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Reduced storage and balancing needs in a fully renewable European power system with excess wind and solar power generation

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ABSTRACT

The storage and balancing needs of a simplified European power system, which is based on wind and solar power generation only, are derived from an extensive weather-driven modeling of hourly power mismatches between generation and load. The storage energy capacity, the annual balancing energy and the balancing power are found to depend significantly on the mixing ratio between wind and solar power generation. They decrease strongly with the overall excess generation. At 50% excess generation the required long-term storage energy capacity and annual balancing energy amount to 1% of the annual consumption. The required balancing power turns out to be 25% of the average hourly load. These numbers are in agreement with current hydro storage lakes in Scandinavia and the Alps, as well as with potential hydrogen storage in mostly North-German salt caverns.

1. Introduction

A fully renewable European power system will be based on various forms of renewable power generation, with a dominant contribution from wind and solar power. These two weather-driven energy sources come with strong temporal fluctuations. In order to absorb these fluctuations, enormous amounts of storage and balancing are required. For a simplified European scenario based on 100% wind and solar power generation the required storage energy capacity has been estimated [1]. Depending on the roundtrip storage technology, it amounts to 12–15% of the annual European consumption. Given the consumption rate of 2007, this corresponds to 400–480 TWh. This number is already an optimal minimum, where 60% wind and 40% solar power generation are mixed, so that their opposite strong seasonal dependences almost cancel each other and follow the weaker seasonal behavior of the load. For a 100% wind-only as well as a 100% solar-only scenario the required storage energy capacity has been estimated to be twice as much.

A storage energy capacity of several hundred TWh represents an incredibly large number. For pumped hydro and compressed air storage in Europe this is fully out of reach [2,3]. A hypothetical hydrogen storage in mostly North-German salt caverns has a potential of a few tens of TWh [4], but even this would still be more than one order of magnitude below the estimate. At present no other large-scale roundtrip storage technologies are in sight. Hydro storage lakes represent a different form of storage. Like gas plants, they do not store excess electricity, but are able to balance electricity deficits. Norway, Sweden, Austria and Switzerland have most of the storage lakes in Europe, with an annual balancing energy of about 150 TWh [5]. Also this is by far not sufficient to match the required amount, which has not been calculated in Ref. [1], but which will be larger than the required energy capacity of 400–480 TWh for roundtrip storage.

A solution has to be found how to reduce the enormous amount of storage needs for a fully renewable European power system. A straightforward part of this solution is to allow, on average, excess wind and solar power generation. Negative, hourly power mismatches in the fluctuating balancing between the combined wind and solar power generation and load will occur less frequently, thus lowering the need for storage. By using the same modeling approach as in Ref. [1], this paper provides quantitative estimates on how the storage and balancing capacities decrease as a function of

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excess power generation. In addition to energy capacity for roundtrip storage, it also considers the annual balancing energy required for hydro storage lakes or gas power plants, as well as the balancing power, which is another important storage characteristics.

Besides the dependence on excess generation, it is also interesting to look at the dependence on the mixing ratio between wind and solar power generation. The minimization of storage energy capacity, balancing energy and balancing power can be seen as three different optimization objectives. Those may result in different optimal mixes between wind and solar power generation. This paper is also addressing this issue. It provides an explanation for the differing outcomes and, with a simple time scale analysis, clarifies under which conditions these optimal mixes may become identical.

The structure of the paper is as follows: Section 2 focuses on the required energy capacity for roundtrip storage. Estimates on the required annual balancing energy are given in Section 3. The balancing power, or discharge power, is discussed in Section 4. Section 5 introduces a separation of time scales, which allows to distinguish between long- and short-term storage needs. The conclusion and an outlook are presented in Section 6.

2. Storage energy capacity as a function of excess generation

The modeling approach of Ref. [1] provides tempo-spatial pattern sequences of wind power generation, solar power generation and load over all of Europe, with a $47 \times 48\ \text{km}^2$ spatial resolution and 1 h temporal resolution over the 8-year-period 2000–2007. Complete spatial aggregation produces time series of the total European wind power generation $W(t)$, solar power generation $S(t)$ and load $L(t)$. An arbitrary one-year and one-month period is illustrated in Fig. 1. For convenience, throughout this paper, all time series have been normalized to their average value, so that $\langle W\rangle = \langle S\rangle = \langle L\rangle = 1$.

The hourly power mismatch,

$$\Delta(t) = \gamma[aW(t) + (1-a)S(t)] - L(t) \tag{1}$$

is key to determine the required storage needs. For $\gamma > 1$, $\gamma - 1$ represents the average excess generation. a and $(1-a)$ are equal to the share of average wind- and solar power generation, respectively. Fig. 2 (top) visualizes the hourly power mismatch for a specific combination of a and γ.

Whenever the mismatch is positive, the excess generation can be stored with efficiency η_{in}. In case of a negative mismatch, the generation deficit can be taken out of the storage with efficiency η_{out}. This defines a simple storage model:

$$H(t) = H(t-1) + \begin{cases} \eta_{\text{in}}\Delta(t) & \text{if } \Delta(t) \geq 0 \\ \eta_{\text{out}}^{-1}\Delta(t) & \text{if } \Delta(t) < 0 \end{cases} \tag{2}$$

The time series $H(t)$ describes the filling level of a non-constrained storage. It works fine for parameter settings γ, η_{in}, η_{out}, where the average power generation minus storage losses exactly matches the average load. For such settings, a simple model for the minimum sufficient storage energy capacity can be expressed as [1]: $E_{\text{H}} = \max_t H(t) - \min_t H(t)$.

However, for parameter settings, where on average power generation minus storage losses is larger than load, the fluctuating storage level (2) will drift in time; see Fig. 2 (middle). In such cases, the simple subtraction of the overall minimum from the overall maximum of the storage-level time series does not make sense. The new definition:

$$E_{\text{H}} = \max_t\left(H(t) - \min_{t' \geq t} H(t')\right) \tag{3}$$

takes care of the positive drift. At time t the non-constrained storage level is $H(t)$. For all larger times $t' \geq t$ the non-constrained

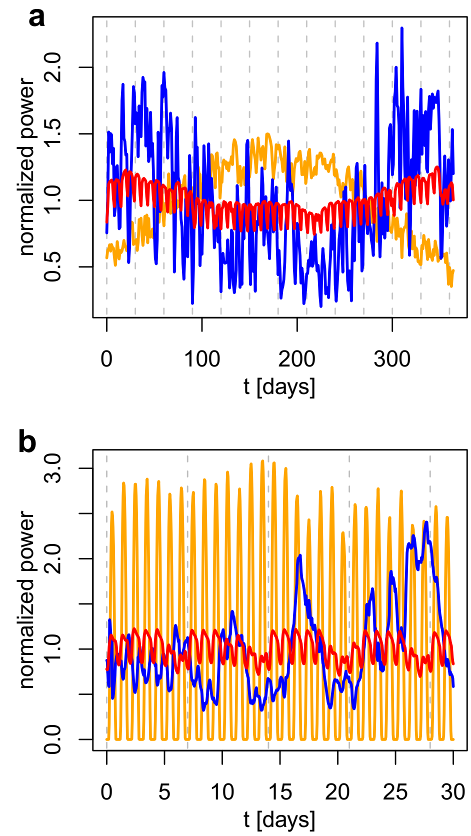

Fig. 1. Normalized (blue) wind power generation, (yellow) solar power generation and (red) load, with spatial aggregation over Europe. (a) One-day resolution over one year, and (b) 1-h resolution over one month. See Ref. [1] for modeling details. The vertical dashed lines indicate months and weeks, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

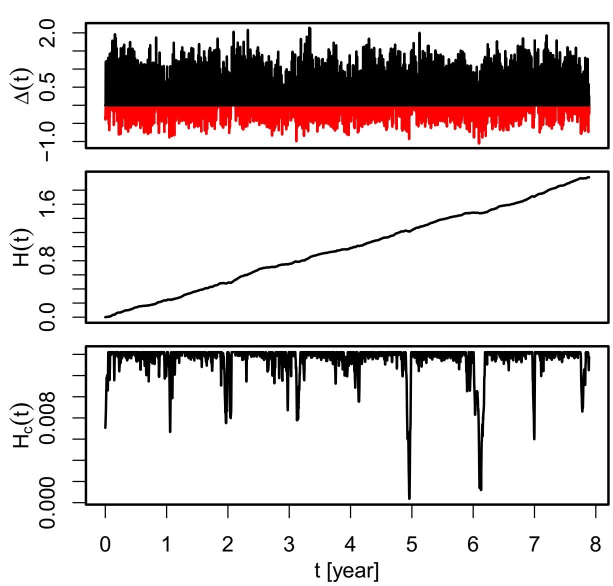

Fig. 2. Time series of (top) positive (black) and negative (red) power mismatch (1), (middle) non-constrained storage level (2), and (bottom) storage level (4) constrained with (3). The unit of the power mismatch is given in average hourly load. The unit of the storage levels is given in annual consumption. Parameters have been set $\gamma = 1.25$, $a = 0.60$, $\eta_{\text{in}} = \eta_{\text{out}} = 1$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)