Energy xxx (2014) 1–10

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

The potential for arbitrage of wind and solar surplus power in Denmark

Gorm B. Andresen [a,*], Rolando A. Rodriguez [b], Sarah Becker [c], Martin Greiner [a,b]

[a] Department of Engineering, Aarhus University, 8200 Aarhus N, Denmark
[b] Department of Mathematics, Aarhus University, 8000 Aarhus C, Denmark
[c] Frankfurt Institute for Advanced Studies, Frankfurt University, 60438 Frankfurt am Main, Germany

ARTICLE INFO

Article history:
Received 8 November 2013
Received in revised form
27 February 2014
Accepted 8 March 2014
Available online xxx

Keywords:
Energy system design
Variable renewable energy
Large-scale integration
Energy storage
Wind power
Solar power

ABSTRACT

We have recently developed a simple yet powerful method to identify key properties of electricity systems with a high share of renewables. Here, our weather-driven methodology is described and applied to model the Danish power system with combined wind and solar energy gross shares of up to 100% of the total demand. We show that in a wind only scenario, surplus energy grows rapidly beyond gross shares of about 50%, while the potential for arbitrage of surplus renewable energy, i.e. demand-side management or high-efficiency storage, is very limited in this case. A scenario with a wind-solar energy mix of 80/20, on the other hand, both decreases the total amount of surplus and has a significantly higher potential for arbitrage of the remaining surplus. However, beyond gross shares of about 75%, only large-scale seasonal storage of, e.g. hydrogen, enables the use of Danish surplus wind and solar energy to cover the residual Danish electricity demand in both scenarios.

1. Introduction

In the ARESG (Aarhus Renewable Energy Systems Group), we have recently developed a simple, yet powerful method to identify key properties of a fully or partly renewable power system. Here, we dub it WDRESM (Weather-Driven Renewable Energy System Modeling). So far, the approach has primarily been applied to a fully renewable pan-European power system, where the future needs for storage, balancing and transmission capacity have been assessed, and a number of synergies between different technologies have been identified [1–5]. Central to WDRESM is the ability to provide a solid benchmark for the integration of VRES (variable renewable energy sources) in the power system, independently of regulatory and economical constraints. We do this by identifying and mapping fundamental properties of the system directly from the analysis of large-scale and high-resolution weather data and detailed historical consumption data. Largely owing to its simplicity and to the extent and detail of the underlying data, nearly any geographic and temporal scale can be modeled.

In this paper, the model is scaled to the Danish power system, where the excellent wind resources are expected to fuel a transition to a renewable power system with a share of VRE (variable renewable energy) which exceeds that of conventional sources [6]. But also solar PV (photovoltaic) may come to play a significant role in the future.

Wind and solar power generation cannot be expected to match the instantaneous demand for electricity, and it is well known that VRE surplus is unavoidable at high penetrations. By combining wind and solar PV, it is possible to optimize the match between the hourly production and consumption patterns and, thus, to reduce surplus VRE in the system [1,2,7]. In addition, arbitrage of surplus VRE, using technologies that allow the energy to be moved in time by using either flexible demand or some form of storage, can be applied to increase the local use of the wind and solar resource.

In this paper, we quantify the minimum amount of surplus VRE in Denmark for any combination of annual wind and solar PV production. We then proceed with a detailed investigation of the interplay between energy arbitrage technologies and surplus VRE for two different scenarios. In one case, we assume that only wind power is built in Denmark. In the other, an optimized wind–solar energy mix is used. For both we show how the energy capacity of a generalized storage unit affects its ability to redistribute surplus VRE. We then analyze the impact of constraining the storage

* Corresponding author.
E-mail addresses: gba@eng.au.dk, 173126@uni.au.dk (G.B. Andresen).

http://dx.doi.org/10.1016/j.energy.2014.03.033
0360-5442/© 2014 Elsevier Ltd. All rights reserved.

charging and discharging power capacities. Finally, we use a simple market model to estimate how many storage units VRE surplus can support in the Danish power system.

Monetary cost of implementing different combinations of wind, solar or energy arbitrage technology is not quantified. Instead, we present and compare the benefit of a wide range of combinations of the three. But since cost projections are abundant [8–11], although with high uncertainties attached, we invite the reader to make his or her own cost estimates.

The effect of combining different VRES in the Danish power system has also been investigated in Ref. [7] for a specific set of technical and regulatory constraints. The results presented here are calculated without any such constraints, and can be viewed as a best case benchmark for what can be achieved by changing the constraints.

Several studies analyze the detailed interaction between high wind penetrations and storage technologies in Denmark and other countries. Typically, a specific technology like PHS (pumped hydro storage) [12,13] or CAES (compressed air energy storage) [14], is analyzed. In this paper, a top-down approach is used to simplify the analysis and generalize the findings. The aim is to allow a broader and more focused discussion of how and if energy arbitrage should be supported to facilitate integration of surplus VRE. In addition, we show how the wind–solar mix has a direct impact on the potential for arbitrage of surplus VRE.

The stoRE project has recently published a report on combining wind power and storage in Denmark [15]. They use a similar methodology as that presented here. But the concept of storage neutrality (see Ref. [3]) is ignored and as a consequence the storage dispatch time series, energy and power capacity estimates are incorrect.

This paper is organized as follows: In Section 2, WDRESM is described. Section 3 is a case study, where WDRESM is applied to analyze the interplay between wind, solar power and energy arbitrage in a future highly renewable Danish power system. Section 4 concludes the paper.

2. Methodology

2.1. General remarks

The central idea in WDRESM is to include the correct temporal and spatial correlation structure of VRES, as these technologies will dominate the dynamics of a future highly renewable energy system. This is achieved by basing the model on high-resolution weather and electricity load data that includes large areas and spans many years. Specifically, normalized time series of wind and solar power generation and electricity load data are currently the only external input. In addition, we reduce the complexity of the model by assuming very few technical constraints and employing optimal operational strategies.

As a result WDRESM can provide hard upper limits on what can be accomplished by better international power network integration [5,4], better technology or better market design [16]. This means that more detailed models have a solid frame of reference or benchmark to be measured up against. At the same time, our results provide precise boundaries for policy makers, allowing for a simpler analysis and a clearer presentation. The price is that a more detailed model is necessary in order to give useful answers to questions regarding specific implementation of, e.g. storage and other dispatchable technologies. Any considerations regarding economic costs are not included in the current implementation of WDRESM.

Three of the most scalable renewable energy sources are wind, solar and biomass. Of these, biomass stands out as being dispatchable, meaning that it can be used for balancing the variable renewable energy sources such as wind and solar power. In WDRESM, dispatchable technologies are not modeled explicitly, as their power output is assumed to exactly match the residual load. Besides wind and solar power, one of the most important non-dispatchable power sources is run-of-river hydropower. Although run-of-river contributes significantly to the present-day power systems of Europe with a few per cent of the total generation, the perspective for future growth is highly limited [17]. However, if data becomes available to us, it is straight-forward and an obvious choice to include. Therefore, only wind and solar power is currently included.

Finally, WDRESM is relatively computationally simple, which means that we do not only provide results for a few end-points, or for a pathway to any such. Rather, we are able to provide a continuous map of results for any combination and penetration level of wind and solar power generation see Refs. [1–5,18].

In the following, WDRESM and our current input wind, solar and electricity load data is described in more detail. The description here applies to a power system with no region-internal transmission bottlenecks. WDRESM can also be combined with constrained transmission flow algorithms. This is the topic of Refs. [4,5].

2.2. Model implementation

2.2.1. Wind and solar PV

Historical weather data with hourly resolution was used to derive potential wind and solar PV power generation time series per MW installed, $w_n(t)$ and $s_n(t)$, for a total of about 2600 grid points in Europe (indexed by n) for the 8-year period 2000–2007. The grid points are spaced by approximately 50-by-50 km^2, and cover 27 European countries including offshore regions. This data set was produced by the German ISET (Fraunhofer-Institut für Solare Energieversorgungstechnick) (now known as the Fraunhofer institute IWES (Fraunhofer-Institut für Windenergie und Energiesystemtechnik)), in 2008, and is described in more detail in Refs. [1,19]. Fig. 1a and b shows the geographical extent of the wind and solar PV data as well as the spatial distribution of their average annual capacity factors. The choice of wind turbine and solar PV technologies represents a best guess for technologies commonly used in the year 2020.

In most of our studies, we aggregate all grid cells belonging to a specific region, such as a common price area, a country, or all of Europe. This means that the absolute generation of wind and solar power time series of all grid cells within this region is added to obtain the generation time series for the entire region. The aggregated wind power time series for a region is calculated as

$$w(t) = \sum c_n^{w} w_n(t) \tag{1}$$

and for solar power the corresponding time series is

$$s(t) = \sum c_n^{s} s_n(t) \tag{2}$$

That is, potential region-internal transmission bottlenecks are neglected. The geographical wind and solar PV power capacity layout c_n^w and c_n^s used in this aggregation, i.e. how many MW of wind and solar capacity are installed in grid cell n, can be varied. In the studies presented here, they are based on a combination of attractiveness of sites as well as political goals for 2020. As a consequence, we implicitly assume a larger effect of geographical dispersion than what can be observed today. The reason being that significantly more sites are assumed to have installed capacities of wind and solar PV. Fig. 1c and d show excerpts of monthly and hourly time series aggregated for Europe. Fig. 2 illustrates the effect of spatial aggregation, which is also discussed in, e.g. Refs. [20,21].

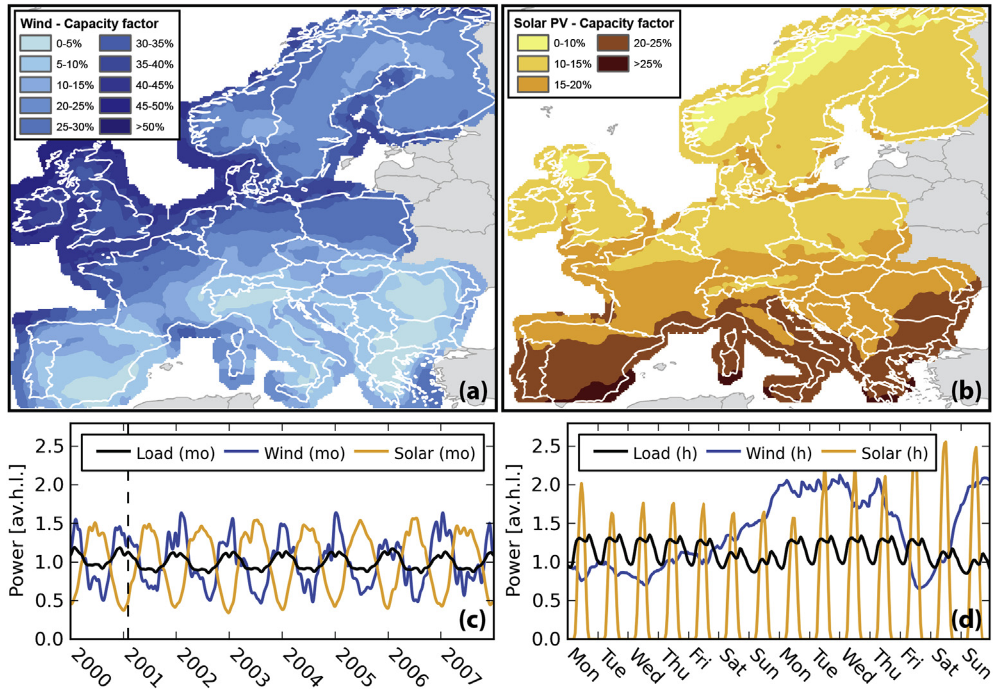


Fig. 1. Panels a and b illustrate the geographical extend of the data set, which covers 27 European countries including offshore regions. In color we show: (a) Annual wind power capacity factor, and (b) annual solar PV power capacity factor. Panels (c) and (d) show normalized monthly and hourly averages of wind and solar PV power generation and electricity demand aggregated for all 27 countries. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2.2. Electricity load

In addition to weather data, historical load data with hourly resolution were obtained for all countries. They were either downloaded directly from UCTE (Union for the Coordination of the Transmission of Electricity) (now ENTSO-E) [22] for the same 8 years, or extrapolated from UCTE data for countries where load data were not available throughout the 8-year simulation period. For additional details see Refs. [1,19]. Finally, the load time series of each country was detrended from an average yearly growth of about 2%. Excerpts of monthly and hourly load time series aggregated for Europe are shown in Fig. 1c and d.

2.2.3. Generation-load mismatch

The central equation in WDRESM is the generation-load mismatch described by Eq. (5) below. In our implementation, the power generation time series $w(t)$ and $s(t)$ and the load time series $l(t)$ are all normalized to the average electrical load, yielding three new time series, $W(t)$, $S(t)$ and $L(t)$, see Eq. (3). Results are then either presented in units of av.h.l. (average hourly load), av.y.l. (average yearly load) or scaled to 2007 values. In the equations below, $\langle\cdot\rangle$ denotes the direct average of the time series in question.

$$\begin{aligned} L(t) &= \frac{l(t)}{\langle l\rangle}\text{av.l.h.},\\ W(t) &= \frac{w(t)}{\langle w\rangle}\text{av.l.h.},\\ S(t) &= \frac{s(t)}{\langle s\rangle}\text{av.l.h..}\end{aligned} \tag{3}$$

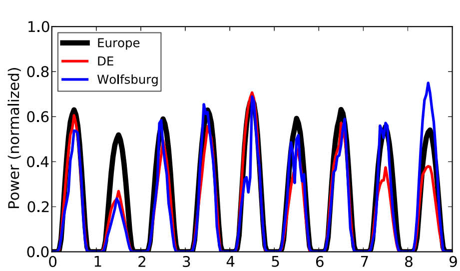
So

$$\langle L\rangle = \langle W\rangle = \langle S\rangle = 1\ \text{av.l.h.} \tag{4}$$

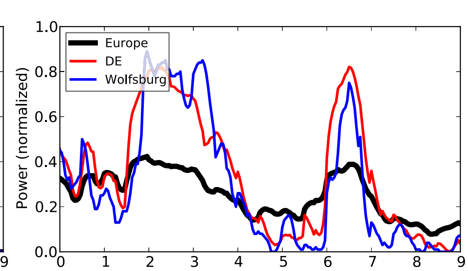
Using this notation, the generation-load mismatch time series $\Delta(t)$ is given as

$$\Delta(t) = \gamma[\alpha_W W(t) + (1-\alpha_W)S(t)] - L(t) \tag{5}$$

Here, α_W denotes the wind power fraction of the average wind and solar power generation, and γ represents the gross share of combined wind and solar PV, i.e. their average output divided by the average load. As an example, a gross share of 100% corresponds to



(a) Solar PV



(b) Wind

Fig. 2. Example of aggregating (a) solar PV and (b) wind power generation over areas of different geographical extend. Here, a European aggregation is compared to aggregating only Germany and to a single location (Wolfsburg) in Germany. It is evident that the effect of aggregation is most significant for wind power. Both time series are normalized to the installed capacity. (a) Solar PV. (b) Wind.

$\gamma = 1$, and an α_{w} of 0.8 corresponds to a wind–solar mix where 80% of their combined average output originates from wind. This is also referred to as an 80/20 wind–solar mix.

2.2.4. Storage

Many different storage dispatch algorithms can be implemented in WDRESM. Here, we employ a storage algorithm that can be mathematically proven to maximize redistribution of VRE surplus to hours where a residual load remains (Eqs. (6) and (7), below). In this implementation, VRE surplus is always stored whenever it is available and the storage volume is not full. Likewise, stored energy is always used to cover residual load as soon as possible. This storage algorithm is discussed further in Ref. [3] for the case where charging and discharging power capacities are assumed unconstrained. In Section 3.6 of this paper, the consequence of constraining these capacities is explored.

Eqs. (6) and (7) describe the basic mathematics of the model in terms of the storage volume C_{s}, the storage filling level time series H and charging and discharging efficiencies η_{in} and η_{out}.

$$H(t) = \begin{cases} C_{\mathrm{s}}, \text{ for } H(t-1) + \widetilde{\Delta}(t) > C_{\mathrm{s}} \\ 0, \text{ for } H(t-1) + \widetilde{\Delta}(t) < 0 \\ H(t-1) + \widetilde{\Delta}(t), \quad \text{otherwise} \end{cases} \tag{6}$$

where $\widetilde{\Delta}(t)$ is given by the equation

$$\widetilde{\Delta}(t) = \eta_{\mathrm{in}}\Delta_{+}(t) - \eta_{\mathrm{out}}^{-1}\Delta_{-}(t) \tag{7}$$

The filling level of the first hour, i.e. $H(0)$ is determined such that it matches the final storage level to ensure that energy is not added or subtracted from the system. Notice that the generation-load mismatch is split in to its positive component Δ_{+} and minus its negative component Δ_{-} in Eq. (7).

In the equations above, storage charging and discharging capacities, P_{in} and P_{out}, are assumed to be unlimited. In the case where these capacities are constrained, Eq. (7) must be modified to

$$\widetilde{\Delta}(t) = \eta_{\mathrm{in}}(\Delta_{+}(t) \wedge P_{\mathrm{in}}) - \eta_{\mathrm{out}}^{-1}(\Delta_{-}(t) \wedge P_{\mathrm{out}}), \tag{8}$$

where $(x \wedge y)$ denotes the minimum of x and y. This modification is used in Sections 3.6 and 3.7, below.

2.2.5. Optimal wind–solar mixes

WDRESM can be used to determine different optimal mixes of wind and solar power. In the papers [1–3,5,4], the characteristics of the European generation-load mismatch time series have been used to determine the balancing optimal wind–solar mix as well as the storage optimal wind–solar mix. Below, these mixes are expressed in terms of the wind share in the following way. The balancing optimal wind–solar mix is defined as:

$$\alpha_{\mathrm{w,balancing\ optimal}} = \min_{\alpha_{\mathrm{w}}} \sum_{t} \Delta_{-}(t, \alpha_{\mathrm{w}}) \tag{9}$$

where the total balancing energy required when insufficient VRE is available is minimized.

The storage optimal wind–solar mix minimizes the requirements for large-scale seasonal storage and is calculated as

$$\alpha_{\mathrm{w,storage\ optimal}} = \min_{\alpha_{\mathrm{w}}} C_{\mathrm{s,seasonal}}(\alpha_{\mathrm{w}}) \tag{10}$$

where the minimum sufficient seasonal storage capacity $C_{\mathrm{s,seasonal}}$ is at a minimum. Details on how to calculate $C_{\mathrm{s,seasonal}}$ can be found in Ref. [3].

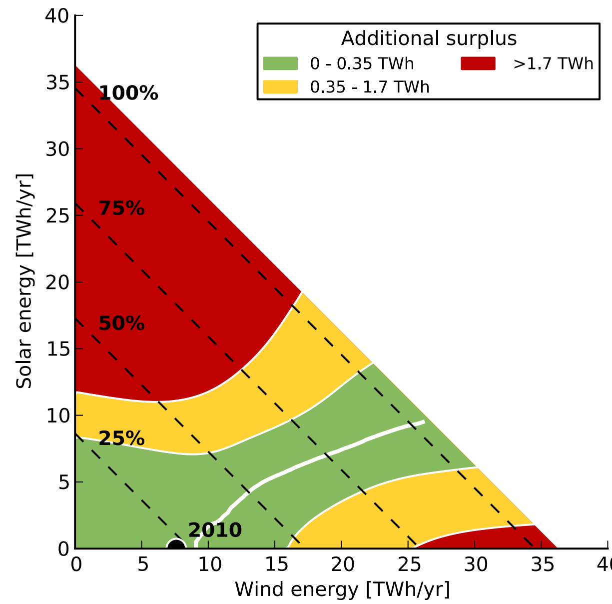


Fig. 3. Color map showing the balancing optimal build-up of wind and solar PV in Denmark (2007 units). The colored contours indicate the amount of VRE surplus that is incurred in addition to the balancing optimal amount for any combination of wind and solar PV energy up to a VRE gross share of 100%. The white line shows the balancing optimal mix, and the dashed lines indicate constant VRE gross shares (γ). The total amount of VRE surplus is shown for selected scenarios in Fig. 4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Case study: the potential of short-term storage to integrate wind and solar surplus in Denmark

One of the official Danish targets for energy is to supply all power and heat from renewable energy sources by 2035 [6]. In this case study, we focus on the role of wind and solar PV in the electricity sector. Currently, the total wind power generation in Denmark corresponds to more than 30% of the electricity consumption. In 2020, the number is targeted to become 52%, and by 2035, wind power generation is expected to correspond to between 75 and 80% of the electricity demand [6,23]. In comparison, the amount of solar power is low, although the installed capacity has seen a large relative increase from 1.4 MW at the beginning of 2011 to more than 200 MW by the end of 2012. Recently, the first Danish long-term target of 800 MW solar PV in 2020 has been announced. This solar capacity would generate about 2% of the annual electricity demand.

In the case study presented here, we define two future scenarios for Denmark. In the first scenario, called wind only, we assume that wind power becomes the only VRES in the country. This scenario is roughly consistent with current political plans. The second scenario is called balancing optimal mix. Here, wind and solar energy is combined to reduce total VRE surplus generation. For reasons explained in Section 3.1 below, one can assume a fixed wind–solar mix of about 80/20 for the second scenario. Thus, this scenario features a significant amount of solar PV.

In the following, we apply WDRESM to derive key properties of i) the total minimum amount of wind and solar surplus energy (VRE surplus) for the two scenarios, and ii) the interplay between short-term round-trip storage and the wind–solar mix. In particular, we calculate an upper bound on the ability of arbitrage of VRE surplus to increase the use of the Danish VRE production in Denmark. Here, round-trip electricity storage is used to model energy arbitrage, but very similar results would apply to demand-side management as well.

3.1. Reducing VRE surplus by mixing wind and solar power in Denmark

The absolute minimum amount of hourly VRE surplus is calculated as the sum of VRE generation that exceeds the hourly demand. Here, it is expressed as the positive part of the generation-load mismatch as given by Eq. (5). In the absence of round-trip electricity storage, we can determine that VRE surplus from Danish sources must begin to grow significantly when the VRE gross share approaches about 50% of the average demand. Exactly when VRE surplus cannot be avoided depends on the wind–solar mix.

The balancing optimal wind–solar mix, defined in Eq. (9), minimizes VRE surplus and is about 75/25 for an isolated, highly renewable Danish power system [4]. In Fig. 3, the balancing optimal mix is indicated (white line) as a function of the annual wind and solar energy in Denmark. The figure also shows the amount of additional VRE surplus incurred by deviating from the optimal mix. Clearly, only little additional surplus is incurred for gross shares lower than about 25%. After this point, deviations from the optimal path become more important as the path narrows for increasing gross shares. However, even at a gross share of 100%, the wind–solar mix can still vary by about ±10% without significant increase in VRE surplus. If the effect of international transmission is included, a balancing optimal mix of 80/20 is more accurate [5]. So, since Denmark is well connected with transmission lines to the neighboring countries, a balancing optimal mix of 80/20 can be assumed, when simplicity is required.

The effect of combining wind and solar power to minimize VRE surplus in Denmark is illustrated in Fig. 4 for the wind only and the balancing optimal mix scenarios. It can be seen that VRE surplus starts to grow at gross shares of about 50%, and the optimal mix can significantly reduce the amount of VRE surplus for gross shares between about 50 and 75%. However, for a gross share of 100%, the amount of VRE surplus has grown to about 25% of the total VRE production, even for an optimized wind–solar mix. For the wind only scenario, the total amount of VRE surplus corresponds to about 33%. At this point, the total surplus increases by 0.75–0.8 TWh per additional TWh of produced wind and solar PV. Only between 20 and 25% of the additional production can be used directly to cover the Danish demand.

In Ref. [7], H. Lund applied the energy system analysis tool EnergyPLAN to identify the wind, solar and wave power mix that minimizes total surplus electricity generation from both conventional and renewable sources for different gross shares of VRES in a Danish reference system. He finds a total surplus generation which is significantly higher than that identified above. However, a large though unspecified fraction of the surplus in Ref. [7] clearly originates from conventional power plants due to a combination of a regulatory framework and strict requirements to ancillary grid services from large central units. As an example, 30% of the power must come from conventional units at any hour. In the case of a wind-only scenario, the effect of changing these requirements is explored in Ref. [24].

These analyses are highly relevant in the context of improving the system integration of VRES in to the reference system. However, the studies do not identify a solid lower bound on VRES surplus. WDRESM, on the other hand, includes no technical, regulatory or economical constraints, and it is designed to identify the best possible integration of VRES. Thus, by comparing results from WDRESM and detailed analysis tools such as EnergyPLAN, one can distinguish between fundamental limitations to the integration of VRES and limitations induced by technical, regulatory or economical constraints. The simple requirement of 30% power from conventional units, mentioned above, is mathematically equivalent to multiplying the gross share in Eq. (5) by $1/(1-0.3)$. As an example, a gross share of 50% in this paper is roughly equivalent to 70% in Ref. [7].

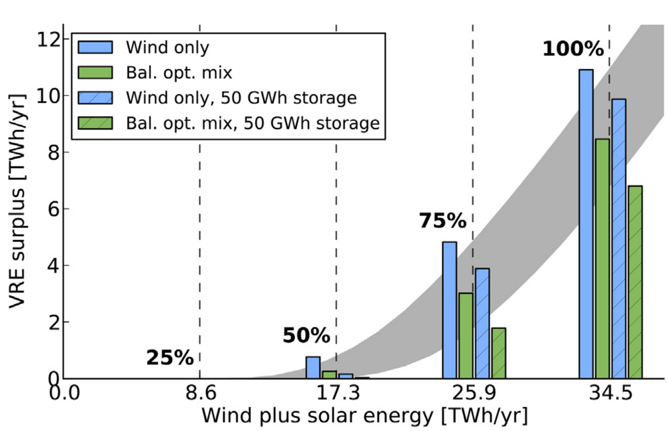


Fig. 4. Minimum annual VRE surplus from wind and solar PV in Denmark (2007 units). Results are shown for the wind only (blue) and the balancing optimal mix (green) with and without a 50 GWh storage included. Dashed lines indicate VRE gross shares (γ) of 25, 50, 75 and 100%. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Short-term storage for Denmark

Another way to reduce VRE surplus is to use storage or flexible demand to redistribute the VRE surplus to hours where it can be used directly. A seasonal storage that can redistribute all surplus takes this idea to the extreme and requires very large storage volumes [1–3]. However, a storage that is small compared to seasonal storage can be used to reduce VRE surplus significantly, and, relative to its size, it has a large potential to reduce VRE surplus in the electricity supply. As an example, a storage volume of 10 GWh can provide up to 34% of the benefit from a seasonal storage of 372 GWh, if a VRE gross share of 75% and a balancing optimal wind–solar mix is assumed. Here, any storage with a volume less than 50 GWh is considered as a short-term storage, in order to have a simple and convenient definition. With this definition, the short-term storage can, in principle, be cycled once per day as 50 GWh corresponds to about 12 times the average hourly electricity demand of 3.9 GWh in Denmark (2007 value). A seasonal storage, on the other hand, will typically require weeks or month to cycle.

For Denmark, between 1 and 50 GWh of storage will require large-scale deployment of storage and/or load displacement technology. But unlike a seasonal storage, many different storage technologies with a high round-trip efficiency could contribute significantly to a short-term storage. An example of direct physical storage could be CAES (compressed air energy storage) [14]. These have a typical volume of a few GWh and a round-trip efficiency of up to 89% [10]. Another popular example could be the batteries of EV (electrical vehicles). Today, about 2 mio. cars are registered in Denmark. If all were equipped with a typical EV battery of about 25 kWh, the total potential approaches 50 GWh with a round-trip efficiency of about 90–100% [10]. Virtual storage such as load displacement can have a near 100% round-trip efficiency, and if, e.g. 10% of the load could be shifted by 12 h on demand, it would correspond to about 5 GWh. Finally, a strong coupling between heating and electricity can also provide virtual storage in the GWh range [25].

In Fig. 4, the impact of a 50 GWh storage with a 100% round-trip efficiency is illustrated for the wind only and the balancing optimal mix scenarios. Notice that there is a synergy between the optimal wind–solar mix and storage, in particular for high VRE gross shares.

Please cite this article in press as: Andresen GB, et al., The potential for arbitrage of wind and solar surplus power in Denmark, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.03.033

This means that the reduction in VRE surplus when going from a wind only scenario to a balancing optimal mix is larger with the storage than it is without.

3.3. The ability of short-term storage to integrate VRE surplus

In this analysis, the success of a storage unit is measured as its ability to redistribute VRE surplus. By definition, a seasonal storage can redistribute all VRE surplus and it represents a full solution to the integration of VRE in the electricity supply. A short-term storage, on the other hand, cannot cycle all VRE surplus, but it can have a much greater impact per unit volume. If the amount of VRE surplus that remains when a short-term storage is in place is relatively small, it may be considered as a sufficient solution to the integration of VRE. Here, the short-term storage is considered to be a sufficient solution when the remaining surplus is less than 0.35 TWh/yr (1 pp (percentage point) of the demand). In the range 0.35–1.7 TWh/yr (1–5 pp of the demand), it is considered to be nearly sufficient, and beyond 1.7 TWh (5 pp), it represents an insufficient solution. The minimum VRE surplus remaining when a short-term storage with a round-trip efficiency of 100% has been applied is shown in Fig. 5a and b as a function of the VRE gross share and the storage volume. Fig. 5a shows the results for the wind only scenario, and 5b the corresponding results for the balancing optimal mix. In general, the remaining surplus decreases with increasing storage volume and increases with increasing gross share.

Because the total amount of surplus is smallest for the balancing optimal wind–solar mix, storage is needed later in this case and the short-term storage represents a sufficient solution for a larger range of VRE gross shares. As an example, a storage of up to 50 GWh is a sufficient solution for gross shares in the interval 44–60% in the wind only scenario. For the balancing optimal mix, the range is 50–70%. The short-term storage has a larger effect on reducing surplus for the balancing optimal mix because surplus appears more frequently and in smaller quantities at a time. Thus, the storage is less likely to overflow and it can be emptied before surplus appears again.

3.4. Storage throughput per unit volume

A direct measure of the storage throughput per unit volume is the average cycle count N_{cycles}. The average cycle count relates the discharge energy, $E_{\mathrm{discharge}}$, to the storage volume, C_s, and it expresses the throughput of the storage in units of its volume:

$$E_{\mathrm{discharge}} = \left(N_{\mathrm{cycles}} C_s\right) \Big/ \eta_{\mathrm{discharge}}, \tag{11}$$

where $\eta_{\mathrm{discharge}}$ is the discharge efficiency of the storage. In this paper, N_{cycles} is measured in the unit of average cycles per year (yr^{-1}). In this unit, it has a similarity to the term FLH (full load hours) in the sense that like for FLH, the annual output to the grid can be calculated directly from N_{cycles}. The annual input to the storage can be calculated using a similar relation.

In Fig. 5c and d, the maximum possible average cycle count is shown as a function of VRE gross share and storage volume for a wind only and a balancing optimal wind–solar mix, respectively. The cycle count decreases with an increasing storage volume, since it takes longer to charge and discharge, and it increases with the gross share, as more surplus becomes available. When the two figures are compared, it is clear that a balancing optimal mix leads to a significantly higher cycle count in most cases. Cycle counts larger than about 150 yr^{-1} are not possible in the wind only scenario despite the fact that surplus is much more abundant in this case. For the balancing optimal mix, the maximum possible cycle count is about 260 yr^{-1}.

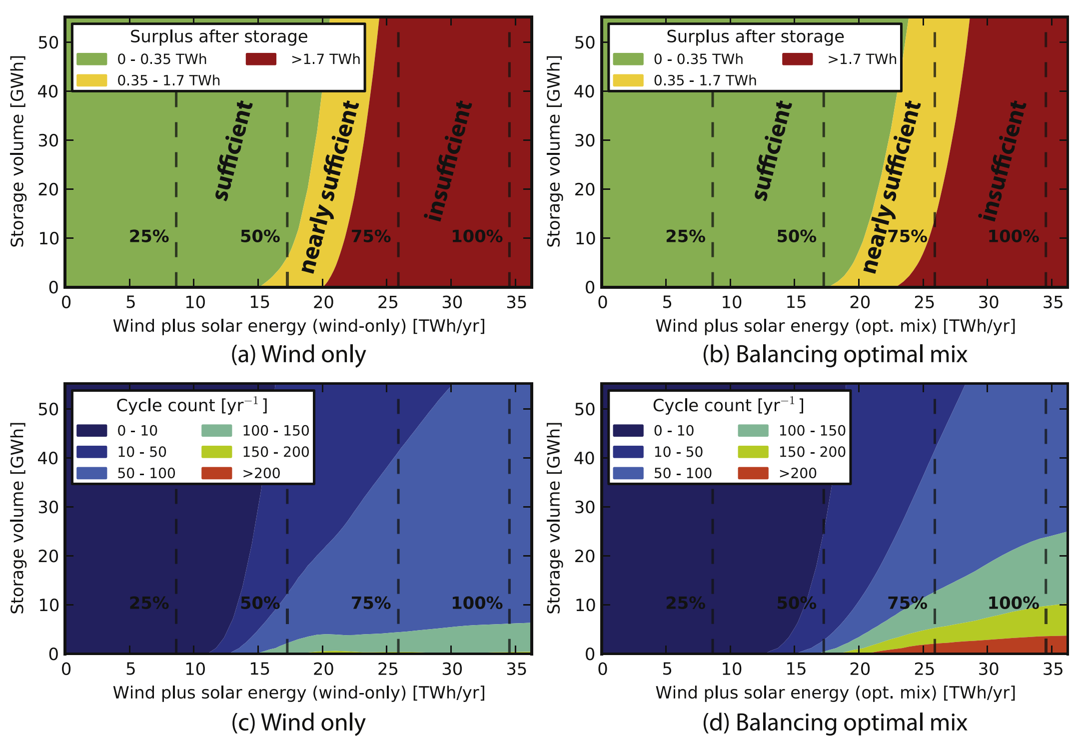
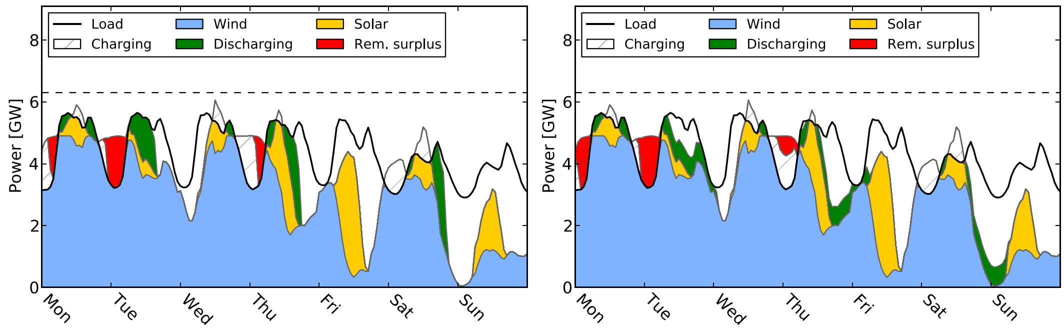


Fig. 5. The impact of applying a small storage of varying volume to the Danish power system is shown for different amounts of total annual VRE production. Dashed lines indicate gross shares of 25, 50, 75 and 100%, respectively. Panel (a) shows the annual VRE surplus that cannot be absorbed by the storage for a wind only mix, and panel (b) shows a similar figure for a balancing optimal wind–solar mix. In panels (c) and (d), the annual number of storage cycles that can be achieved for the two mixes is shown. For the wind only mix, the average annual cycle count never exceeds about 150 yr^{-1}. For the balancing optimal wind–solar mix, the maximum number is about 260 yr^{-1}.



(a) Limited charging and discharging (100% gain). (b) Limited charging and discharging (90% gain).

Fig. 6. Redistribution of VRE surplus using a 10 GWh storage system. The charging and discharging capacities of the storage are limited using a gain of (a) 100% and (b) 90%, a VRE gross share of 75% and a balancing optimal wind–solar mix is assumed in all cases. The round-trip efficiency is 100%. (a) Limited charging and discharging (100% gain). (b) Limited charging and discharging (90% gain).

3.5. Arbitrage of VRE surplus in Denmark

Some form of storage or flexible demand is often considered as a possible mean of integrating more VRE surplus in the Danish system. To facilitate a storage dispatch strategy that would allow this, charging the storage must be the most favorable form of energy consumption after satisfying the ordinary demand for electricity. In addition, the storage must have sufficiently high merit order for producing electricity when a residual load remains. In this way, one can realize the highest annual throughput of the storage. In Denmark, wind and solar power is currently guaranteed the highest merit order in the market via a combination of direct subsidy per kWh produced and by a favorable market framework. Similar measures could be implemented to support arbitrage of VRE surplus.

In this case, a simple economical model for the revenue generated by a storage unit can be assumed:

$$\text{revenue per year} = N_{\text{cycles}}(\text{revenue per cycle} - \text{cost per cycle}) - \text{fixed cost per year}. \tag{12}$$

Each full storage cycle is assumed to generate a fixed revenue and the cost is divided between a fixed annual cost of operation and a cost per cycle. A storage system can also provide ancillary services and earn revenue that is not directly related to the average cycle count. However, unlike energy arbitrage, these services do not reduce VRE surplus directly, and the revenue generated from them is not considered here.

Using the simple revenue model, it is clear that to generate positive revenue from round-trip storage operation: i) the revenue per cycle must be higher than the cost per cycle, and ii) the average cycle count must at least be high enough to offset the fixed cost. Because the average cycle count is decreasing for an increasing storage volume (see Fig. 5c and d), the revenue per unit storage is also decreasing with an increasing storage volume. For this reason, the last unit to be installed in the system will determine the maximum average cycle count and annual revenue for all storage units. It is assumed that free market mechanisms will lead to a number of storage units that will dynamically self-regulate towards a particular average cycle count that allows a minimum acceptable revenue per year.

In this case, the free-market-like build-up of storage units can be identified as contours of constant average cycle count in Fig. 5c and d. From the figures, it is clear that if a minimum acceptable revenue can be achieved with an average count of only 50 yr^{-1}, both a wind only and a balancing optimal mix will lead to a gradual build-up of storage units with a total volume that eventually exceeds 50 GWh. However, if more than 100 yr^{-1} are required, only a wind–solar mix with a relatively high share of solar PV, such as the balancing optimal mix, can sustain a significant number of storage units.

As an example, consider a situation where an average cycle count of 100 yr^{-1} is the stable market equilibrium. In this case, each 1 GWh storage unit would be able to redistribute 100 GWh VRE surplus per year. In the wind-only scenario, a maximum of three to four such units could be built in Denmark. However, for a balancing optimal wind–solar mix, the number could increase gradually to more than twenty 1 GWh units at a VRE gross share of 100%.

3.6. Storage charging and discharging power

In the previous sections, the charging and discharging capacities of the storage are assumed to be unlimited. This means that the maximum average cycle count only depends on the storage energy capacity (see Eq. (11)). In this section, we let the average cycle count be a function of the charging and discharging capacities. This is expressed as $N_{\text{cycles}}(P_{\text{in}},P_{\text{out}})$.

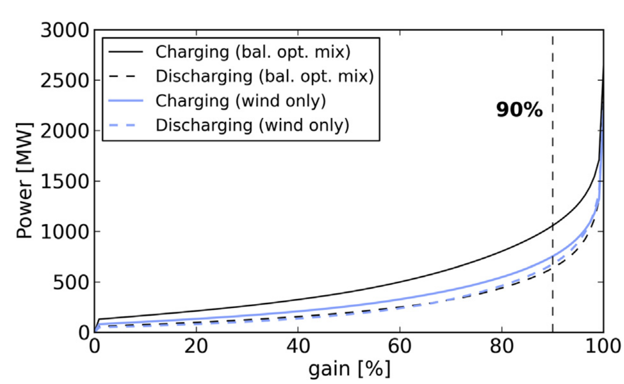


Fig. 7. Minimum charging and discharging capacities required to realize a gain between 0 and 100%. A 10 GWh loss-less round-trip electricity storage operated in the Danish electricity system with a 75% VRE gross share is assumed. Results are shown for the wind only (blue) and balancing optimal mix scenarios (black). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

By gradually decreasing the charging and discharging capacities in the storage model (Eqs. (6)–(8)), a set of minimum sufficient charging and discharging capacities can be identified as

$$P^0_{\mathrm{in}} = \min P_{\mathrm{in}}, \tag{13}$$

where $N_{\mathrm{cycles}}(P_{\mathrm{in}}, \infty) = N_{\mathrm{cycles}}(\infty, \infty)$, and

$$P^0_{\mathrm{out}} = \min P_{\mathrm{out}}, \tag{14}$$

where $N_{\mathrm{cycles}}(P^0_{\mathrm{in}}, P_{\mathrm{out}}) = N_{\mathrm{cycles}}(\infty, \infty)$.

Although these capacities do not limit the maximum average cycle count, they can influence the charging and discharging time series as charging and discharging is spread out more evenly in time. Note that the order in which P^0_{in} and P^0_{out} are determined has only little practical implication.

When the charging and discharging capacities are lowered further than their minimum sufficient values, the average cycle count will naturally decrease below the maximum too. This decrease is quantified by the storage gain parameter.

$$\mathrm{gain}(P_{\mathrm{in}}, P_{\mathrm{out}}) = 100\% \times \frac{N_{\mathrm{cycles}}(P_{\mathrm{in}}, P_{\mathrm{out}})}{N_{\mathrm{cycles}}(\infty, \infty)} \tag{15}$$

At a gain of 100%, the charging and discharging capacities are larger than or equal to P^0_{in} and P^0_{out}, respectively. Thus, the maximum average cycle count for a given storage volume is achieved. At a gain below 100%, either one or both of the charging and discharging capacities limits the cycle count to the gain percentage of its maximum. In this paper P_{in}, and P_{in} are determined for a certain gain g_0 such that

$$\mathrm{gain}\left(P_{\mathrm{in}}, P^0_{\mathrm{out}}\right) = 50\% + g_0/2 \tag{16}$$

and

$$\mathrm{gain}(P_{\mathrm{in}}, P_{\mathrm{out}}) = g_0. \tag{17}$$

In Fig. 6, it can be observed how the charging and discharging of a 10 GWh storage is spread out more evenly in time, when the gain is reduced from 100 to 90%.

The relationship between gain, charging and discharging power is illustrated in Fig. 7, where the charging and discharging capacities of a 10 GWh storage are minimized as a function of the gain. In the calculation, a fixed 75% VRE gross share is assumed and the results for both wind only mix and a balancing optimal wind–solar mix are shown. All of the power capacities shown in the figure increase at a roughly constant rate for gains lower than about 90%, but in the interval 90–100% the required power capacity more than doubles, because extreme and relatively rare weather events begin to dominate. For the charging capacity, the power required to achieve a gain of 100% is about 2200 MW for a wind only and 2700 MW for a balancing optimal mix. However, if the gain is reduced to 99%, both are reduced by about 1/3 to 1300 and 1700 MW, respectively. At a gain of 90%, the charging capacities are further reduced to 750 and 1100 MW.

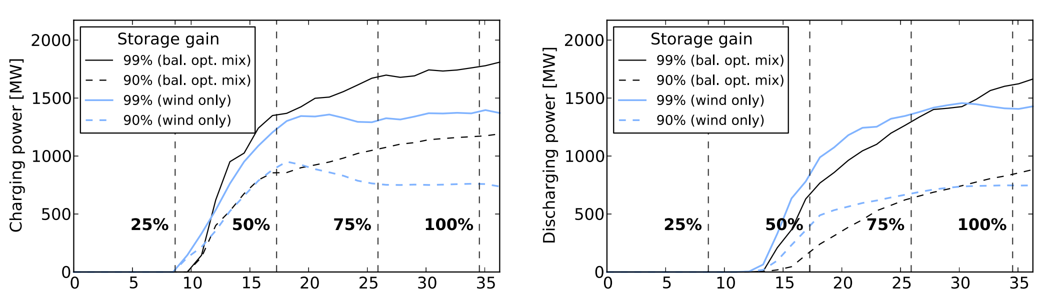
A similar substantial decrease in power requirements can be observed for all VRE gross shares and storage energy capacities in the interval 1–50 GWh. This is illustrated by Fig. 8, where the charging and discharging power required to achieve a gain of 90 and 99% are shown for a 10 GWh storage volume as a function of combined annual wind and solar power. In both cases, the power requirements are roughly halved when the gain is reduced from 99 to 90%. The power required to reach a gain of 100% (not shown) is generally about 50% higher than for a gain of 99%.

Because of the rapid increase in required charging and discharging power for gains higher than about 90%, there are significantly diminishing returns per MW installed charging and discharging capacity beyond this point. For this reason, a gain of 90% has been chosen as high but not unrealistic gain for a storage with a particular volume. It will be used as a basis for comparison and discussion in the summary Section 3.7 below. Note though that exactly 90% is chosen for simplicity. A more elaborate analysis would be required to determine the cost optimal gain for each storage energy capacity, VRE gross share and mix.

Fig. 8 also illustrates that the charge and discharge capacities of a given storage volume rise quickly for VRE gross shares below 50% after which they become nearly constant. Very similar charging and discharging capacities are required for both a wind only and a balancing optimal mix if the storage volume is the same. However, as discussed in the previous section, the average cycle count is generally higher for the balancing optimal mix. The implication is that similar storage installation in terms of volume, charging and discharging capacity will have an increased cycle count and, thus, a higher annual revenue, as more solar PV is installed in the Danish system.

3.7. Summary of the Danish case study

As shown in Section 3.1, total VRE surplus can be reduced by combining wind and solar energy in a balancing optimal mix. But



(a) Charging power, 10 GWh storage. (b) Discharging power, 10 GWh storage.

Fig. 8. Charging and discharging capacities for storage volumes of 10 GWh at VRE gross shares between 0 and 100% of the Danish electricity demand (2007 units). Results are shown for the wind only (blue) and the balancing optimal mix (black) for gains of 99 (fully drawn) and 90% (dashed). Dashed vertical lines indicate gross shares of 25, 50, 75 and 100%, respectively. (a) Charging power, 10 GWh storage. (b) Discharging power, 10 GWh storage. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Please cite this article in press as: Andresen GB, et al., The potential for arbitrage of wind and solar surplus power in Denmark, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.03.033

even for an optimized mix, surplus starts to increase quickly for VRE gross shares higher than about 50%.

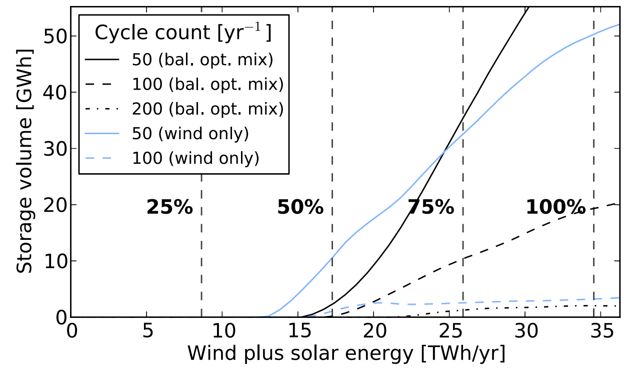
In this regime, energy arbitrage may be used to redistribute part of the surplus to hours where a residual load remains. In Section 3.3, we showed that a short-term storage with an energy capacity of up to 50 GWh can enable nearly full integration of VRE gross shares up to between 60 and 75% in the Danish electricity supply, depending on the wind–solar mix. Beyond this point, a short-term storage alone is an insufficient solution, and other measures are required to make use of all VRE surplus.

More specifically, the value of a fixed volume of short-term storage will increase with an increasing VRE gross share, in particular, with an increasing amount of solar PV in the power system. The primary reason for the synergy between short-term storage and solar PV is the day–night pattern of solar power. This pattern will typically cause the storage to charge during day-time and discharge the following night. For wind power, the most dominant time scale is the synoptic, which is about 4–10 days. This is too long to fully exploit redistribution of surplus VRE by means of a short-term storage.

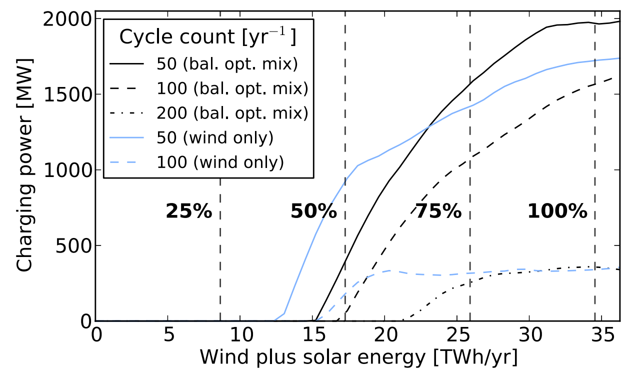
In Section 3.5, a simple market model for energy arbitrage is presented. The model allows us to estimate a free-market-like build-up of storage energy capacity in the Danish electricity system. A central assumption in this estimate is that arbitrage of VRE surplus is the only source of income for the storage. Here, the market model (Eq. (12)) has been combined with storage charging and discharging capacities determined such that the gain is 90% (see Section 3.6). As a consequence, the average cycle count is about 10% lower when compared to the calculations presented in Fig. 5c and d. The results of the new calculation are shown in Fig. 9, where five examples for the build-up of storage are presented as a function of the VRE gross share. Three examples with average cycle counts of either 50, 100 or 200 yr^{-1} belong to the balancing optimal mix scenario. For the wind only scenario 200 yr^{-1} is not possible, and only examples with either 50 or 100 yr^{-1} are presented.

In the case of a wind only scenario, it is evident from Fig. 9 that a significant amount of storage is only possible if a cycle count of about 50 yr^{-1} or less is favored in the market. As an example, a 10 GWh storage can achieve a cycle count of about 50 at a gross share of 50%. This means that 70% out of 800 GWh surplus can be redistributed at this point. For a gross share of 75%, only about 30% out of 4800 GWh surplus can be cycled at 50 yr^{-1}.

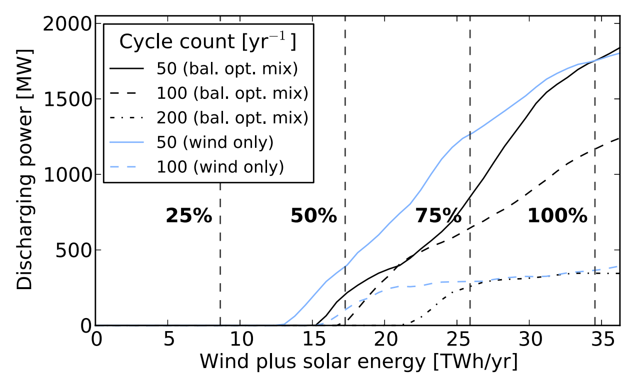
For a balancing optimal mix, the total amount of surplus is smaller (see Fig. 4) and higher cycle numbers are available (Figs. 5d and 9). This would allow either a lower number of storage units to create a similar impact as in the wind only case or a higher total impact by using the same number of units. An example which combines both of these is a 10 GWh storage unit operated at a VRE gross share of 75%. In this case, about 1000 of 3000 GWh surplus is redistributed per year. The same storage would only cycle about 700 out of 4800 GWh per year in a wind only scenario.



(a) Storage volume.



(b) Storage charging capacity.



(c) Storage discharging capacity.

Fig. 9. Stable market build-up of (a) storage volume, (b) charging and (c) discharging power capacities for the wind only and the balancing optimal mix scenarios. The calculations are performed for average annual cycle counts of 50, 100 and 200 yr^{-1}. A storage gain of 90% and a round-trip efficiency of 100% are assumed. Dashed lines indicate VRE gross shares of 25, 50, 75 and 100%, respectively. (a) Storage volume. (b) Storage charging capacity. (c) Storage discharging capacity.

4. Conclusion

In this paper, the new WDRESM approach developed by ARESG has been applied to analyze the interplay between wind, solar PV and energy arbitrage for a future Danish power system with high shares of VRE.

The analysis shows that, compared to a scenario with only wind power, a wind–solar mix with a 20% share of solar PV can sustain a significantly larger number of storage units and a higher annual throughput of VRE surplus. A likely consequence is that the concept of energy arbitrage, in the form of smart grid technologies such as storage and flexible demand, can only be used to efficiently integrate VRE surplus if significant amounts of solar PV are introduced in the Danish system. If, on the other hand, only wind power is built, the potential for short-term arbitrage of VRE surplus is limited.

Other solutions to reduce or use VRE surplus could be more cost effective than energy arbitrage. These include export to other countries or conversion of VRE surplus electricity to cover heating or transportation needs. If Denmark remains one of few European countries relying on VRES, it is reasonable to expect that most, if not all VRE surplus can be exported. However, detailed analysis of the

Please cite this article in press as: Andresen GB, et al., The potential for arbitrage of wind and solar surplus power in Denmark, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.03.033

effect of international transmission in a European power system, where the European ambition of a highly renewable power supply is implemented by the year 2050, shows that only about 40% of the total VRE surplus can be exported [4,5]. This leaves conversion of VRE surplus to cover heating or transportation demands as a strong alternative to round-trip electricity storage or demand-side management. Scenarios including these options are explored in Ref. [25]. As a last resort, VRE surplus can also be curtailed if other options are not considered attractive.

Acknowledgments

GBA gratefully acknowledges financial support from DONG Energy and the Danish Advanced Technology Foundation (140-2012-5), and SB from M. and H. Puschmann as well as O. and H. Stöcker.

References

[1] Heide D, von Bremen L, Greiner M, Hoffmann C, Speckmann M, Bofinger S. Seasonal optimal mix of wind and solar power in a future, highly renewable Europe. Renew Energy 2010;35(11):2483–9.
[2] Heide D, Greiner M, von Bremen L, Hoffmann C. Reduced storage and balancing needs in a fully renewable European power system with excess wind and solar power generation. Renew Energy 2011;36(9):2515–23.
[3] Rasmussen MG, Andresen GB, Greiner M. Storage and balancing synergies in a fully or highly renewable pan-European power system. Energy Policy 2012;51(0):642–51.
[4] Rodriguez RA, Becker S, Andresen GB, Heide D, Greiner M. Transmission needs across a fully renewable European power system. Renew Energy 2014;63(0):467–76.
[5] Becker S, Rodriguez R, Andresen G, Schramm S, Greiner M. Transmission grid extensions during the build-up of a fully renewable pan-European electricity supply. Energy 2014;64(0):404–18.
[6] Government D. Vores energi. Official energy strategy, Klima-, Energi- og Bygningsministeriet; 2011.
[7] Lund H. Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply. Renew Energy 2006;31(4):503–15.
[8] The Danish Energy Agency, Energinet.dk. Technology data for energy plants. Tech. rep. The Danish Energy Agency; January 2014 http://www.ens.dk/node/2252
[9] Kost C, Mayer JN, Thomsen J, Hartmann N, Senkpiel C, Philipps S, et al. Stromgestehungskosten Erneubare Energien. Tech. rep. Fraunhofer-Institut für Solar Energiesysteme ISE; November 2013 http://www.ise.fraunhofer.de/de/veroeffentlichungen/veroeffentlichungen-pdf-dateien/studien-und-konzeptpapiere/studie-stromgestehungskosten-erneuerbare-energien.pdf
[10] Beaudin M, Zareipour H, Schellenberglabe A, Rosehart W. Energy storage for mitigating the variability of renewable electricity sources: an updated review. Energy Sustain Dev 2010;14(4):302–14.
[11] Ferreira HL, Garde R, Fulli G, Kling W, Lopes JP. Characterisation of electrical energy storage technologies. Energy 2013;53(0):288–98.
[12] Connolly D, Lund H, Mathiesen B, Pican E, Leahy M. The technical and economic implications of integrating fluctuating renewable energy using energy storage. Renew Energy 2012;43(0):47–60.
[13] Anagnostopoulos JS, Papantonis DE. Study of pumped storage schemes to support high RES penetration in the electric power system of Greece. Energy 2012;45(1):416–23.
[14] Salgi G, Lund H. System behaviour of compressed-air energy-storage in Denmark with a high penetration of renewable energy sources. Appl Energy 2008;85(4):182–9.
[15] Sorknæs P, Mæng H, Weiss T, Andersen AN. Overview of current status and future development scenarios of the electricity system in Denmark—allowing integration of large quantities of wind power. Tech. rep. http://www.store-project.eu/documents/target-country-results/en_GB/energy-storage-needs-in-denmark; July 2013
[16] Lund H. Large-scale integration of wind power into different energy systems. Energy 2005;30(13):2402–12.
[17] Lehner B, Czisch G, Vassolo S. The impact of global change on the hydropower potential of Europe: a model-based analysis. Energy Policy 2005;33(7):839–55.
[18] Schaber K, Steinke F, Hamacher T. Transmission grid extensions for the integration of variable renewable energies in Europe: who benefits where? Energy Policy 2012;43:123–35.
[19] Bofinger S, von Bremen L, Knorr K, Lesch K, Rohrig K, Saint-Drenan Y-M, et al. Raum-zeitliche Erzeugungsmuster von Wind- und Solarenergie in der UCTE-Region und deren Einfluss auf elektrische Transportnetze. Tech. rep. Institut für Solare Energieversorgungstechnik, ISET e.V.; November 2008
[20] Widén J. Correlations between large-scale solar and wind power in a future scenario for Sweden. IEEE Trans Sustain Energy 2011;2(2):177–84.
[21] Kempton W, Pimenta FM, Veron DE, Colle BA. Electric power from offshore wind via synoptic-scale interconnection. Proc Natl Acad Sci U S A 2010;107(16):7240–5.
[22] ENTSO-E. Country-specific hourly load data https://www.entsoe.eu/resources/data-portal/consumption/; 2011.
[23] Energinet.dk. Energinet.dk's analyseforudsætninger 2013-2035. Tech. rep. http://www.energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/El/Energinet.dks%20analyseforuds%C3%A6tninger%202013-2035,%20april%202013.pdf; April 2013
[24] Lund H. Electric grid stability and the design of sustainable energy systems. Int J Sustain Energy 2005;24(1):45–54.
[25] Mathiesen BV, Lund H, Karlsson K. Background report to IDA's climate plan 2050. Tech. rep. The Danish Society of Engineers, IDA; August 2009 https://ida.dk/sites/prod.ida.dk/files/uk-future_climates_background_report.pdf