Adv. Sci. Res., 12, 91–95, 2015
www.adv-sci-res.net/12/91/2015/
doi:10.5194/asr-12-91-2015

Advances in Science & Research
Open Access Proceedings

14th EMS Annual Meeting & 10th European Conference on Applied Climatology (ECAC)

Investigation of balancing effects in long term renewable energy feed-in with respect to the transmission grid

A. Kies[1,2], K. Nag[2], L. von Bremen[1,2], E. Lorenz[2], and D. Heinemann[1,2]

[1]ForWind, Center for Wind Energy Research, University of Oldenburg, Oldenburg, Germany
[2]Institute of Physics, University of Oldenburg, Oldenburg, Germany

Correspondence to: A. Kies (alexander.kies@uni-oldenburg.de)

Received: 15 January 2015 – Revised: 21 April 2015 – Accepted: 2 May 2015 – Published: 26 May 2015

Abstract. A European power system mainly based on renewable sources will have dominant contributions from wind and solar power. However, wind and solar generation facilities have, due to the weather dependent nature of their resources, highly fluctuating feed-in profiles. To overcome the mismatch between power consumption and generation it is important to study and understand the generation patterns and balancing potentials. High temporally and spatially resolved long term weather data was used to simulate the feed-in from wind and photovoltaics for European countries for the years 2003 to 2012. We investigate storage energy and capacity needs in Europe in dependency of the generation mix from wind onshore, wind offshore and photovoltaics and the share of renewables. Furthermore we compute the storage energy and capacity needs for different transmission scenarios. We show that for unlimited transmission storage needs are reduced mostly by high wind offshore shares. We also show that higher shares above 100 % of renewables can decrease the required storage capacity to a higher extent than the required storage energy.

1 Introduction

The European energy transition is Europe's path towards non-fossil sustainable energy generation. In 2012 the share of renewables in the power sector was already 25 % and it is expected to increase tremendously in the upcoming decades. In such a power system wind and solar power will have most likely the highest shares. To ensure stable electricity transmission grids, supply and demand need to match reliably. However, the feed-in profiles of wind and solar generation facilities depend on the weather. This makes their integration into the power system difficult. Several solutions have been proposed and investigated to solve or reduce the problem of the resulting generation-load mismatch. These are for example excess generation (Heide et al., 2010) or transmission grid extensions (Becker et al., 2014; Rodriguez et al., 2014). Other relevant papers investigating European power systems based on renewable energies are for example (Huber et al., 2014; Rasmussen et al., 2012; Schaber et al., 2012; Steinke et al., 2013). In the following, balancing is investigated by the calculation of storage needs from feed-in for wind and solar and load data. We study storage energy and capacity needs in dependency of the generation mix and for different transmission scenarios.

2 Data

We investigate a renewable European power system for 34 countries (EU-28, Norway, Switzerland and the Balkan states). The background scenario of this work is Pfluger et al. (2011). Generation capacities of the single countries have been adopted from this scenario. Within the single countries the capacities were distributed according to an empirically derived approach: the cumulative distribution function of the capacities dependent on the average resource (wind speed for wind and irradiance for pv) was derived for Germany and adopted for all countries (Fig. 1). No grid points of the on- and offshore regions were filtered out.

2.1 Weather data

A large weather database to model feed-in from renewable sources has been set up. This database has a spatial resolution

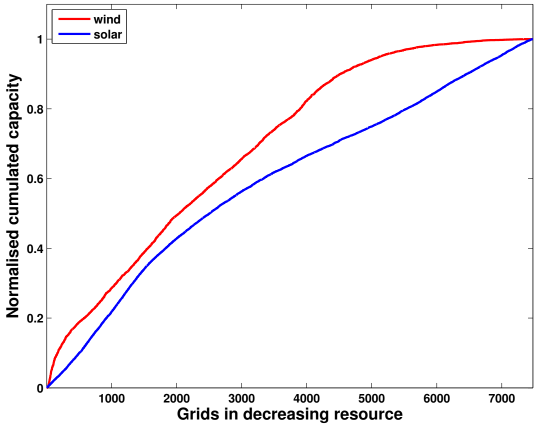

Figure 1. Cumulative distribution function of wind and photovoltaic capacities in order by decreasing resource of wind speed and irradiance on a 7 km × 7 km grid for Germany (2013).

of 7 km × 7 km covering most of Europe at hourly temporal resolution for the years 2003 to 2012. It consists of wind speeds in 140 m and temperatures in 2 m height, that have been derived by statistical downscaling from MERRA reanalysis data (Rienicker et al., 2011). Since MERRA reanalysis only provides hourly wind speeds in 10 and 50 m height with a spatial resolution of $1/2° \times 2/3°$, the MERRA wind speeds were statistically downscaled to the desired resolution of 7 km × 7 km. The grid points of this resolution were chosen to be the grid points of the COSMO-EU analysis (Schulz and Schättler, 2009). The statistical downscaling consists of three steps: in the first step the MERRA wind speeds were spatially interpolated to the 7 km × 7 km grid. In the second step they were logarithmically extrapolated to 140 m under the assumption of a logarithmic wind profile with surface roughness lengths provided by COSMO-EU. The logarithmic wind profile is given implicitly by

$$\frac{s(z)}{s(z_0)} = \frac{\log(z/z_\mathrm{r})}{\log(z_0/z_\mathrm{r})}, \tag{1}$$

where $s(x)$ is the wind speed at height x, z is the desired height to be extrapolated to, z_0 is the height for which the wind speed is available and z_r is the surface roughness length. The surface roughness length is the parameter to model the logarithmic wind profile. The final step of the downscaling process consisted of the calculation of linear regression coefficients between MERRA reanalysis and COSMO-EU analysis wind speeds for the year 2012. It means, that the relationship between COSMO-EU windspeeds s_c and MERRA wind speeds s_m is assumed to be

$$s_\mathrm{c} = \epsilon + b s_\mathrm{m}, \tag{2}$$

where ϵ and b are the calculated parameters of the linear regression for a single grid point. After calculation of these coefficients this regression was applied on all investigated years.

For the pv power calculations images from Meteosat First Generation (MFG) and Meteosat Second Generation (MSG) satellites were used. The Heliosat method (Cano et al., 1986; Hammer et al., 1998) was then applied to derive surface irradiance which is used for pv power calculations.

2.2 Calculation of feed-in time series

The powercurve of an Enercon E-126 at 140 m hub height with additional 5 % plain losses was used to convert wind speeds into produced power for every grid cell. Photovoltaics power has been calculated by using the global horizontal irradiation and configurations of pv modules (tilt angles, azimuthal orientations, types, etc.) adopted from the background scenario. The conversion of global horizontal irradiance to the tilted module is based on the Klucher model (Klucher, 1979). Module temperatures were computed as

$$T_\mathrm{m} = T_\mathrm{a} + \sigma I_t, \tag{3}$$

where T_a is the ambient temperature, T_m the module temperature and I_t the irradiance on the inclined surface. σ is a factor that was chosen to be 0.036. The module efficiency $\eta(T_\mathrm{m})$ is then calculated as a function of the module temperature for a given irradiance

$$\eta(T_\mathrm{m}) = \eta(25°)(1 + a T_\mathrm{m}), \tag{4}$$

where a is a device-specific parameter. Then DC power can be calculated by using the installed capacity C

$$P = \eta(T_\mathrm{m}) I_t C \tag{5}$$

for any grid point. DC power was converted into AC power using the parameter of a Sunny Mini Central 8000TL converter. Feed-in of the single grid cells aggregated to the country levels for wind and pv.

2.3 Load data and transmission capacities

Load data was retrieved from ENTSO-E for the countries investigated and slightly modified to account for the background scenario. We investigate the storage needs in this work for several scenarios: one with unlimited (copperplate model), one without any inter-country transmission in Europe and the other ones with multiples of net transfer capacities. These net transfer capacities (NTC) are calculated and provided by ENTSO-E. The NTC values for summer 2010 have been used to limit transmission between countries.

3 Balancing by storages and transmission

This section explains how storage capacity and energy needs, which are the central measures of this investigation, are defined and computed from this data. For every country we have computed a generation time series

$$G_n(t) = P_n(t) + W_n(t) + U_n(t), \tag{6}$$

where P_n is the generation from photovoltaics of country n, W_n is the generation from wind onshore and U_n is the generation from wind offshore. Together with the load data the time series of the mismatch can then for every node n directly be computed as

$$\Delta_n(t) = G_n(t) - L_n(t) + \sum_m F^m(t), \tag{7}$$

where $G_n(t)$ is the produced power, $L_n(t)$ is the load and F^m is the transfered power via a link m between two different countries. We assume that storages are charged by excess energy and discharged when the mismatch is negative. The overall mismatch at time t is given by

$$\Delta(t) = \sum_n \Delta_n(t). \tag{8}$$

The storage filling level can then be described as

$$S(t) = S^0 + \int_{t_0}^{t} \Delta(t')\mathrm{d}t', \tag{9}$$

where S^0 is the initial storage filling level at time t_0. This is not a detailed storage model, but a measure to quantify the generation-load mismatch problem. It is equivalent to one large storage, that is connected to all countries of the investigated power system.

The measures to quantify the results of our investigations in this work are the required storage energy S^{E} and the required storage capacity S^{C}. The required storage energy is the energy that is needed to eliminate the negative mismatch (residual load after transmission) and is defined by

$$S^{\mathrm{E}} = -\int_{t_0}^{t_1} \Theta(-\Delta(t'))\Delta(t')\mathrm{d}t, \tag{10}$$

where Θ is the Heaviside function, i.e.

$$\Theta(t) = \begin{cases} 1 & \text{for } t > 0 \\ 0 & \text{for } t < 0 \end{cases}. \tag{11}$$

It is assumed that no storage losses occur. If the required storage energy reduces to zero all loads can be covered by generation at any time. No additional balancing options are therefore necessary. The required storage capacity is the amount of energy the storage needs to be able to store (reservoir capacity). It is defined for a time interval $[t_0, t_1]$ by

$$S^{\mathrm{C}} = -\inf\left[\int_{t_2}^{t_3} \Delta(t')\mathrm{d}t'\right], \; [t_2, t_3] \subset [t_0, t_1]. \tag{12}$$

It can be directly seen from the definitions, that $S^{\mathrm{C}} = 0$ if and only if $S^{\mathrm{E}} = 0$. We calculate storage energies in units of the overall load, while storage capacities are measured in units of the average yearly load. The flow has been formulated as an optimization problem to minimize the required energy from storages at every timestep:

$$\underset{F_m}{\text{minimize}} \sum_n -\Delta_n(t)\Theta(-\Delta_n(t))$$
$$\text{subject to } \mathrm{NTC}_m^- < F_m \le \mathrm{NTC}_m^+. \tag{13}$$

The solution of this optimization problem yields the required energy from storage after transmission.

4 Results

In this section the storage needs are calculated in dependency of the installation factor (share of renewables) α. It is defined by

$$\langle G_n(t)\rangle = \alpha\langle L_n(t)\rangle, \tag{14}$$

so it describes the ratio between average generation and average load. For $\alpha = 1$ load and generation are on average the same.

4.1 Optimal mix

Storage energy needs in this section are computed for the mix between wind onshore and offshore in Europe with unlimited transmission. This mix is described by the parameters β and γ in a recursive way as follows:

$$\beta = \frac{\langle P\rangle}{\langle P\rangle + \langle W\rangle + \langle U\rangle}, \; \beta \in [0, 1], \tag{15}$$

$$\gamma = \frac{\langle W\rangle}{\langle W\rangle + \langle U\rangle}, \; \gamma \in [0, 1]. \tag{16}$$

The storage energy needs for a Europe with unlimited intercountry transmission in dependency of the tupel (α, β, γ) can be seen in Fig. 2 and the storage capacity needs in Fig. 3. Both are strongly depending on the generation mix. Storage energy needs have a minimum at around 12 % of the overall consumption for a mix of $\beta = 0.2$ and $\gamma = 0.0$. They reduce even further for the same β, γ to 9 % for 20 % of over-installation ($\alpha = 1.2$). For storage capacity needs the minimum is at the same shares.It is around 12% of the average yearly consumption and reduces to less than 1 % at these shares for over-installation of 20 %. In general, over-installation reduces storage capacity needs much stronger than storage energy needs. This can be seen in Fig. 4. It shows the relative reductions between storage energy and capacity needs in dependency of β and γ from $\alpha = 1.0$ to $\alpha = 1.1$.

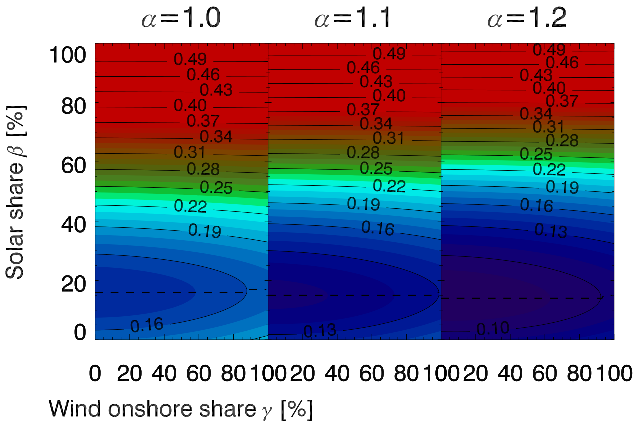

Figure 2. Storage energy needs in units of the consumption in Europe. They are computed with unlimited transmission in dependency of the solar share β and the wind onshore share γ for installation factor $\alpha = 1.0$, 1.1 and 1.2. The dashed lines indicate the optimal solar share in dependency of the wind onshore share.

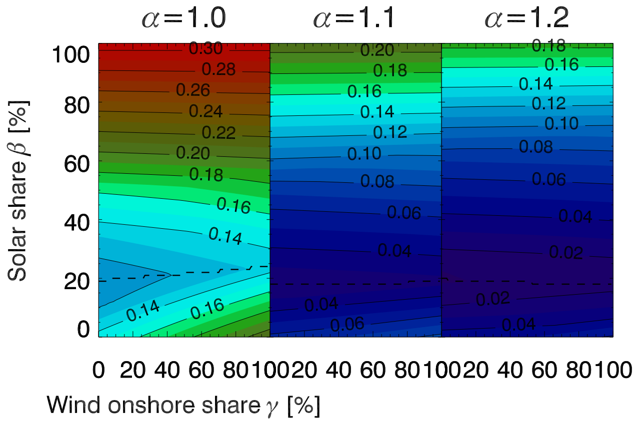

Figure 3. Same as Fig. 2 but for storage capacity needs.

4.2 Storage needs in dependency of the transmission grid

We calculate storage energy needs for installation factors α from 1.0 to 1.2 for four different transmission scenarios (Fig. 5). The generation mix was kept for these calculations from the background scenario. For $\alpha = 1.0$ today's transmission grid has the potential to reduce the storage energy needs by ca. 12 %. Extension of every line capacity by the factor 1.5 would reduce storage needs by additional 5 %. This is still comparably low to the reduction by around 45 % that could be achieved by unlimited transmission. At $\alpha = 1.2$ storage energy needs reduce for unlimited transmission to less than 8 % of the mean load.

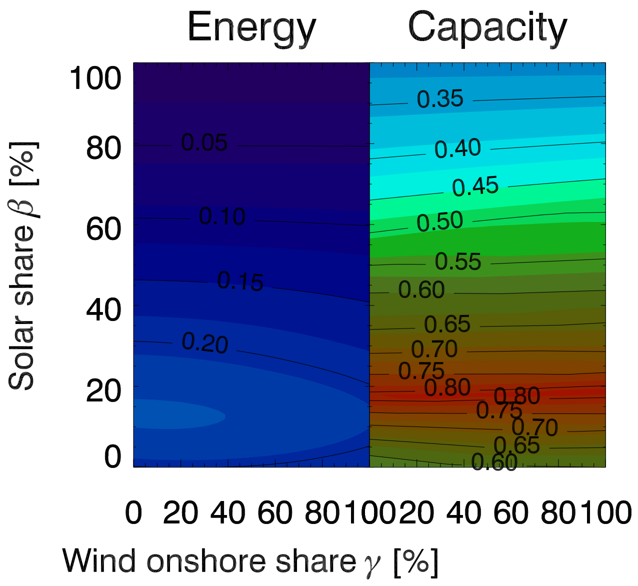

Figure 4. Reduction of relative storage energy (left) and storage capacity (right) needs for an increase of the installation factor $\alpha = 1.0$ to 1.1 for a Europe with unlimited transmission in dependency of the solar β and wind onshore share γ.

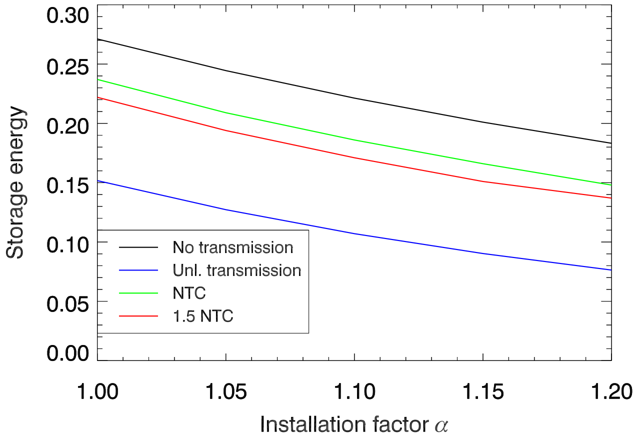

Figure 5. Storage energy needs in Europe in dependency of the installation factor α for different transmission scenarios in units of the overall load.

5 Conclusions

Based on a highly spatially and temporally resolved weather data set, we investigated balancing in terms of storage capacity and storage energy needs for 34 European countries in dependency of the generation mix between wind onshore, wind offshore and photovoltaics. For a scenario with unlimited transmission in Europe we concluded, that in 100 % renewable scenarios storage energy and capacity needs are considerably reduced by high shares of wind offshore compared to wind onshore and photovoltaics. Furthermore we showed, that storage capacity needs can be reduced by over-installation of 10 % ($\alpha = 1.1$) by 70 to 80 %. For the same over-installation of 10 % the relative reduction of storage energy needs is around 25 %. However, transmission is not unlimited in Europe today. We have computed storage needs for different transmission grid scenarios and shown, that today's inter-country transmission grid can reduce storage energy needs by ca. 12 % for a 100 % renewable share. This is still highly extendable because unlimited transmission would reduce storage energy needs in the 100 % renewables scenario by ca. 45 %.

Acknowledgements. The work is part of the RESTORE 2050 project (Wuppertal Institute, Next Energy, University of Oldenburg) that is financed by the Federal Ministry of Education and Research (BMBF, Fkz. 03SFF0439A). We would like to thank our project partners from Wuppertal Institute and Next Energy for helpful discussions and suggestions and the supply of load data. We would also like to thank Matthias Huber and an anonymous referee for helpful suggestions and comments.

Edited by: M. Schroedter-Homscheidt
Reviewed by: M. Huber and another anonymous referee

References

Becker, S., Frew, B. A., Andresen, G. B., Jacobson, M. Z., Schramm, S., and Greiner, M.: Transmission grid extensions during the buildup of a fully renewable pan-european electricity supply, Energy, 64, 404–418, 2014.

Cano, D., Monget, J. M., Albuisson, M., Guillard, H., Regas, N., and Wald, L.: A method for the determination of the global solar radiation from meteorological satellite data, Solar Energy, 37, 31–39, 1986.

Hammer, A., Heinemann, D., and Westerhellweg, A.: Derivation of daylight and solar irradiance data from satellite observations, Proceedings 9th Conference on Satellite Meteorology and Oceanography, May 1998, Paris, 747–750, 1998.

Heide, D., von Bremen, L., Greiner, M., Hoffmann, C., Speckmann, M., and Bofinger, S.: Seasonal optimal mix of wind and solar power in a future, highly renewable europe, Energy, 64, 404–418, 2014.

Huber, M., Dimkova, D., and Hamacher, T.: Integration of wind and solar power in Europe: Assessment of flexibility requirements, Energy, 69, 236–246, 2014.

Klucher, T. M.: Evaluation of models to predict insolation on tilted surfaces, Solar Energy, 23, 111–114, 1979.

Pfluger, B., Sensfuß, F., Schubert, G., and Leisentritt, J.: Tangible ways towards climate protection in the European Union (EU long-term scenarios 2050), Technical report, Fraunhofer ISI, Karlsruhe, September 2011.

Rasmussen, M. G., Andresen, G. B., and Greiner, M.: Storage and balancing synergies in a fully or highly renewable pan-European power system, Energy Policy, 51, 642–651, 2012.

Rienecker, M. M., Suarez, M. J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M. G., Schubert, S. D., Takacs, L., Kim, G.-K., Bloom, S., Chen, J., Collins, D., Conaty, A., da Silva, A., Gu, W., Joiner, J., Koster, R. D., Lucchesi, R., Molod, A., Owens, T., Pawson, S., Pegion, P., Redder, C. R., Reichle, R., Robertson, F. R., Ruddick, A. G., Sienkiewicz, M., and Woollen, J.: MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications, J. Climate, 24, 3624–3648, 2011.

Rodriguez, R. A., Becker, S., Andresen, G. B., Heide, D., and Greiner, M.: Transmission needs across a fully renewable European power system, Renewable Energy, 63, 467–476, 2014.

Schaber, K., Steinke, F., Mühlich, P., and Hamacher, T.: Parametric study of variable renewable energy integration in Europe: Advantages and costs of transmission grid extensions, Energy Policy, 42, 498–508, 2012.

Schulz, J. P. and Schättler, U.: Kurze Beschreibung des Lokal-Modells Europa COSMO-EU(LME) und seiner Datenbanken auf dem Datenserver des DWD, Deutscher Wetterdienst, Web, http://www.dwd.de/bvbw/generator/DWDWWW/Content/Forschung/FE1/Veroeffentlichungen/Download/LMK__DBbeschr__1104__en,templateId=raw,property=publicationFile.pdf (last access: 3 February 2015), 2009.

Steinke, F., Wolfrum, P., and Hoffmann, C.: Grid vs. storage in a 100 % renewable Europe, Renewable Energy, 50, 826–832, 2013.