind power and correspond to about 1300 h at full load (full load hours, flh, = harvested annual electrical energy/installed power) or, equivalently, to a capacity factor ( availability factor, cf = flh/8760) in the use of the installations of 15 % (2010 was a low-wind year). The up scaled 13,4 TWh from PV are based on 16.8 GW installed PV power and correspond to about 800 h of full load or to a capacity factor of 9 %. The operation of the Alpha Ventus wind farm for a full year would have yielded 0.203 TWh for the 60 MW installed power. This corresponds to 3400 h at full load or a capacity factor of 39%.

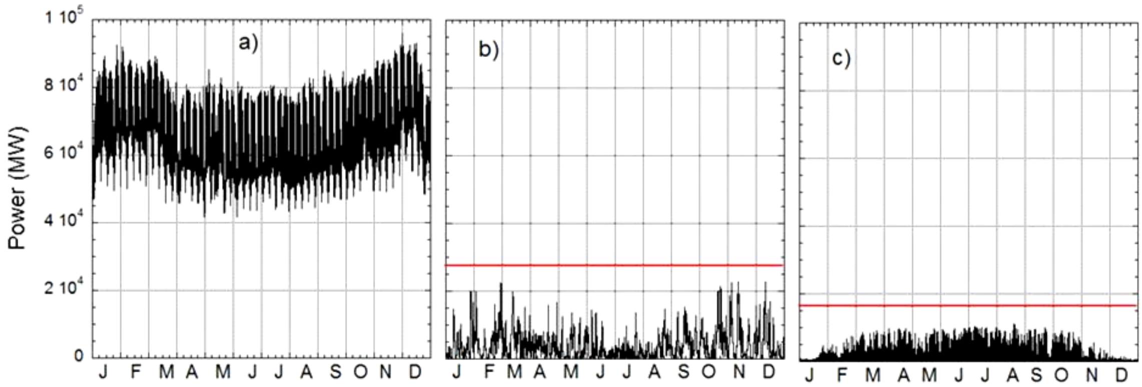


***Fig. 1.*** *a) Variation of the load during 2010; b) onshore wind power in 2010; the red line denotes the installed wind power; c) PV power in 2010 but for constant installed power of 16.8 GW (red line); the strong built-up of PV systems through the year has been corrected.*

Figures 1 a) to c) depict the data base constructed from actual data of 2010 as described above. Plotted are a) the demand (load), b) the onshore wind power and c) the PV power in their temporal developments through the year 2010. The PV data have been corrected for constant installed power. The horizontal lines in Fig. 1 b) and c) represent the installed power levels, which are found to be larger than the power peaks in the data sets indicating a reduced average availability. Figure 1 shows both the weekly and the seasonal variation of the reduced load; the daily variation is not resolved.

Figure 2. plots the load, onshore wind, and, on top of it, the PV contributions for January and

July 2010 from the data set of Fig. 1 in more detail with the daily variation being resolved now. The demand is lower during the weekends; wind is erratic and larger in winter and spring. PV responds in a periodic form – clearly visible in July - with maxima coinciding with the load maxima around noon-time.

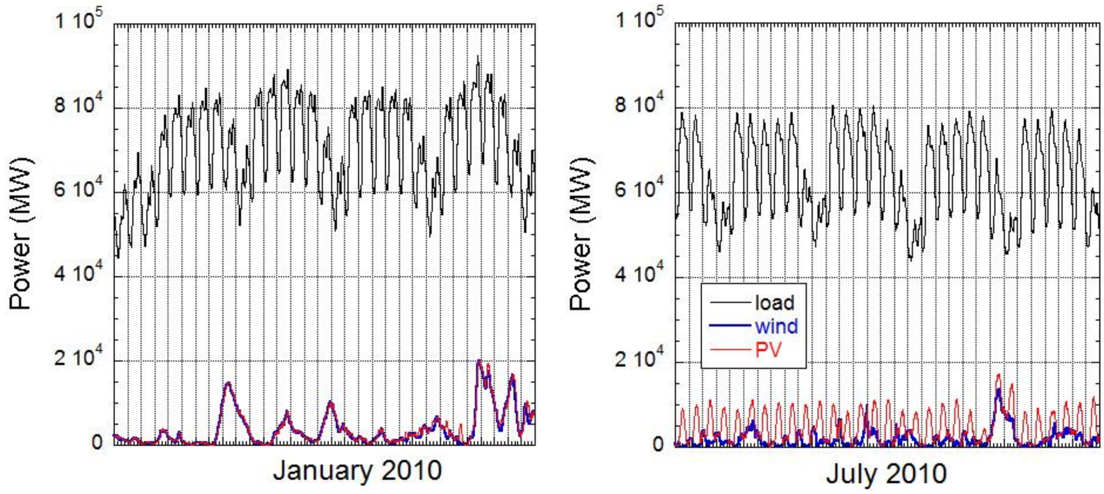


***Fig. 2.*** *Load, onshore wind and, on top of it, PV are shown for January (left) and July 2010.*

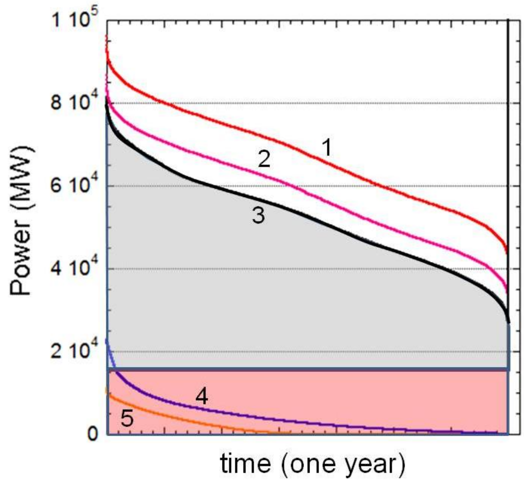


***Fig. 3****. Duration curves for 2010. (1) denotes the load; (2) the reduced load with contributions from hydro electricity, storage and waste subtracted from the load; (3) denotes the residual load when wind (4) and PV (5) are additionally subtracted. The horizontal line denotes the nuclear power contribution; the grey area represents the contributions of fossil fuel power plants.*

Figure 3 shows the duration curves for the load and the contributions from wind and PV for 2010. In this plot, the data are not ordered chronologically, but rather is the respective power (averaged over 15 min) ordered in descending sequence. This diagram allows categorizing the different contributions into base-load, mid-load and peak-load. It also helps to see the impact of an increasing share of renewable energies onto the park of conventional systems. Curve 1 corresponds to the load of 2010; curve 2, which is dubbed "reduced load" in this paper, is obtained when the electricity contributions from hydro, storage and waste are subtracted;

curve 3 represents the load after wind and PV contributions are subtracted (residual load).

Curve 4 and 5 are the duration curves of wind and PV, respectively. The horizontal line and the area beneath denote the corresponding nuclear base-load contribution; the grey area corresponds to the production of fossil power stations with $CO_2$ release. Curve 4 shows that wind blows nearly throughout the year, whereas PV contributes for about half a year.

Figure 3 points to a fundamental problem in the use of RE. The load curve is - seen from above – largely convex. The duration curves of wind and PV, however, are concave. Scaling to higher levels of wind and PV power capacity in order to ultimately match the annual energy consumption leads to large energy surpluses for extended periods. Figure 4 illustrates this consequence of the different duration curve curvatures in an exemplary way for onshore wind scaled up to increasing shares of the annual electricity production. For the case that onshore wind delivers the same amount of energy as the load demands (100% curve in Fig. 4) the areas beneath this curve and the one beneath the load curve are the same. The temporal distributions of available power and demand do, however, not fit. The area where the 100% curve is above the load represents the surplus energy; the area with the load being above the 100% curve has to be delivered additionally by a back-up system satisfying the residual load. This 100% case is denoted in this paper as the “equal energy case”.

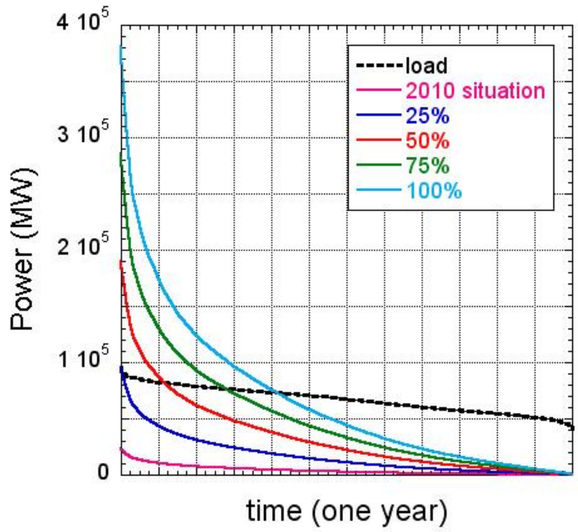


***Fig. 4.*** *Duration curves representing the load (black) and onshore wind electricity (in colour) of 2010 along with scaled up values representing up to 100% of the average annual electricity demand.*

Large RE power capacities have to be installed for substantial contributions to the annual energy demand. As a consequence, the peak power loads are greatly different for the surplus power and the back-up power cases. The power peaks dispatched into the grid can be as large as 400 GW, those which have to be handled as surplus power can be as large as 300 GW for the “equal energy case”. The peak powers in the back-up system do – of course - not surpass the level of the load. They can be lower to the extent the RE have contributions ensured throughout the year. These characteristics of variable supply are discussed in more detail in the following chapters.

## 3. Scaling studies

Whereas the net electricity production in 2010 is 588 TWh, the reference load value for the scaling studies of this paper is the "reduced load" of 562 TWh with the contributions from hydro, waste and storage electricity subtracted. Basis and starting point are the 2010 data. We will not consider a bio-mass contribution assuming that the energy from bio-mass will be used in the future more for transportation, preferably for air traffic and less for electricity production. We further assume that the electricity consumption will not change expecting that effects of higher efficiency will be compensated by an expansion of the use of electricity e.g. in the field of mobility and smart supply systems or by technical measures, which will help reducing the primary energy consumption like a wide use of heat pumps. Nuclear energy and net electricity import are not considered.

For each time point i in the data base the load, the on- and offshore wind power and the PV power are given. A positive difference between load and the sum of the three RE forms defines the back-up power at the time interval i. A negative difference (RE power > load) gives the surplus power.

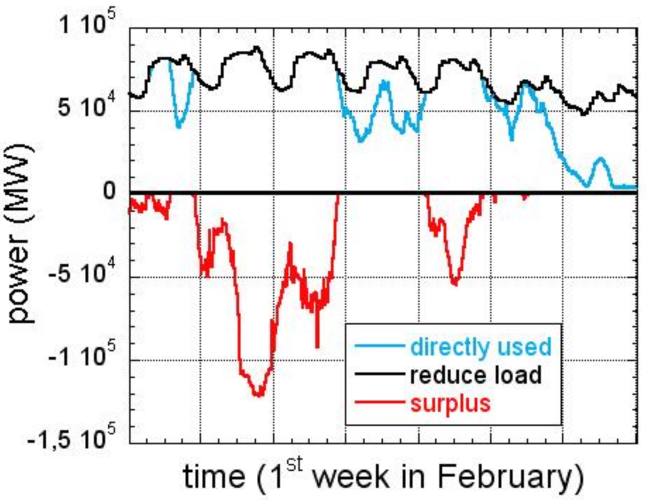


***Fig. 5.*** *For the conditions of the first week in February 2010 the load (black), directly used RE power (blue) and surplus power (red) are plotted. The RE part is scaled such that the annual energy of load and RE are the same ("equal energy case"). Wind and PV are mixed in the form of the "optimal mix" as will be discussed in Chapt. 4.*

Figure 5 shows the different contributions for – as an example - the first week in February 2010 and shows the sharing between the different contributions – reduced load, directly used RE power and surplus power. As the powers do not agree for each moment, surplus energy needs to be collected and back-up power has to be available. The directly used power is limited by the load. The part surpassing the load adds to surplus power (negative). In periods where the RE contribution falls below the load, the surplus power is zero; the differences to the load are covered by the back-up system. The case shown in Fig. 5 is constructed such that the annual energies of load and RE sources are the same – the so-called "equal energy case".

In this specific case the integral energies of the back-up system is equivalent to that of the surplus. The mix of RE energies in Fig. 5 corresponds to the so-called "optimal mix" to be discussed in Chapt. 4.

### 3.1. RE produce 100% of the annual electricity

Each of the RE supply forms has its own characteristics. In order to elucidate these features we first analyse and discuss them separately. The RE power in these cases is selected such that for each form separately the RE produces as much energy as the load integrally demands. The intention with the termination at this point is that the surplus power - if proper storage were available – would just be sufficient to compensate the primarily missing energy. In this case, no back-up power would be required any longer. Transfer and other process losses are not considered here.

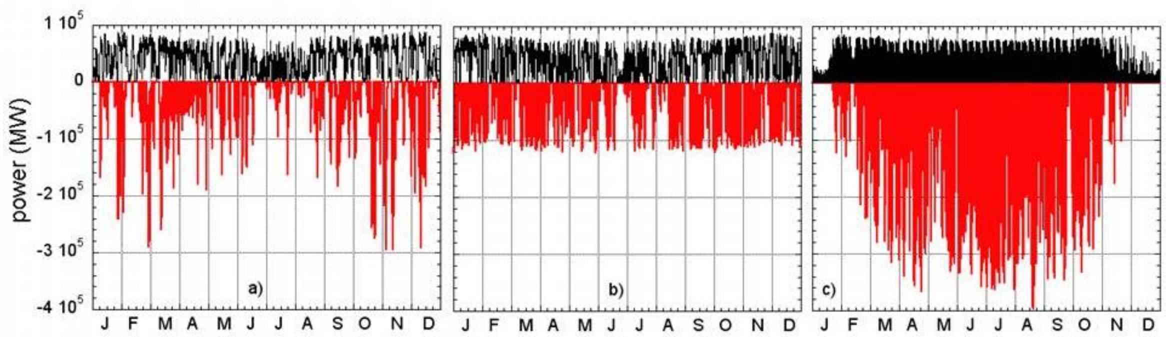


***Fig. 6.*** *a) The scaled RE power is plotted for the case that the annual electricity production by RE is equal to the annual demand. Black represents the directly used power with the load as upper limit; red (negative) the surplus power. a) represents onshore, b) offshore wind and c) PV.*

Figure 6 a) to c) represent the power of onshore and offshore wind and of PV. Positive values denote the power directly contributing to satisfy the demand. The upper limit of the curves is determined by the load. What goes beyond the load represents the surplus power and is plotted negatively.

- Onshore wind power fluctuates with large amplitudes truly reflecting the variability of wind velocity. Onshore turbines rarely meet the conditions of strong winds where the wind turbines are switched to the constant output power mode.

- Opposite to this, offshore wind power is rather constant in amplitude because strong wind leads to prolonged phases with the turbines regulated at the rated output power point.

- PV power is again different because its power is periodic with daily peak contributions well matched to the high-demand periods. The cyclic behaviour of PV is reflected in the upper part of Fig. 6 c) marking well the demand peaks.

The two wind cases show lower power coverage of the load in summer whereas, reciprocally, the low coverage by PV is in the winter months. The surplus power peaks can be exceedingly high in the limit considered here ("equal energy case") and reach values frequently beyond

300 GW in case of PV and onshore wind.

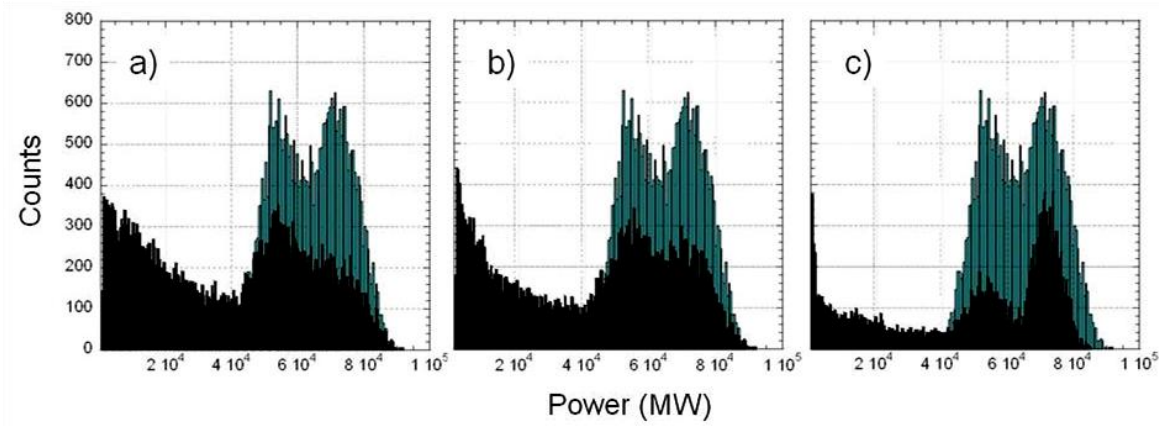


***Fig. 7.*** *Histograms of the directly used RE power (black) scaled to the 100% limit – the "equal energy case". As a reference, the histogram of the reduced load is shown. a) onshore wind; b) offshore wind; c) PV.*

The histograms in Fig. 7 plot the directly used power (black) produced by the three RE forms, which is delivered into the grid. It is compared with the load (green). The load distribution is characterized by two maxima, the higher-power one representing rather the load during the day, the lower-power one the load more during the night and weekends. The width of the two profiles is mostly given by the seasonal cycle. The RE powers show typically the concave distribution with the frequency of occurrence decreasing toward higher powers. The distribution of the directly used power increases, however, in the power range of the load because all power values falling into this interval but also all higher ones contribute to it. Because of the decay of the distribution toward higher powers, the "filling" of the power band of the load requires a large installed power so that specifically the excess power levels can be used to fill the load power band, which is offset from zero by a gap – the base load. The selectiveness of this process is obvious from Fig. 7 c). In case of PV, the highest peaks are delivered during daytime. Therefore, the day-peak of the load is preferentially filled.

| | Maximal power (GW) | Directly used energy (TWh) | Back-up = surplus energy (TWh) |
|---|---|---|---|
| Wind onshore | 365 | 344 | 218 |
| Wind offshore | 165 | 344 | 218 |
| PV | 463 | 214 | 348 |

***Table 2.*** *Given are the key characteristics of the three RE cases under the condition that the annual energy produced by the RE system is equal to the annual energy demand. Given are the maximal power (identified as a lower limit to the installed power, because the average availability factor < 1, see Fig. 1), the directly used energy into the grid and the energy delivered by the back-up system being equal to the surplus energy.*

Both onshore and offshore wind produce powers up to the level of the demand curve. But the highest power peaks of the load occur in winter during daytime with little PV contribution. Therefore, this part of the load is – unlike the other cases - not covered in case of PV; a gap remains between the peak load and the PV distribution at the highest powers. For these periods, when exclusively PV is considered, the back-up system must be available up to the maximal required power.

The integrals of the directly used power distributions are not the same for the three cases (though the conditions RE energy = annual energy demand is the same). PV produces substantially more surplus energy than the other two cases – but in summer, which does not help the needs in winter.

Table 2 shows the various key characteristics of the three RE forms under the limiting condition of the “equal energy case”.

For the same annual energy, the necessary wind power to be installed is lower by a factor of more than 2 in case of offshore than onshore wind. The energy values for directly used and surplus/back-up energies, respectively, are the same for the wind cases because of a similar data structure representative of turbulent generation processes; they are different for PV with a more periodic spectral content. In a control run with random numbers replacing actual wind or PV data, the directly used, surplus and back-up power levels are equal at 281 TWh adding up to the reduced load of 562 TWh.

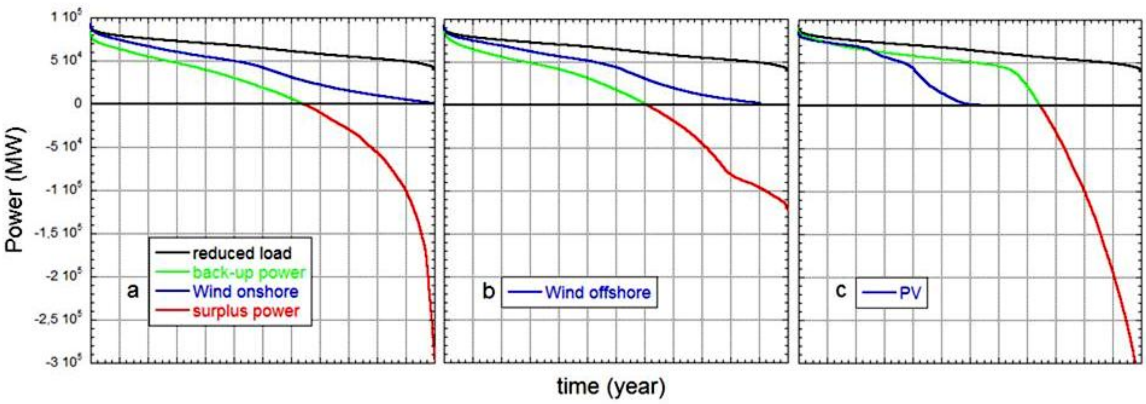


***Fig. 8.*** *shows the duration curves for a) onshore, b) offshore and c) PV. The black curve is the reduced load; the blue curve represents the RE contribution; the green curve the residual back-up power and the red branch the surplus power.*

Figure 8 a) to c) show the duration curves for the three cases considered. The black curve is the reduced load as defined above. The blue curves represent the RE power, which can directly be used. On- and offshore wind have contributions almost throughout the year. PV covers only about 50% of the year because of nighttimes without delivery. The green curves denote the duration curve for the residual back-up power. Its contribution is strongly reduced compared to the original situation without RE contribution (see table 2); it loses the characteristics of a base load. The negative red curves represent the surplus power reproducing the already known effect that the surplus power is limited in case of offshore wind and extreme in case of PV.

### 3.2. Surplus power and operation mode of the back-up system

With controllable sources, the power supply system responds to the periodic variation of the day/night cycle, the weekly and the seasonal variation: Electricity production is demand driven. The load variations are periodic and predictable. With RE the supply system splits up into the primary sources wind and PV and the secondary source, the back-up system based on thermal power for the near future covering the residual load. With increasing RE shares, the periodic variation of the back-up systems is changed to an erratic one reflecting the spectral character of the stochastic supply and to a lesser extent the periodic pattern of the load: Electricity production becomes supply driven.

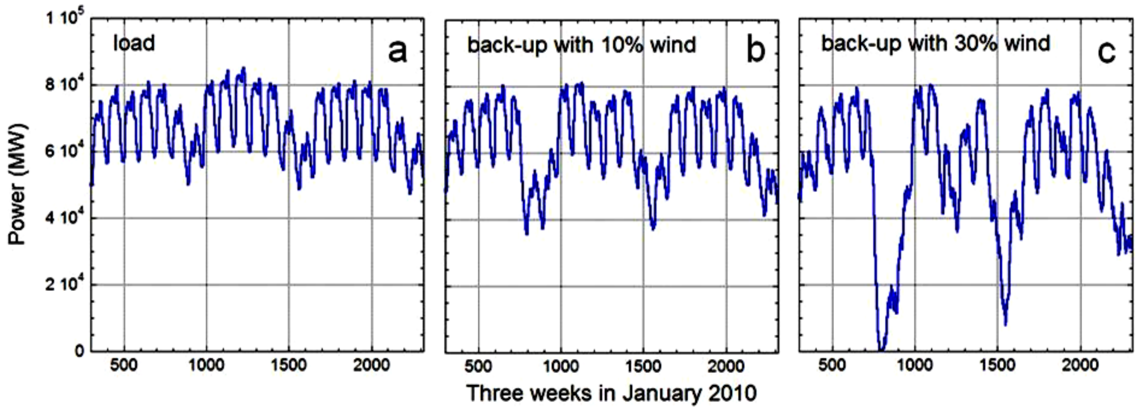


***Fig. 9.*** *a) Plotted is the load of the period from mid-February to mid-March 2010. Fig. b) and c) represent the variation of the back-up systems when 10 % or 30% (Fig. 6c)), respectively is obtained from onshore wind.*

Figure 9 shows the variation of the back-up power with onshore wind energy shares increasing from 0 to 30% of the annual demands. With 10% wind contribution the periodic pattern of the load is largely maintained. This reflects roughly the 2011 situation in Germany (wind and PV: 66 TWh = 11% of the demand [9]). With 30 % share, the periodic pattern is dissolved and the temporal characteristics of the residual power display chaotic traits.

In the following, we discuss the features in the transition from continuous to variable supply along power histograms. Figure 10 a) shows the power histogram of the reduced load. The peak and the base load powers are shown as vertical lines. The double-hump structure has already been discussed.

In the case that onshore wind contributes with 10% to the annual demand (Fig. 10 b)) the main feature – the residual back-up power (black) distributed between base and peak load limits and separated from zero – is largely maintained. The lower level of the base-load is slightly shifted to lower power values. With 30% wind contribution to the annual electricity (Fig. 10 c)), the base load has disappeared and the back-up system has to supply all power levels from 0 to the maxima of the reduced load. In this case, already a distinct amount of surplus electricity is produced, which is plotted on the negative axis (red). This trend continues to larger wind electricity shares (Fig. 10d) with surplus power levels reaching beyond 100 GW. Figure 10 e) represents the case where the annually produced wind energy (sum of directly used and surplus energies) is equivalent to the annual demand ("equal energy case"). Figure 10e) also shows the small shift of the power range of the back-up system away from the original peak load line to a slightly lower value. For this case, close to 10 % of the installed back-up capacity can be saved owing to the installed wind system and its continuous contribution throughout the year (see also Table 3).

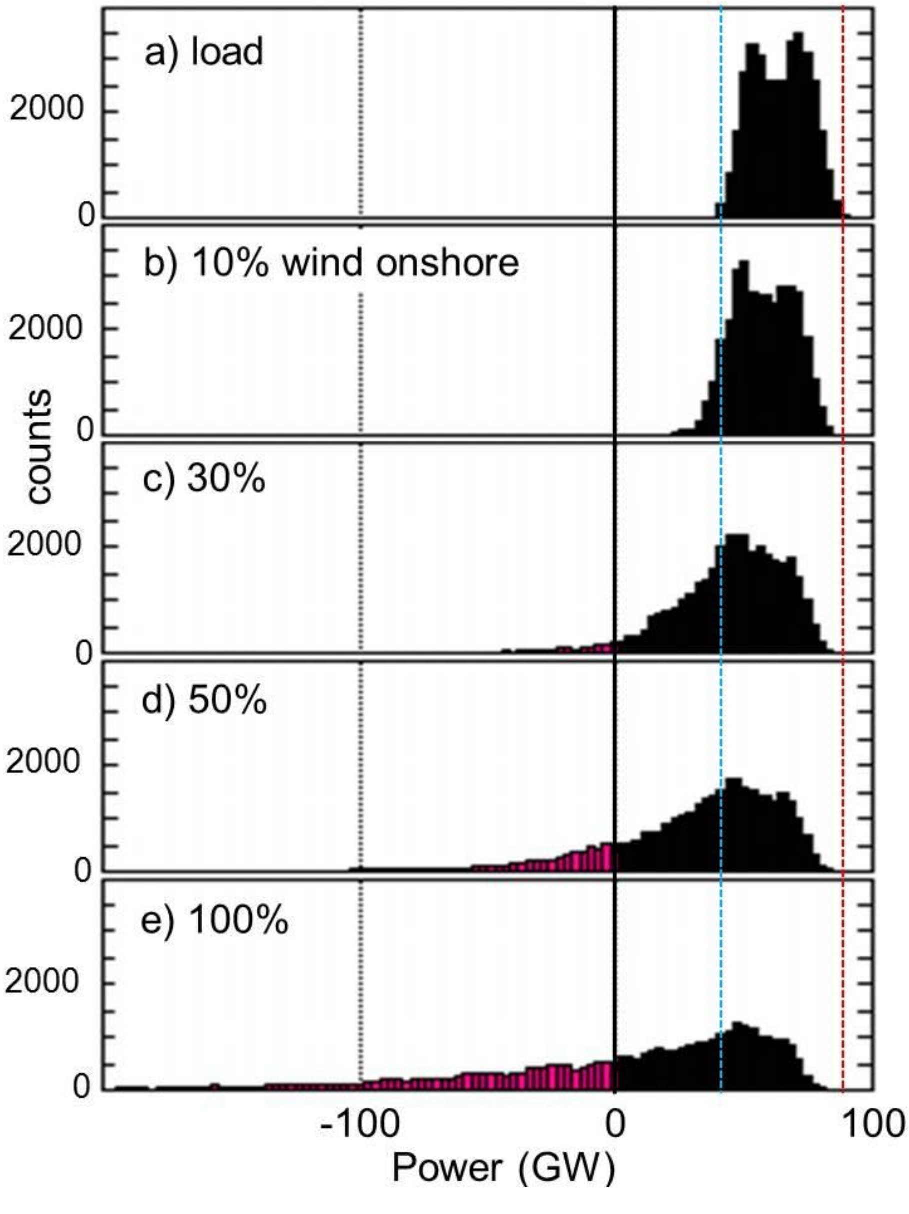


***Fig. 10.*** *Histograms of the reduced load and the power delivered by back-up systems (black) and of the surplus power (red) with onshore wind contributions increasing from 10% to 100% of the annually demanded electricity in 2010. The vertical lines denote the base-load (blue) and the peak-load (red) power levels.*

Figure 11 shows power histograms of the back-up system and the surplus power for offshore wind and PV in the limit of the "equal energy case". The histograms are distinctively different to those of onshore wind. In the case of offshore wind, the maximal power is limited because

– unlike onshore - the individual turbine is frequently operated under the conditions of constant rated power. The negative power hump is caused by the excess power, which lies between maximum wind converter power and the peak load.

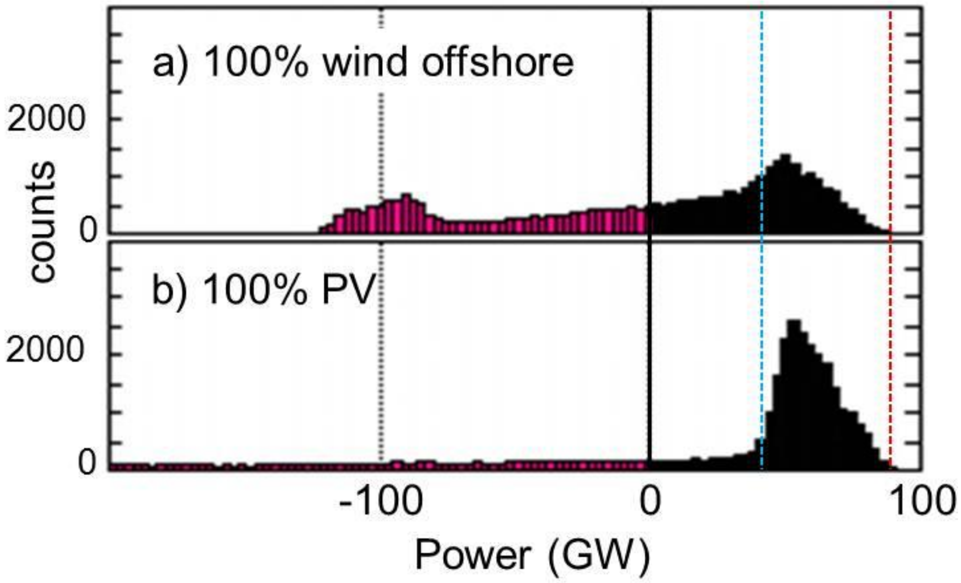


***Fig. 11.*** *Histograms of the power delivered by the back-up system (black) and the surplus power (red) with offshore wind and PV contributions, respectively, of 100% of the annually produced electricity in 2010. The vertical lines denote the base-load (blue) and the peak-load (red) levels.*

In case of PV only, small power contributions occupy the power range from 0 to the original base load (blue line). The reason is the distribution of the power in a wide range reaching beyond 300 GW. The day peak is reduced in the back-up power spectrum; the night peak remains, however. The original base-load is marked in the histogram of the back-up power because PV is not able to cover this part of the load representing demands during the night.

The available back-up power has to remain at full capacity. No savings are possible and the back-up power has to be able to fully meet the peak load. The histogram shown in Fig. 11 b) reflects the lack of PV support during winter-day peak loads from the perspective of the back-up power. In winter, 100% of the back-up system can be in operation. PV alone does not allow saving conventional power plant capacity.

| Energy source and contribution | RE contribution (used+surplus) (%) | Capacity factor of back-up system | Maximal power of back-up system (GW) |
|---|---|---|---|
| | 0 | 0.70 | 92 |
| Wind onshore | 10 | 0.67 | 86 |
| Wind onshore | 30 | 0.53 | 85 |
| Wind onshore | 50 | 0.43 | 84 |
| Wind onshore | 100 | 0.30 | 83 |
| Wind offshore | 100 | 0.29 | 87 |
| PV | 100 | 0.43 | 92 |

***Table 3.*** *Shown is the utilization of the back-up system (capacity factor) and its maximal power at variable RE contributions to the annual demand.*

Table 3 lists the capacity factors of the back-up system defining its annual utilisation for varying contributions of the RE systems and also gives the maximal back-up power observed in the data set averaged over 15 min. Given are the results for variable contributions of onshore wind and for 100% energy from offshore wind or PV, respectively. For the “equal energy case” onshore and offshore wind reduces the back-up capacity factors to about 30%. In case of PV, the back-up system is more frequently in use. As already shown in Figs. 6 and 11, PV does not allow a reduction in installed back-up power – unlike wind electricity with a reduction from 92 to 83 GW (- 8%). The jump from 92 GW installed power to 86 GW with already 10 % onshore wind is caused by the removal of peak load demands from the back-up system, which happens for about 50 h in the year. This effect may be a particularity of the wind situation in 2010.

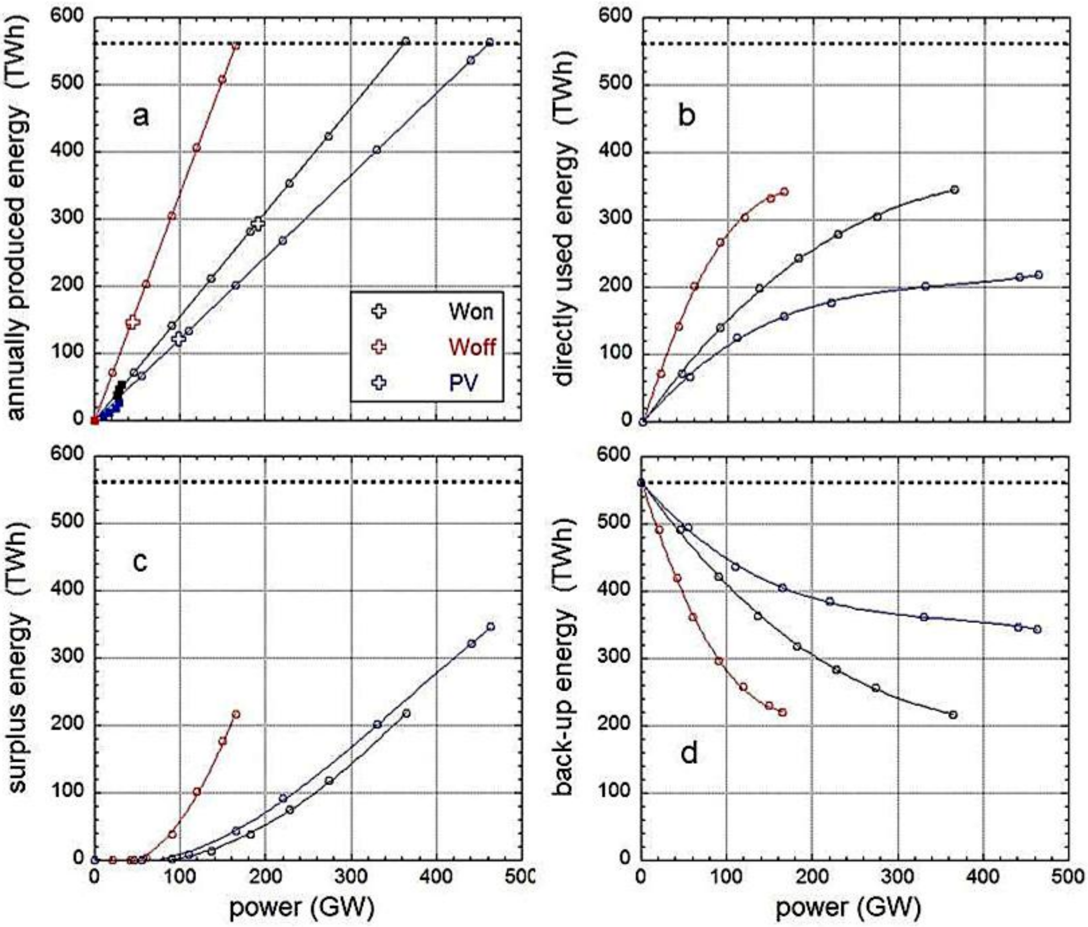


***Fig. 12.*** *a) Plotted is the produced energy against the maximal RE power in the data set (lower limit of the installed power) for on- and offshore wind and PV. The horizontal line represents the level of the reduced load in Germany in 2010. The squares close to the origin represent energy and installed power of onshore wind (black), offshore wind (red) and PV (blue) for 2010, 2011, and as expected for 2012. The open crosses represent the key data of the optimal mix of RE system as described in Chapt. 4. b) directly used energy; c) surplus energy; d) back-up energy. The curves in Fig. 12 end when the total energy delivered by the RE systems is equal to the annual demand (see Fig. 12 a).*

### 3.3. Summary of scaling studies

In Fig. 12 a) the produced RE electricity (directly used and surplus) is plotted against the maximal RE power in the data set of the respective scan for on- and offshore wind and PV. The relation is – of course – linear. Technical losses in production or transmission are neglected because they are not relevant for the considerations of this paper. The necessary installed power capacities are actually larger than the power values quoted here[2] by a factor of 1.2 for onshore wind or 1.5 for PV, respectively. For the truly installed power and the corresponding capital costs for their implementation, the maximal power values of Fig. 12 represent therefore lower limits.

The horizontal dotted line in Fig. 12 a) corresponds to the reduced load of integrally 562 TWh, which has to be produced to meet the 588 TWh net electricity target together with electricity from hydro and waste. The solid data points close to the origin represent energy and installed power of onshore wind (black squares), offshore wind (red square), and PV (blue square) at the end of 2010, and 2011 and as expected for 2012. These data points indicate the still infant nature of the RE deployment in Germany in spite of tremendous efforts. The open crosses indicate the locations of the three RE components in case of the optimal mix as described in Chapt. 4. All curves in Fig. 12 end when the energy produced by RE agrees with the annual demand – at the conditions of the "equal energy case" (e.g. see Fig. 12a)).

Figure 12 b) plots the annually produced energy, which is directly used for the three systems under consideration against the maximal power occurring in the data base. Figure 12 c) shows the annual surplus energy and finally, in Fig. 12 d) the energy of the back-up system is plotted.

The slopes in Fig. 12 a) correspond to the annual full load hours which are 1550 h (wind on), 3385 h (wind off), and 1200 h (PV). The values are too high because the maximal power in the data set is smaller than the actually installed power (see footnote 2). Particularly, the actual full load hour of PV is closer to 900 h when the actually installed power is used as reference.

The directly used energy of Fig. 12 b) shows the tendency to saturate. This effect is specifically distinct for PV. The non-linear elements causing the saturation are the periods without RE electricity production irrespective of the installed power - wind velocity below the cut-in level or the nights in case of PV. All of the three RE forms stay well below the reduced load (dotted line in Fig. 12) for the conditions considered here.

Owing to their falling power spectrum (e.g. see Fig. 4) RE systems produce large amounts of excess power (see Fig. 12 c), which cannot be accommodated within the national grid without storage. PV produces the largest amount of surplus power.

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[2] E.g. in 2010, the maximal power of onshore wind in the data base was 22.8 GW whereas the installed power was actually 27.2 GW (see Fig. 1); similarly, the maximal PV power in the data set of 11 GW compares with 16.8 GW installed power.

Figure 12 d) plots the energy delivered by the back-up system for the three RE cases considered, which deceases with increasing RE share. This dependence corresponds to the desired objectives in the use of RE. Back-up power is required up to the "equal energy case" and beyond. An exclusive PV system would necessitate the largest thermal power back-up system.

In conclusion, without storage, offshore wind as the "best" RE electricity source produces about 50% of the annual load with about twice the presently installed conventional thermal power. The other extreme is PV, which produces with close to 500 GW installed power only about 1/3 of the annual electricity.

**4. Optimal mix between wind and PV installations.**

The averaged load curve has a maximum in winter and a minimum in summer. This is also the case for wind electricity, which helps to match the seasonal cycle and is contrary to photovoltaic electricity production, which has a minimum in winter (see Fig. 1). On the other hand, photovoltaic electricity is produced during the day when the demand is highest. Therefore, wind has a good annual and PV a good daily match to the load curve. The consequence is that there is an optimal mix for these two renewable energy forms. We define the optimum as the proper mix of wind and PV power, which minimizes the demand of back-up power (and therefore the amount of $CO_2$ production as long as the back-up system is based on fossil fuels). We further assume that offshore wind produces 1/3 of the wind energy.

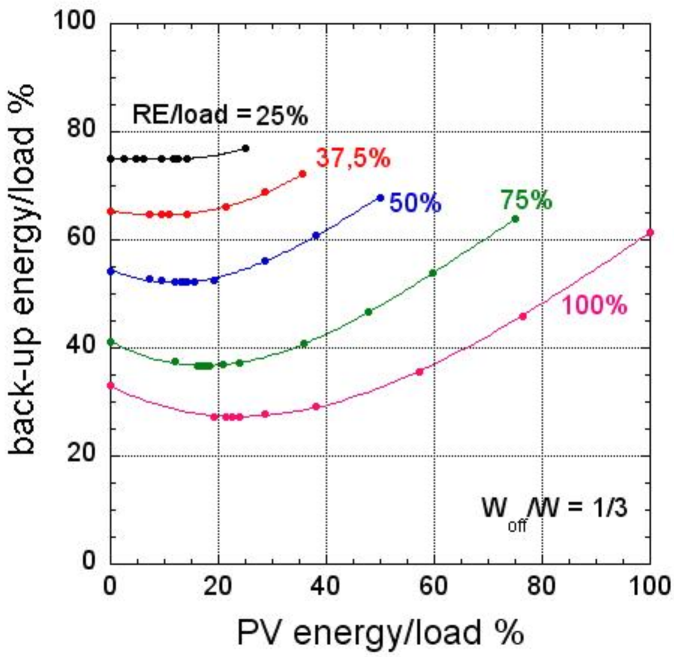


***Fig. 13.*** *The ratio of the back-up energy to the annual reduced electricity demand is plotted against the energy contribution of the PV system, also normalized to the reduced load. The parameter of the curves is the ratio of the energy delivered by the RE normalized against the reduced load. The offshore wind energy is assumed to be 1/3 of the total wind contribution.*

Figure 13 plots the annually produced energy of the back-up systems normalized to the reduced load against the PV energy production also normalized to the reduced load. Parameter of the set of curves is the total contribution of RE also normalized to the reduced load. The curves show a minimum, which moves to larger PV contributions when the share of RE increases. The curves do not represent a symmetric case for wind and PV. The wind-only case is not much above the minimum whereas the PV-only case requires much more back-up contributions.

| | Power (GW) | Energy (TWh) |
|---|---|---|
| Wind onshore | 191 | 294 |
| Wind offshore | 44 | 147 |
| PV | 99 | 121 |
| Back-up system | 84 | 153 |
| Surplus | | 153 |
| Directly used RE energy | | 409 |

***Table 4.*** *Key data for the case that the RE systems produce under the optimal mix conditions the amount of energy corresponding to the demand ("equal energy case").*

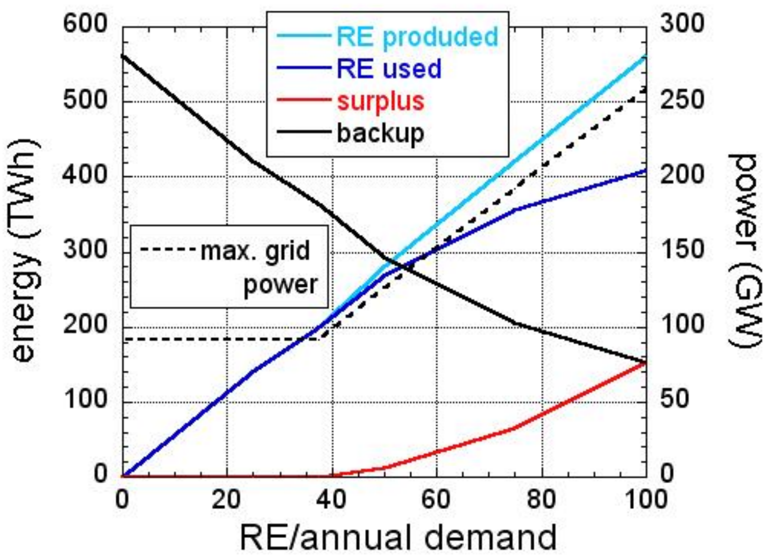


***Fig. 14.*** *Plotted are the various energies involved and the maximal grid power versus the total annual energy from renewable sources normalized to the annual demand (RE share) for the optimal mix case.*

In the "equal energy case" the optimal PV contribution to the annual demand is 22%; in case of 37.5% RE share this value drops to 10%. However, for a 25% share and below, the ratio of wind to PV does not affect much the level of back-up power. Though the share of PV increases with the RE contribution under optimal mix conditions, the ratio of PV to wind decreases from about 1 at 37.5% RE share to 0.27 for 100% RE share. The ratio of offshore to onshore wind is found to not change much the results of Fig. 13.

Table 4 shows the key parameters for the case that RE matches the reduced annual electricity production (562 TWh) under the optimized conditions of minimal back-up need. Onshore wind produces 2/3 of the total wind production in the case considered. Given is the power of each of the systems along with the energy it produces. As the RE do not match the load for each of the time points, 153 TWh have to be delivered by the back-up system (being equal to the surplus energy). The necessary installed power for this purpose is 84 GW.

Figure14 shows the energies involved in meeting the annual demand – the one produced by RE, the directly used one, the surplus energy, and the residual energy of the back-up system. Shown is also the maximal grid power. The results are obtained under optimal mix conditions. The directly used RE energy (dark blue curve) increases non-linearly indicating – like in Fig. 12 b) for the individual supply techniques – that RE as considered here will not meet the demand completely. The red curve in Fig. 14 represents the surplus power. Surplus power starts playing a role beyond about 40% of RE share. The dotted curve is the dispatched power. The maximal power into the grid is 260 GW and is determined by the RE alone. The loading of the grid by the back-up systems does, of course, not affect its maximal loading capacity. The back-up power, which is not plotted, decreases slightly from 92 GW to 84 GW for the "equal energy case" - an 8% reduction in installed thermal power capacity. At an installed RE power equal to that of the back-up system (= the presently installed power system), the RE deliver 25-30% of the annual demand. A distinct difference in supply characteristics happens for RE shares > 40% with a pronounced increase in surplus energy and in the power to the grid.

The crosses plotted in Fig. 12 a) represent the key data in RE power and energy for the optimal mix case.

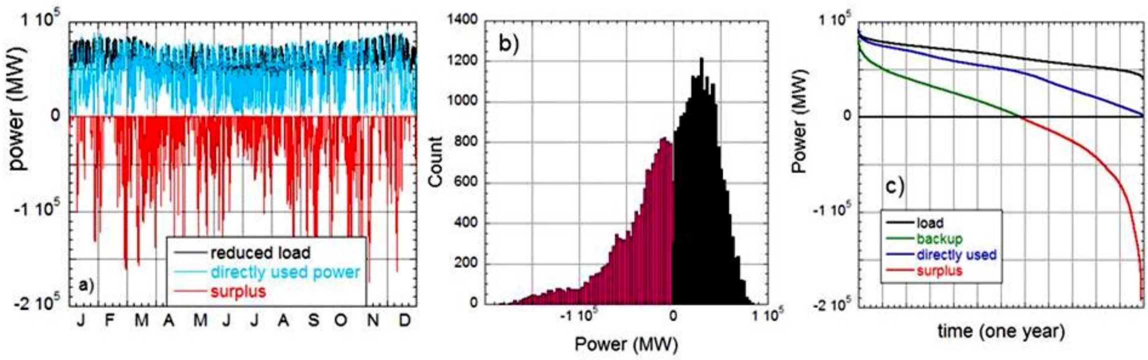


***Fig. 15.*** *All plots refer to the optimal mix case. a) shows the reduced load (black), directly used RE power (blue) and surplus power (red) through the year; b) shows the histogram of back-up and surplus power (red); c) shows the duration curves of the various contributions. The results are obtained for the "equal energy case".*

Figure 15 gives some further details on the power supply under the conditions of the optimal mix. In Fig. 15 a) the temporal development of load, directly used power and surplus power is shown. Figure 15 b) plots the histogram of the residual back-up power (black) and surplus power (red) and c) shows the duration curves for the reduced load (black), the directly used RE contribution with a discontinuity in the slope as soon as PV is not contributing any longer (blue). Finally the situation of the back-up power (green) and the surplus power (red) is shown. The back-up system is in use for close to 7 months with 1824 full-load hours. Also under optimized conditions large power peaks appear up to 200 GW, which may be a challenge to the grid, specifically to the grids of neighbour countries if this power is to be exported.

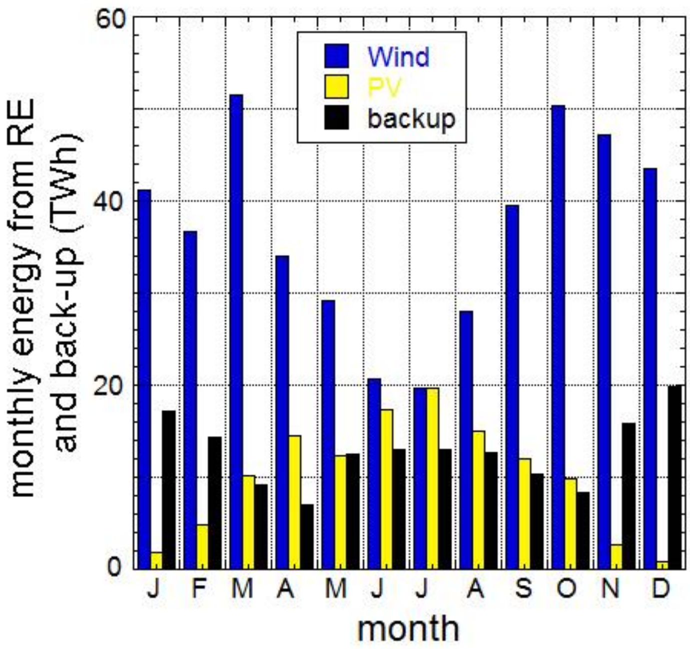


***Fig. 16.*** *Monthly distribution of wind, PV and back-up electricity for the optimal mix case.*

In Fig. 16 the monthly distribution of the energy of the three supply systems is shown under optimum mix conditions. The sum of onshore and offshore wind in blue, the PV energy in yellow and the energy from the back-system in black.

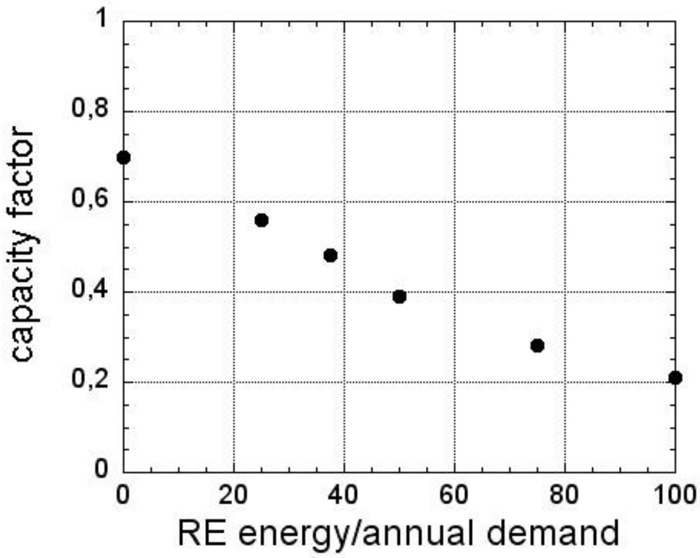


***Fig. 17.*** *Capacity factor against the RE energy share for the back-up system.*

The seasonal particularities of wind and PV electricity are reproduced. The back-up system is needed throughout the year. Its supply has maxima in summer, when wind is lowest and in winter, when PV is lowest. The minima in the back-up system are rather symmetric in April and October.

The major challenge for the back-up power system is the reduction of the full load hours with increasing RE share. In Fig. 17, the capacity factor is plotted against the RE share. It continuously decreases with increasing RE contribution. If the RE are considered individually the capacity factors of the back-up system are larger than in the optimal mix case (see table 3). Below a capacity factor of about 0.5, the economic operation of power plants, which were in use under base-load conditions in the past, might become critical. The corresponding RE share for this to happen is around 40%.

The optimal mix case is not suggested here as a development scenario. This is not possible under the present deployment strategy in Germany and  may not be possible at all. It rather serves as a reference case to assess and qualify alternatives.

## 5. Temporal characteristics of power loading to the grid

The historic situation is characterized by power delivery by demand with controllable power plants categorized in base-, medium- and peak-loads. The dynamics of the power system was determined by the periodic and rather predictable variation of the load.. With increasing stochastic contributions both amplitude and response change and are now governed by the temporal characteristics of the fluctuating sources (see Fig. 9). A detailed account of the consequences on the conventional power plants in Germany is given in Ref. [10].

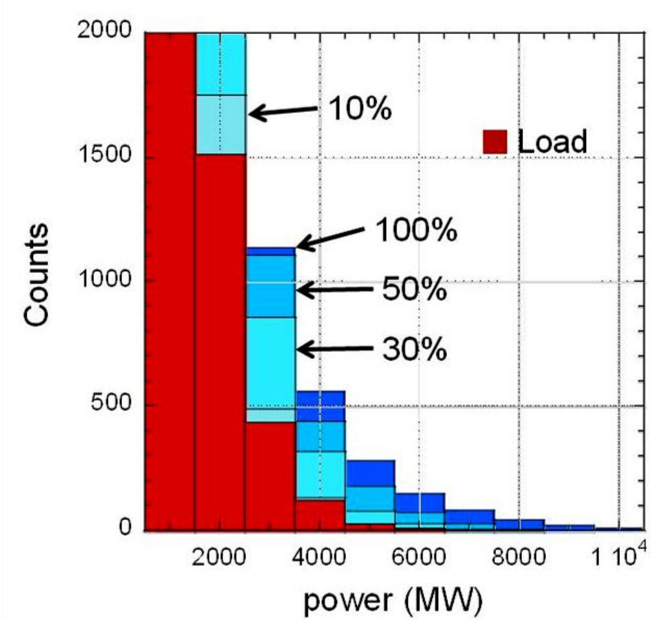


***Fig. 18.*** *Histogram of the power levels in the reduced load (red) and with onshore wind varied from 10 to 100% of the annually consumed electric energy.*

Figure 18 is a histogram of the positive power level changes to the grid occurring within 15 min. The range of small and uncritical changes with P < 0,5 GW/15min is removed. The red curve represents the power amplitude variation of the load. In order to get the full dynamics of the system, the Tennet load data [2] are taken, which are resolved in 15 min time increments. The vast majority of amplitude changes occur at power levels below 2.5 GW. Excursions to even higher power levels are possible but rare. As expected, with 10% onshore wind contribution, the situation does not change much. The frequency increases happen mostly in the incremental power ranges characteristic for the load itself. With 30% wind, the number of power switches between 3.5 and 4.5 GW per 15 min increases by a factor of 2.5. With 100% onshore wind the number of power switches between 5.5 and 6.5 GW correspond to the number of load switches between 3.5 and 4.5 GW. Even higher power increments can occur.

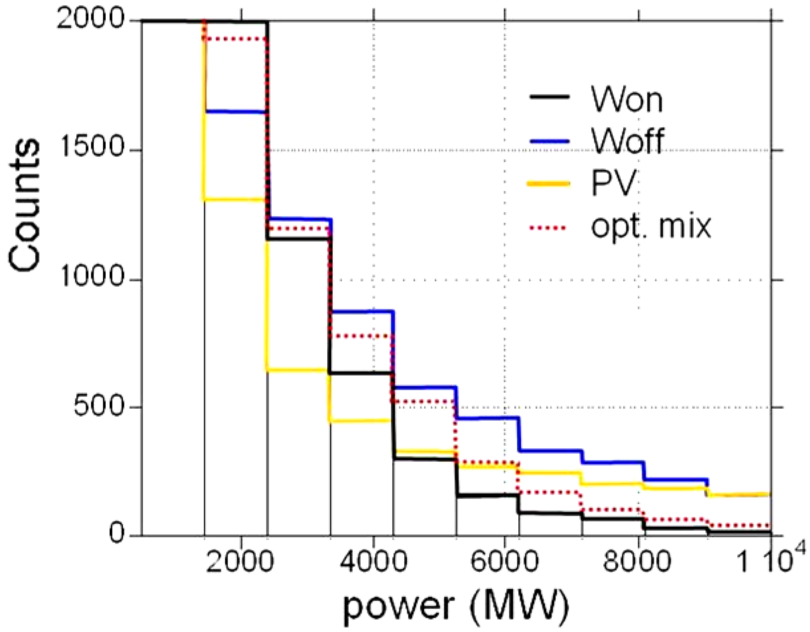


***Fig. 19.*** *Histogram of the power levels of on- and offshore wind, PV and the optimal mix case under the conditions of the "equal energy case".*

The histogram shown in Fig. 19 plots the power steps occurring with onshore wind and compares it with offshore wind, PV and the optimal mix case as defined in Chapt. 4. The "equal energy case" is considered for each of the scenarios. The distributions of the three RE forms differ quite substantially with offshore wind producing the largest number of power steps beyond 2.5 GW. Like offshore wind, PV produces high power increments within 15 min at high power levels of 10 GW and beyond. This corresponds to about half of the day-night cycle of the load but occurring within 15 min. A grid is required with the technical capability to handle such extraordinary events. This dynamics implies that e.g. thirty 300 MW G&D power stations are cycled from 0 to full power. The consequence would be that many of Germany's thermal power stations act synchronously.

The benefit of the optimal mix is obvious from Fig. 19. The power step values are close to those of onshore wind electricity. In all cases, however, the power increments beyond 4.5 GW are distinctively larger than the load alone would cause.

We have seen that with increasing RE share the capacity factor of the back-up system drops.

The periods become longer where the back-up system is not in operation. It can be expected that the number of power cycles for the back-up system therefore decreases with increasing RE contribution. The number of cycles above 1 GW power increment is plotted in Fig. 20 for onshore wind with different shares and for offshore wind, PV and the optimal mix case for the 100% "equal energy case". The cases $|\Delta P| <$ GW are excluded to separate the frequent small power steps from the critical excursions of interest here.

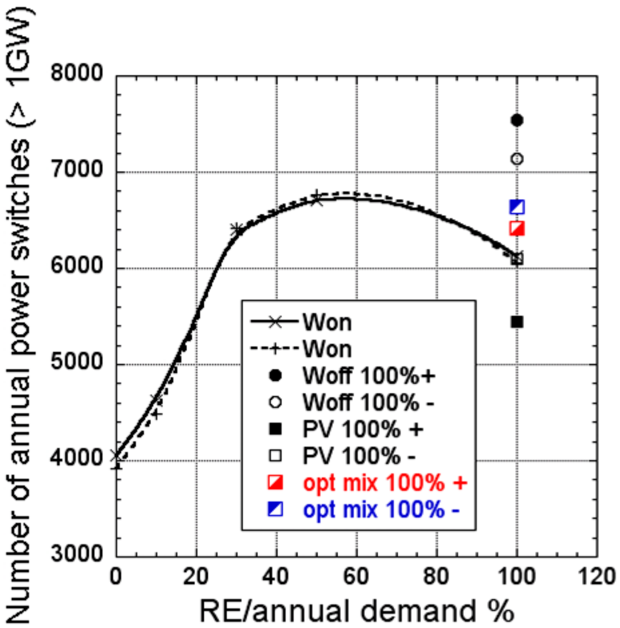


***Fig. 20.*** *The number of power switches of the back-up system > 1GW are plotted against the annual RE normalized against the annual demand. The results for both positive and negative excursions are shown. For onshore wind, the continuous development from 0 to 100% RE contribution to the load is plotted; for the other cases (offshore, PV and the optimal mix case) only the results of the 100% ("equal energy") cases are given. The solid curve is a guide to the eye for positive and the dashed curve for negative* $W_{on}$ *power increments.*

The distribution between positive and negative power increments is rather symmetric. As expected, the number of power switches drops toward high fractions of onshore wind. The maximum is at about an onshore power fraction of 60% with nearly 14000 bipolar large power cycles in a year. This goes nearly a factor of two beyond the number of equivalent cycles of the load. The consequence is a much stronger operational demand for the back-up system and represents a challenge to its technical integrity specifically for the larger power excursions necessitating a nearly coherent response of the back-up system. Some of the technical consequences are analysed in Ref. [11].

In the following, we carry out the same analysis for the surplus power, which has to be exported or avoided as long as no other technical use (e.g. storage) is available. For the back-up systems the power is limited by the level of the load and the power increments $\Delta P$ are, therefore, limited in power. This is different in case of the surplus power and its excursions can be much larger than those of the back-up system (see Fig. 6).

Fig. 21 a) to f) indicates the range of surplus power and surplus power steps ΔP as they occur in the cases of onshore wind (varied between 30 and 100% of the load), offshore wind, PV and the optimal mix case (each for the “equal energy case”). In this diagram, each power increment $\Delta P_i = P_{i+1} - P_i$ is associated with the surplus power value $P_i$. As we have already seen, the power values reach beyond 300 GW. Specifically large values appear for PV. In case of offshore wind, the power is limited by the features of turbine operation (see Chapt. 2). But in this case, the changes in power are specifically large. For positive surplus power values, the range $\Delta P > P$ is not covered (see e.g. Fig. 21 d)). The reason is the way the data are plotted ($\Delta P_i$ versus $P_i$), which limits, for positive power values, the minimal surplus power step size to the power itself. For the “equal energy/optimal mix case” the rate of change of the back-up system power per minute is between ±2% related to its power of 84 GW.

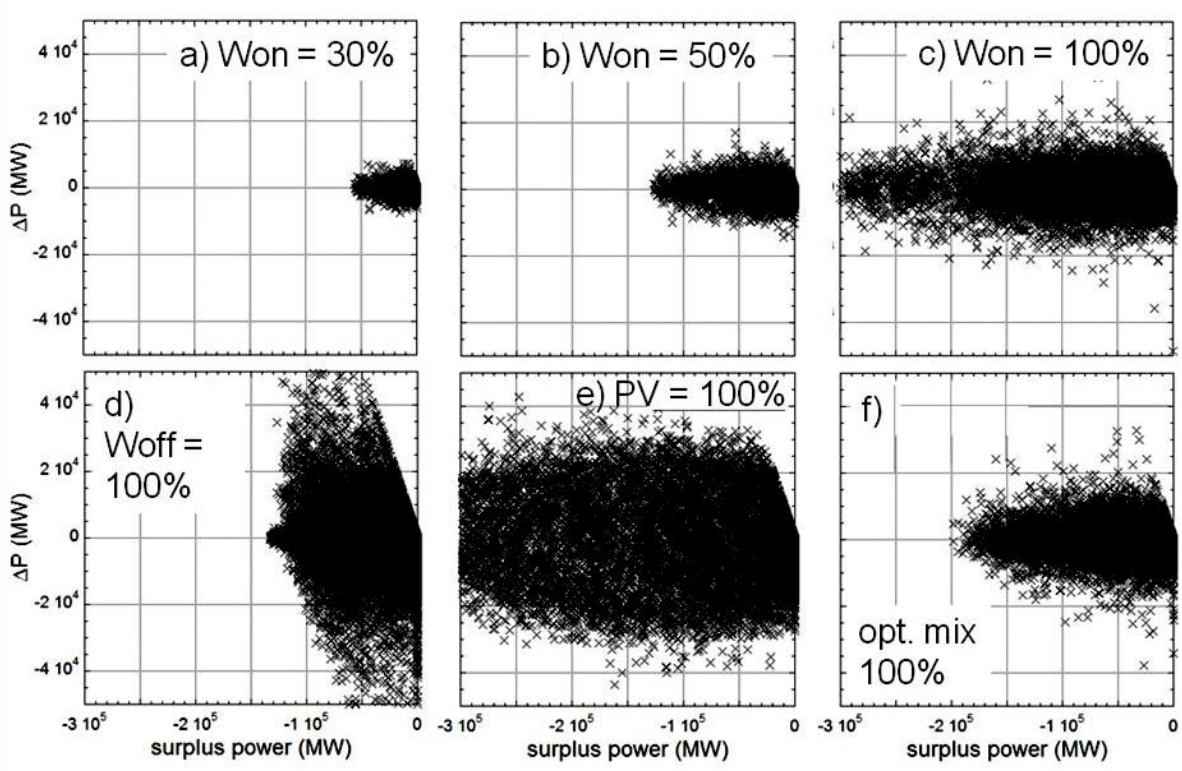


*__Fig. 21.__ Plotted is the increment of surplus power from one level to the next one 15 min later against the power prior to the change for the cases studied here: In a) to c) the results for onshore wind are shown with different contributions to the annual consumption (30 – 100%). In the cases d) to f) the 100% (“equal energy”) cases are plotted for offshore wind, PV and for the optimal mix case.*

### 6. Storage

Storage would allow to use the surplus power and to ultimately replace the thermal technology of the back-up system achieving thus completely $CO_2$-free electricity supply and would allow smoothing the fluctuations on RE electricity production. No specific storage technology is assumed here.

### 6.1. Long-term storage

In the following, we investigate the external conditions for large-scale electricity storage, which would serve a complete annual cycle. The storage parameters are developed first from the characteristics of the three types of sources assumed – on- and offshore wind or PV, respectively. At first, we discuss each source type separately. A condition for a long-term storage system is that its variation is periodic. As we consider one year, the storage conditions at the end of the year have to be the same as at the beginning. Under idealized model assumptions, we fix the initial storage level so that during the year, the complete storage capacity will be used.

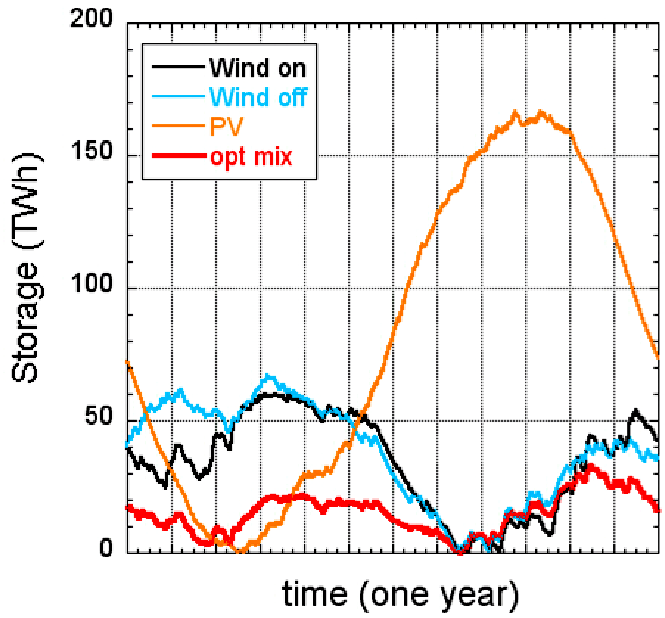


***Fig. 22.*** *The variation of the storage loading with time through the year for the 4 cases considered.*

| | Storage energy (TWh) | Maximal storage power (GW) |
|---|---|---|
| Onshore wind | 60 | +296, -83 (1 month) |
| Offshore wind | 67 | +123, -87 (24 days) |
| PV | 166 | +397, -92 (two months) |
| Optimal mix | 33 | +179, -85 (11 days) |

***Table 5.*** *Storage capacity and maximal storage power for the 4 cases considered under the conditions of the "equal energy/optimal mix case"; positive: charging; negative: dispatching; see Fig. 22. The respective period for the power > 100 GW is given in brackets.*

Figure 22 shows the variation of the storage level over the year separately for onshore and offshore wind and PV. The "equal energy case" is considered because in this case the surplus energy (to be stored) equals the back-up energy (to be substituted). For the wind cases, the storage level has the tendency to increase in the first months of the year. The storage minimum is reached in August. For PV a larger storage has to be provided because it first empties in the first months till the minimum is reached mid-March. In the months following March the storage steadily fills with the filling maximum in September-October. The PV storage follows a sinusoidal curve like the solar radiation, however 90° out of phase.

The red curve in Fig. 22 depicts the "optimal mix case" presented in Chapt. 4. The required storage is strongly reduced with two filling minima in February-March and in August.

Table 5 summarises the key parameters of the storage system. PV requires by far the largest storage. Again, the benefit of the optimal mix is evident requiring the smallest capacity. The seasonal differences in input add up rather favourably in this case and reduce the size of storage. The maximal discharging power values (negative) are rather similar for the four cases and they are at the level of the back-up system to be replaced. The charging power levels (positive) are high and vary strongly, depending on the type of source. The maximal power is required, however, for shorter periods only. The figures in brackets in Table 5 denote the periods where the power is above 100 GW. The smallest seasonal storage with a capacity of 33 TWh – as required for the optimal mix case - surpasses the one presently available in Germany by a factor of 500. Such a storage cannot be realised irrespective of the technology employed. Seasonal storage in a closed German system does not seem possible.

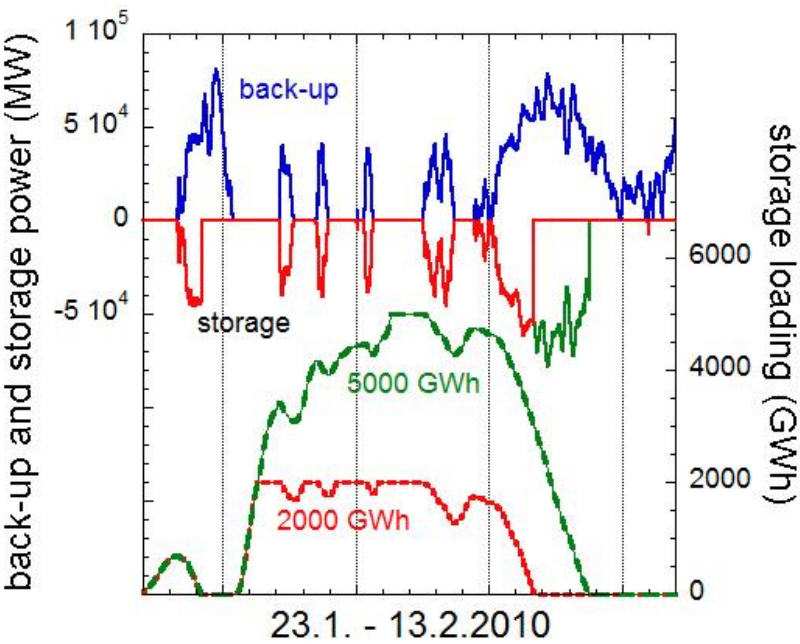


***Fig. 23.*** *For the period shown, the needed back-up power is plotted without storage for the standard "equal energy/optimal mix case". The negative values show the storage power for two cases, which differ in storage capacity, 2000 and 5000 GWh, respectively. The right ordinate shows the storage loading for the two capacities considered (lower traces).*

### 6.2. Short-term storage

In the following we investigate continuous operation of the storage – loading whenever surplus power is available up to a specified storage capacity and discharging whenever the RE delivery is insufficient till the storage is empty or a re-loading period starts. Figure 23 shows for the period – Jan. 23 till Feb. 13 – first the time traces of the back-up power in a system without storage and then the storage power (plotted negatively) for two storage capacities – 2 and 5 TWh. Considered again is the "equal energy case". Also, the storage loadings (lower curves) are shown. This diagram serves to elucidate the operation of the storage and its impact on the dynamics of the back-up power system. When the storage is sufficiently filled, the power from the storage matches (and substitutes) the back-up power. The larger the storage capacity, the shorter are the remaining periods needing back-up support. When the storage is empty its power becomes zero and this happens for the larger capacity storage at a later time. When the storage is full, surplus power is not fully used and available for other means.

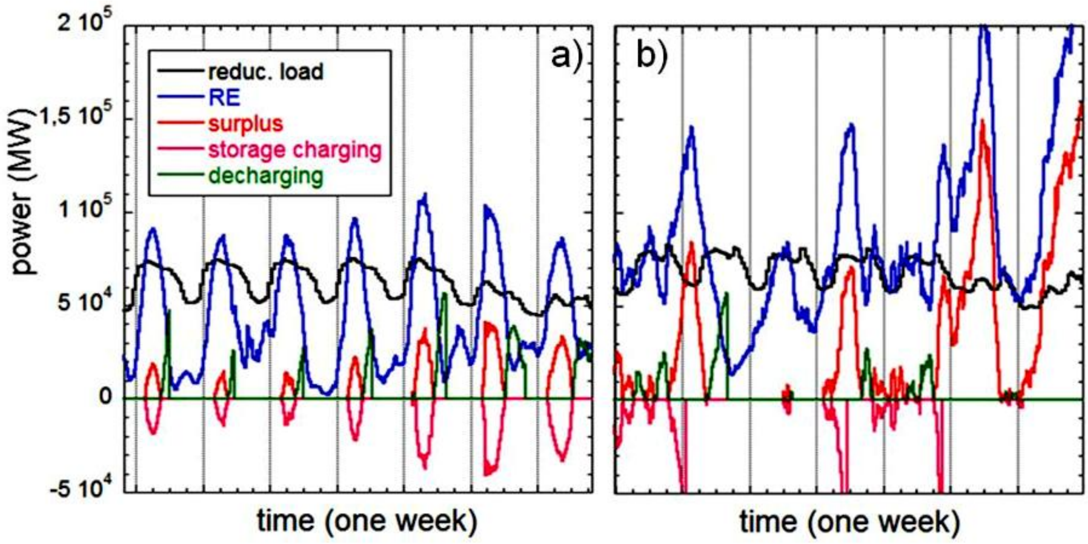


***Fig. 24.*** *For one week in summer (a) and one in winter (b) the reduced load is shown for the standard "equal energy/optimal mix case" along with the RE power, the surplus power, and the power from charging (neg) and discharging the storage.*

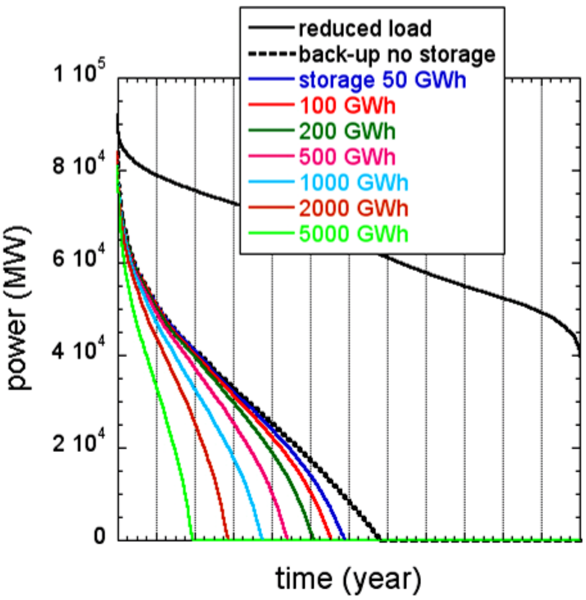


***Fig. 25.*** *Annual duration curves of the back-up system starting from the reduced load and the residual load without storage (dotted curve). The results are shown for the standard "equal energy/optimal mix case".*

Figure 24 exemplifies the operation with an assumed 200 GWh storage (about 4 times the presently installed storage capacity in Germany) in the limit that the energy produced by RE is equal to the demand ("equal energy case") and for the optimal mix. Shown is one week in summer (28.6. – 4.7.) and one in winter (21.2. – 27.2.). The weeks start with Monday. In summer, the RE electricity is produced by PV systems and is fairly periodic. The surplus power fills the storage, which then delivers the power mostly in the following night. In the winter week, the power is delivered primarily by wind. The surplus power is generally too large to be accommodated by the storage system. Storage stops in the middle of the period with available surplus power because of capacity limitation. Discharging of the storage is erratic and is interrupted for longer periods in phases of large RE power with sufficient surplus production at a full storage or in periods of an empty storage without surplus production. The necessary back-up energy reduces from annually 153 TWh to 128 TWh in this case whereas the back-up power does not change.

Figure 25 shows the duration curve for the reduced load to start with and subsequently the residual back-up powers for the standard "equal energy/optimal mix case". The dotted curve shows the residual power without storage. The difference is covered by the RE share. The following curves show the further reduction of the residual power with electricity storage of different capacities. The operational period of the back-up system successively shortens with increased storages capacity. This is, of course, the intended effect. But even with an unrealistic storage of 5000 GWh capacity, back-up power is still needed but operated in the sum for two months only.

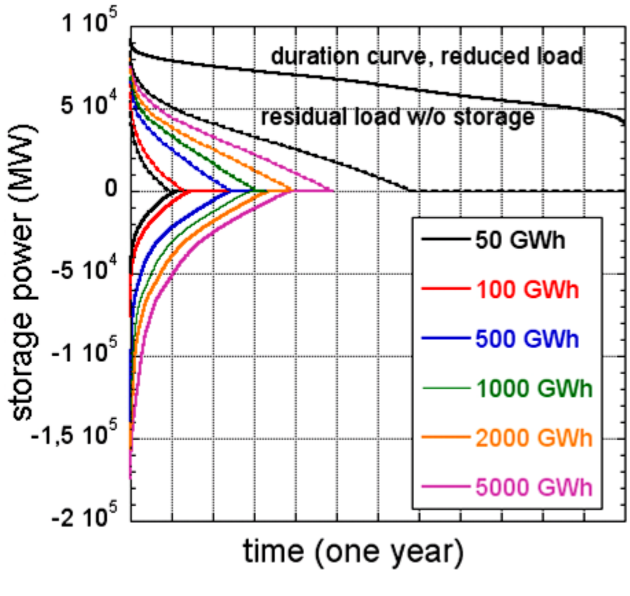


***Fig. 26.*** *Annual duration curves of the storage power starting with the reduced load for various storage capacities. Both the charging and discharging (negative) periods are plotted. The calculations are done for the standard "equal energy/optimal mix case". Shown is also the residual load (with the RE contribution subtracted from the reduced load) without storage.*

Figure 26 shows the duration curve, now of the storage system of different capacities starting from the reduced load and the residual load without storage in the limit of the "equal energy/optimal mix case". The positive branches show the discharging, the negative ones the charging periods. At low capacity, the charging periods are slightly longer than the discharging ones. This turns around for large storage capacities, which are able to accommodate large power peaks shortening the charging periods.

| Storage capacity (GWh) | flh storage (h) | Capacity factor storage | flh back-up system (h) | Capacity factor back-up system |
|---|---|---|---|---|
| 50 | 177 | 0.02 | 1711 | 0.195 |
| 100 | 241 | 0.027 | 1636 | 0.187 |
| 500 | 541 | 0.062 | 1343 | 0.153 |
| 1000 | 768 | 0.088 | 1140 | 0.130 |
| 2000 | 957 | 0.109 | 899 | 0.103 |
| 5000 | 1244 | 0.142 | 603 | 0.069 |

***Table 6*** *Shown are the full-load hours (flh) and the capacity factors for storage and back-up system for the cases plotted in Fig. 25 and 26.*

Table 6 describes the use of storage and that of the back-up system in terms of full-load hours or capacity factors, respectively. These values address the question of economic use of the infrastructure. Full-load hours and capacity factors increase with storage capacity whereas those of the back-up system decrease. For the full range of storage capacity assumed the economic operation of storage and back-up system can be questioned. The lowest storage capacity of 50 GWh corresponds to the one presently available in Germany. This storage operates presently under economic conditions. Here, however, we consider exclusively the conditions for surplus power storage.

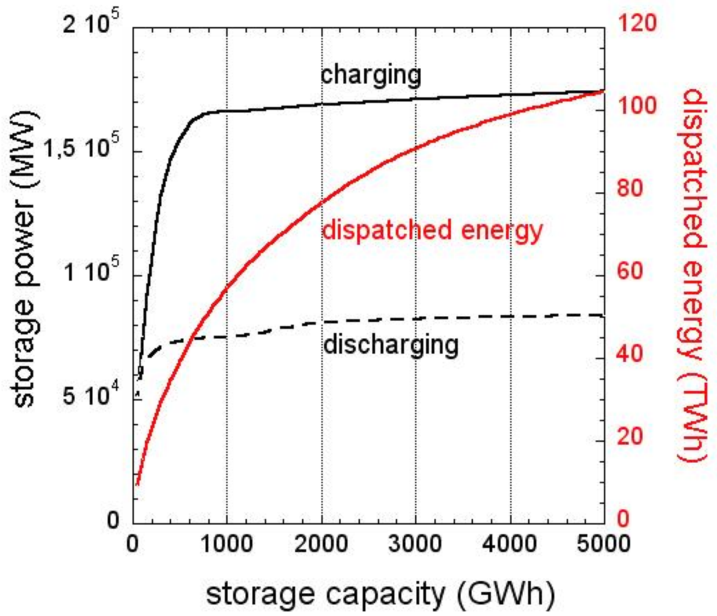


***Fig. 27.*** *The storage power for the charging and discharging phases and the dispatched annual energy is plotted against the storage capacity (for the standard "equal energy" and optimal mix case).*

Figure 27 plots the storage energy dispatched over the year (replacing back-up energy) and the charging and discharging powers. The energy which is handled by the storage is small in comparison to the annual demand (562 TWh) even at storages of unrealistically large capacity. The charging power is larger than the discharging power roughly by a factor of two. The latter is determined largely by the dynamics of the load, the former more by the stronger dynamics of the RE input. Remarkable is that already at a storage of 500 GWh, a high level of charging power appears. The situation giving rise to this strong non-linearity between storage capacity and charging power is elucidated in Fig. 28.

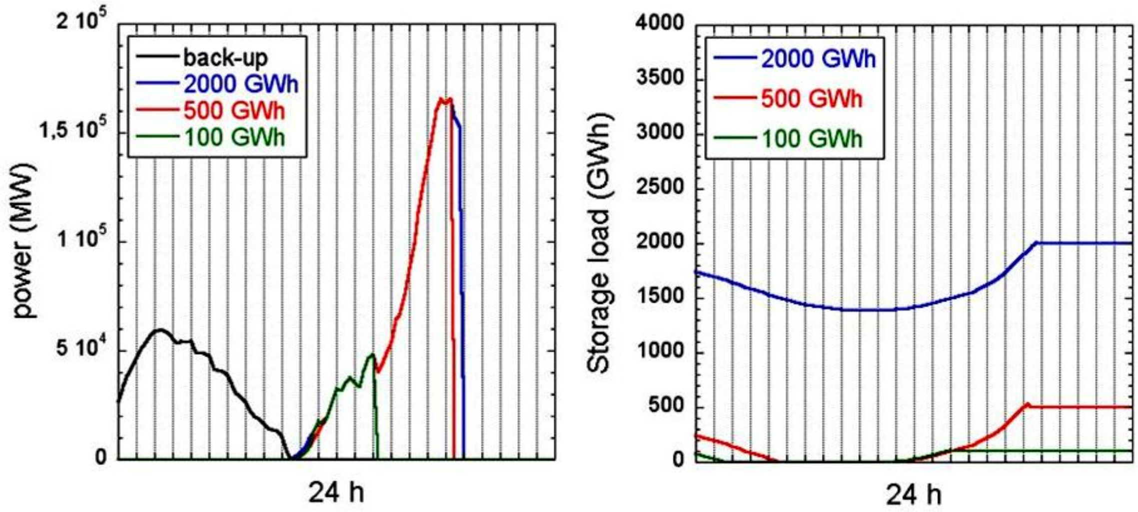


***Fig. 28.*** *a) For the standard "equal energy case" the temporal development of the back-up power is plotted along with the variation of storage power for three storage capacities; b) shows the storage loading for the three cases. The time window is one day for both plots.*

For three different storage capacities the back-up power and the charging power are plotted in Fig. 28 a) and the storage loading is shown in b). A case is shown for April where the back-up power happens to go to zero (between 9:00 and 10:00) because the demand is met by the RE offer. According to the pre-history, the storage for a capacity < 500 GWh happens to be empty at this moment. A 2000 GWh storage, however, would be filled to ¾ of its capacity. In the following period, the surplus fills the storage, the 100 GWh storage is quickly filled whereas the 500 GWh storage reaches its capacity limit nearly simultaneously with the 2000 GWh one. Therefore, the charging power is nearly the same in these two cases independent of the storage capacity.

As a consequence, already small storage capacities can give rise to large charging powers. If there are technical limitations in the transfer and distribution of the power, this example shows how rather critical conditions can be constructed by the superposition of processes with different time characteristics. With the assumption of a 200 GWh storage, which is about 4 times larger than the one presently realized in Germany and more than a factor of 10 above the projects presently under realization [12], already extraordinary power levels have to be handled.

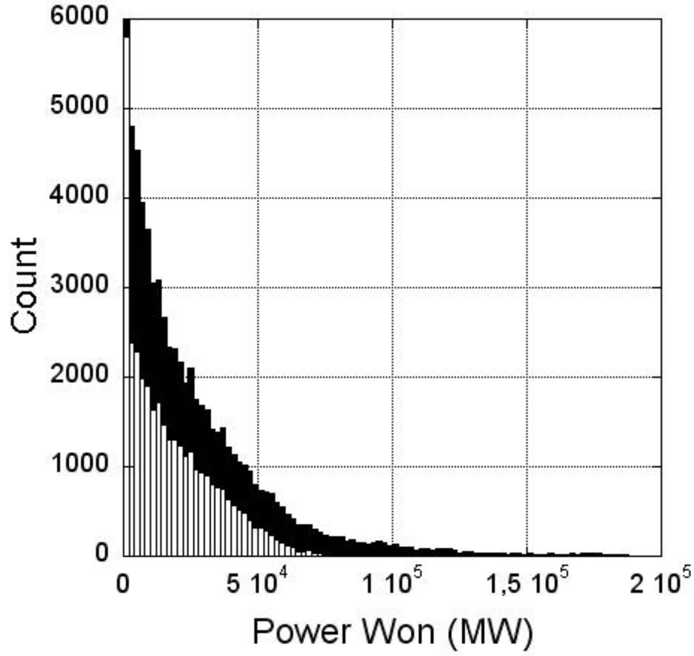


***Fig. 29.*** *Histograms of onshore wind power for the standard optimal mix, "equal energy case" compared to that of reduced onshore wind to avoid the production of surplus power.*

| Technlogy | Installed power (GW) | Annually produced energy (TWh) | Increase/decrease in power compared to 2011 | flh (h) |
|---|---|---|---|---|
| Reduced load | 91 | 562 | | 6116 |
| Onshore wind | 69 (82) | 106 | ×2.4 (2.8) | 1545 |
| Offshore wind | 16 | 53 | ×~80 | 3384 |
| PV | 55 (84) | 66 | ×2.2 (3.4) | 1217 |
| Back-up system | 86 | 340 | - 5.5 % | 3974 |
| Surplus power | 35 | 3 | | |
| Storage | 35 (charging) | 2,7 | | 77 |
| Storage | 47 (discharging) | | ×7.3 | |
| Maximal grid power | 101 | | | |

***Table 7.*** *Key-parameters describing the installed power and annual energy values for the case that 40% of the annual electricity demand are covered by RE under optimal mix conditions. The increase with respect to the situation in 2011 is also given. The values in brackets include the correction of the maximal power values in the data base to the actually installed powers (see Fig. 1).*

The simplest, however uneconomic way to avoid surplus power is to stop dispatching RE into the grid. This may be technically more easily possible with wind converters than with PV systems. We consider the "equal energy, optimal mix case". The sequence of interventions starts with reducing onshore wind power and continues – if necessary - via offshore wind to PV. If surplus power is available, first onshore wind is correspondingly reduced. If this is not sufficient, offshore wind is also reduced. The full-load hours of onshore wind drop from 1545 h to 828 h, those of offshore drop from 3385 h to 3117 h whereas there is no need to also reduce PV – which represents anyway the technically most complex form of intervention. Figure 29 plots the histogram of the original onshore wind power and compares it with the reduced one to avoid excessive surplus power. As a consequence the peak onshore wind power values > 100 GW are avoided; the system use is, however, practically halved with corresponding economic consequences.

### 7. Scenario characteristics of a probable upper limit: 40% energy from RE sources.

If a total coverage of the German electricity demand by RE were hardly possible, what could realistically be envisaged and what are the limiting elements? There are several reasons for limitations – technical problems like grid stability or conflicting technical solutions like in Denmark between prioritized RE feed-in and CHP production by thermal power stations [13]. Here we assume that the limitations are given by an excessive level of surplus power and the short-term power increments, which can still be handled by the size of the storage needed, by the need to operate a back-up system economically and by the option to limit grid expansion capacity because of costs and its inherent societal complexity. Within these limits, we assume that RE can deliver 40% of the annual energy demand and that Germany has available a storage capacity of 200 GWh. The key-data of such an electricity infrastructure are given in table 7.

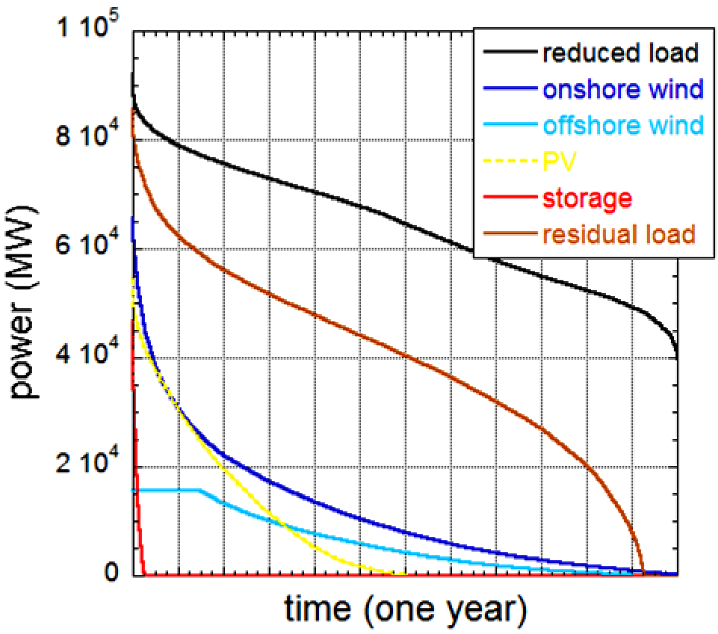


***Fig. 30.*** *Shown are the annual duration curves for the case that 40% of the electricity demand is provided by RE supported by a storage capacity of 200 GWh.*

In this setting, the RE is used well. Only 3 TWh are produced as surplus energy and from this, 2.7 TWh are dispatched via the storage. Only 300 GWh (representing an economic value of several Mill €) have to be exported or avoided by temporarily reducing production capacity. The storage uses, therefore, the surplus energy well but at a low energy turnaround. Of course, such a storage would not be used for exclusively storing the surplus energy but it would operate like today using the available power and charge and discharge according to the market situation. Still, the problem is evident: The excess power levels reaching up to 35 GW to be handled are too large for simple export; the surplus energy levels on the other hand seem to be too small for economic storage. Even at the assumed RE contribution of 40%, the rational to operate a storage will come from economic considerations and less from the intension to maximally use of surplus energy and thus reduce $CO_2$ emission. A higher RE fraction will increase the surplus power but will risk the economic operation of the back-up system without improving much the one of the storage system (see Fig. 25 and 26).

Figure 30 summarises the 40% RE share scenario in the form of duration curves. Reference is the reduced load. PV is not available for half of the year. Offshore wind is limited in power level because of the way the turbines are operated during strong-wind periods (see Chapt. 1). Storage plays a negligible role because only its interaction with the surplus power is considered. The supply backbone remains the back-up system. The concern with this scenario is therefore the unavoidable $CO_2$ production if the back-up system uses fossil fuels. $CO_2$ production will be the topic of the following chapter.

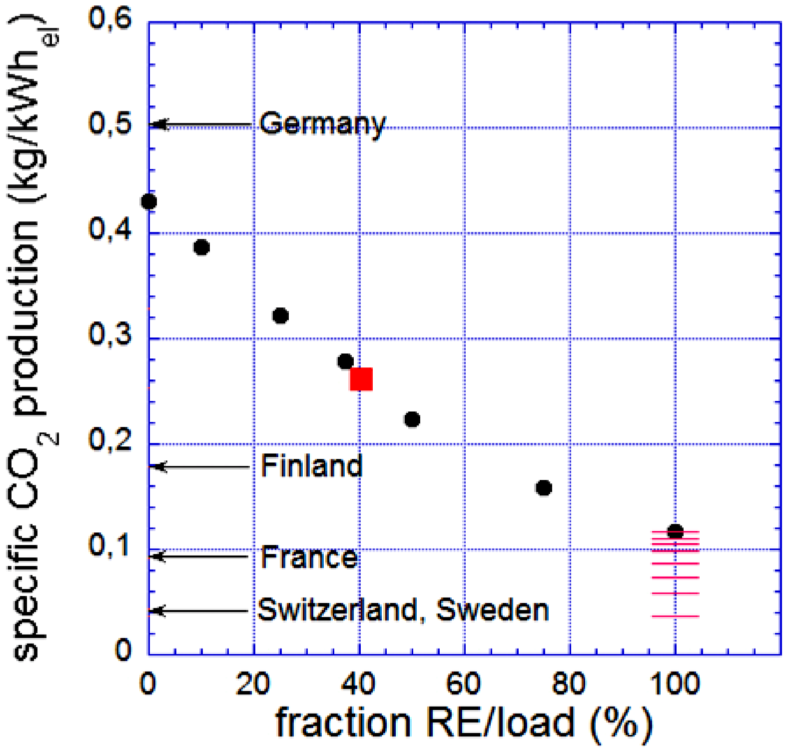


***Fig. 31.*** *The specific $CO_2$ production is plotted against the normalized RE fraction for the optimal mix case without storage. For the 100% equal energy case the effect of storage is also shown (short horizontal lines). The storage capacity is varied from 50, 100, 200, 500, 1000, 2000, and 5000 GWh. The RE/load = 40% case with 200 GWh storage is shown as red square. The arrows indicate the present levels of specific $CO_2$ production of Germany and various EU countries with strong nuclear contribution.*

## 8. $CO_2$ production

We calculate the $CO_2$ production for the optimal mix case on the basis of gas power stations only, ignoring any coal burning power plants in the future mix. We assume for the fuel 0.43 $kgCO_2/kWh_{el}$. The exact value here is rather irrelevant because the climate relevance of the use of gas is difficult to predict. Besides the $CO_2$ radiation forcing, it depends on the obviously unavoidable methane losses during transportation, which are typically 3-5%. Methane contributes to the radiative forcing with a factor > 20 compared to that of $CO_2$. Thus, the use of gas can be equally damaging globally as the one of coal.

Figure 31 shows the reduction of the specific $CO_2$ production with increasing RE fraction. Reference for each case is a constant electricity need per year. A substantial reduction in $CO_2$ production is already achieved with the replacement of fossil power plants by RE. For the "equal energy case" also the impact of storage is shown. The horizontal lines indicate the progressive further reduction of $CO_2$ release with storage capacity of 50, 100, 200, 500, 1000, 2000, and 5000 GWh. The further improvement is small specifically when compared with the large investments needed. Shown is also the RE=40% case with 200 GWh storage of Chapt. 7 (red square).

Arrows along the ordinate indicate the present specific $CO_2$ release for electricity production of various European countries. The present German specific $CO_2$ production is about 0.5 $kgCO_2/kWh_{el}$ resulting from the fossil fuel mix, an about 20% nuclear contribution and a similar contribution from RE. Countries which produce electricity by hydro and nuclear power show outstandingly low specific $CO_2$ production figures.

## 9. Analysis and comments

The production of electricity with variable sources is not the problem. If a society agrees to the corresponding use of land and finances the necessary investments the electricity to be produced can be increased proportional to the allocated area[3].

The following actual problems and issues in the large-scale use of RE have been identified:

**Power and the grid:** RE requires large power installations. The necessary investments can be reduced by a proper mix of wind and PV power. For the optimal mix the installed powers for on- and offshore wind and PV are 191, 44 and 99 GW, respectively. With these installations, the RE deliver the energy equivalent of the annual demand ("equal energy case") whereas wind contributes with 441 TWh and PV with 121 TWh. For wind power, 2/3 is assumed to come from onshore and 1/3 from offshore turbines. For the optimal mix case, the energy, which has to be delivered by the back-up system and the associated $CO_2$ output are minimized. 84 GW installed power contributes with 153 GWh.

It can be doubted that an optimization in the mix of the different technologies can be realized in practice having in mind the strong north-south variation of wind and PV installations and

[3] We have not considered restrictions in development zones for RE systems as they are presently defined in Germany. These zones are subject to political decisions and are expanding with time.

the differences in market participants between typical wind-energy and PV investors. There is also no convincing precedence for an optimized course of action, quite the opposite looking at the different speeds of deployment in Germany of RE electricity sources on the one hand and the necessary onshore and offshore grids on the other.

With the assumption of this paper (no electricity import, no use of bio-mass apart from waste), variable sources cannot meet the electricity demand alone. By increasing their share, the directly used power saturates well below the demand (see Figs. 12 b and 14) whereas the surplus power rises steeply (see Fig. 12 c). Reasons are the differences in the power distribution of load and RE with a rather flat and convex duration curve for the load and a strongly concave duration curve for RE. In order to produce more energy and cover the load – represented by the areas beneath the curves - excessively high power peaks have to be accepted (see Fig. 4).

Already at lower RE shares, close to and above 40% of the energy demand, the surplus power reaches a level, which can be handled neither by reasonable technology nor by cross-border trade. It also cannot be simply wasted because of its high economic value. The systems – preferably wind turbines - have to be throttled in this case accepting economic losses (see Fig. 29). Germany, though leading in the installation of RE systems, is still below any of these critical limits (see Fig. 12 a).

PV is the most ineffective RE supply form. It requires the largest installed power per delivered energy unit and it causes extreme surplus power peaks. This negative aspect adds to those which are well know and documented: PV has the highest material use, the highest primary energy use and the highest costs per unit of electricity produced [14]. On the other hand, in combination with wind the amount of surplus electricity can be minimized somewhat in comparison to wind alone, however, at the expense of slightly increased total power.

The grid has to accommodate the load and the surplus power if its production is not prevented. Under optimal mix conditions the grid power can increase beyond 250 GW (see Fig. 14). At a RE energy production of 40% of the annual demand the excess power levels reach the power capacity of the electricity grid of Poland and the Czech Republic (see table 7). As these neighbour-countries are pursuing a supply policy based on controllable power, erratic interference with their grid system will be neither welcome nor technically manageable.

**Back-up system:** Without proper storage, the RE use cannot prevent the need for a back-up system of conventional power plants – preferably on gas basis to minimize the specific $CO_2$ release. The nominal power of the back-up system has to remain high and is hardly reduced by the addition of RE power. Its energy supply, however, which is the economic factor, decreases with increasing RE share (see Fig. 17). At about 40% of RE energy the energy capacity factor is 0.5 - approaching the limit of economic acceptability (see also Fig. 33).

The back-up system has to be operated under strongly varying conditions. The number of thermal cycles increases because the system dynamics is no longer determined by that of the demand rather by that of the supply (see Fig. 20). Additionally, the increments in power (positive and negative) increase involving an increasing number of back-up power plants in the system dynamics (see Figs. 18 and 19). This unfavourable stop-and-go-and-idle mode of operation adds to the economic problem of thermal power stations - their operational costs will increase but their capacity factors decrease (see Fig. 17).

For extended periods, the back-up system operates in a rather coherent mode and the involved units share the consequences of thermal cycling. Such systems cannot be "must-run" plants like CHP stations.

**Storage:** Large storage capacity both in energy and power handling capability is necessary replacing the back-up system of thermal power stations and thus optimize the $CO_2$ balance. Pumped hydropower storage is an established and economic technique in periods of peak loads. In Germany, about 50 GWh are installed and about 20 GWh are under construction [11]. In case of the optimal mix with the storage capacity being defined by the surplus energy matching that of the back-up system – the required storage capacity is 1.8 TWh for the back-up energy contribution being reduced by a factor of two. A notable effect on reducing the size of the back-up supply requires, therefore, a storage, which is far beyond any chances of realization.  Even a storage of 200 GWh, which we assumed for the 40% RE-share case, requires a fourfold increase of the present installation - hardly feasible by pumped storage inside Germany.

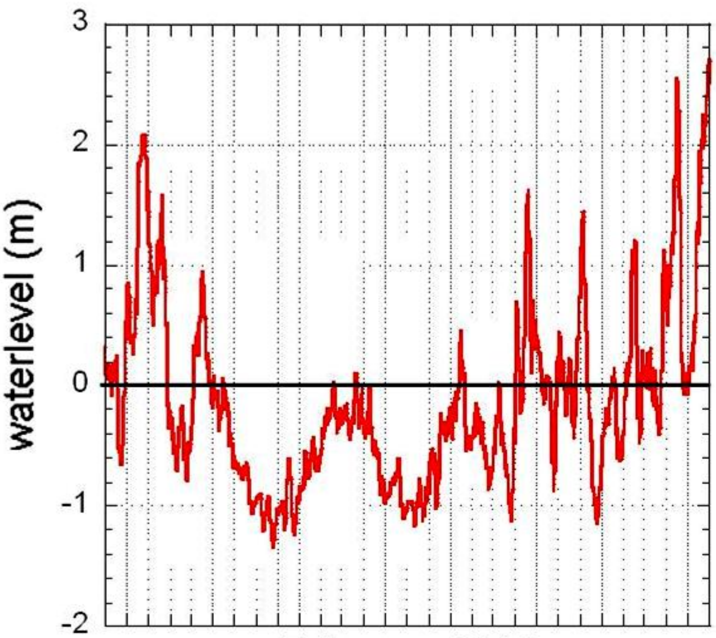


***Fig. 32.*** *Shown is the variation of the Lake Constance level in February if it could be used as a storage in the "equal energy/optimal mix case". The example serves to demonstrate the mere size of storage in case of a substantial RE share.*

In order to better visualise the criticality of the storage problem, we exemplify the operational conditions using Lake Constance as fictitious storage. Its area is 536 $km^2$. We orient ourselves on the local circumstances of the Schaffhausen hydropower station and assume 10 m for the water fall. Figure 32 shows the variation of the Lake Constance water level for the month of February for the “optimal mix” and the “equal energy” case. The average water level variation per 15 min is ±30 cm; maximal variations of +3 and -1.5 m happen during the year. These are values representative for the tidal heights at the North Sea coast – happening, however, once a day. This example also allows highlighting the criticality of power handling by the storage system. The average storage power corresponds to a water flow of 180000 $m^3$/s. The average inflow into Lake Constance is about 380 $m^3$/s - a factor of 500 smaller. Correspondingly, the power rating of the Schaffhausen hydropower station is smaller by a comparable number (factor 900).

Storage at these scales needs therefore a new technical solution, which might be found in the production of synthetic hydrocarbons. This technology – based on electrolysis for $H_2$ production using surplus electricity and available $CO_2$ – works well at small scales. Critical is the $H_2$ electrolysis in large scales. At present, most of the $H_2$ technically required is produced by thermal steam reforming of methane. The development of stable, economic, and environmentally acceptable electrolysis technology for large scales and intermittent operation is still missing. But also with this technology the effort is gigantic. In order to produce the necessary synthetic hydrocarbons a proper infrastructure is necessary, comparable to the present German oil refining one.

The alternative – a “hydrogen economy” is known to be highly uneconomic because the circle from electricity to hydrogen and back to electricity causes losses of a factor 4-5. This would give rise to a tremendous price discrepancy between primary and secondary electricity with a strong impact on the economy.

The geological conditions of Norway are often presented as the basis for Germany’s future electricity storage. One has to be aware that at present pumped storage in Norway is just sufficient to handle the wind in- and export electricity from and to Denmark. The addition of large-scale water storage may be questioned out of environmental reasons though the economic potential might be quite attractive. On the other hand, one may not expect that a country with 5 Mill inhabitants will provided the technical resources to contribute to the demand of 80 Mill people.

**$CO_2$ reduction:** A strong reduction of $CO_2$ release and an improvement of specific $CO_2$ production can be achieved by the application of RE. Figure 31 shows that the German electricity production is presently characterized by a high specific $CO_2$ production coefficient. The technical effort is, however, tremendous if the release level of those countries should be met, whose electricity supply mix consists of nuclear and hydro energy (Switzerland, Sweden and France). This environmental quality can hardly be realized by the considered RE techniques under reasonable practical and economic conditions.

There are additionally critical political and economic problems to be considered and commented:

**European development strategy:** Many of the problems related to the effort to totally change a basis technology in a rather short period of time could be ameliorated by a European wide approach. This is documented well in the scientific literature [15, 16]. Within an EU-wide grid the load variation and the degree of intermittency is reduced. In the period where the German supply situation may become critical because the RE share increases above 40% Germany may be rather isolated with its enforced expansion in the use of RE. A similar change may not be initiated in its neighbourhood, characterized by a supply structure dominated by controllable power. This applies to Poland, Czech Republic, Switzerland, France, Belgium, Sweden and Norway. In some countries, new nuclear power stations are planned like in Poland, Czech Republic, Lithuania and Kaliningrad/Russia. Their grids will not accommodate large amounts of variable electricity.

The different technologies to produce electricity used in Europe and the largely different per-capita $CO_2$-production as a corollary may further prohibit an EU-wide strategy for jointly implementing RE on short notice. Some European countries like Switzerland, Sweden, Norway and soon Finland meet already now the 2050 $CO_2$-goals of Europe and will hardly see any reason to change their supply technology with the consequence of a temporary increase in $CO_2$-production by commissioning fast thermal power stations to smooth out the variable RE supply.

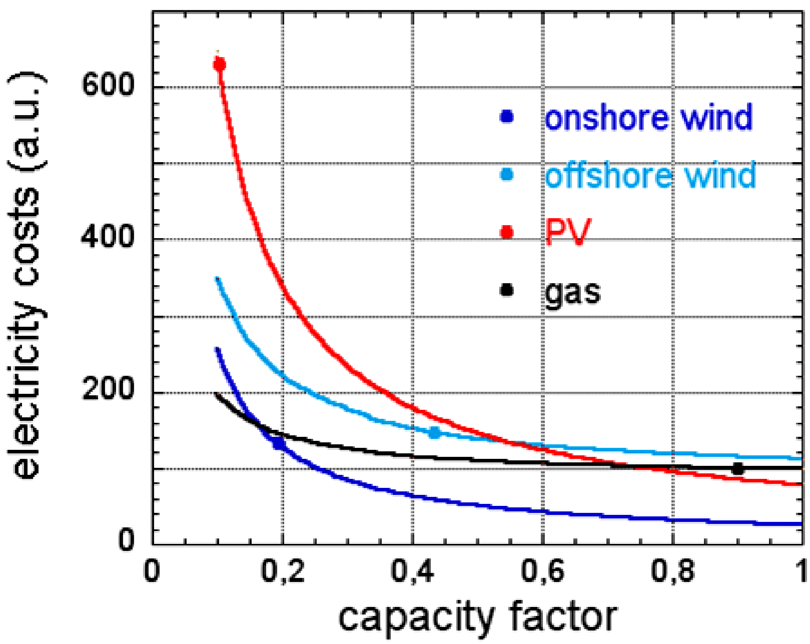


***Fig. 33.*** *Plotted is the electricity price in arbitrary units (the costs for gas are stet to 100% at its cf-factor) versus the capacity factor for the technologies considered in this report.*

**Economy:** A RE dominated supply system for Germany requires an installed RE power of about 240 GW, conventional power of about 84 GW, and a storage system with a capacity of a few 100 GWh. The present storage is, however, mostly used to cope with peak-load demands rather storing surplus electricity. The full-load hours of onshore and offshore wind are well defined with about 1700 hours or 3800 h, respectively. Those of PV in Germany are about 900 h. The use of variable sources with short full-load hours forces the other components of the supply system operated during the gaps also to low capacity factors. Specifically, the increase in power installation causes a corresponding decrease of the full-load hours of the back-up system. The storage, when seen exclusively as a means to store surplus power, is subject to the same shortcomings causing low capacity factors. The complete system comprises of components, which are not operated adequately in an economic sense. Figure 33 shows the relation of electricity cost C and capacity factor cf for different systems. The basic relation is $C = \alpha/cf + OC$. The lower cf, the higher are the electricity costs. OC are the operational and management costs. $\alpha$ contains the investment costs, the system power, the interest rate and the economic plant life time [17]. The electricity costs shown in Fig. 33 are in arbitrary units because the error bars are large and we are only interested in the inner relation between the systems considered here. The solid dot on each curve denotes the typical cf of the systems considered. The electricity price of gas is set to 100% at its rated cf-value. The other supply forms are scaled according to their individual $\alpha$ and OC values. Onshore wind electricity is about 30% more expensive than gas; offshore wind about 50%. PV suffers strongly from its low capacity factor.

The costs vs. cf curve is rather flat for gas. The reason is that in this case a lower cf compensates the economic losses because without operation at least fuel costs are saved. This is different in the other cases, which show a more sensitive dependence on cf. Offshore wind is also characterized by high O&M costs, which, however, have large error bars (not shown) because specifically the maintenance logistics is not yet fully optimised. A future large-scale storage would also be subject to a high sensitivity on the capacity factor. Therefore, it is difficult to see the economic viability of a large-scale storage system for surplus energy irrespective of the selected technology. All $CO_2$-free technologies with no fuel costs (wind, PV, solar thermal) or with low fuel costs (fission, fusion) show a sensitive dependence on cf.

The use of low capacity factor supply systems ultimately touches the question of their economic use and realisation in the frame of a free economy resting on basic market rules. Already now utilities in Germany seem to be hesitant to build new thermal power stations because of economic uncertainties caused predominantly by short full load hours. Possibly first the economic models for the future operation of storage systems have to be clarified before initiating large scale projects in this field.

**Limit of RE use:** For a possibly manageable case, 40% of RE energy share has been concluded from the studies presented here. The total nominal power arsenal corresponds to 140 GW RE and 86 GW back-up power. Within this limitation, the surplus power and the dispatched grid powers remains small (see Fig. 14). The full-load hours of the back-up system is close to 4000 h – maybe a border case for economic operation. The specific $CO_2$ production drops from presently 0.5 $kgCO_2/kWh$ to about 0.25 $kgCO_2/kWh$.

**Discussion of the assumptions:** Here we would like to discuss the assumptions we made for the analyses presented:

(1) <u>Constancy of demand</u>: We have assumed that the annual demand will not drop rather stay constant. The motivation is given in the main text e.g. the expectation of the additional demand by a larger fraction of electric cars. Just to back this assertion, we analyse the additional electricity demand for electro-vehicles by considering an upper limit. In 2010, the passenger cars covered about $6\ 10^{11}$ km in Germany. This corresponds to an individual

mileage of 7500 km per year. With the assumption for electro-cars of 200 Wh/km, the additional electricity need adds up to 120 TWh, which increases the present demand by more than 20%. This increase can hardly be compensated not to speak about overcompensated by saving measures elsewhere.

We have also assumed that the load curves as given in Figs. 1 and 2 remain invariant. As a consequence, we have discarded major effects from "demand-side adaptive management" in the interpretation of demand response. The reason is the unfavourable daily structure of load, back-up and surplus power as presented in the following. The demand response concept foresees to move part of the demand into the low-load periods driven by the economic stimulus of lower electricity costs. The phasing for this concept does not match, however. The summed-up surplus during the night is 56 TWh under the optimal mix conditions for the "equal energy case". This compares to 97 TWh produced during the day. The back-up figures are 89 TWh during the night and 62 TWh during the day. Surplus coincides with the peak-load period. The reason is the high PV production during the day as already pointed out in [18].

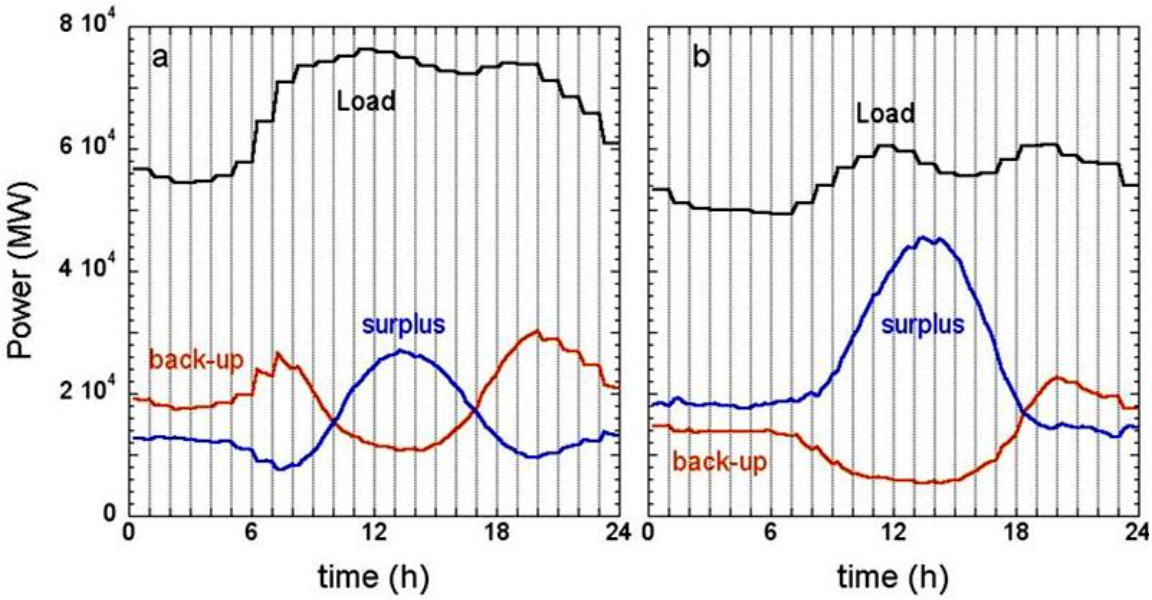


***Fig. 34.*** *Plotted are the daily variation of reduced load, surplus and back-up power averaged over the year. a) represents the average over the week days Monday to Friday and b) those of the weekends, Saturday and Sunday.*

The up-scaled 2010 data for the optimal mix and "equal energy case" yield the expected typical daily variation of load, back-up and surplus power. We average over the weeks of 2010 but discriminate between Monday-Friday and Saturday/Sunday because of different load structures (see e.g. Fig. 2). The averaging is appropriate for the consideration of this chapter – behaviourism and industrial process changes in the frame of demand-side management - because also demand-side management has to orient itself on the daily and weekly cycles. The organisation of erratic shifts of industrial processes following the electricity cost pattern clocked by the RE offer does not seem practical even for mostly automatic processes.

Figure 34 plots the variation of load, back-up and surplus power for the two weekly periods considered. Plotted is the remaining back-up, which cannot be traded-off against the surplus power because the timing does not fit. During the week, the surplus power is rather periodic by PV production during the day in periods where, however, the load is also largest. Surplus energy is not produced preferentially in low-load periods. The wrong phasing leads to a contradicting situation; a fundamental financial stimulation for demand response is not provided.

Back-up power is mostly needed in the mornings and the evenings because the activity profile represented by the load is wider than the one of the average solar radiation. Again, a better use of the surplus power and reduction of back-up power requires an intensification of the activities mostly during the day. If nevertheless, the nightly surplus energy is used to reduce the back-up power during the day, about 7 TWh can be properly dispatched over the year. The back-up demand is reduced by 4.5% - hardly justifying the investment for such a scheme.

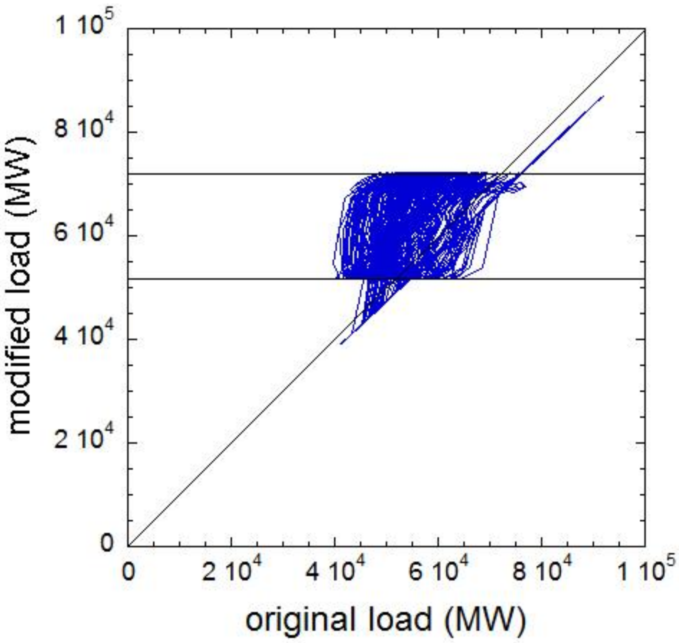


***Fig. 35.*** *The modified load with the weekend load pattern replaced by the average load pattern during the week (Monday through Friday) is plotted against the original load.*

Facing the structures shown in Fig. 34 a) and b), dominated by the coincidence of maximal load and maximal surplus energy, it is difficult to see how larger shares of the energy demand could be shifted in time. During the weekend, a large part of the surplus is collected because the load is low. The back-up power fully responds to the relatively increased surplus offer and is reduced in this period. More electricity consuming processes could, therefore, be moved to the weekends smoothing out the weekly load pattern. This seems to be the largest effect in the effort to adjust the demand to the varying supply in the frame of demand-side management. When we replace the low-demand weekends by the average demand during the week (leaving the overall annual energy demand at 562 TWh) a better use of the surplus power is possible. Figure 35 plots the modified load against the original one. The overall power level during the week is reduced (lower slope) owing to the increased demand during the weekend. The minimal and maximal loads during the weekends are fixed (see horizontal lines in Fig. 34) in the case of the modified load (the constant average Monday to Friday load values replace the original and lower values of Saturday and Sunday) whereas the original Saturday/Sunday loads vary slightly. The use of the weekends allows reducing the peak residual power from 84 GW to 80 GW and extends the full-load hours of the back-up system from 1825 h to 1902 h. The integral energy savings from improved use of back-up or surplus powers, respectively, are small – in the range of 1.5%. The savings in $CO_2$ emission are in the same range. Facing the supply and demand structure as shown in Fig. 34, the use of the weekends seem to provide the largest margins in demand-side management. Nevertheless, its effect is small justifying the original assumptions taken in this paper.

(2) Discarding of bio-gas for electricity production: In this paper we assumed that bio-gas is not used for electricity production rather that bio-energy will be used for transportation, most probably for aviation where alternatives to liquid high-density fuels may not be available. In 2010, 14.5 TWh are produced from Biogas in Germany [19]. This value compares to 153 TWh back-up energy for the „equal energy/optimal mix case". Less than 10% could be substituted in a $CO_2$-free form using bio-energy. This would ease but not solve the problem.

The recent study by the Leopoldina National Academy of Sciences on the use of bio-energy [20] confirms the findings of global studies on the limits of bio-mass use [21] viz only a few percent to the primary energy can be contributed by bio-mass. Reserving the maximal bio-mass available in Germany of 140 TWh for electricity production [17] would replace less than 50% of the back-up energy (with an assumed efficiency of 50%). Though a large contribution comes about by considering an unrealistic limit, the problem would still not be solved. Using bio-mass for aviation where hardly convincing sustainable fuel alternatives exist at present would require for Germany replacing about 85 TWh fossil fuel. Also this is a border-line case.

(3) The technology change as isolated process in Germany without the benefit of a more integral European approach: We have already mentioned the difficulties of Germany to match the expansion of the high-voltage grid to that of RE sources. One reason for the delays is socio-economic and lies in the local resistance of concerned communities. It can hardly be expected that additional grids and connectors are put in place in EU countries just for transmitting electricity from remote sources (Spain, southern Italy, North Africa) to Germany. The melioration of the operational disadvantages of RE by a larger integrating area will happen when Europe in total changes its supply technology. For this purpose, new grids have to be build mostly motivated and executed by national interests. The time scales between the German transition to a RE electricity supply and the possible one of Europe do not match. Therefore, in this paper, we assumed that the energy turnaround of Germany cannot rely on the meliorating benefits of a more integrated approach.

We have also ignored large-scale electricity import, which, on the other hand, is a vital element of the Germany planning for 2050. Thermal power stations reach their operational limits not only in Germany but also in Europe and there will be a deficiency of several 100 GW power in the next decade. The possible import of nuclear power from the newly erected power stations in the East of Germany has not been considered in this paper but may be a realistic option for the future.

**Literature search:** There is vast material available on the topic of this report, which I will not cover the more so because of the bias of many of them. I will point out, however, the PhD-theses “Strommarktdesign angesichts des Ausbaus fluktuierender Stromerzeugung” of Niels Ehlers [22] and “Hohe Anteile von Solar- und Windstrom unter Berücksichtigung hoher zeitlicher Auflösung von Angebot und Nachfrage“ by Th. Große Böckmann [23]. Both books have an objective and approach similar to the present report. Ehlers stresses more the economic aspects, Große Böckmann the system related and technological issues. Both works go beyond what has been presented here.

Ehlers is concerned about the economic operation of storage and also concludes that seasonal storage is not possible even with optimistic assumptions. Große Böckmann observed also an optimum in the mix of wind and PV power and devotes detailed investigations to the handling of surplus power. The paper also addresses the economy of storage and its criticality in handling large power levels.

A detailed study on the German electricity development was recently published by DENA, the German Energy Agency, guided by the political framework for electricty supply with goals fixed for 2020 and 2050. The report is entitled “Integration der erneuerbaren Energien in den deutsch-europäischen Strommarkt“ [24]. The report is concerned with the large power capacity needed and addresses ways to handle the surplus, deals with the aspects of import, storage and demand-side management.

The deficiencies of a supply system based largely on fluctuating sources with large shares are evident – a complete demand coverage is not possible, a back-up system is needed, which will mostly be fossil fuel based and not allow a complete $CO_2$-free system. From this point of view, RE alone are not able to provide a sustainable supply system. The economy of a large-scale RE electricity supply system and its viability for a highly industrialised society has to be demonstrated. Like in the past, the most probable outcome of such a demonstration will be a powerful and reliable electricity system based on different and complementary concepts in which RE playing an important role.

It is difficult to see that other countries will follow Germany in the rather exclusive strategy it took to change the sources for a commodity of this high economic relevance. For others, the implementation of RE in large scales may be too expensive, not on top of the political agenda or the natural conditions are simply inadequate.

As a consequence, the development of alternative electricity supply forms is still of highest relevance and may become even more urgent after a realistic view into the capabilities and the limits of RE. Because of the limitations and shortcomings in their use, the most obvious question will be whether and how an electricity system based on variable sources can be improved and supplemented. This will be a question classically posed to research and engineering because these disciplines have found the ways in the past to liberate mankind from the imponderabilities and perils of nature.

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As we concentrate on wind and photo voltaic energies, the reader may turn to “Introduction to Wind Energy Systems” by H-J Wagner and J. Mathur and to “Physics of Solar Cells” by P. Würfel introducing into the physics background of these technologies.
A general overview over the German electricity supply is provided by the study of the “Arbeitskreis Energie” of the German Physical Society: “Electricity: The key to a sustainable and climatecompatible energy system”: www.dpg-physik.de/veroeffentlichung/broschueren/studien/energy_2011.pdf.

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