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Seasonal optimal mix of wind and solar power in a future, highly renewable Europe

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ABSTRACT

The renewable power generation aggregated across Europe exhibits strong seasonal behaviors. Wind power generation is much stronger in winter than in summer. The opposite is true for solar power generation. In a future Europe with a very high share of renewable power generation those two opposite behaviors are able to counterbalance each other to a certain extent to follow the seasonal load curve. The best point of counterbalancing represents the seasonal optimal mix between wind and solar power generation. It leads to a pronounced minimum in required stored energy. For a 100% renewable Europe the seasonal optimal mix becomes 55% wind and 45% solar power generation. For less than 100% renewable scenarios the fraction of wind power generation increases and that of solar power generation decreases.

1. Introduction

We investigate the design of a future European power supply system based on a very high share of Renewables. Some key questions are: How much wind, solar, hydro and geothermal power is good for Europe? Is there an optimal mix between them? How much storage and balancing is needed? How much transmission is needed? Is it better to design the future power-supply system for one Europe or for several separate regions?

These days wind power has emerged as the most dominant contributor to renewable power generation, with potential for more in the future. A straightforward and simple answer to the first question has been pointed out [1,2]: there are enough wind resources around the globe to supply all continents with only wind power. However, due to its weather-driven fluctuations wind power generation is not a simple stand-alone solution. An enormous amount of balancing and storage will be needed on top of this wind-only scenario.

The balancing and storage needs are already now very important issues and will increase even more in the near future, when wind power is totaling up to twenty percent of the overall European power generation. Currently, for such a relatively small share, the weather-driven wind power fluctuations are dominated by time scales of the order one day and below. The respective spatial scales range from the level of a single transformer to the level of interconnected regions. This paves the way for regional smart grids, which will integrate short-term wind power fluctuations with market-driven balancing and load flexibility.

In a renewable future well beyond 2020 the share of wind power generation may well increase beyond fifty percent [2]. For such a large amount, the spatial and temporal scales that have to be looked at increase substantially. Regions with a momentary excess of wind power will try to export it, whereas deficit regions are depending on import. This spatial horizon beyond regions and countries helps to smoothen short-term wind power fluctuations and to reduce the short-term balancing and storage needs. In [3] it has been shown that in a 100% wind-only scenario the need for stored energy due to the mismatch between wind generation and load is 41% lower in a European-wide smoothing of fluctuations compared to selfish balancing in several regions in Europe.

Besides the short-term time scales ranging from minute to a few days, the weather follows a distinct seasonal time scale. Winds across Europe are stronger during winter than in summer. As a consequence,

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the wind power aggregated over all of Europe is larger in winter than in summer. This is shown in Fig. 1. In fact, the winter maximum is about double the summer minimum.

If wind were the only power source in a fictitious future Europe, then the seasonal wind power curve has to be directly compared to the European load curve. This is also illustrated in Fig. 1. In this 100% wind-only scenario the yearly average of wind power generation and load is the same. However, the seasonal behavior is different. The seasonal load curve also comes with a maximum in winter and a minimum in summer, but the seasonal variation strength is much smaller than for the wind power generation. As a consequence an enormous amount of stored and balancing energy is required. Over summer the storage and balancing plants have to feed the deficit. During winter the large wind power excess is put into the storage.

Like wind, also the solar community has its own solar-only answer to the first question of the first paragraph [2]. If solar were the only power source in another fictitious European future, then the seasonal generation curve would look like the orange one in Fig. 1. The solar power generation is much larger during summer than in winter. Since it anticorrelates with the seasonal load curve, a 100% solar-only scenario will lead to even larger seasonal storage and balancing needs than for the wind-only case.

Let us summarize Fig. 1 in another way. For Europe the seasonal wind power generation nicely correlates with the seasonal load behavior. The seasonal solar power generation anticorrelates with the seasonal load behavior. The seasonal wind and solar power variation strengths are roughly the same. Both are significantly larger than for the seasonal load.

When listening to these facts set by weather-driven mother nature, an idea is created immediately. Future Europe is able to counterbalance seasonal wind with solar power generation! Their share should be almost the same, with a small extra contribution from wind power due to its seasonal correlation with the load. Fig. 2 takes 60% from the wind curve and 40% from the solar curve of Fig. 1. The resulting curve is able to nicely follow the seasonal load curve. It is expected that this optimal mix brings seasonal storage and balancing needs to a minimum.

In this paper we will further quantify the seasonal optimal mix between wind and solar power generation in Europe, and the resulting seasonal storage needs. Due to the expected dominance of wind and solar power, all other renewable sources are neglected for the moment. Section 2 focuses on the European 100% wind-plus-solar-only scenario. Section 3 generalizes to transitional scenarios, where wind-plus-solar power generation contribute less than the load demand and where the rest is coming from fossil and nuclear power. The conclusion is given in Section 4. The Appendix describes the weather-driven time series modeling of the wind and solar power generation and the estimation of the load curve across all of Europe.

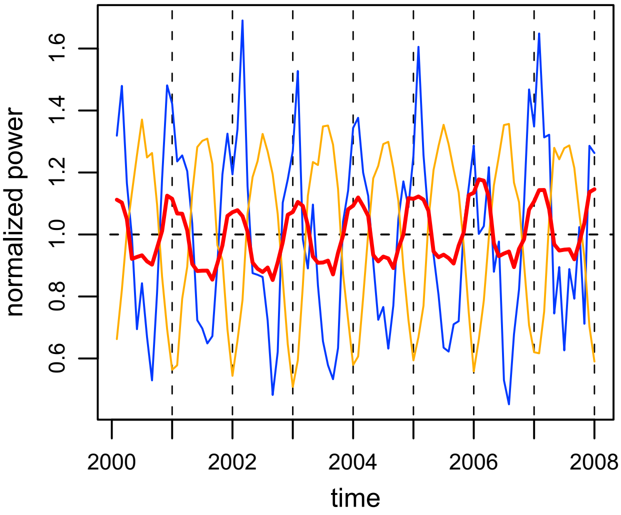

Fig. 1. Normalized wind power generation (blue), solar power generation (orange) and load (red) time series aggregated over Europe. Each series is shown in one-month resolution and is normalized to its 8 years average. More details on the calculation of all three seasonal curves are given in the Appendix. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

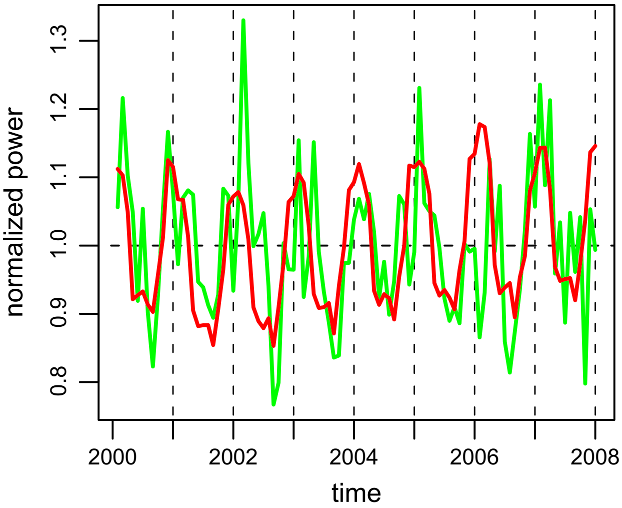

Fig. 2. Same as Fig. 1, only that the wind and solar power generation time series are combined with a 60%/40% weighting (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

This Paper is the first within a series of three. The two followups address the remaining questions of the first paragraph. They focus on a detailed analysis of the balancing and transmission needs in a future Europe with a very high share of wind and solar power generation [4,5].

2. The 100% wind-plus-solar-only scenario

Based on seasonal time series such as shown in Figs. 1 and 2 it is straightforward to quantify a seasonal optimal mix between wind and solar power generation in a 100% wind-plus-solar-only scenario for a future Europe. Key to such quantifications is the mismatch energy

$$\Delta(t) = a\frac{W(t)}{\langle W\rangle} + b\frac{S(t)}{\langle S\rangle} - \frac{L(t)}{\langle L\rangle}. \tag{1}$$

$W(t)$ represents the total European wind power generation during month t, and $\langle W\rangle$ its average over all 96 months contained in the eight-years-long time series. $S(t)$ and $L(t)$ are the respective solar power and load time series. The coefficients $a = \langle W\rangle/\langle L\rangle$ and $b = \langle S\rangle/\langle L\rangle$ tell how much of the load is on average covered by wind and solar power generation. For the 100% wind-plus-solar-only scenario these coefficients are constrained to $a + \mathrm{b} = 1$.

A first approach to quantify the seasonal optimal mix is to find the minimum of the standard deviation

$$\sigma_\Delta = \sqrt{\left\langle \Delta^2 \right\rangle - \langle\Delta\rangle^2} \tag{2}$$

of the mismatch energy as a function of $a = 1 - b$. Since any mismatch in the system requires balancing and the use of stored energy, σ_Δ can be regarded as a simple measure for balancing costs

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[6]. The standard deviation is shown in Fig. 3a. Its minimum comes at $a = 0.62$.

Another approach to the seasonal optimal mix constructs a simple storage model out of the mismatch energy [1]:

$$H(t) = H(t-1) + \begin{cases} \eta_{\text{in}}\Delta(t) & \text{if } \Delta(t) \geq 0, \\ \eta_{\text{out}}^{-1}\Delta(t) & \text{if } \Delta(t) < 0. \end{cases} \quad (3)$$

Whenever the mismatch is positive, the surplus generation is stored with efficiency η_{in}. In case of a negative mismatch the generation deficit is taken out of the storage with efficiency η_{out}. The time series $H(t)$ describes the filling level of the storage. Its maximum and minimum determines the maximum required stored energy

$$H_{\max} = \max_t H(t) - \min_t H(t). \quad (4)$$

It is equivalent to the size of the storage capacity. This quantity is shown in Fig. 3b as a function of the wind fraction $a = 1 - b$. It comes with a rather flat minimum at $a = 0.47$. The storage efficiencies have been set to $\eta_{\text{in}} = \eta_{\text{out}} = 1$. Also shown in Fig. 3b is the 90% quantile $Q(95\%) - Q(5\%)$ of the stored energy, which is determined from the distribution $p(H)$ and $\int_0^Q p(H)\mathrm{d}H = 0.95\ (0.05)$. This second variant of the required stored energy reveals a pronounced minimum at $a = 0.57$.

The used idealized storage efficiencies $\eta_{\text{in}} = \eta_{\text{out}} = 1$ are not realistic. Pumped hydro has $\eta_{\text{in}} = \eta_{\text{out}} = 0.9$ and hydrogen storage has $\eta_{\text{in}} = \eta_{\text{out}} = 0.6$. Since efficiencies smaller than one lead to storage losses, the wind and solar power generation has to be increased in order to compensate for the losses. The surplus generation factor $\gamma = a + b > 1$ is determined from the requirement that the storage level $H(t = 8\text{y}) = H(t = 0)$ reached after 8 years is equal to the initial storage level. It is important to note that due to the storage losses γ is depending on the time resolution. This is why for Fig. 4 we switch from monthly to hourly wind, solar and load time series. Fig. 4a shows that the smaller the storage efficiencies turn out to be the larger the maximum stored energy becomes. However, the location of the seasonal optimal mix does not change. The surplus generation factor is illustrated in Fig. 4b. For $a = b$ it amounts to $\gamma = 1.05$ (pumped hydro) and 1.28 (hydrogen).

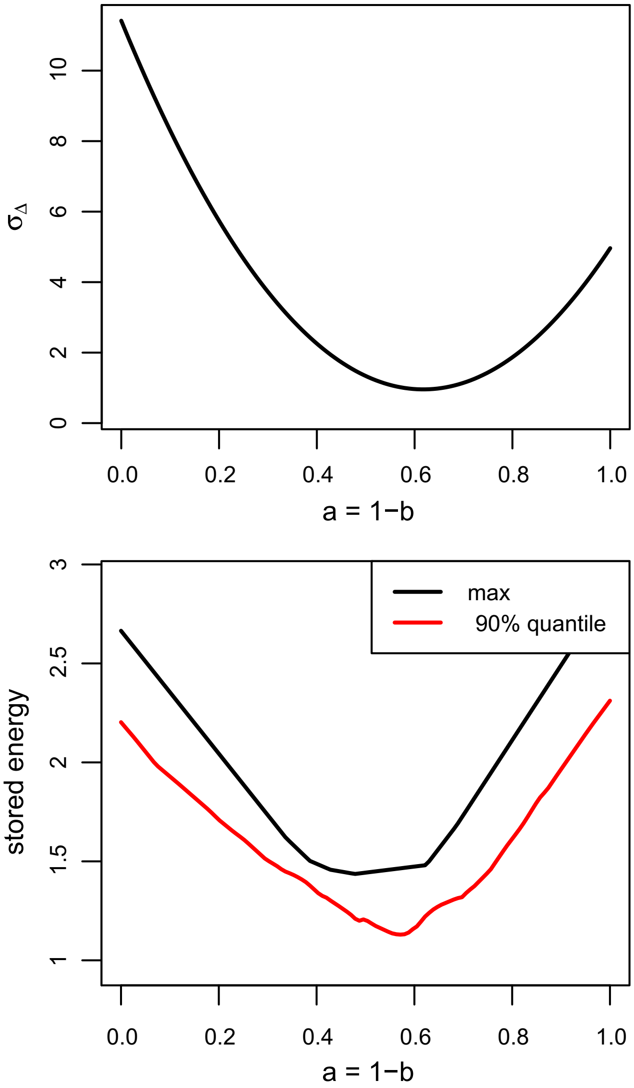

Fig. 3. (a) Standard deviation (2) of the mismatch energy (1) and (b) stored energy (3) as a function of the wind fraction $a = 1 - b$ in a 100% wind-plus-solar-only scenario for a future Europe based on monthly time resolution. For the storage energy its maximum (black) and 90% quantile (red) is shown. The unit of the stored energy is in average monthly load. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

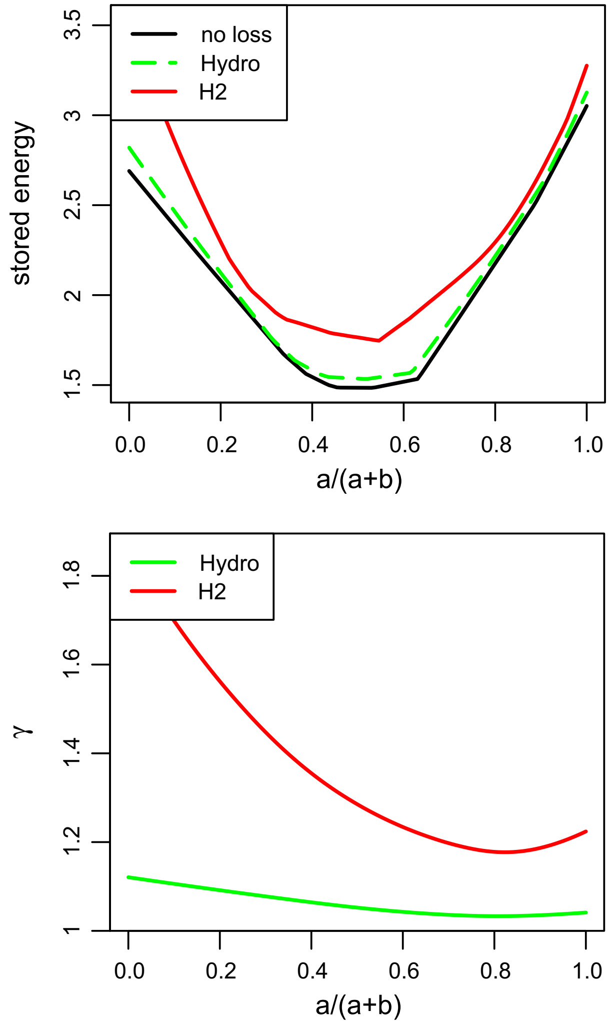

Fig. 4. (a) Comparison of the maximum stored energies for an idealized storage (black), pumped hydro (green) and hydrogen storage (red), derived from hourly wind, solar and load time series. The unit of the stored energy is in average monthly load. Within numerical uncertainties the black curve is identical to the black curve of Fig. 3b based on the monthly time series. (b) Surplus generation of wind and solar power needed to compensate the storage losses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

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The different approaches based on the standard deviation of the mismatch energy and the stored energy lead to a seasonal optimal mix of 50–60% wind and 50–40% solar power generation. These results agree nicely with the intuition obtained from the introductory Figs. 1 and 2.

From these findings on the seasonal optimal mix a few more conclusions can be given for a 100% wind-plus-solar-only scenario in a future Europe. Just for demonstration we freeze the average yearly load for all of Europe to its 2007 value, which is 3240TWh. 55% of this makes 1780TWh and requires 670 GW of installed wind power capacity; here the wind load factor 0.30 has been used, which has been directly determined from the used weather data. The remaining 45% make 1460TWh and require 810 GW of installed solar photovoltaic power; here the PV load factor 0.21 has been used, which again has been directly determined from the used weather data.

670 GW of installed wind power capacity across Europe translate into 335 000 2 MW turbines, or 135 000 5 MW turbines, or 4000 wind farms of the size of the first offshore wind farms Horns Rev I and Nysted. As a rule of thumb [7], one MW of installed capacity requires 0.07 km^2 onshore and 0.11 km^2 offshore, respectively. This translates 670 GW into 50,000 km^2 onshore or 75,000 km^2 offshore. For comparison, Denmark has an area of 43,000 km^2.

The spatial and temporal mean global radiation 169 W/m^2 is computed from the weather data and translates 1460TWh-producing 810 GW-installed solar photovoltaic power into a PV-panel area of 5000 km^2. For comparison, Germany has the potential to cover 1330 km^2 of roofs with ideal slopes and direction [8].

As can be seen in Figs. 3b and 4a, the required maximum stored energy has to be 1.5 (without storage losses) and 1.8 (for hydrogen storage) times the monthly load and amounts to 400 and 480 TWh, respectively. These are very large numbers. They will even double once future Europe decides to switch to a wind-only or a solar-only scenario.

Currently, Germany has about 190 GWh of pumped hydro facilities in operation, with only little room for more. The exact amount of pumped hydro across all of Europe is not known to us. Even if it is a factor of ten more, still two orders of magnitude are missing to reach the required 400–480 TWh.

New forms of bulk storage like hydrogen will be needed. Its storage density is 187 kWh/m^3, assuming a pressure difference of 120 bar and an efficiency of 0.4. This translates 400–480 TWh stored energy into a volume of 2.2–2.6 km^3, which does not appear to be completely out of reach.

3. Transitional scenarios with wind, solar and fossil-nuclear power

The investigations on the 100% wind-plus-solar-only scenario can be extended to transitional scenarios by modifying the mismatch energy (1) to

$$\Delta(t) = a\frac{W(t)}{\langle W\rangle} + b\frac{S(t)}{\langle S\rangle} + c\frac{F(t)}{\langle F\rangle} - \frac{L(t)}{\langle L\rangle}. \qquad (5)$$

$F(t) = \langle F\rangle$ represents fossil-nuclear power generation and is assumed to be time-independent. It may even include a contribution from geothermal power.

The three coefficients $a + b + c = 1$ add up to one and match the average load. The choice $a = 0.27$, $b = 0.00$, $c = 0.73$ leads to Fig. 5. The seasonal power generation curve follows the seasonal load curve more closely than for the $a = 0.60$, $b = 0.40$, $c = 0.00$ example shown in Fig. 2. This indicates already, that as long as a fraction of fossil-nuclear power remains in the generation mix the need for stored energy will be smaller than for the 100% wind-plus-solar-only scenario.

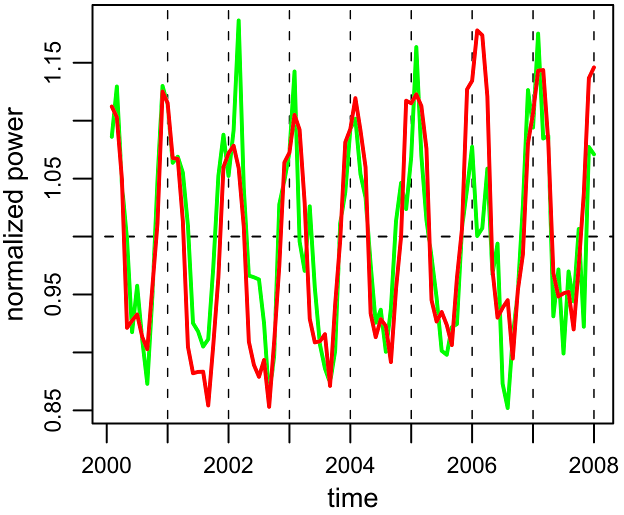

Fig. 5. A mix of 27% wind, 0% solar and 73% fossil-nuclear power generation (green) is also able to follow the (red) seasonal load curve. See Figs. 1 and 2 for comparison. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Fig. 6 shows the required maximum stored energy (4), which has been deduced from (3) with $\eta_{\rm in} = \eta_{\rm out} = 1$ and (5). It is a function of the two independent coefficients c and $a/(a + b)$. The smallest stored energy is obtained for $a = 0.27$, $b = 0.00$, $c = 0.73$, which are the values used for Fig. 5. For large fossil-nuclear fractions $1 \geq c \geq 0.73$ the stored energy reaches a minimum when only wind power generation covers the remaining fraction $a = 1-c$. This is because the seasonal wind power generation curve correlates with the seasonal load curve; confer again Fig. 1. Due to its anticorrelation it is not favorable to include solar power into the fossil-nuclear-dominated generation mix.

Solar power is needed once the fossil-nuclear power generation is reduced below $c < 0.73$. The seasonal solar power generation then has to counterbalance the seasonal wind power generation. Otherwise the absolute seasonal wind power variation would become larger than the absolute seasonal load variation. The

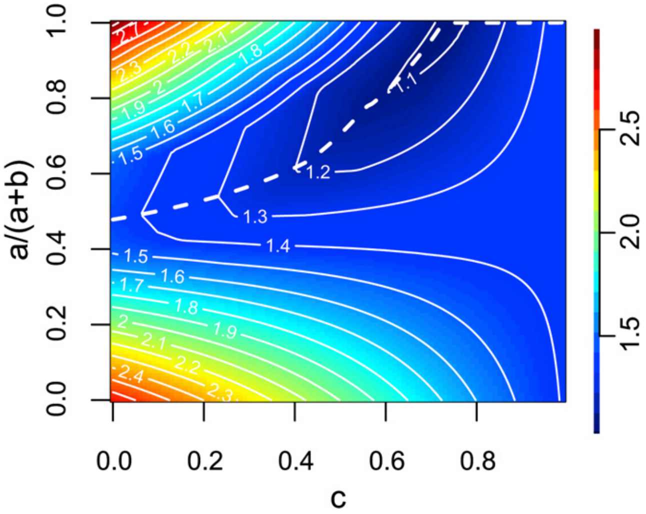

Fig. 6. Maximum stored energy (4) required for all of Europe as a function of the two independent coefficients c and $a/(a + b)$. The dashed curve represents the seasonal optimal mix between wind and solar power generation as a function of the remaining fossil-nuclear power generation. The unit of the contours is given in average monthly load over Europe.

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dashed curve in Fig. 6 follows the bottom of the storage valley and represents the seasonal optimal mix between wind and solar power generation as a function of the remaining fossil-nuclear power generation. In the limit $c \to 0$ the wind and solar coefficients $a \approx b \approx 0.5$ become about the same. Obviously, this result agrees with the earlier result obtained in Fig. 3b.

Let us follow the dashed optimal mix-curve once more, from right to left. At $c = 1$ the required maximum stored energy amounts to 1.36 times the average monthly load. From $c = 1$ down to $c = 0.73$ the required maximum stored energy decreases down to 1.08 times the average monthly load. From $c = 0.73$ to $c = 0$ the required maximum stored energy increases again and reaches 1.44 times the average monthly load at $c = 0$.

We close this Section with an additional remark. If the seasonal load curve had come with a maximum in summer and a minimum in winter, then the optimal mix curve would have been different. For a large fossil-nuclear fraction c close to one it would have been solar only with $b = 1-c$ and $a = 0$. Wind power generation will be necessary to counterbalance the reduced solar generation in winter once c becomes smaller. This might be of relevance for some large countries outside Europe.

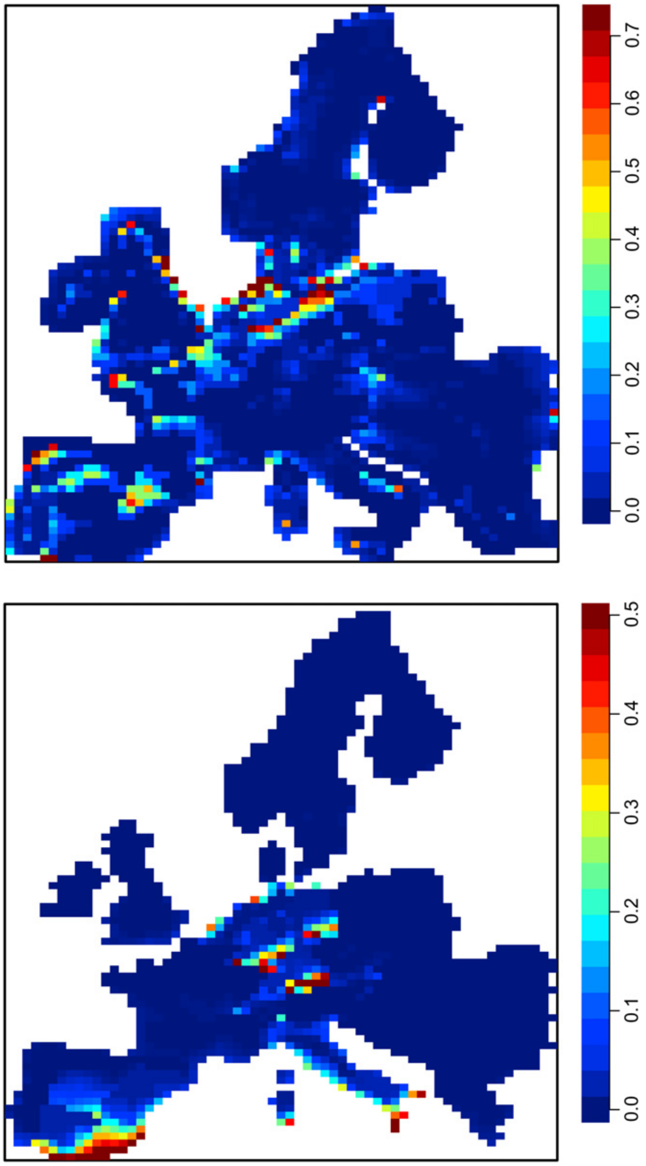

Fig. 7. Expected (a) wind power and (b) solar photovoltaics power capacities [GW] per grid cell across Europe in 2020. The spatial grid-cell resolution of 47×48 km^2 has been adapted to the weather data. For a better visualization capacities larger than 0.73 GW for wind and 0.50 GW for PV are indicated in dark red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

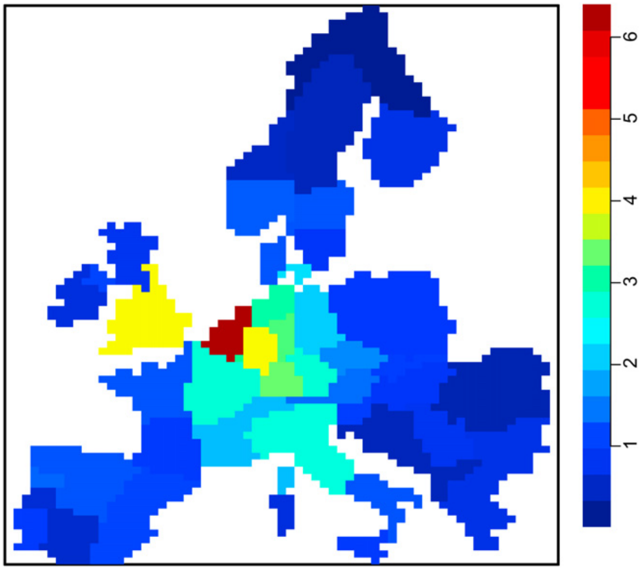

Fig. 8. Average annual load [TWh] per grid cell in the 50 coarse-grained onshore regions.

4. Conclusions

Besides short-term fluctuations, wind and solar power generation across Europe follow the seasonal cycle of the weather. Wind power generation in winter is much stronger than during summer. For solar power generation the summer season produces much larger yields than during winter. In this way mother nature determines how to design a future European power supply system based on a very high share of renewables. When mixed together in a specific ratio, the opposite strong seasonal behaviors of wind and solar power generation almost cancel each other and follow the weaker seasonal load behavior. For a European 100% wind-plus-solar-only scenario, this seasonal optimal mix is found to be 55% wind and 45% solar power generation. Compared to other scenarios like wind-only or solar-only, the optimal mix reduces the need for stored energy by a factor of two. The reduced stored energy for all of Europe amounts to 1.5–1.8 times its monthly load. For transitional scenarios with a fraction of fossil-nuclear power generation left in the system, the optimal mix between renewables is shifted in favor of wind power generation. This is because of the seasonal correlation between wind power generation and load across Europe.

We have addressed only a few of the key questions raised in the first paragraph of the Introduction. Answers to the other questions will be given in two subsequent publications [4,5]. With hourly data at hand (see Appendix), they will focus on the balancing-power and power-transmission needs across a future, highly renewable Europe.

5. Appendix: Modeling of wind-, solar power generation and loads

Key to the modeling of wind and solar power generation is a large weather data set with good spatial and temporal resolution all over Europe. Its convolution with future-projected wind and solar power capacities reveals how much wind and solar power is

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generated when and where across Europe. The following subsections will explain the details. The load modeling is described in the last subsection.

5.1 Weather data

Weather data for all of Europe is available from various sources with different spatial and temporal resolutions. For our purposes three selection criteria have been important: (i) In order to resolve the passing of synoptic systems related to high winds and opaque clouds a spatial resolution of at least $50 \times 50\ \mathrm{km}^2$ is required. (ii) The correct modeling of intra-day solar and wind power ramps require a good time resolution of at least 1 h. (iii) In order to gain representative and significant statistics covering all possible seasonal and extreme weather situations a rather long time window is required, ranging over a couple of years.

These criteria have been met by the private weather service provider WEPROG (Weather & Wind Energy Prognosis) [9]. With regional models it downscales medium-resolved analysis data from the US Weather Service NCEP (National Center for Environmental Prediction) [10] down to $47 \times 48\ \mathrm{km}^2$ spatial and 1 h time resolution over an eight-years period (2000–2007).

This high-resolution data provides direct information on the wind speed and direction 100 m above ground. The solar global radiation is not a standard output, but can be computed directly from the data on the net short wave radiation at the surface, the total cloud cover, and a standard cloud and surface albedo.

5.2 Wind and solar power capacities

The national 2020 targets serve as guidance for a rough distribution of wind and photovoltaic capacities in Europe. Fig. 7 illustrates the installed wind power and solar photovoltaics power capacities across Europe expected in 2020. They total to 227 and 68 GW, respectively. 66 GW of wind power is assumed to be installed offshore. The subsequent finer distribution within each country onto the grid cells of the weather data is done empirically, giving more capacity to those grid cells with large average wind speed and large average global radiation, respectively.

5.3 Wind and solar power generation

The conversion of hourly WEPROG wind speeds into wind power at each grid cell was done using typical wind power curves at 100 m hub height. Different power curves have been assigned for onshore and offshore grid points. Losses due to wake effects have been modeled explicitly for offshore grid points by assuming a park layout of 7×7 turbines in offshore wind farms. Additional 7% losses have been introduced due to electrical losses and turbine non-availability. The same 7% of losses have also been applied to onshore grid points. The turbine cut-off due to extreme winds is empirically parameterized by an additional modification of the power curve, which mimics the gradual power-lowering-behavior of wind turbines with storm-control.

The solar photovoltaic power generation within the grid cells has been calculated based on the available meteorological data (global radiation, air temperature), assumptions on the characteristics of the photovoltaic plants (tilt angle, orientation, fixed or with solar tracker) and the geographical coordinate of the grid cell considered. A mix of different photovoltaic plant technologies was considered for each grid cell.

This convolution of the weather data with the wind and solar power capacities produces spatio-temporal power generation patterns across Europe. These patterns are important for the calculation of power flows [5]. For the current paper we discard the spatial part and assume Europe to be one big copper plate. For each hour the total wind as well as solar power generation is integrated over all grid cells.

The blue time series in Fig. 1 shows the monthly wind energy integral over all of Europe. It is normalized to the monthly average over the 8 years period. Due to this normalization, also the same time series would have been obtained, if the wind power capacities of Fig. 7a had been upscaled. An upscaling factor of 5.2 turns 227 GW installed wind power capacity into 1180 GW. With 2650 full-load hours per year directly calculated from the used weather data, this then produces 3130TWh per year, exactly corresponding to the average annual European load between 2000 and 2007.

The orange time series in Fig. 1 shows the normalized monthly solar photovoltaics energy integral over all of Europe. Analogous to the arguments given for wind, also this time series does not change upon an upscaling of the solar photovoltaics power capacities of Fig. 7b. For a 100% solar photovoltaics power scenario the upscaling factor would be 25.5, turning 68 GW installed solar power capacity into 1730 GW. With 1800 full-load hours this then produces the load-equivalent 3130TWh per year. The orange solar time series may change in a certain direction, once solar thermal power complements photovoltaics. Since those plants would be installed mostly in southern Europe, the relative difference between the seasonal summer maximum and winter minimum is expected to become smaller to some extent.

5.4 Load modeling

It is impossible to retrieve the load profiles on the spatial $47 \times 48\ \mathrm{km}^2$ grid-cell scale set by the weather data. However, a coarser resolution is fine for our purposes. For almost all European countries the load profiles have been downloaded either from the UCTE-homepage [11] or from the national transmission providers. At least for the two recent years those have an hourly resolution. For the remaining six years they have been replicated with the known relative annual electric power consumption; special care was given to a proper handling of the weekend effect.

Some countries, especially the larger ones, come with a very large average load. Those have been further subdivided into regions, with some spatial correlation to the territories of the respective network transmission providers. The regional load profiles have been obtained from the country profiles with a multiplicative factor obtained from a linear regression between the annual electric power consumption on the one hand and population and gross domestic product on the other hand.

Fig. 8 shows the average annual load of the 50 onshore regions during the years 2000–2007. Offshore regions come with no load and are not shown. The sum over all regions totals to 3130TWh annual consumption. Its seasonal dependence is shown in Fig. 1. Note, that for the seasonal storage calculations in Sections 2 and 3 the European load curve has been detrended.

References

[1] Lu X, McElroy M, Kiviluoma J. Global potential for wind-generated electricity. Proc Natl Acad Sci USA 2009;106:10933–8.

[2] Jacobson M, Delucchi M. A path to sustainable energy by 2030. Sci Am; Nov 2009:58–65.

[3] von Bremen L, Greiner M, Knorr K, Hoffmann C, Bofinger S, Lange B. A full renewable power supply scenario for Europe - the weather determines storage and transport, In: Proc. of the 8th Int. workshop on large-scale integration of wind power into power systems as well as on transmission networks for offshore wind farms, Bremen, Germany; October 2009.

[4] Heide D, von Bremen L, Greiner M, Hoffmann C. Storage and balancing needs in a future Europe with only wind and solar power generation, in preparation.

[5] Heide D, Knorr K, von Bremen L, Greiner M, Hoffmann C. Transmission needs for a cooperative future Europe with a very high share of wind and solar power generation, in preparation.

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[6] von Bremen L. Large-scale variability of weather-dependent renewable energy sources. NATO science for peace and security series -C: environmental security. In: Troccoli A, editor. Management of weather and climate risk in the energy industry. Springer, ISBN 978-90-481-3691-9; 2009.
[7] DENA, Energiewirtschaftliche Planung für die Netzintegration von Windenergie in Deutschland an Land und Offshore bis zum Jahr 2020, Köln [accessed 24.02.05].
[8] Quaschning V. Systemtechnik einer klimaverträglichen Elektrizitätsversorgung in Deutschland für das 21.Jahrhundert, Fortschritt Berichte VDI, Reihe 6, Nr. 437. Düsseldorf: VDI Verlag; 2000.
[9] http://www.weprog.de/.
[10] http://www.ncep.noaa.gov/.
[11] http://www.ucte.org/resources/dataportal/consumption/.

Please cite this article in press as: Heide D, et al., Seasonal optimal mix of wind and solar power in a future, highly renewable Europe, Renewable Energy (2010), doi:10.1016/j.renene.2010.03.012