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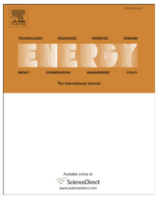

The potential for arbitrage of wind and solar surplus power in Denmark

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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

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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

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

and for solar power the corresponding time series is

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

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].

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