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Integration of Renewable Energy Sources in future power systems: The role of storage

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ABSTRACT

Integrating a high share of electricity from non-dispatchable Renewable Energy Sources in a power supply system is a challenging task. One option considered in many studies dealing with prospective power systems is the installation of storage devices to balance the fluctuations in power production. However, it is not yet clear how soon storage devices will be needed and how the integration process depends on different storage parameters. Using long-term solar and wind energy power production data series, we present a modelling approach to investigate the influence of storage size and efficiency on the pathway towards a 100% RES scenario. Applying our approach to data for Germany, we found that up to 50% of the overall electricity demand can be met by an optimum combination of wind and solar resources without both curtailment and storage devices if the remaining energy is provided by sufficiently flexible power plants. Our findings show further that the installation of small, but highly efficient storage devices is already highly beneficial for the RES integration, while seasonal storage devices are only needed when more than 80% of the electricity demand can be met by wind and solar energy. Our results imply that a compromise between the installation of additional generation capacities and storage capacities is required.

1. Introduction

On the pathway towards a prospective low carbon energy system, the share of electricity produced from Renewable Energy Sources (RES) in the European power supply system has increased significantly over the past years [1]. Ongoing concerns about climate change and the aim of many countries to become more independent from energy imports will likely lead to a further increase in the share of RES in the European electricity supply system [2].

In such a system, the major share of energy would be provided by wind and solar energy as they are considered to have the highest potential in Europe [3]. Due to their natural origin the electricity produced from these sources is fluctuating strongly on both short-term (seconds to hours) and long-term scales (months, years) [4,5]. As production and consumption in a power supply system always need to be balanced, there is a requirement for reserve power capacities to ensure the security of supply, in the form of either quickly adjustable back-up power plants (operated e.g. on gas) or storage units [2,5–8]. Storages can store surplus electricity generated when the production from RES exceeds the demand and, hence, reduce the need for curtailment of electricity produced from RES [9].

Already with today's European power supply system with slightly more than 20% of the electricity demand covered from RES [1], it is debated which share of electricity produced from fluctuating RES the current power supply system can handle. According to a contribution by Hart et al. [9] the integration of RES in the power system can generally be characterised by two phases: Up to a certain penetration of RES, all the electricity produced from RES can be fed into the system, thus the integration of RES scales linearly with RES capacities [9]. After a certain transition point, the electricity production from RES occasionally exceeds the energy demand implying the need for curtailment of RES to ensure grid stability [9]. In this second phase the integration of RES scales less than linear with the installed capacities [9].

Another contribution investigated the effect of transmission grid extension on this integration process [10]. The authors showed that a powerful overlay transmission grid significantly reduced overproduction and back-up capacity requirements [10]. Furthermore, grid expansion was found to be also favourable from an economic perspective over only installing more variable renewable energy capacities [10,11].

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In addition to back-up power plants many studies dealing with prospective power supply systems with a high share of RES investigate the utilisation of storage devices to balance the fluctuations in the electricity production from RES (see e.g. Refs. [5–8,12–16] for Europe, [17,18] for Australia and [19,20] for the United States). Some of these studies implement very detailed assumptions on the cost for installation and operation of relevant units [7,13,17–20]. In order to promote a deeper understanding of the dependencies and implications relevant for the transformation of the power supply system, however, systematic investigations of fundamental aspects of the integration of RES are required. This paper addresses the impact of storages on the integration of RES in general and the importance of their size and efficiency in particular. Both the general approach and the results obtained for Germany are intended to set the stage for more detailed studies on the economic aspects on their integration and operation.

2. Modelling storage in power systems

A prospective power supply system based almost entirely on RES will depend strongly on wind and solar resources and, hence, needs to deal with their intrinsic variability. This work focusses on the large-scale integration of RES from a meteorological perspective. For this purpose we assume that representative data on power generation from wind $W(t_i)$ and solar $S(t_i)$ resources and load data $L(t_i)$ is available at discrete times $t_i = i\tau$ with $1 \le i \le N$, where τ is an arbitrary but fixed time increment. Each data point here corresponds to the accumulated energy generated or consumed in the respective time lag τ.[1] It is assumed that the data is corrected for systematic changes during the period of analysis.

The resource data can either stem from measurements on existing systems or, as in the case investigated in more detail in Section 3, from meteorological simulations. In order to ease a scaling of the generation data for the investigation of different installed capacities the generation data is normalised and expressed in units of the average electricity demand in the respective observation intervals. With $\langle X(t)\rangle_t := N^{-1}\sum_{i=1}^{N} X(t_i)$ we define normalised data sets w and s as

$$w(t) := \frac{W(t)}{\langle W(t)\rangle_t}\cdot\langle L(t)\rangle_t, \quad s(t) := \frac{S(t)}{\langle S(t)\rangle_t}\cdot\langle L(t)\rangle_t. \tag{1}$$

The production potential is then put into relation to the corresponding load data. A general form of the mismatch in generation from RES and energy demand at time t can be defined as

$$\Delta_{\alpha,\gamma}(t) := \gamma(\alpha w(t) + (1-\alpha)s(t)) - L(t). \tag{2}$$

Here, $\gamma\alpha$ and $\gamma(1-\alpha)$ render the respective shares of wind and solar power generation of the gross electricity demand. γ determines the total electricity produced from RES and is termed the average renewable energy power generation factor (cf. Ref. [14]).

In order to study the role of storage devices for the integration of RES, we choose the following procedure: first, we investigate which share of electricity demand can be met by RES if no storage devices are present. Second, we add an infinitely large storage device with round-trip efficiency η to the system, and third, we alter the storage device to one with limited size $H^{\max}$.

In the first case without any storages, the energy production from RES needs to be curtailed in periods of overproduction ($\Delta_{\alpha,\gamma}(t) > 0$), whereas negative mismatches ($\Delta_{\alpha,\gamma}(t) < 0$) need to be balanced by back-up power plants. The total amount of curtailed energy in multiples of the total demand is in this case determined by the overproduction function $O_0(\alpha,\gamma)$,

$$O_0(\alpha,\gamma) = \frac{\langle \max[0, \Delta_{\alpha,\gamma}(t)]\rangle_t}{\langle L(t)\rangle_t}. \tag{3}$$

The share of energy demand met by wind or solar energy after curtailment for a certain configuration α and γ, which we will call renewable integration function $\mathrm{RE}_0(\alpha,\gamma)$, is then calculated as

$$\mathrm{RE}_0(\alpha,\gamma) = \frac{\langle \gamma(\alpha w(t) + (1-\alpha)s(t))\rangle_t - O_0(\alpha,\gamma)\langle L(t)\rangle_t}{\langle L(t)\rangle_t} = \gamma - O_0(\alpha,\gamma). \tag{4}$$

A scenario without any contribution from RES (0% RES scenario) consequently results in $\mathrm{RE}_0(\alpha,\gamma) = 0$. By means of eq. (4) scenarios can then be categorised with respect to their contribution from RES. Since by construction $O_0(\alpha,\gamma) \ge \gamma - 1$ the renewable integration function $\mathrm{RE}_0(\alpha,\gamma)$ has a maximum of 1, which is realised when all demand is provided by RES (100% RES scenario).

Taking, secondly, also into account storages, this approach can be generalised. For storage of sufficient size boundary effects can be neglected. Then it is sufficient to take into account that parts of the overproduction can be fed into the system again. If we assume fully flexible and infinitely large storages with no self-discharging and with a round-trip efficiency η, the share of energy demand met by wind and solar energy is defined as the renewable integration function $\mathrm{RE}^{\eta}_{\infty}(\alpha,\gamma)$,

$$\begin{aligned}\mathrm{RE}^{\eta}_{\infty}(\alpha,\gamma) &= \gamma - \max[\gamma - 1, (1-\eta)O_0(\alpha,\gamma)] \\ &= \gamma - \max[\gamma - 1, O_{\infty}(\alpha,\gamma)].\end{aligned} \tag{5}$$

In this definition the max function guarantees that the electricity directly produced from RES plus the electricity re-injected from the storages does not exceed the total demand. This becomes relevant in particular at large γ, where one would obtain $\mathrm{RE}^{\eta}_{\infty}(\alpha,\gamma) > 1$ otherwise. Note that with $\eta = 0$ this equation also includes the case without any storages (i.e. $\mathrm{RE}^{\eta=0}_{\infty}(\alpha,\gamma) = \mathrm{RE}_0(\alpha,\gamma)$).

Thirdly, we address the most general case, the integration of RES with limited storage capacities of size $H^{\max}$ (in units of $\langle L(t)\rangle_t$). For a given wind share α and given average renewable energy power generation factor γ, the storage time series $H^{\eta}_{\alpha,\gamma}(t)$ describing the energy available to the grid is defined iteratively as

$$H^{\eta}_{\alpha,\gamma}(t) = \begin{cases} \text{if } \Delta_{\alpha,\gamma}(t) \ge 0: \\ \min\left[H^{\max}, H^{\eta}_{\alpha,\gamma}(t-\tau) + \eta\Delta_{\alpha,\gamma}(t)\right] \\ \text{if } \Delta_{\alpha,\gamma}(t) < 0: \\ \max\left[0, H^{\eta}_{\alpha,\gamma}(t-\tau) + \Delta_{\alpha,\gamma}(t)\right] \end{cases} \tag{6}$$

with η being the round-trip efficiency of the fully flexible storage. This expression is evaluated at integer multiples of τ, with τ being the fixed time increment of the time series as defined earlier in this section. The initial charging level of the storage $H^{\eta}_{\alpha,\gamma}(t=0)$ has to be specified when the approach is applied to actual data (cf. Section 3.1).

In this case, the total amount of unusable energy (due to curtailment and efficiency losses) in multiples of the total demand is determined by the overproduction function.

$$O^{\eta}_{H}(\alpha,\gamma) = \frac{\left\langle \max\left[0, \Delta_{\alpha,\gamma}(t) - \left(H^{\eta}_{\alpha,\gamma}(t) - H^{\eta}_{\alpha,\gamma}(t-\tau)\right)\right]\right\rangle_t}{\langle L(t)\rangle_t}. \tag{7}$$

This expression merges into the respective expressions O_0 and O_{∞} as defined in eqs. (3) and (5) for the respective assumptions $\eta = 0$ and $H^{\max} \gg H^{\eta}_{\alpha,\gamma}(t=0) \gg 0$.

[1] In simulations in this work typically $\tau = 1$ h is used. For reasonable conclusions regarding the required storage size, the time increment τ needs to be sufficiently small, since relevant effects might disappear at larger time scales.