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.

Keywords: Energy System Modeling, Energy Storage, Large-scale integration, Germany

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 \cite{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 \cite{2}.

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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 [8]. 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 [3]. In this second phase the integration of RES scales less than linear with the installed capacities [4].

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].

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. [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 \( 1 \leq i \leq N \), where \( \tau \) is an arbitrary but fixed time increment. Each data point here corresponds to the accumulated energy generated or consumed in the respective time lag
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 
\[ \langle X(t) \rangle_t := \frac{1}{N-1} \sum_{i=1}^{N} X(t_i) \]
we define normalised data sets \( w \) and \( s \) as
\[ w(t) := \frac{W(t)}{\langle W(t) \rangle_t} \cdot \langle L(t) \rangle_t, \quad s(t) := \frac{S(t)}{\langle S(t) \rangle_t} \cdot \langle L(t) \rangle_t. \] (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
\[ \Delta_{\alpha,\gamma}(t) := \gamma (\alpha w(t) + (1 - \alpha) s(t)) - L(t) \] . (2)
Here, \( \gamma \alpha \) and \( \gamma(1 - \alpha) \) render the respective shares of wind and solar power generation of the gross electricity demand. \( \gamma \) determines the total electricity produced from RES and is termed the average renewable energy power generation factor (cf. [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 \( \eta \) to the system, and third, we alter the storage device to one with limited size \( H_{\text{max}} \).

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

The share of energy demand met by wind or solar energy after curtailment for a certain configuration \( \alpha \) and \( \gamma \), which we will call renewable integration function \( RE_0(\alpha, \gamma) \), is then calculated as
\[ RE_0(\alpha, \gamma) = \frac{\gamma (\alpha w(t) + (1 - \alpha) s(t)) - O_0(\alpha, \gamma) \langle L(t) \rangle_t}{\langle L(t) \rangle_t} = \gamma - O_0(\alpha, \gamma) \] . (4)

A scenario without any contribution from RES (0% RES scenario) consequently results in \( RE_0(\alpha, \gamma) = 0 \). By means of eq. (4) scenarios can then be categorized with respect to their contribution from RES. Since by construction \( O_0(\alpha, \gamma) \geq \gamma - 1 \) the renewable

\footnote{In simulations in this work typically \( \tau = 1 \) h is used. For reasonable conclusions regarding the required storage size, the time increment \( \tau \) needs to be sufficiently small, since relevant effects might disappear at larger time scales.}
integration function $RE_0(\alpha, \gamma)$ 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 $\eta$, the share of energy demand met by wind and solar energy is defined as the renewable integration function $RE_\infty(\alpha, \gamma)$,

$$RE_\infty^\eta(\alpha, \gamma) = \gamma - \max[\gamma - 1, (1 - \eta)O_0(\alpha, \gamma)] = \gamma - \max[\gamma - 1, O_\infty(\alpha, \gamma)] . \quad (5)$$

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 $\gamma$, where one would obtain $RE_\infty^\eta(\alpha, \gamma) > 1$ otherwise. Note that with $\eta = 0$ this equation also includes the case without any storages (i.e. $RE_\infty^0(\alpha, \gamma) = RE_0(\alpha, \gamma)$).

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 $\alpha$ and given average renewable energy power generation factor $\gamma$, the storage time series $H_{\alpha, \gamma}^\eta(t)$ describing the energy available to the grid is defined iteratively as

$$H_{\alpha, \gamma}^\eta(t) = \begin{cases} \min[H_{max}^\eta, H_{\alpha, \gamma}^\eta(t - \tau) + \eta \Delta_{\alpha, \gamma}(t)] & \text{if } \Delta_{\alpha, \gamma}(t) \geq 0 \\ \max[0, H_{\alpha, \gamma}^\eta(t - \tau) + \Delta_{\alpha, \gamma}(t)] & \text{if } \Delta_{\alpha, \gamma}(t) < 0 \end{cases} \quad (6)$$

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

$$O_H^\eta(\alpha, \gamma) = \frac{\langle \max[0, \Delta_{\alpha, \gamma}(t) - (H_{\alpha, \gamma}^\eta(t) - H_{\alpha, \gamma}^\eta(t - \tau))] \rangle_t}{\langle L(t) \rangle_t} . \quad (7)$$

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

The share of energy demand met by RES with a storage of size $H_{max}$ available in the system is then defined as

$$RE_H^\eta(\alpha, \gamma) = \gamma - \max[\gamma - 1, O_H^\eta(\alpha, \gamma)] . \quad (8)$$

3. Application to Germany

The methods developed in the previous section are now applied to specific data in order to study the role of energy storage devices for the integration of RES in future power systems. Due to the availability of resource and demand data as well as a RES penetration of over 20% in its electricity system [1], Germany is chosen for this purpose.
3.1. Data used for calculations

The production from RES in Germany is estimated using long-term solar \((S(t))\) and wind energy \((W(t))\) power output data series with hourly resolution \((\tau = 1\text{ h})\) spanning eight years from 2000 to 2007 and based on reanalysis data (for details we refer to [5]). We only handle aggregated time series and do not consider limitations and effects of the national grid. Exports and imports of electricity are not considered in this work (see also section [4.3] for the potential implications). The production from the fluctuating RES is put into relation to the demand load time series \((L(t))\), which is available from ENTSO-E. All time series are normalised to the average load, hence a power generation factor \(\gamma = 1\) corresponds to scenarios where the total electricity producible by wind and solar resources in the eight-year period is identical to the overall load during this time. This way, our results do not depend explicitly on the absolute power generation capacities.

With the data for Germany we now evaluate the renewable integration functions (eq. (4), (5) and (8)) and investigate their dependence on the wind share \(\alpha\) and the generation factor \(\gamma\). The storage size \(H^{\text{max}}\) is chosen to be equivalent to 0, 2, 4, 6, 8, 10, 12, 24, 36, 48, 72, 168, 360, 720, 1440 average load hours (av.l.h.); for the case presented in this work (Germany) holds 1 av.l.h. = 54.2 GWh. We checked if the initial charging level of the storage \(H_{\eta,\alpha,\gamma}(t = 0)\) has an influence on the results and we found that the results only change by a maximum of 0.1% in all cases considered in this work. Hence, the initial charging level of the storage was set to \(H_{\eta,\alpha,\gamma}(t = 0) = 0\) without further discussion.

3.2. Results

The renewable integration function \(RE_0(\alpha, \gamma)\) for the case of no storage and selected wind shares \(\alpha\) is shown in figure 1. For \(\gamma < 0.2\), there is no overproduction, hence all curves rise linearly in this section. With increasing power generation factor \(\gamma\) overproduction occurs more and more frequently and the curves bend down due to curtailment. The transition point between the linear regime and the curtailment regime depends on the wind share \(\alpha\). In a solar-only scenario \((\alpha = 0.00)\) the effects of curtailment become relevant already at \(\gamma = 0.2\). Previous investigations have shown that the overproduction is mainly due to the solar production peak around noon. The curves with \(0.60 \leq \alpha \leq 0.80\) are the topmost, in accordance with [5] the overproduction is least with a mix of solar and wind energy in this regime. Unless otherwise noted, we will use a wind share of \(\alpha = 0.60\) for the following results. For this wind share, the transition occurs at about \(\gamma = 0.5\). However, sooner or later the renewable integration functions flatten out significantly independently of the wind share \(\alpha\), implying that a massive installation of additional production capacities would be needed to increase the integration of RES up to 100%. Thus, after a certain penetration of RES, the installation of storage capacities is likely to be worthwhile.

If storages are available, parts of the otherwise curtailed energy can be fed into the system again, whereas the amount of reusable energy depends on storage size and round-trip efficiency (cf. eq. (5)). Hence, the renewable integration function \(RE_{\eta}(\alpha, \gamma)\) after the transition point increases compared to the case without any storage.

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2The respective data series for both production and load have also been used in previous publications by other authors, [3, 8, 14, 16, 21].
For an unlimited storage without any losses ($\eta = 1$), all electricity produced during periods of overproduction can be fed into the system again in times of underproduction. Hence, the transition point between the linear regime and the curtailment regime moves to $\gamma = 1$. We estimated the storage size required to have the same properties as an infinitely large storage device by calculating the spread of the cumulative sum of the mismatch function $\Delta_{\alpha, \gamma}(t)$. In a scenario for Germany with a wind share of $\alpha = 0.60$ and an average renewable energy power generation factor of $\gamma = 1.00$, a loss-free storage device ($\eta = 1$) would need to have a size in the order of 80 TWh. This is orders of magnitudes higher than today’s storage capacities in Germany (39 GWh for pumped-hydro storage according to [22]) and even higher than Europe’s total hydrogen storage potential in salt caverns (32 TWh according to [23]).

As can be seen from equation (5) with unlimited storage capacities, a 100% RES scenario would always be possible. In order to balance the losses of the storage, however, additional generation capacities would need to be installed. The extent of these overcapacities depends on the round-trip and increases e.g. to $\gamma \approx 2.0$ for $\eta = 0.1$.

We will now proceed to storages of limited sizes. Figure 2 shows the renewable integration function $RE_{\eta=0.8}(\alpha = 0.60, \gamma)$ for different storage sizes $H_{\text{max}}$ and storage round-trip efficiency $\eta = 0.8$ (which is a typical value for pumped-hydro storage facilities). The wind share $\alpha$ has been fixed to $\alpha = 0.60$, which previously was found to be close to the mix at which overproduction occurs last (cf. fig. 1). In figure 2 the transition between the previously discussed cases of no storage and unlimited storage capacities can be observed. Furthermore, one can see that already a storage with a capacity of only $H_{\text{max}} = 2 \text{ av.l.h.}=0.1$ TWh significantly increases the integration of RES. This can be understood from the fact that already the availability of small storage devices increases.

Figure 1: Renewable integration function $RE_{\eta}(\alpha, \gamma)$ for the case without any storage and selected wind shares $\alpha$.
the integration of solar energy significantly and extents its usability to the evenings. The effect of storages decreases with their size.

Finally, let us come back to the question raised in the introduction, how soon will we need storage devices when increasing the share of RES. Figure 3 shows the evolution of the renewable integration function $RE^{\eta=0.8}_{H}(\alpha = 0.60, \gamma)$ for two different storage classes, first, small and highly efficient storages ($H^{\text{max}} = 4$ av.l.h. = 0.2 TWh, $\eta=0.8$) such as e.g. pumped-hydro storage facilities and second, large storages with reduced efficiency ($H^{\text{max}} = 168$ av.l.h. = 9.1 TWh, $\eta=0.3$), as it e.g. can be assumed for seasonal storages based on synthetic hydrogen. For comparison, the evolution of the renewable integration function without storage $RE_{0}(\alpha = 0.60, \gamma)$ and unlimited storage without any losses $RE^{\eta=1}_{H}(\alpha = 0.60, \gamma)$ are also plotted. One can see that up to a share of about 50% of the energy demand met by RES the curves do not exhibit significant differences. That is, no storage would be needed until this point, provided that the remaining load can be met by fully flexible power plants as assumed in this approach. For a share of about 50-80% of the energy demand met by wind and solar energy, a small but efficient storage can achieve a better integration of RES than a large but less efficient storage device. Only for higher shares of RES their integration is higher with large seasonal storage. With this storage a 100% RES scenario would be possible with a power generation factor $\gamma$ in the order of about $\gamma=1.5$. For a better discussion of the results and a comparison with more recent data, corresponding calculations were done using a different data source spanning the years from 2006 to 2012. Apart from minor quantitative differences, both data sets lead to the comparable results that up to 50% of the electricity demand could be met without storage; and small but highly efficient storage devices should be favoured over large but less efficient storage devices to reach a share of about 80% of the electricity demand being met by RES. Systematic differences between the observation periods 2000-2008
and 2006-2012 were not found. For details we refer to [Appendix A](#).

These results mean that at the beginning of the RES integration process rather small and highly efficient storage devices are sufficient if combined with flexible fossil power plants. Only when it comes to integrating very high shares of RES, hence having a system of almost 100% RES, seasonal storage devices are needed. Alternatively, overcapacities could be installed to reach a 100% RES system while requiring less storage capacity. Hence, a compromise between the installation of overcapacities and the installation of storage capacities has to be found.

4. Further aspects of storage integration

In the previous section, we focussed on the conceptual question on how to include different storage parameters when studying the integration of RES in prospective power supply systems. We now take a look at three further aspects closely related to the previous results, namely the dependence of the storage requirements on the mix between wind and solar resources, the economic impact of our previous findings and the implications of the size of the investigated region.

4.1. Storage and the optimal mix

We have shown above that the penetration of RES at which overproduction and hence possible curtailment starts to take place depends on the mix between solar and wind energy (cf. fig. 1). In the subsequent results, the wind share was fixed to $\alpha = 0.6$, which was found to be in the range of the optimal mix for minimum storage capacities. To investigate the influence of the mix in more detail, figure 4 shows for each generation
4.2. Economic impact of storage integration

The results shown in this work are based mainly on meteorological aspects and the resulting fluctuations in the power production from solar and wind resources as well as the load patterns in the current power supply system. We eventually take a look at the economic impact of our previous findings. As shown in figures [1][3] there is a linear regime at the beginning of the integration of renewable energy sources, implying all electricity produced by RES can be integrated completely into the electricity grid. Provided that...
Figure 5: Slope $c$ of the renewable integration function $RE^\eta_H(\alpha, \gamma)$ as a function of the renewable energy power generation factor $\gamma$ for two different storage classes as well as the case of no storage and infinitely large storages.

the remaining back-up power plants are fully flexible, the installation of storage devices is economically not directly profitable in this regime. Once curtailment sets in implying that the curves for the respective renewable integration functions bend downwards, there are different pathways to increase the share of energy demand met by RES: One option is to install storage capacities (cf. fig. 2). Alternatively, the same share can be achieved by constructing additional power generation capacities, hence increase the generation factor $\gamma$. If the latter option is chosen, however, the system operator (referring to e.g. the grid operator, the government, the overall society or anyone responsible for the stable supply of electricity) has to find a way to make the new investments profitable for an investor.

Let us look again at the case of Germany shown before in figure 3. Figure 5 shows the slope, denoted $c$, of the renewable integration function $RE^\eta_H(\alpha, \gamma)$ as a function of the generation factor $\gamma$ for the different cases discussed previously. For scenarios with a share of energy demand being met by RES above 80%, hence $\gamma > 1.00$ (cf. fig. 3), the slope $c$ is at a value of $c \leq 0.5$. This would mean that in this simplified scenario less than half of the additionally producible electricity could be fed into the system. Either this would seriously affect the return on investment of additional conversion facilities or alternatively all previously installed RES capacities would have to slightly curtail their electricity production. Both effects would have a high impact on decisions regarding the investment into additional generation capacities.

In addition to the capacity of the storages, from an economic point of view also the required converter power for charging and discharging are relevant. The model presented

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3The surplus energy could be transferred to the heat or transport sector using additional conversion capacities; investigating this option in detail is beyond the scope of this work though.
in this work for reasons of simplicity does not incorporate any restrictions in the converter power and, hence, does not enforce an economic utilisation of the converters. In the scenario with a wind share $\alpha = 0.60$ and a power generation factor $\gamma = 1.0$ the realised power of a storage device with $H_{\text{max}} = 4 \text{ av.l.h.}$ and round-trip efficiency $\eta = 0.8$ e.g. was about $1.23\langle L(t)\rangle_t = 67 \text{ GW}$ (95% quantile: $0.81\langle L(t)\rangle_t = 44 \text{ GW}$) for discharging and $1.69\langle L(t)\rangle_t = 92 \text{ GW}$ (95% quantile: $1.05\langle L(t)\rangle_t = 57 \text{ GW}$) for charging, respectively. These values are much higher than the converter power requirements found in a similar studies (see e.g. [24]), which do take into account economic aspects in the operation of storages and backup power. Since the utilization of converters in the present contribution is not optimized, derived parameters such as capacity factors for the storage devices are not meaningful and cannot be included in an evaluation of economic aspects as e.g. done by [25].

Limiting the admissible converter power of the storage devices in the simulations presented here in particular for smaller storage sizes does not necessarily imply significant changes in the results for the renewable integration function, since the limits initially only change the interaction between storage devices and back-up power plants (restricting e.g. the power of the storage with size $H_{\text{max}} = 4 \text{ av.l.h.}$ to their 95% quantile did not have any significant effect). A detailed and systematic discussion of the impact of converter power, which would be required for full evaluation of economical aspects of the integration of storages, however, is beyond the scope of this manuscript and will instead be subject of future work.

### 4.3. Implications of size of the simulation domain

The model developed in this work focusses on the role of storage devices for the integration of RES while treating the simulated domain as a copper plate. Grid limitations are not considered. Instead we assume that the production from RES and the demand can be balanced without constraints throughout the entire simulation domain. Consequently the integration of renewables is generally promoted with increasing size of the simulation domain [26], since fluctuations in production and consumption decorrelate with increasing scales. By expanding our model to a European scale the renewable integration function for a storage device with size $H_{\text{max}} = 4 \text{ av.l.h.}$ for instance increases from $RE_{\eta=0.8}^{H_{\text{max}}}(\alpha = 0.60, \gamma = 1.50) \approx 0.88$ for Germany to $RE_{\eta=0.8}^{H_{\text{max}}}(\alpha = 0.60, \gamma = 1.50) \approx 0.94$. In this respect, the effect of imports and exports to foreign grids could be regarded as a virtual storage. However, the positive effects of enlarging the investigated region are restricted by the capacity of the grid (in particular but not limited to interconnectors) [21]. In practise these restrictions would need to be solved either by expansion and enforcement of distribution and transmission grids or by the installation of additional storages to overcome local bottlenecks. For this reason the results derived from our approach for large-scale systems with rather mature transmission grids (such as e.g. Germany and Europe) exhibit lower bounds for the actual storage demand.

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4The analysis includes the former UCTE member countries as well as Ireland, United Kingdom, Norway, Sweden, Finland and Denmark. For details we refer to [3].
5. Conclusions

The transformation of the European power supply system to one based on Renewable Energy Sources (RES) is a challenging task – yet it is achievable. In order to balance the fluctuations in the power production from wind and solar energy, the installation of storage capacities will likely be required. The storage modelling approach developed in this work allows to systematically study the integration process of RES in a power system depending on the round-trip efficiency and the size of the storage.

Applying our approach to data for Germany, we found that up to 50% of the electricity demand could be met by RES without storage – provided that an optimal mix between wind and solar power generation is chosen and the remaining power plants are fully flexible. This result is in line with recently published case studies for Germany [13] and Denmark [16]. The required flexibility is, however, currently only the case for parts of the German generation portfolio. In a scenario with these flexible back-up power plants, though, small but highly efficient storage devices should be favoured over large but less efficient (seasonal) storage devices to reach a share of about 80% of the electricity demand being met by RES. Eventually a balance between the installation of additional generation capacities and of storage capacities has to be found. In this context also the required power of the storage converters needs to be taken into account, which is economically relevant but beyond the scope of the current modelling approach.

The overall transformation process involves many different aspects. Even if only technological parameters are considered, current energy system models tend to get very complex. By focussing our work on two key parameters of modelling energy storage devices, we are able to systematically study the role of storage devices for the integration process of RES. Our approach and its findings can now be used in upcoming modelling approaches of future power systems. By considering more and more elements that very likely have an impact on a future power supply system, detailed scenarios can be investigated to achieve the goal of a cost-effective and stable supply of electricity based on RES.

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Appendix A. Comparison of results using different data sets

For a better discussion of the results presented in section 3 (the corresponding data set henceforth is referred to as data set A) we applied our model on a second data set
for Germany spanning the years 2006-2012 also with $\tau = 1h$ (data set B). As in data set A, the wind and solar power generation time series of data set B are based on weather data with a high spatial and temporal resolution. The time-dependent availability of resources were estimated from Meteosat satellite measurements and from a numerical weather prediction model. Within each grid cell, sub-models for PV and wind power generation capacities transfer the weather data to power generation, whereupon the exact spatial distribution of the generation capacities is based on a combination of statistical and empirical methods. Eventually, the power generation time series are acquired by a summation over all grid cells. The corresponding load data were obtained from ENTSO-E.

The two data sets A and B differ not only in the period of observation but also in the underlying data sources: The solar power output data is now based on satellite measurements instead of simulations with a mesoscale model as in data set A. PV generation simulated from satellite measurements generally reproduce the local weather conditions more accurately and therefore show a higher variability in time, even if accumulated to the country scale. Furthermore, parameters like the spatial distribution of the generation capacities within the country are slightly different.

The analysis from the core part of the manuscript was now repeated on data set B. Figure A.6 exhibits a comparison of the results with the initial results for data set A as shown in fig. 3. While the integration function for all relevant cases (limited storage or no storage at all) for data set B is slightly lower than for data set A the gross effect of the installation of storages and the interplay between storages of different size is similar: Also for data set B the results suggest that initially (and until $\gamma \approx 1$) the effect of the installation of small and efficient storage devices is beneficial to the installation of large and less-efficient storage capacities.

Both data sets cover a comparable period of time, which is important to obtain a reasonable representation of regularly and extreme weather phenomena. The smaller values for the integration function for data set B can be attributed to the higher variability of the solar production data, which are not correlated with the demand and therefore have a negative impact. From this analysis and further investigations performed we cannot attribute the differences to any systematic differences between the years covered by the respective data sets. This is not astonishing since the underlying data (weather data and load data) except for the PV data do not differ significantly between data sets A and B.

In summary, the general results are the same for both data sets A and B: Up to 50% of the electricity demand could be met without storage; and small but highly efficient storage devices should be favoured over large but less efficient (seasonal) storage devices to reach a share of about 80% of the electricity demand being met by RES.

References

[1] Eurostat. Electricity generated from renewable sources (tsdcc330). http://epp.eurostat.ec.europa.eu. Accessed 17/02/2014.
[2] European Climate Foundation. Roadmap 2050: A practical guide to a prosperous, low-carbon Europe. Technical report, 2010.
Figure A.6: Comparison between two different data sets: Renewable integration function $RE_H^\alpha(\alpha = 0.60, \gamma)$ for different storage classes (cf. fig. [3]) using two different data sets: Thick lines represent the original data set (A), results derived from the new, second data set (B) are presented in thick lines.

[3] Mark Z Jacobson and Mark A Delucchi. Providing all global energy with wind, water, and solar power, part i: Technologies, energy resources, quantities and areas of infrastructure, and materials. Energy Policy, 39(3):1154–1169, 2011.

[4] Pavlos S Georgilakis. Technical challenges associated with the integration of wind power into power systems. Renewable and Sustainable Energy Reviews, 12(3):852–863, 2008.

[5] Dominik Heide, Lueder von Bremen, Martin Greiner, Clemens Hoffmann, Markus Speckmann, and Stefan Bolinger. Seasonal optimal mix of wind and solar power in a future, highly renewable Europe. Renewable Energy, 35(11):2483–2489, 2010.

[6] Ulrich Bünger. Energiespeicher in Stromversorgungssystemen mit hohem Anteil erneuerbarer Energieträger. VDE, 2009.

[7] Wolf-Dieter Schill. Residual load, renewable surplus generation and storage requirements in Germany. Technical report, DIW - Deutsches Institut für Wirtschaftsforschung, 2013.

[8] Morten Grud Rasmussen, Gorm Bruun Andresen, and Martin Greiner. Storage and balancing synergies in a fully or highly renewable pan-European power system. Energy Policy, 51:642–651, 2012.

[9] Elaine K. Hart, Eric D. Stoutenburg, and Mark Z. Jacobson. The potential of intermittent renewables to meet electric power demand: Current methods and emerging analytical techniques. Proceedings of the IEEE, 100(2):322–334, 2012.

[10] Katrin Schaber, Florian Steinke, Pascal Mühlisch, and Thomas Hamacher. Parametric study of variable renewable energy integration in Europe: Advantages and costs of transmission grid extensions. Energy Policy, 42:498–508, 2012.

[11] Michaela Fürsch, Simeon Hagspiel, Cosima Jägemann, Stephan Nagl, Dietmar Lindenberger, and Eckehard Tröster. The role of grid extensions in a cost-efficient transformation of the European electricity system until 2050. Applied Energy, 104:642 – 652, 2013.

[12] Frauke Wiese, Gesine Bökenkamp, Clemens Wingenbach, and Olav Hohmeyer. An open source energy system simulation model as an instrument for public participation in the development of strategies for a sustainable future. Wiley Interdisciplinary Reviews: Energy and Environment, 2014.

[13] Henrik Lund and Brian Vad Mathiesen. Energy system analysis of 100% renewable energy systems – the case of Denmark in years 2030 and 2050. Energy, 34(5):524–531, 2009.

[14] Dominik Heide, Martin Greiner, Lueder von Bremen, and Clemens Hoffmann. Reduced storage...
and balancing needs in a fully renewable European power system with excess wind and solar power generation. *Renewable Energy*, 36(9):2515–2523, 2011.

[15] Thomas Weiss and Detlef Schulz. Germany: Overview of the electricity supply system and an estimation of future energy storage needs (stoRE project). Technical report, 2013.

[16] Gorm B. Andresen, Rolando A. Rodríguez, Sarah Becker, and Martin Greiner. The potential for arbitrage of wind and solar surplus power in Denmark. *Energy*, 2014. (in press)

[17] Ben Elliston, Mark Diesendorf, and Iain MacGill. Simulations of scenarios with 100% renewable electricity in the Australian national electricity market. *Energy Policy*, 45:606–613, 2012.

[18] Ben Elliston, Iain Macgill, and Mark Diesendorf. Least cost 100% renewable electricity scenarios in the Australian national electricity market. *Energy Policy*, 59:270–282, 2013.

[19] Cory Budischak, DeAnna Sewell, Heather Thomson, Leon Mach, Dana E Veron, and Willett Kempton. Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time. *Journal of Power Sources*, 2012.

[20] James Nelson, Josiah Johnston, Ana Mileva, Matthias Früpp, Ian Hoffman, Autumn Petros-Good, Christian Blanco, and Daniel M Kammen. High-resolution modeling of the western North American power system demonstrates low-cost and low-carbon futures. *Energy Policy*, 43:436–447, 2012.

[21] Rolando A Rodriguez, Sarah Becker, Gorm B Andresen, Dominik Heide, and Martin Greiner. Transmission needs across a fully renewable European power system. *Renewable Energy*, 63:467–476, 2013.

[22] Eurelectric - Union of the Electricity Industry. Hydro in Europe: Repowering renewables. Technical report, Eurelectric, Union of the Electricity Industry, 2011.

[23] Alfonso Arias Perez and Thomas Vogt. Life cycle assessment of conversion processes for the large-scale underground storage of electricity from renewables in Europe. In *EPJ Web of Conferences - 3rd European Energy Conference (E2C 2013)*, 2013 (accepted).

[24] T. Weiss and D. Schulz. Development of fluctuating renewable energy sources and its influence on the future energy storage needs of selected European countries. In *Energy (IYCE), 2013 4th International Youth Conference on*, pages 1–5, June 2013.

[25] John S. Anagnostopoulos and Dimitris E. Papantonis. Study of pumped storage schemes to support high RES penetration in the electric power system of Greece. *Energy*, 45(1):416 – 423, 2012.

[26] Florian Steinke, Philipp Wolfrum, and Clemens Hoffmann. Grid vs. storage in a 100% renewable Europe. *Renewable Energy*, 50:826–832, 2013.