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Electricity by intermittent sources: An analysis based on the German situation 2012

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Abstract. The 2012 data of the German load, the on- and offshore and the photo-voltaic energy production are used and scaled to the limit of supplying the annual demand (100% case). The reference mix of the renewable energy (RE) forms is selected such that the remaining back-up energy is minimised. For the 100% case, the RE power installation has to be about 3 times the present peak load. The back-up system can be reduced by 12% in this case. The surplus energy corresponds to 26% of the demand. The back-up system and more so the grid must be able to cope with large power excursions. All components of the electricity supply system operate at low capacity factors. Large-scale storage can hardly be motivated by the effort to further reduce CO_2 emission. Demand-side management will intensify the present periods of high economic activities. Its rigorous implementation will expand the economic activities into the weekends. On the basis of a simple criterion, the increase of periods with negative electricity prices in Germany is assessed. It will be difficult with RE to meet the low CO_2 emission factors which characterise those European Countries which produce electricity mostly by nuclear and hydro power.

1 Introduction

In this paper we describe the major characteristics of an electricity supply system being predominantly composed of the scalable renewable energy (RE) forms wind and photovoltaic power. The analysis is based on the actual data of 2012 from the German electricity system. The 2012 data will be scaled to larger shares of REs in the electricity production up to the 100% case where REs generate as much electricity as needed in a year. Similar studies, which emphasise different aspects and which are based on older data are given in refs. [1,2]. Germany will soon demonstrate the pros and cons of a rapid technology change from electricity production following the demand to one which is governed by intermittent supply.

2 Construction of the data set

We determine the characteristics of an electricity supply system with increasing contributions from the RE forms wind (on- and offshore, W_{on} and W_{off}) and photovoltaic (PV) power. A data base for the load, W_{on}, W_{off} and PV power averaged over 15 min has been established for 35136 time points using the data provided by the German electricity suppliers for 2012, refs. [3–8].

The net electricity production of Germany in 2012 was 582.6 TWh [9] originating from the different sources as shown in table 1 for the gross production. 46.1 TWh were produced by 29.9 GW onshore wind power; PV contributed with 28.1 TWh from 32.4 GW installed at the end of the year.

The data base power values have been corrected for the continuous addition of installed capacity over the year. A constant PV power of 32.4 GW would have yielded 31.3 TWh in 2012. This corresponds to 966 h at full load (full load hours, flh = annual electrical energy produced/installed power) or, equivalently, to a capacity factor cf (cf = flh/8784) of 0.11. With 29.9 GW installed onshore wind power, 46.3 TWh would have been gained. In this case, flh = 1547 h and

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Table 1. Gross electricity production in Germany in 2012 (under conditions of increasing RE installations during the year) [9].

Source	TWh	%
Coal	118.0	19.1
Lignite	159.0	25.7
Nuclear	99.5	16.1
Gas	70.0	11.3
Oil	9.0	1.5
others	26.0	4.2
Sum thermal plants	**481.5**	
Wind onshore	46.1	7.5
Wind offshore	0.51	0.1
Photovoltaic	28.1	4.5
Bio-mass	41.0	6.6
Hydro electricity	21.1	3.4
Sum RE	**136.3**	

cf = 0.18. The flh and cf values for each technology represent average values over the regions of source installations. The thus corrected data base is used for scaling studies.

The offshore wind power development in Germany is still in its infancy. Data published by Tennet [10] are used from the Alpha Ventus [11,12] and the Bard offshore 1 [13] wind parks. The maximal observed power in the data base is 164 MW (approximately 60 MW Alpha Ventus, approximately 100 MW Bard offshore 1). The total offshore wind energy in 2012 was 0.68 TWh; flh = 4134 h; cf = 0.47. These data can be corroborated with the wind velocity measurements of FINO-3 [14] located also in the German Bay. The correlation coefficient between wind velocity and published offshore power data is 0.79. The annual energy calculated from the wind velocity data on the basis of the installed offshore power and the converter characteristics is nearly the same (FINO-3 data yield a 7.3% higher energy yield).

Figures 1 a) to d) depict the data base constructed from actual data of 2012 with constant installed power as described above. Plotted as time traces through the year 2012 are a) the load (demand), b) the PV power, c) the onshore wind power, and d) the offshore one (in this case, the data are multiplied by a factor of 200 to fit to the ordinate). The load varies typically between a lower limit of about 35 GW to an upper one of about 85 GW caused by the seasonal, weekly and daily demand variation. The spectral composition of wind and PV power is different, wind represented by a chaotic, PV by a periodic behaviour. W_{off} is characterised by rather constant power amplitude close to or at the rated power —a feature of offshore turbines operating frequently in the extended constant power range between rated and cut-out wind velocity [15]. The horizontal lines in figs. 1 b) to d) represent the installed power levels, which are never reached during the year for W_{on} and PV because not all systems are simultaneously in operation at maximal performance. The ratio of the maximal power to the installed power had been dubbed utilisation factor uf. uf = 0.83 or 0.82 for onshore wind and PV, respectively. For offshore wind, uf = 1 has been adopted (a more detailed consideration is not possible at the present implementation stage).

Figure 2 shows the duration curves of load, wind and PV for 2012. Curve 1 corresponds to the load of 2012; curves 2 to 4 are the duration curves of wind and PV, respectively. The W_{off} power has been multiplied by a factor of 200 to provide a trace which can be compared with the others. Wind contributes over the whole year, PV, of course, for half a year only. Onshore wind power is offered with more than 50% of the installed power for less than a month only. This is different in case of W_{off}, where the power is larger than 50% of the installed power for nearly half a year.

3 The reference case

Whereas the net electricity production in 2012 was 582.6 TWh the reference target for the scaling studies of this paper is the "reduced load" summing up to a target demand of 500 TWh with the contributions from hydro power and waste subtracted. Their contributions are assumed constant and ensured. We will also not consider a bio-mass contribution assuming that the energy from bio-mass will be used in the future more for transportation, preferably for aviation and less for electricity production (the direct way via PV would be more efficient anyway). We further assume that the electricity consumption will not change in the future expecting a shift toward electric vehicles, the expansion of smart supply systems and a wider use of heat pumps. Nuclear energy and net electricity import/export are not considered. Also technically caused losses are ignored.

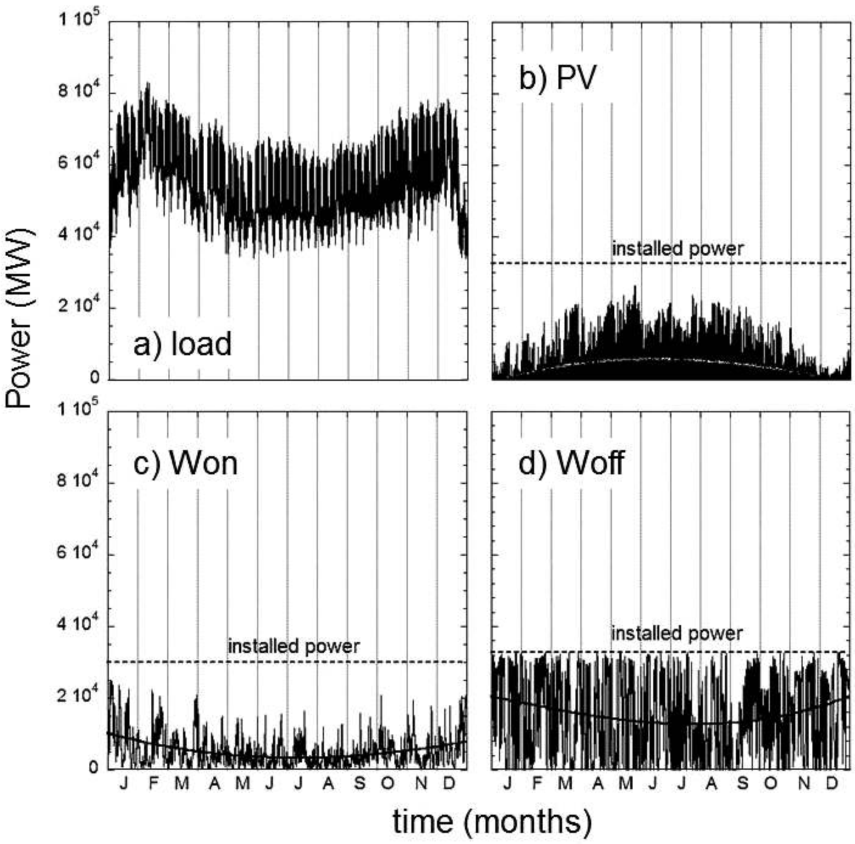

Fig. 1. a) Variation of the German load during 2012; b) photo voltaic power (PV), c) onshore wind power W_{on}, and d) offshore wind power W_{off} in 2012. The increase in installed power through the year has been corrected; the RE data correspond to the installed power (horizontal lines) at the end of the year. W_{off} is multiplied by a factor of 200.

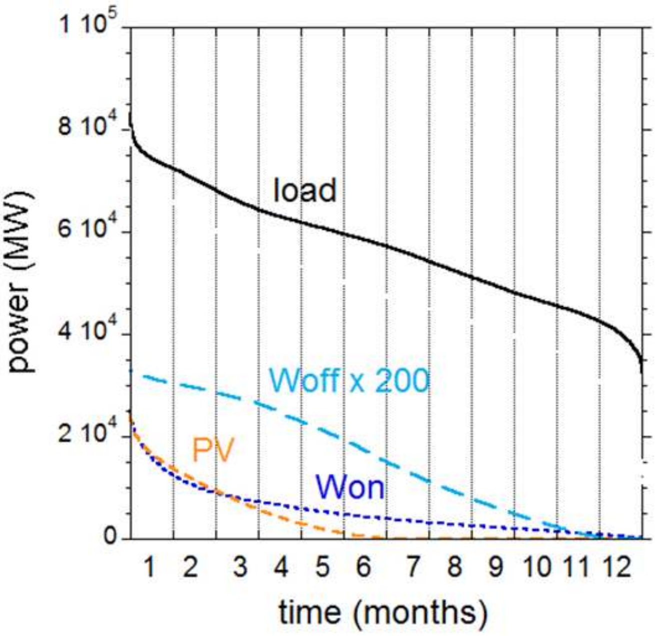

Fig. 2. Duration curves for 2012 of the load, onshore wind W_{on}, offshore wind W_{off} and PV power. W_{off} is multiplied by a factor of 200.

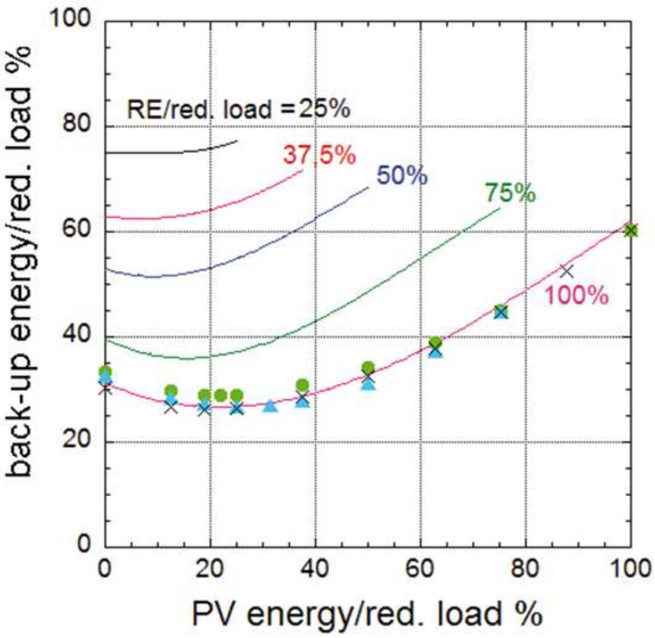

Fig. 3. The ratio of the back-up energy to the annual reduced electricity demand is plotted against the energy contribution of the PV system, also normalized to the reduced load. The parameter of the curves is the ratio of the RE energy also normalized against the reduced load. The lines are based on 2010 data, the crosses for the 100% case on 2012 data. The offshore wind energy is assumed to be 1/3 of the total wind contribution. In case of the dots, exclusively onshore wind, in case of the triangles, exclusively offshore wind is mixed with PV (100% cases).

For each time point i in the data base the load, the on- and offshore wind power and the PV power are given. 2012 was a leap year: $1 \leq i \leq 35136$. The directly used RE power is limited by the load. As the supply does not add up to the load for each moment i, back-up power has to be provided and surplus energy accrues. A positive difference between reduced load and the sum of the three RE forms defines the back-up power at the time point i; a negative difference (RE power > reduced load) defines the surplus power.

The averaged load curve has a maximum in winter and a minimum in summer. Wind power helps to match the seasonal cycle contrary to photovoltaic electricity production, which has a minimum in winter. 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 of 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.

Figure 3 plots the annually produced energy of the back-up systems normalized to the target demand of 500 TWh against the normalized PV energy production. Parameter of the set of curves is the total contribution of REs also normalized to the demand. The curves show a minimum, which moves to larger PV contributions when the share of REs 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 power.

With increasing RE share, the relative PV contribution reduces. For the 100% case, the optimum PV contribution is about 20%; the optimum is, however, shallow. The curves in fig. 3 are based on 2010 data; the crosses are from 2012 and confirm the original results indicating certain independence of the optimal mix from the variable weather conditions. The dots are obtained when only onshore wind, the triangles when only offshore wind is mixed with PV in the 100% case. The results do not indicate a sensitive dependence on the specific mix of onshore and offshore wind power. Therefore, the arbitrarily assumed contribution of 1/3 W_{off} does not critically affect the major findings of this study.

Table 2 summarizes key characteristics of the electricity system with REs producing exactly the amount of energy corresponding to the demand ("100% case") under optimal-mix conditions. For the 100%, optimal-mix case, 369 TWh (74%) of the RE production can directly be used. The rest, 131 TWh is surplus and has to be replaced by contributions from controllable power systems. The total installed power is 388 GW. The back-up system needs to produce 131 TWh electricity to compensate the surplus. For this purpose, a controllable power of 73 GW is necessary. About 10 GW (12%) of installed thermal back-up power can be saved by the use of RE. The flh and cf values of the back-up system are low, below the necessary levels for an economic operation of these systems.

Table 2. Key data of the electricity system with REs producing exactly the amount of energy corresponding to the demand ("100% case") under the "optimal-mix" conditions.

	Energy (TWh)	Max P (GW)	Installed P (GW)	flh (h)	cf
Reduced load	500	83	83	6020	0.69
W_{on}	271	146	175	1543	0.18
W_{off}	135	33	33	4134	0.47
PV	94	79	97	971	0.11
Directly used RE energy	369				
Back-up	131	73		1795	0.20
Surplus	131				

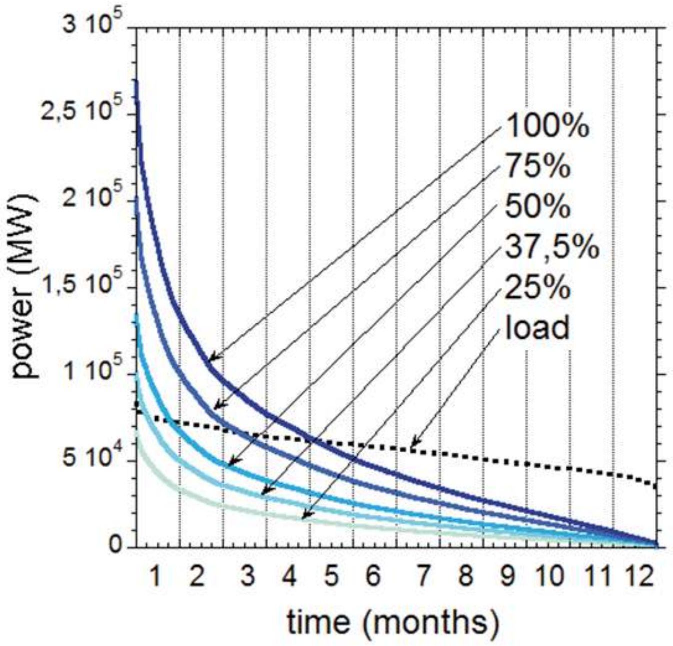

Fig. 4. Duration curves representing the load (dotted) and onshore wind electricity (lines) scaled to different annual energy contributions to the load.

The optimal-mix case is not suggested here as a development scenario to be realised. It rather serves as a well-defined reference case, which minimises the system consequences presented and discussed in the following.

4 Scaling studies

Figure 2 points to a fundamental problem in the use of REs. The load duration curve is largely a straight line. The duration curves of onshore wind and PV, however, are —seen from above— concave. Scaling to higher powers with the goal to ultimately match the annual energy consumption leads to large energy surpluses. Figure 4 illustrates this consequence of the different duration curve curvatures in an exemplary way for onshore wind scaled up to the total annual electricity demand (100% curve in fig. 4). The 100% onshore wind case delivers the same amount of energy as the load demands. 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% W_{on} curve represents the energy, which has to be delivered by the back-up system with controlled output satisfying the residual load.

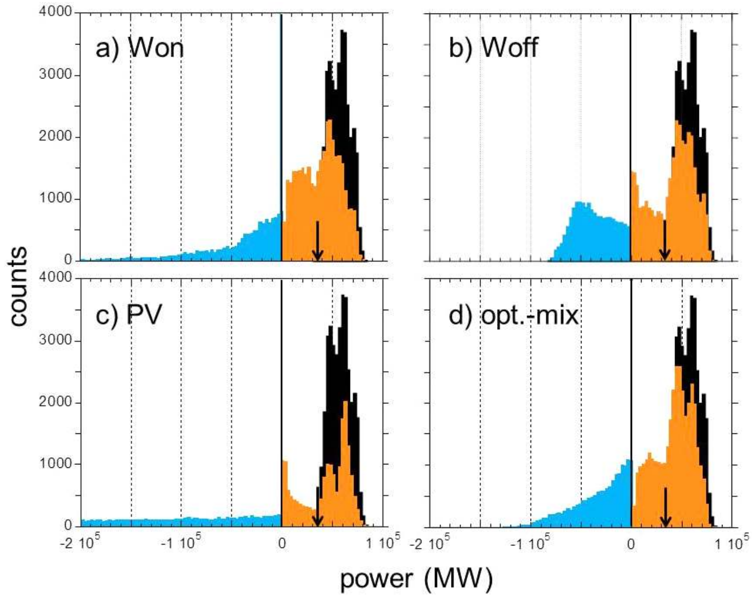

Fig. 5. The four histograms show the directly used RE power (positive axis) and the surplus power (negative axis) for 100% cases. Panel a) shows the distribution for onshore, b) for offshore, c) for PV power and d) for the optimal-mix case. As a reference, the histogram of the reduced load is shown in black. The arrows indicate the location of the base load level.

Scaling is limited to the "100% case" because the production by REs would just be sufficient to compensate the primarily missing energy if proper storage were available. In this case, no back-up power is required any longer. Efforts to produce more than 100% of the demand lead to a drastic further increase of grid power at an only modest decrease of back-up power and do not seem to be a viable concept neither for downscaling storage capacity nor replacing back-up power.

Each of the RE supply forms has its own supply characteristics. In order to elucidate these features in more detail we first analyse and discuss them separately. The RE power is selected such that for each form separately it produces as much energy as the load integrally demands (100% cases).

The histograms of fig. 5 plot the power produced by the three RE forms, which is delivered directly into the grid (positive values). The load profile in the background serves as reference. The surplus power distribution is plotted along the negative power axis. The power distribution within these two categories is also shown for the optimal-mix case. 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 predominately during the night and the weekends. The width of the two load profile features is largely given by the seasonal cycle. Though REs fill the power band of the load closely up to the highest demand values, nevertheless, the back-up system has to nearly meet the peak power levels of the load for all four cases considered. The RE powers show typically the concave distribution with the frequency of occurrence decreasing toward higher powers in the range $0 < P < P_{\text{base load}}$. The directly used RE power increases, however, in the power range of the load because all power values falling into this interval contribute as well as the higher ones. Because of the decay of the RE power distribution toward higher powers, the "filling" of the power band of the load requires a large installed capacity so that specifically the excess power levels can be used to meet the load. The use of REs unavoidably produces therefore surplus power. The selectiveness of this process is obvious from fig. 5 c). In case of PV, the highest peaks are delivered during daytime. Therefore, the day-peak of the load is preferentially filled. PV does not contribute much at the base-load power level because this part of the demand originates mostly from night periods.

All four cases produce surplus energy with PV going beyond the 200 GW power level. In case of offshore wind, the surplus power levels are limited as the convertors frequently operate in the constant output power branch of their characteristics. The negative power hump is caused by the excess power, which lies between maximum wind converter power and peak load. In case of the optimal mix, the power band of the load is well filled. The need for back-up energy is minimised as defined by the optimisation criterion. The surplus peak power is limited to about 100 GW.

In fig. 6 a) the produced energy is plotted against the installed power individually for the four cases considered. The maximum energy values correspond to the 100% cases. The relation is linear because saturation effects, which appear with increasing power as soon as less qualified sites have to be included into electricity production, have not been considered. The slopes of the lines correspond to the annual full load hours. The squares close to the origin denote the installed RE power and the produced energy at the end of 2012. Offshore wind is still ignorable at the scales of the diagram. The dots indicate the parameters of the three RE components in case of the optimal mix and indicate the goal of a 100% electricity production by REs (under the assumptions of this paper). The comparison demonstrates the still infant nature of the RE deployment in Germany in spite of tremendous efforts in the last years.

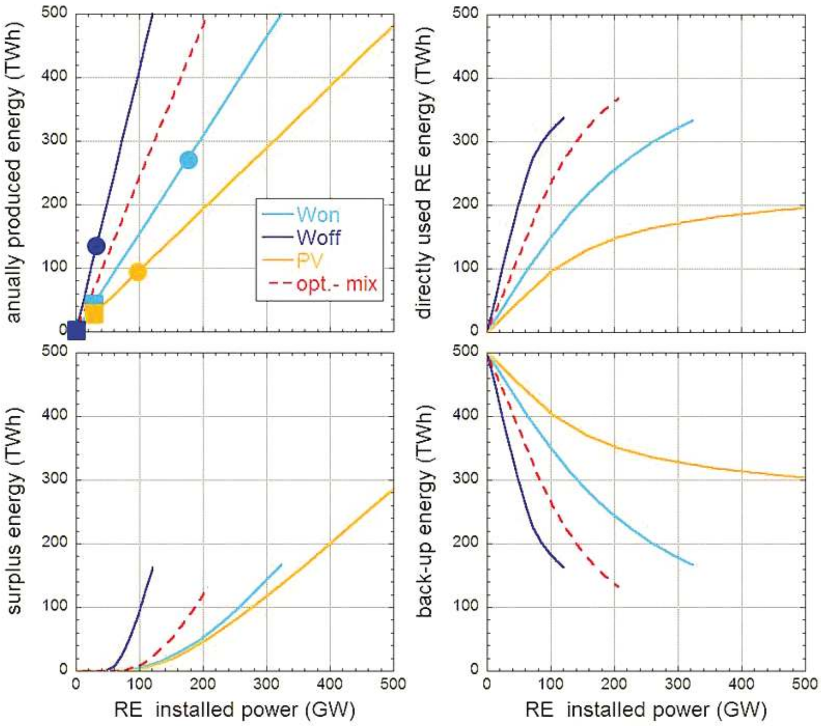

Fig. 6. a) Plotted is the produced energy against the installed RE power for on- and offshore wind and PV and the optimal-mix case (dashed line). The squares denote the installed power and the harvested energies for 2012 of the 3 systems. The dots show the contributions of the 3 RE systems considered for the 100%, optimal-mix case. Panel b) plots the directly used RE energy, c) the surplus energy and d) the back-up energy for the 4 cases considered.

Figure 6 b) plots the annually produced RE energy, which can directly be used; fig. 6 c) shows the annual surplus energy and fig. 6 d) the needed contribution of the back-up system. The directly used energy 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 targeted demand of 500 TWh. In the optimal-mix case, 74% of the produced RE energy can directly be used. For 100% W_{on}, W_{off} or PV, respectively, the useful fractions are 67, 67 and 40%.

Surplus power appears at RE powers close to the peak load level[1]; lower values are absorbed by the grid. PV produces the largest amount of surplus energy and requires the highest installed power.

Figure 6 d) plots the energy delivered by the back-up system for the three RE cases considered, which deceases with increasing RE share. This dependence fulfils one of the intended objectives in the use of REs. But back-up power is required up to the 100% case and beyond. An exclusive PV system would necessitate by far the largest thermal power back-up system.

In conclusion, without storage, offshore wind as the "best" RE electricity source produces about 2/3 of the annual demand with a power capacity, which corresponds to the present thermal one. The other extreme is PV, which produces with close to 500 GW installed power less than 1/2 of the annual electricity. This is obvious because the total annual energy has to be produced during the day.

5 Operational conditions for back-up system and grid

With controllable sources, the supply system responds to the periodic variation of day and night and the weekly and the seasonal cycles of the load: electricity production is demand driven. The load variations are periodic and largely 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

[1] The actural situation that back-up power still contributes to surplus even in periods of high RE shares is not considered here.

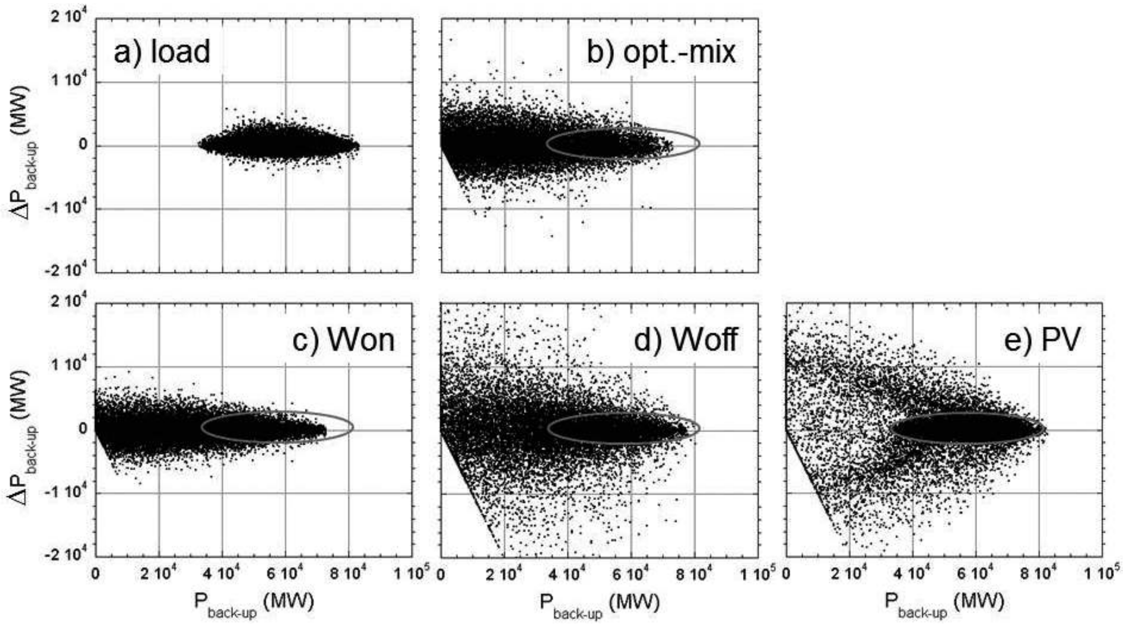

Fig. 7. Plotted are the power increments of the back-up system $\Delta P_{\text{back-up}}$ from one moment to the next one ($\Delta t = 15$ min) against the initial power $P_{\text{back-up}}$ for a) the load, b) the optimal-mix case, c) onshore wind, d) offshore wind, and e) PV power. In each case, the energy corresponds to the 100% case. The ellipses serve as reference representing the envelope of the load.

Table 3. Given are the maximal and minimal values of the load P_{load}, and for the back-up power under optimal mix conditions ($P_{\text{b-up,o-mix}}$), and when the RE power is exclusively produced by onshore ($P_{\text{b-up,Won}}$) or offshore ($P_{\text{b-up,Woff}}$) wind or by PV ($P_{\text{b-up,PV}}$). In each of these four cases 100% energy is produced by REs. In addition to the power values P also the maximal positive and negative power increments ΔP from one moment to the next ($\Delta t = 15$ min) are given together with the standard deviations of the power fluctuations.

(MW)	P_{load}	ΔP_{load}	$P_{\text{b-up,o-mix}}$	$\Delta P_{\text{b-up,o-mix}}$		
min power	32641	−462	0	−24036		
max power	83053	5789	73187	27271		
std		686		1604		
(MW)	$P_{\text{b-up,W}_{\text{on}}}$	$\Delta P_{\text{b-up,W}_{\text{on}}}$	$P_{\text{b-up,W}_{\text{off}}}$	$\Delta P_{\text{b-up,W}_{\text{off}}}$	$P_{\text{b-up,PV}}$	$\Delta P_{\text{b-up,PV}}$
min power	0	−8486	0	−62838	0	−20042
max power	72907	9128	80489	60210	82754	41171
std		1216		3371		2988

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.

The power of the back-up system does —of course— not surpass the level of the load. In the case that onshore wind contributes with 10% to the annual demand the main feature —the residual back-up power distributed between base and peak load— is largely maintained. With 30% wind contribution to the annual electricity the base load has disappeared and the back-up system has to supply all power levels from 0 up to the peaks of the reduced load. With increasing stochastic contributions both amplitude and temporal response change and are governed now by the characteristics of the fluctuating sources.

Figure 7 addresses the dynamics of the back-up system for the 100% RE cases. Each RE source is analysed separately along with the optimal-mix case. Plotted are the positive and negative power increments $\Delta P_i = P_{i+1} - P_i$ against P_i occurring within $\Delta t = 15$ min of a) the reduced load and b) to d) the residual load of the back-up system. For the reduced load, the power ranges between 33 GW, the base load, and 83 GW, the peak load, and ΔP varies between ±5 GW. With 100% REs, the back-up system has to supply all power levels from zero up close to the maximal load values. The ellipse, plotted into the diagrams denotes the original ΔP-P area of the load. Table 3 shows the limits of the power ranges in P and ΔP. The maximal reduction for the thermal back-up system happens for W_{on} and the optimal-mix from 83 to 73 GW corresponding to a decrease by 12%. No significant reduction happens in case of exclusively PV.

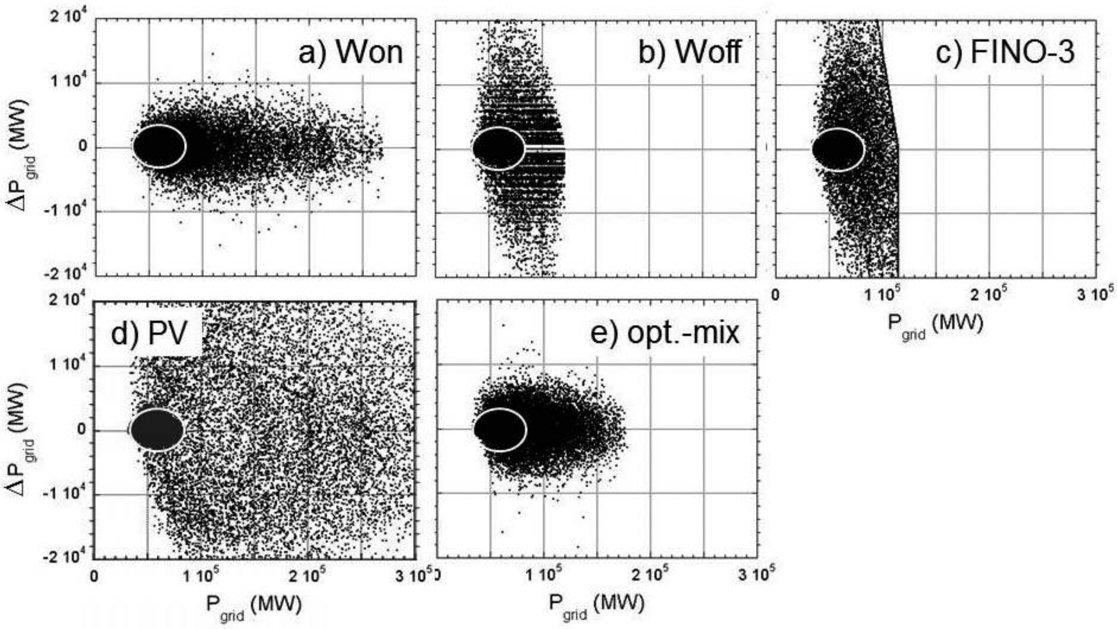

Fig. 8. Plotted are the power increments of the grid ΔP_{grid} from one moment to the next one (Δt = 15 min) against the initial power P_{grid} for a) onshore wind, b) offshore wind, c) again offshore wind but constructed from wind velocity data from FINO-3 [14], d) PV power, and e) for the optimal mix case. In each case, the energy corresponds to the 100% case. The ellipses serve as reference representing the envelope of the load (see fig. 7 a).

As the decrease of P by ΔP is limited to P itself, the lower left triangle in figs. 7 b) to e) is empty up to the line $\Delta P = -P$. The ΔP distributions are characterized by extended wings, which are specifically large for PV and offshore wind. In the case of offshore wind, the fluctuation amplitudes approach the level of the installed back-up power. The positive and negative amplitudes are rather symmetric apart from PV where the positive increments are twice as large as the negative ones. The majority of the power excursions are smaller and better characterised by the standard deviation, which is also quoted for each case in table 3. From about 700 MW characteristic for the load, it increases by a factor of more than two for the optimal-mix case.

Whereas the incremental variation of the back-up power is limited by the load, the power excursions for the grid are much larger limited only by the installed RE power. Figure 8 shows the grid power excursions ΔP for the four 100% cases. The original ΔP-P range of the load is shown as ellipse. PV covers the range of the load quite well. This is due to the periodicity and the partial collinearity of load and PV power. In order to corroborate the $\mathrm{W_{off}}$ data, which are available at present at low power levels only, offshore powers were additionally constructed from FINO-3 wind velocity data (see fig. 8c)).

In addition to the amplitudes, also the frequency of power jumps increases for the back-up system and the grid. Figure 9 shows the number of power increments $|\Delta P|$ from 0 to 10 GW ordered in steps of 1 GW (horizontal bars). Reference is the dynamics of the load. For the load, there were 4 power jumps in 2012 from one time increment to the next one, 15 min later, with amplitudes of 5–6 GW. For the 100%, optimal-mix case, the jumps of the back-up system in this power range amounts to nearly 400. The number of high-power steps increases despite the reduced flh in the operation of the back-up system. The optimal-mix case is qualified from the point of view of low power steps. The other 100% cases, $\mathrm{W_{on}}$, $\mathrm{W_{off}}$ and PV are also shown but only in the amplitude range 9–10 GW. There is a distinct increase in the frequency of high-power steps for $\mathrm{W_{off}}$ and PV.

6 Surplus power, storage and demand-side management

One of the major problems in the use of REs is the handling and proper use of surplus power. We recollect the large amount of annually produced surplus energy of 131 TWh for the 100%, optimal-mix case.

One possibility is to avoid surplus by regulating the RE sources. The most reasonable candidate would be onshore wind. The regulation would, of course, hamper the economic use of the system. This would be even more severe in case of throttling offshore wind with its higher capital costs per kWh produced. PV sources are rather distributed and feed into a large distributed grid making large-scale regulation more complex. Its reduction is also less effective. From the 3949 hours with surplus energy in the 100%, optimal-mix frame, the PV contribution is larger than the one from wind

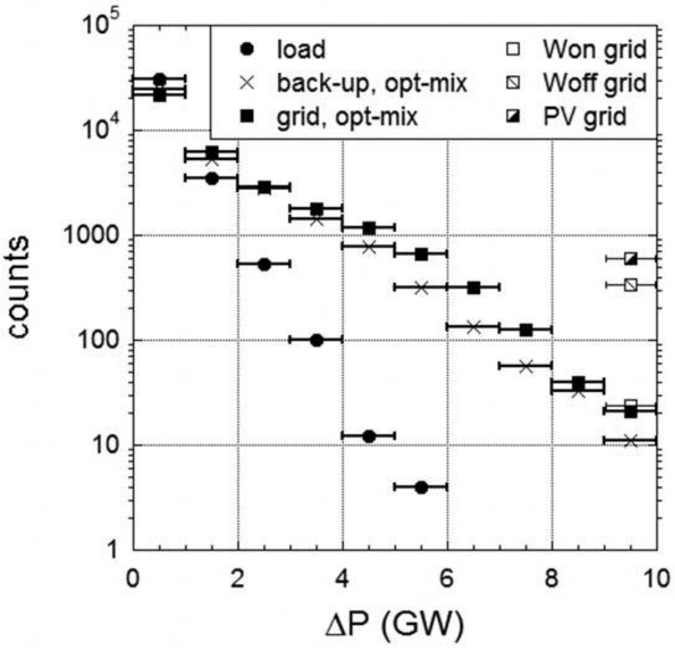

Fig. 9. Plotted is the frequency of power increments from 1–10 GW from one moment to the next one ($\Delta t = 15$ min) for the load, the back-up system and the grid under optimal mix conditions. Plotted are additionally for the 100% cases the frequency of power steps between 9 and 10 GW for exclusively onshore, offshore wind or PV power, respectively.

for 569 hours only. The removal of sources from the grid will, however, reduce the flh and cf values of the concerned system components even further. For example, if the surplus power should be minimized by a corresponding reduction of onshore wind power only, surplus can be reduced from 131 TWh to minimally 9.7 TWh at the expense of the W_{on} system whose flh or cf, respectively, drop from flh = 1543 h and cf = 0.18 to flh = 461 h and cf = 0.05.

In a situation where the surplus power is not avoided on one hand but cannot yet be stored on the other it can be exported into neighbouring countries of Germany. Most of them have, however, different supply policies with corresponding technologies based on energy delivery by demand. Therefore, specific challenges might arise in exports at large scales. For the 100%, optimal-mix case the power excursions of the surplus-power range from +27 to −31 GW, respectively, and the number of power increments ΔP of 5–10 GW is more than 1100. To compare with, the grid capacity of Poland is about 35 GW [16]. Already today, the unintended cross-border electricity flow causes severe problems with neighbour Countries of Germany [17]. As long as sufficient grids inside Germany and storage at large scales are not available this problem can only be meliorated by disconnecting concerned supply systems from the grid.

Simple ways to use the surplus energy would be for heating purposes. 76 TWh could be used in winter to reduce the overall household heating demand of 550 TWh in Germany; 55 TWh would be available in summer; 20 TWh of it could be used to satisfy the present domestic cooling needs [18].

Storage would allow using the surplus power and to ultimately replace the back-up system achieving thus completely CO_2-free electricity supply. The 100% case is considered because the surplus energy (to be stored) equals the back-up energy (to be substituted). No specific storage technology is assumed. The capacity is lowest in case of the optimal mix because the storage can be filled in both seasons —during winter with wind and during summer predominantly with PV power [19] allowing thus two periods per year where the storage level is minimal. A complete storage of the surplus energy for the optimal-mix case would require a storage capacity of 33 TWh. This is a factor of ~ 660 above the presently installed pumped water storage in Germany and is a target, which cannot be realised in this form.

A storage capacity of 5 TWh is already very effective and reduces the back-up energy needs from 131 TWh to 42 TWh. We will demonstrate the dominant system characteristics with a storage capacity of 5 TWh though it is clear that the necessary technology for such a system —most probably chemical storage— is not yet available at the required large scales.

Figure 10 shows the annual duration curves for the 100%, optimal-mix case with an assumed storage of 5 TWh. The storage traces show the de-charging and, negatively, the charging periods. Such a storage is in operation for 6756 h with 3198 h charging and 3558 h discharging periods. A back-up system providing the residual energy with 71 GW installed power is still required which operates less than two months per year.

Table 4 summarises the key parameters of the system with storage for the optimal-mix case. The first line gives the characteristics of a conventional system able to satisfy the load and serves as reference. The alternative RE system with storage of the following lines is composed of 305 GW installed RE power. The back-up system is reduced from

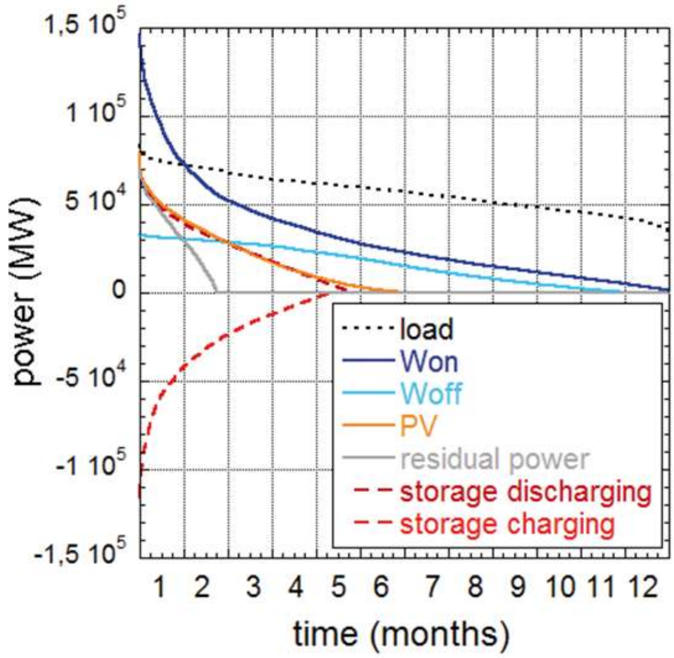

Fig. 10. Duration curves representing the load (dotted) and the contributions from onshore, offshore wind, PV power and the back-up system (residual load). Shown is also the distribution of a storage of 5 TWh for the discharging (dashed curve positive) and the charging (dashed curve negative) periods. The duration curves are calculated for the 100%, optimal-mix case.

Table 4. Component characteristics of a system with 5 TWh storage for the 100%, optimal-mix case.

	Energy (TWh)	max P (GW)	min P (GW)	installed P (GW)	flh (h)	cf
Reduced load	500	83	33	83	6020	0.69
W_{on}	271	146	~ 0	175	1543	0.18
W_{off}	135	33	~ 0	33	4134	0.47
PV	94	79	0	97	971	0.11
Storage	5	73	-123		1938	0.22
Back-up	42	71	0	71	490	0.06

73 GW installed power necessary for the 100%, optimal-mix case without storage (see table 3) to 71 GW with storage. Whereas the power of the back-up system is hardly reduced by storage, its utilisation in terms of flh or cf is further reduced by a factor 3–4. The charging power of the storage is about 70% higher than the discharging power. The first one is determined by the RE power, the second one by the load characteristics. The duration curve shows that the removal of the peak charging powers in excess of those of the discharging period sacrifices less than 2 weeks out of 19 weeks of storage operation.

One can formally discuss the storage in terms of flh and cf which are both given in table 4. The storage is empty on ~ 1300 h and full on ~ 750 h of the year (the numbers depend on the definition of empty and full).

With empty storage, the back-up system has to be operated which sums up to a production of 42 TWh; for periods of full storage, the surplus power cannot be absorbed, which adds up to 89 TWh. In summary, a storage of 5 TWh reduces the annual energy delivered by the back-up system from 131 to 42 TWh and the surplus energy from 131 to 89 TWh (corresponding to the electricity consumption of Belgium). A specific aspect of the storage technology is that it has to handle large charging powers, which are independent of the storage capacity. Also small storage capacity has to cope with large power levels if the use of most of the surplus power is intended. In a thought experiment one could try to maintain the grid power level at the peak of the load by regulating W_{on}. In this case, the annual onshore contribution would drop from 271 TWh to 218 TWh. The flh (cf) values would drop from 1543 (0.18) to 1241 (0.15) and would aggravate the economic aspects of onshore wind energy production.

Also storage —like the other grid components— is characterized by a large capacity which is mostly not used. Therefore, it is questionable whether large storage operation will be economic irrespective of the storage technology yet to be developed.

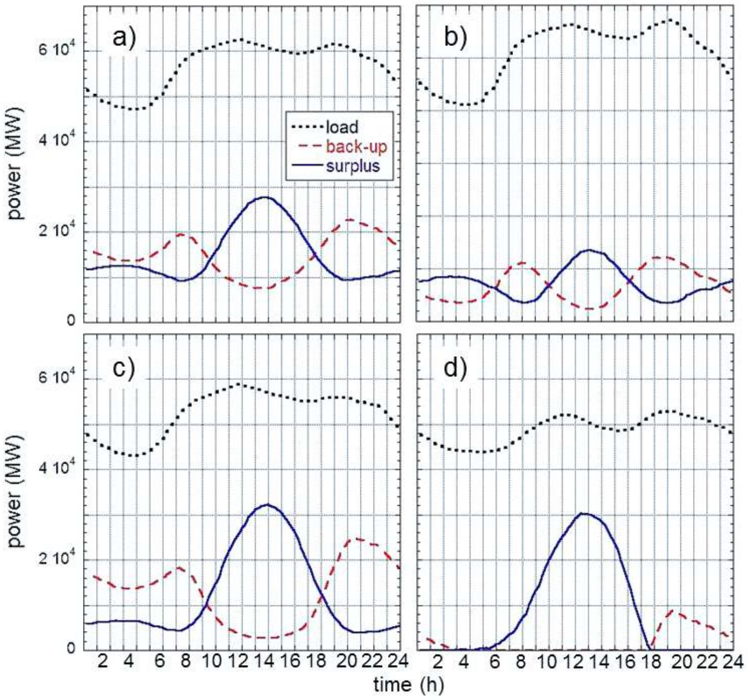

Fig. 11. Averaged daily curves of the load (dotted), the back-up power (dashed) and the surplus power (solid): a) annual average; b) average during winter (October to April); c) average during summer; d) average for Saturdays and Sundays.

Demand-side adaptive management is expected to meliorate the mismatch between production and demand. The goal is to better use periods with high surplus and low back-up needs with the expectation of low electricity prices for storage or intensified economic activities shifted off of periods with high demand and consequently high prices. The canonical examples are to use washing machines and to charge batteries of electric cars during the night.

Also with developed demand-side management techniques, there will be certain repetitiveness from day to day in the human economic behaviour. Therefore, we form the annual average of the daily variation of load, surplus and back-up power and study their relationships to identify potentially low and high electricity cost periods.

The integral situation is as follows: The summed-up surplus during the night is 48 TWh for the 100%, optimal-mix case. This compares to 83 TWh produced during the day. The back-up figures are 75 TWh during the night and 56 TWh during the day. Surplus is preferentially produced during the high- and not the low-load period. The opposite is the case for the back-up energy predominantly needed during presently low-load periods. Therefore, one can expect that the electricity prices are lower during the, presently, economical active periods.

Figure 11 a) compares the averaged load curve of 2012 plotted for 24 h along with surplus and back-up power. Till 9:30 in the morning and from 17:30 on the surplus power level is below the back-up curve. Spot-market prices will reflect the need to operate the back-up systems and can be expected to be high. Because of PV power, surplus power dominates during the day and electricity prices can be expected to be lower. The maximum difference between surplus and back-up power is between 13:00 and 14:00 around the maximum of the load. Already today, the usual peak-price periods around noon have frequently disappeared with the corollary that the economic operation of peak-load supply systems like pumped storage and gas turbines is not guaranteed any longer. In conclusion, the conditions for demand-side management are such that the periods with traditionally high economic activities during the day are additionally favoured by high surplus and low back-up power needs.

The situation is not much different when one considers the winter (October to March) and summer (April to September) half years separately (see fig. 11, b) and c)). In winter, the excursions of average surplus and back-up power during the day are small and —from the electricity price point of view— there will hardly be a strong drive to motivate the move of electricity consuming processes into other periods of the day. In the summer half year the cost drive to utilise the day at the expense of the night is even stronger.

Extreme is the cost situation during the low-activity weekends. Little back-up power is needed in the night periods of Saturday and Sunday and none at all during the day, which, on the contrary, is characterized by strong surplus. It can be expected that low electricity costs will drive the demand-side management activities into the weekends.

If the low-demand weekends are fully integrated into the economic activities the peak load reduces from 83 to 71 MW at the same consumed electricity of 500 TWh. The directly used RE energy increases from 369 to 376 TWh.

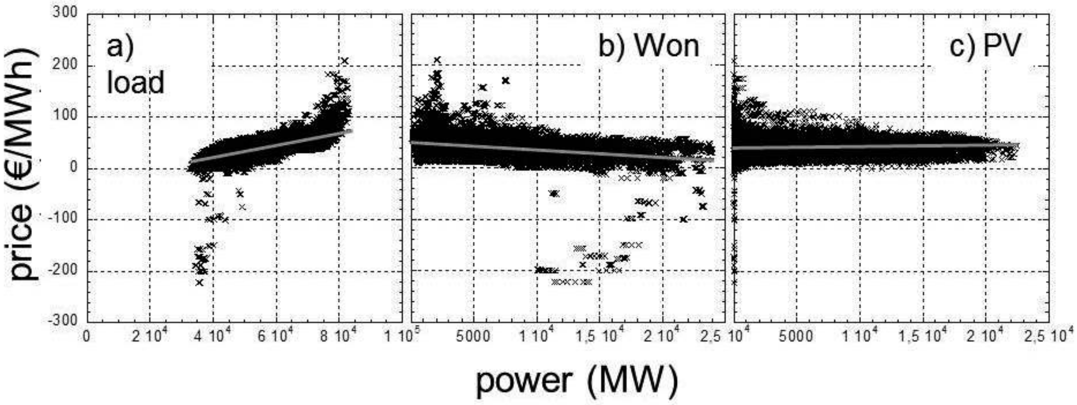

Fig. 12. Spot market price of electricity in Germany in 2012 plotted *versus* the power of a) the load, b) onshore wind power and c) PV power. The lines are linear fits to the data points.

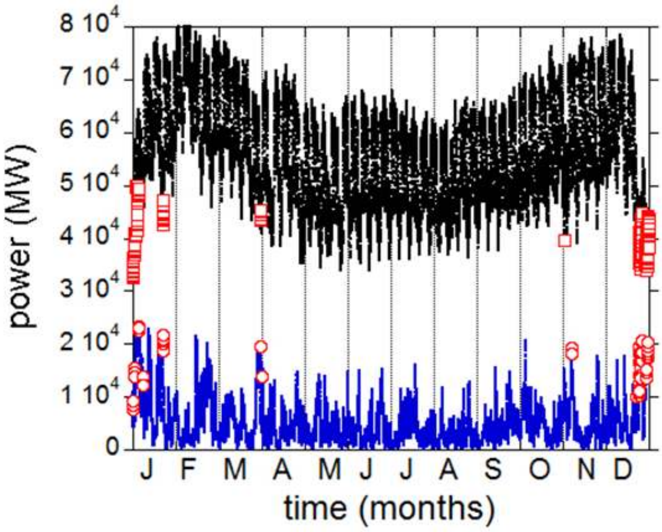

Fig. 13. Load and onshore wind during 2012. The squares of the load denote periods of negative electricity prices; the circles denote the predicted periods of negative electricity prices.

The back-up system has to deliver 123 instead of 131 TWh whereas its flh increases from 1795 to 1919 h. Surplus energy is reduced by 5.7%.

7 Periods with negative electricity prices

In this section, we will analyse the spot market electricity prices and try to conclude on the frequency of negative prices expected for larger installed RE powers. Figure 12 a) plots the spot-market prices of 2012 [20] against the load. Increasing demand causes a corresponding increase of the average electricity prices. Figure 12 a) also shows two additional data groups, one of specifically large prices at higher loads and one of negative prices at low loads. As shown in fig. 12 b) and c), electricity prices decrease with onshore wind but do not show much dependence on PV power. The variation with wind follows market rules and is understandable. Prices do, however, not drop toward higher PV powers because PV is offered during the generally high-demand periods around noon time characterized presently by a higher price tendency. Figure 12 b) and c) also show that the high cost group is located at lower wind and PV power whereas the negative price group happens at higher wind levels and during the night.

The occurrence of negative prices is the result of a complex market process involving the economics in the operation of the back-up system. Therefore, any predictions have to be done with the understanding that their basis might be vague. Nevertheless, a simple criterion allows identifying the present periods with negative prices. Negative prices depend on the gap between load and wind power and appear when $P_{\text{load}} - P_{\text{Won}} < 26.3\,\text{GW}$. Figure 13 plots the actual load and W_{on} power data of 2012 and marks the periods of negative prices, in the load curve as they actually

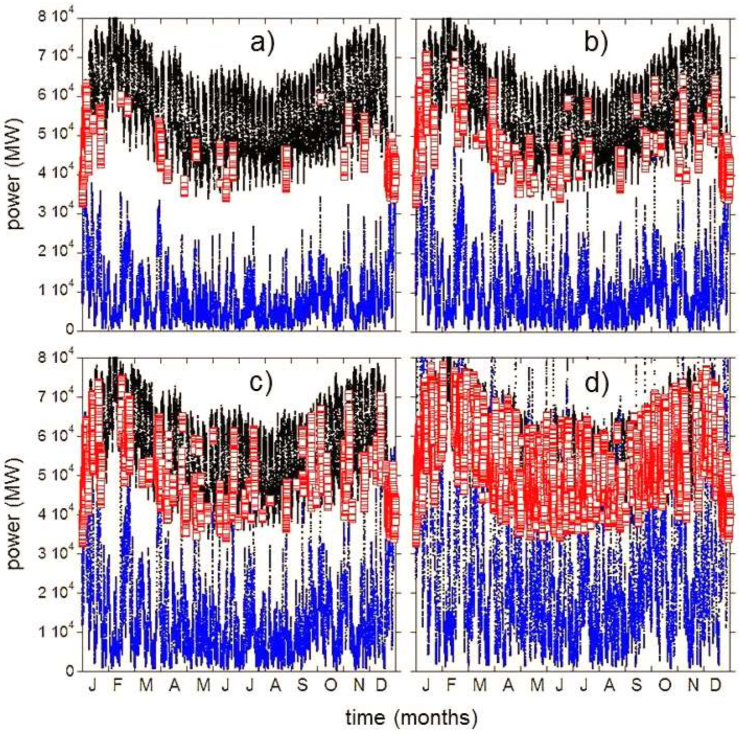

Fig. 14. Load and onshore wind, scaled to a) 15%, b) 20%, c) 25%, and d) 50% of the demand (500 TWh). The plusses denote the predicted periods of negative electricity prices.

occurred, in the W_{on} curve as they were predicted on the basis of the above criterion. Though the criterion is rather simple, all periods with negative prices in 2012 are identified.

One can use this criterion now and tentatively explore the growth of periods with negative prices as they develop when onshore wind power is increased. PV is not considered as the presently installed power is too low to yield scalable data. Figure 14 a) to d) mark the periods with negative prices when onshore wind energy is increased from 15, 20, 25 to 50% of the annual demand. Whereas in case of 2012 with 7.5% energy contribution from onshore wind, the periods with negative electricity prices are located at the extreme low-demand seasons at the end of the year, they appear during all weekends at a 15–25% share and scatter over the load band at a 50% share. Increasing the W_{on} energy share of the load the hours with negative prices increase from 446 h at 15%, to 826 h at 20%, to 1218 h at 25%, to 3359 h at 50%, and to 5662 h at 100%. These figures indicate, of course, only a tendency.

8 CO_2 production

Summing up the CO_2 production since World War II, Germany shares the position #4 with Japan after China, USA and Russia. Germany is one of the major CO_2 polluters of the environment and therefore, the avoidance of CO_2 is a major political motif for the substitution of fossil electricity production. The total CO_2 release in Germany in 2012 is about 810 Mill t, leading to a *per capita* CO_2 release of about 10.1 t. The one for electricity production is 317 Mill t; the specific CO_2 emission factor for electricity generation is $\eta_{el} = 0.576$ kgCO_2/kWh [21]. With the CO_2-producing fuels of table 1 and the respective η_{el} values (coal: 0.92, lignite: 0.99, gas: 0.4, oil: 0.63, others: 0.65 kgCO_2/kWh [22]) the total CO_2 production for electricity reproduces the value, quoted above and yields $\eta_{el} = 0.51$ kgCO_2/kWh, somewhat lower than the official figure but within the uncertainty of this quantity [23]. $\eta_{el} = 0.83$ kgCO_2/kWh for electricity production by fossil fuels in Germany in 2012.

We calculate the specific CO_2 emission factor η_{el} related to electricity generation for the optimal-mix case depending on the RE fraction for two cases: 1) when the back-up system providing the residual energy is operated with the present fossil fuel mix (see table 1) with $\eta_{el} = 0.83$ kgCO_2/kWh and 2) for the case that only natural gas is burnt with $\eta_{el} = 0.4$ kgCO_2/kWh. Reference for each case is a constant electricity need of 500 TWh per year. The reduction of η_{el} with increasing RE fraction for the two cases is shown in fig. 15 a). Figure 15 b) continues this development when additionally storage capacity is added. Also from the CO_2-production point of view, a 5 TWh storage may be sufficient. The diagram also reveals that the additional use of storage leads only to a small further CO_2 reduction

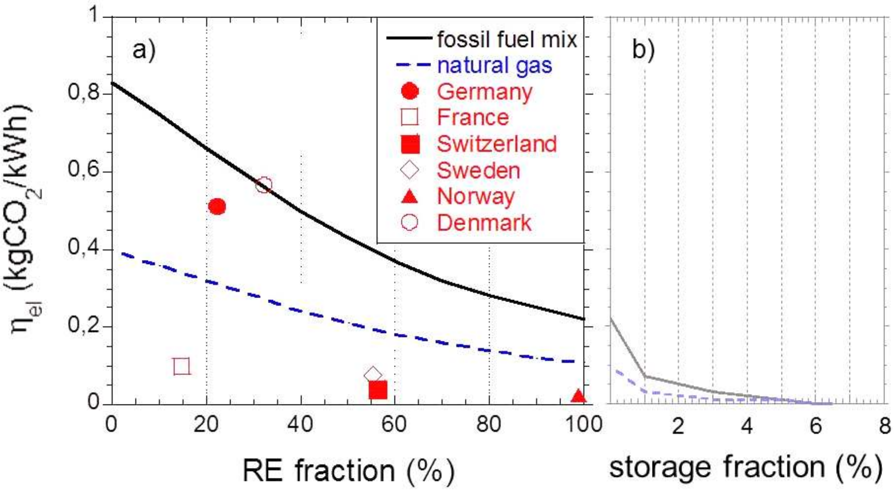

Fig. 15. The specific CO_2 emission factor of electricity generation η_{el} is plotted against the normalized RE fraction for the optimal-mix case without storage (a)) and when storage is added (b)). The solid line is based on the CO_2 production according to the present mix of fossil fuel power of Germany, the dashed line on exclusively gas burning power stations. The symbols denote η_{el} for various European Countries.

beyond the major step introduced by the move to RE sources. The CO_2 saving aspect does not seem to be a major driver to motivate the development of storage systems.

Figure 15 a) also shows the 2012 η_{el} values for Germany and other European countries (2010 values[2]). The German data point is below the upper curve because of the present nuclear energy contribution. Even for the 100% RE case the low η_{el} values of France, Sweden, Switzerland and Norway will hardly be attained by the use of RE in Germany. This goal requires indeed additional storage replacing a further part of the back-up system. The quoted countries with low η_{el} values produce electricity predominantly by a mix of hydro and nuclear power, Norway exclusively with hydro power. Denmark, with a high RE fraction (32%) based predominantly on wind power has nevertheless a high η_{el} value.

9 Analysis and comments

Electricity production from wind and solar radiation is easily possible in a society which agrees to the corresponding use of land, accepts the impact on its cultural landscape, and finances the necessary infrastructure. The electricity to be produced can be increased proportional to the allocated area which has to be large, however, due to the low densities of the natural power fluxes.

The following problems and issues have been identified in the use of REs at large scales.

Technology: REs require large power installations. The necessary investments can be reduced by the proper mix of wind and PV power selected as the final target in this study. For the 100%, optimal-mix case 305 GW RE (wind and PV) and 73 GW back-up capacities have to be installed for producing 500 TWh electricity. This is about 4.5 times the peak power value of the German demand. Under peak conditions, this generating power is nearly capable of meeting the EU demand. Germany, though leading in the installation of RE systems, is still a factor of 5 below this goal.

From 500 TWh RE energy, 74% can be directly used; the rest is surplus. The back-up system fills the low-power periods of REs. 131 TWh surplus energy corresponds to the energy produced by offshore wind (in the frame of the assumptions in this paper) and would allow meeting the electricity needs of Poland. Even for the 100%, optimal-mix case the surplus reaches a level, which cannot be handled by available technology or by cross-border trade. Avoiding surplus by throttling the sources represents a major economic loss for a system, whose components in any case cannot be operated in an economic fashion (at the present price structure).

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 known and documented: PV has the highest material use, the highest primary energy use and the highest costs per unit of electricity produced [24]. On the other hand, in combination with wind the need for back-up can be minimized somewhat in comparison to wind alone, however, at the expense of slightly increased total power capacity.

[2] To allow comparison with the calculated values of this graph, η_{el} was determined as ratio of annual CO_2 production for electricity generation/annual electricity production. The data are taken from ref. [22]. This definition does not confuse the issue with the simultaneous heat production and allows a better quantification of the virtue of CO_2-free sources in the overall mix.

Without proper storage, a back-up system of conventional power plants —preferably on gas basis to minimize the specific CO_2 release— is still necessary. The nominal power of the back-up system has to remain high and is reduced by the addition of RE power by not more than 12%. Its energy production, which is the economic factor, decreases, however, with increasing RE share. This is —of course— one of the objectives of the "Energiewende", which deprives, however, the conventional power systems the economic basis. This corollary starts to play a role now in Germany.

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 load rather by that of the supply. Additionally, the increments in power (positive and negative) increase involving an increasing number of back-up power plants in the system dynamics and enforce a coherent operation of a large number of conventional power stations. This unfavourable stop-and-go-and-idle mode of operation adds to the economic problems of thermal power stations. Their η_{el} values will increase because they are not kept at the optimal operational point. The increased frequency of large amplitude excursions will lead to extended periods of maintenance as analysed in ref. [25]. "Must-run" plants like CHP stations have to be excluded in such a scheme. The actual dynamics will depend, however, on the difference between forecasted and actually arising conditions. From this point of view, the results shown in fig. 9 represent an envelope to the conditions, which can be expected with REs producing 100% of the electricity.

Large storage capacity both in energy and power handling capability is necessary collecting surplus and replacing the back-up system of thermal power stations. Pumped hydro power 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 development. The 100%, optimal-mix case operated completely CO_2 free requires storage of 33 TWh, which is a factor of 660 above the present potential and by far beyond any chances of realization.

Storage in the range of TWh coping with the surplus power levels needs a new technical solution based on chemical processes, *e.g.* the production of hydrogen or synthetic hydrocarbons (power to gas). A large industrial complex has to be realised for this purpose. The overall efficiency of the circular process back to electricity is ~ 0.2–0.3. As a consequence, a large price discrepancy would form between primary and secondary electricity with a strong impact on the economy specifically as the low-price periods can be expected to develop during the day. In addition, chemical storage will have a direct low-cost competitor most probably far beyond 2050 *viz.* natural gas as source for electricity. Its use is not CO_2 free but happens at a comparatively low specific emission factor.

Environment: A strong reduction of specific CO_2 release for electricity production can be achieved by the application of REs. At present, the German electricity production is 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 power (Switzerland, Sweden and France). This environmental quality can hardly be realized by the considered RE techniques under reasonable practical and economic conditions.

Economy: The capacity factors cf of onshore and offshore wind vary from year to year around 0.17 or 0.4, respectively. Those of PV in Germany are about 0.1. The basic relation between costs C and the capacity factor cf is $C = \alpha/\mathrm{cf} + \mathrm{OC}$ [26]. α represents economy factors (capital costs, interest rate...) and OC operational and CO_2 emission costs. The use of variable sources with low cf values forces the other components of the supply system, which are operated during the gaps, also to low capacity factors. It is already a concern today in Germany that the increase in RE power causes a corresponding decrease of the capacity factor of the back-up system.

All CO_2-free technologies with no or low fuel costs (wind, PV, solar thermal, nuclear) show a sensitive dependence on cf. A future large-scale storage would also be subject to a high sensitivity on cf. Therefore, it is difficult to see the economic viability of large-scale storage for surplus energy irrespective of the selected technology.

European development strategy: Electricity is produced in Europe from 100% CO_2 free to nearly 100% from fossil fuels. The methods of electricity production in Europe are a matter of national decisions. The "Energiewende" itself is a good example of the administration of national energy sovereignty. Electricity prices, *per capita* CO_2 release, the stages of electricity market liberalisation differ widely in Europe as the acceptance of nuclear electricity production does. It is difficult to see how in near future a joint European energy policy will emerge which would initiate a joint approach to such a large, complex and risky technology change as initiated in Germany. Many of the problems related to the exchange of the electricity supply technology in a rather short period could be ameliorated by a European wide approach. This is well documented in the scientific literature [27,28]. Within an EU-wide grid the degree of intermittency and to a lesser extent the variation of the load 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 technology change. A comparable initiative can hardly be expected by its neighbours whose electricity production is characterized by a supply structure dominated by controllable power. The technical manifestation of the German isolation are the national measures of its neighbours to surround Germany by an array of phase shifters, which will allow control of cross-border energy flows [29].

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 REs on short notice. Some European countries like Switzerland, Sweden, Norway and soon Finland meet already now the 2050 CO_2 goals of Germany in electricity generation and will hardly see any reason to change their supply technology on short notice with the consequence of a temporary increase in CO_2 production by commissioning fast thermal power stations to smooth out the added intermittent supply.

The German "Energiewende" may split up into the phases of technology replacement with gradual increase in the RE fraction and the final stage when electricity is produced largely or exclusively by REs. The first phase is characterised by a solitary attempt with all its challenges —set-up of high production capacity, extension of grids, development and realisation of storages, technologies to ensure grid stability, market acceptance of gas burning power stations and others measures. The cost rise of electricity will be a societal issue, which will not only affect Germany but all partners of the common EU electricity market. The competition with countries benefitting from the availability of cheap fuels (USA with shale gas) could lead to economic problems. This transient period will also be accompanied by conflicts with the eastern German neighbours whose grids are used as electricity by-pass from north to south Germany suffering technically without participating economically [17].

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 in the use of REs. Because of their limitations and shortcomings, the most obvious question will be whether and how an electricity system based on variable sources can be improved or replaced. 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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