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The smoothing effect for renewable resources in an Afro-Eurasian power grid

Maria Krutova[1,2], **Alexander Kies**[1,3], **Bruno U. Schyska**[1], and **Lueder von Bremen**[1]

[1]ForWind, Center for Wind Energy Research, University of Oldenburg, Oldenburg, Germany
[2]Wind Energy Department, Technical University of Denmark, Lyngby, Denmark
[3]Frankfurt Institute for Advanced Studies, Goethe University Frankfurt, Frankfurt, Germany

Correspondence to: Maria Krutova (maria.krutova@uni-oldenburg.de)

Abstract. Renewable power systems have to cope with highly variable generation. Increasing the spatial extent of an interconnected power transmission grid smooths the feed-in by exchange of excess energy over long distances and therefore supports renewable power integration. In this work, we investigate and quantify the balancing potential of a supergrid covering Europe, Africa and Asia. We use ten years of historical weather data to model the interplay of renewable generation and consumption and show that a pan-continental Afro-Eurasian supergrid can smooth renewable generation to a large extent and reduce the need for backup energy by around 50 %. In addition, we show that results for different weather years vary by up to approximately 50 %.

1 Introduction

The growing shares of feed-in from renewable sources of wind and photovoltaics (PV) pose a demanding challenge to stable operation of power systems (Lund, 2008; Kies et al., 2016a). Generation from renewable sources is not dispatchable, but highly fluctuating and therefore cannot replace dispatchable generation from conventional sources directly. Instead, power systems, which rely on renewable generation sources, need additional balancing means. Possibilities include backup, storage (Weitemeyer et al., 2016; Pleßmann, 2014; Heide et al., 2011) or reinforced transmission grid (Brown, 2014).

Alternatives aim to increase the usage of system-friendly renewables (Hirth et al., 2016; Chattopadhyay et al., 2017), which describe, for instance, the deployment of renewable generation facilities with respect to being part of a highly renewable power system instead of focusing on meteorological conditions alone. An example is to optimize the mix of renewables (Santos-Alamillos et al., 2012; Tafarte et al., 2014; Kies et al., 2016c; Heide et al., 2010; Lund, 2006; Vidal-Amaro et al., 2015; Francois et al., 2016; Jurasz and Ciapała, 2017). Besides taking measures on the generation side, it is possible to modify the consumption side via demand side management (which usually refers to load shifting; Strbac, 2008; Kies et al., 2016d or sector coupling Brown et al., 2017).

In the final consequence, increasing the spatial extent of a power grid leads to a pan-continental or even global supergrid. A vision of such global grid was put forward by (Chatzivasileiadis et al., 2013, 2014). Furthermore, Chinese president Xi Jinping proposed discussions on a "global energy internet" in a keynote speech at the UN Sustainable Development Summit[1] in September 2015. The concept was also discussed in more detail by the State Grid Corporation of China (Wang, 2015). The needs for infrastructure of a global supergrid were recently discussed by (Dahl et al., 2017).

In this paper, we investigate the potential benefit from the smoothing effect for renewable feed-in in a pan-continental supergrid connecting large parts of Europe, Asia and Africa. For this purpose, we quantify the benefit as a reduction in the need for backup energy in a highly renewable power system where renewable generation equals demand on average. In addition, we quantify the year-to-year variability of the need for backup energy. First, we determine the optimal mix of wind and photovoltaics generation for every node in the network independently (Sect. 3). Using these optimal mixes, we

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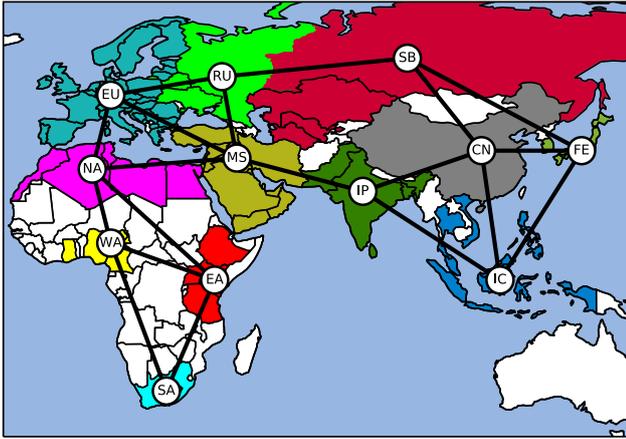[1]www.sgcc.com.cn/ywlm/mediacenter/corporatenews/

Figure 1. The investigated simplified power system consists of super regions connected by long distance transmission lines.

investigate the potential reduction of the need for backup in the grid connecting three continents in Sect. 4. In Sect. 5 we investigate the smoothing effect further by iteratively connecting nodes to the grid starting with Europe processing eastwards.

2   Methodology

We simulate a simplified power network covering large parts of Eurasia and Africa. Super regions within this network are represented as nodes (Fig. 1), which are connected by long-distance transmission lines.

Each node produces energy from the renewable sources of wind and photovoltaics (PV). The time series of renewable production of node n is given by $G_n(t) = G_n^W(t) + G_n^S(t)$, where G_n^W and G_n^S refer to the partial generation time series from wind and PV, respectively. In addition, each node has a load time series $L_n(t)$. The mismatch between generation from renewable sources and load, $\Delta_n(t) = G_n(t) - L_n(t)$ needs to be balanced by the system, i.e.,

$$\Delta_n(t) = C_n(t) - B_n(t) + P_n(t). \tag{1}$$

$C_n(t)$ is curtailment time series, $B_n(t)$ is backup generation from perfectly flexible power plants and $P_n(t)$ is the injection pattern (exports – imports), which describes the usage of the transmission grid. Backup time series are calculated via

$$B_n(t) = -\min\{0, \Delta_n(t) - P_n(t)\} \tag{2}$$

We are interested in two major quantities concerning the need for backup:

1. the need for backup energy B_n^E of a node, defined via

$$B_n^E = \int B_n(t)\mathrm{d}t \tag{3}$$

Table 1. Considered regions and their average load.

Region	Countries	$\langle L \rangle$ [GW]
EU	EU countries	572
NA	Algeria, Egypt, Libya, Morocco, Tunisia	63
WA	Cameroon, Ghana, Nigeria	19
EA	Ethiopia, Kenya, Tanzania, Uganda	20
SA	South Africa	14
RU	European Russia, Belarus, Ukraine	66
MS	Arabic countries, Israel, Turkey	159
IP	Bangladesh, India, Pakistan, Sri Lanka	258
SB	Asian Russia, Kazakhstan, Uzbekistan	19
IC	Indonesia, Malaysia, Philippines, Thailand, Vietnam	163
CN	China	676
FE	South Korea, Japan	226

2. the need for backup capacity B_n^C, i.e., the generation capacity of dispatchable generation that needs to be kept at hand, defined via

$$0.99 = \int_0^{B_n^C} p\big(B_n(t)\big)\mathrm{d}p, \tag{4}$$

$p(.)$ describes the distribution function of backup events. The 99th percentile is chosen to reduce the sensitivity towards the weather database. The same assumption is made for instance by (Dahl et al., 2017).

Transmission bottlenecks within single regions are not considered in these calculations.

2.1   Generation and load data

For Europe, we model generation and load data with a temporal resolution of one hour and a spatial resolution of 7 km covering years 2003–2012. Load data is taken from ENTSO-E and modified according to expected changes due to electrification of transport and heating within the R&D project RESTORE 2050. Wind speeds are taken from statistically downscaled MERRA reanalysis data (Rienecker et al., 2011). Details on generation data are given by (Kies et al., 2016b, 2015). For all other regions, we use data from MERRA reanalysis without downscaling.

Since real time-resolved load data is only for Europe available to us, the load time series of node $n \neq$ EU is modelled as

$$L_n(t) = \langle L_n \rangle \left[1 - \frac{1}{4}\cos\left(\frac{\pi t}{4380}\right) \right. $$
$$\left. - \frac{1}{4}\sin\left(\frac{\pi(t + \tau + 4)}{12}\right) \right] + \varepsilon_t, \tag{5}$$

where τ is the GMT time zone offset and $\langle L_n \rangle$ is proportional to the projected GDP by 2050 (Ward, 2012). Table 1 shows

average load per node,

$$\langle L_n \rangle = \langle L_{EU} \rangle \frac{\text{GDP}_n^{2050}}{\text{GDP}_{EU}^{2050}}. \tag{6}$$

ε_t is a random normally distributed value $\mathcal{N}(0, 0.04\langle L_n \rangle)$ representing short term fluctuations.

Use of projected GDP determines the nodes which we consider in our model. GDP, and therefore load, of the countries not listed is assumed negligible. Russia is split into two parts. However, all of its demand is assumed to be concentrated in the European part (RU), which is more densely populated and industrialized. Asian part of Russia (SB) is considered solely a renewable energy provider.

2.2 Transmission

We use power flow equations in a common linear approximation. F_l denotes the flow over link l and can be either positive or negative (the sign indicates the direction of the flow). Flows and the injection pattern P are related via

$$F = \text{PTDF} \cdot P, \tag{7}$$

PTDF is the Power Transfer Distribution Factor matrix, which we calculate via

$$\text{PTDF} = K^T L^+, \tag{8}$$

where K is the incidence matrix and L^+ the Moore-Penrose pseudoinverse of the Laplacian matrix of the network defined as $L = K^T K$. The transmission system is operated to minimize the need for backup energy and modelled as a two-step optimization problem. The first step reads

$$\begin{aligned} \underset{P(t)}{\text{minimize}} \quad & \sum_n B_n(t) =: B^{\min}(t) \\ \text{subject to} \quad & \sum_n P_n(t) = 0 \\ & F_l^- < F_l(t) \le F_l^+. \end{aligned} \tag{9}$$

However, the solution F_l of this optimization problem is usually degenerate. The second step ensures the uniqueness of the solution by minimizing the squared flows. This can be understood as minimizing dissipation losses (which are $\propto F^2$) and reads

$$\begin{aligned} \underset{P(t)}{\text{minimize}} \quad & \sum_l F_l^2 \\ \text{subject to} \quad & \sum_n P_n(t) = 0 \\ & F_l^- < F_l(t) \le F_l^+ \\ & \sum_n B_n(t) = B^{\min}(t). \end{aligned} \tag{10}$$
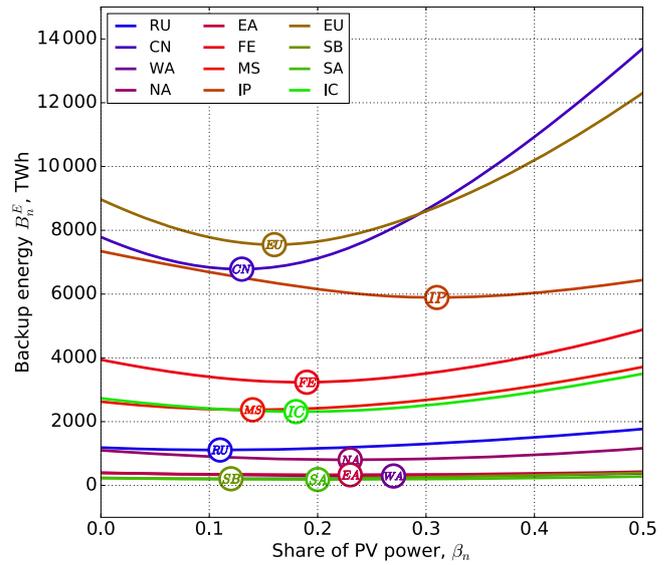

Figure 2. Backup energy need in dependency of the corresponding wind/PV mix. Markers are placed at the position of the optimal power mix.
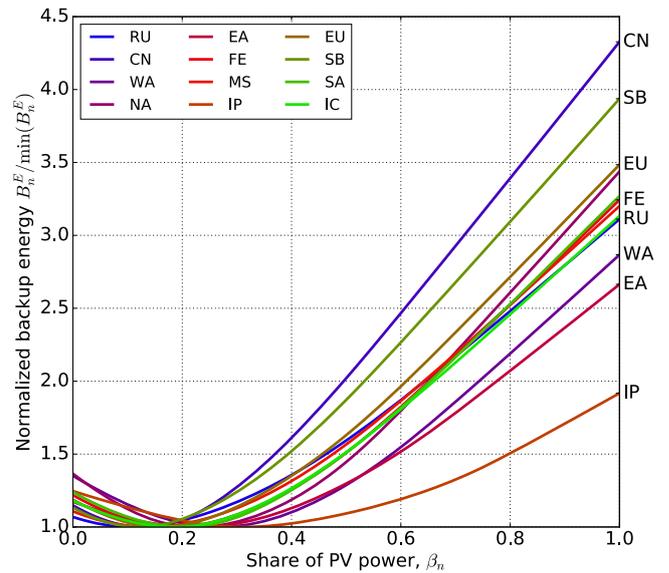

Figure 3. Growth of the backup energy need in dependency of wind/PV mix. Backup energy is normalized to the corresponding minimum values.

Once the time series of flows via a certain link l are known, its required transmission capacity T_l^C can be computed via

$$0.99 = \int_0^{T_l^C} p\big(|F_l(t)|\big) \mathrm{d}p, \tag{11}$$

An equivalent transmission model is, for instance, used by (Kies et al., 2016d).

Table 2. Optimal PV share for each autonomous node.

Region	β_n^{opt}	Region	β_n^{opt}	Region	β_n^{opt}
RU	0.11	EU	0.16	EA	0.23
SB	0.12	IC	0.18	NA	0.23
CN	0.13	FE	0.19	WA	0.27
MS	0.14	SA	0.2	IP	0.31

3   Wind/PV mix

Before we investigate benefits resulting from smoothing in the following sections, we neglect transmission and optimize the mix of wind/PV for every node independently. We define the mix to be optimal, if the resulting need for backup energy is minimized. The corresponding optimization problem for node n reads

$$
\begin{aligned}
\underset{\beta_n}{\text{minimize}} \quad & B_n^E \\
\text{subject to} \quad & 0 \leq \beta_n \leq 1 \\
& \alpha_n = 1 \\
& F_l = 0 \forall l,
\end{aligned}
\tag{12}
$$

where β_n is the share of PV power in the renewable generation mix and α_n is the renewable penetration at the node n.

$$
\beta_n = \frac{\langle G_n^S(t) \rangle}{\langle G_n(t) \rangle}
\tag{13}
$$

$$
\alpha_n = \frac{\langle G_n(t) \rangle}{\langle L_n(t) \rangle}.
\tag{14}
$$

The need for backup energy in dependency of the renewable mix is shown for all nodes in Fig. 2. The optimal share values are provided in Table 2.

It can be observed that the optimal solar shares for all nodes lie between 0.11 and 0.31. Similar investigations have shown that in Europe a solar share of ca. 0.4 minimizes monthly standard deviation (Heide et al., 2010).

An obvious outlier is the IP node, containing India. It has the highest value as optimal PV share and also an interesting property of being the node, where the relative need for backup energy is lowest in a PV-dominated scenario (Fig. 3). This seems to be caused by a lower correlation of PV feed-in. However, further investigation is required to quantify the reason for this effect. Optimal shares of African nodes are grouped in range 0.2–0.3 with West Africa node (WA) having the highest β_n^{opt} of them.

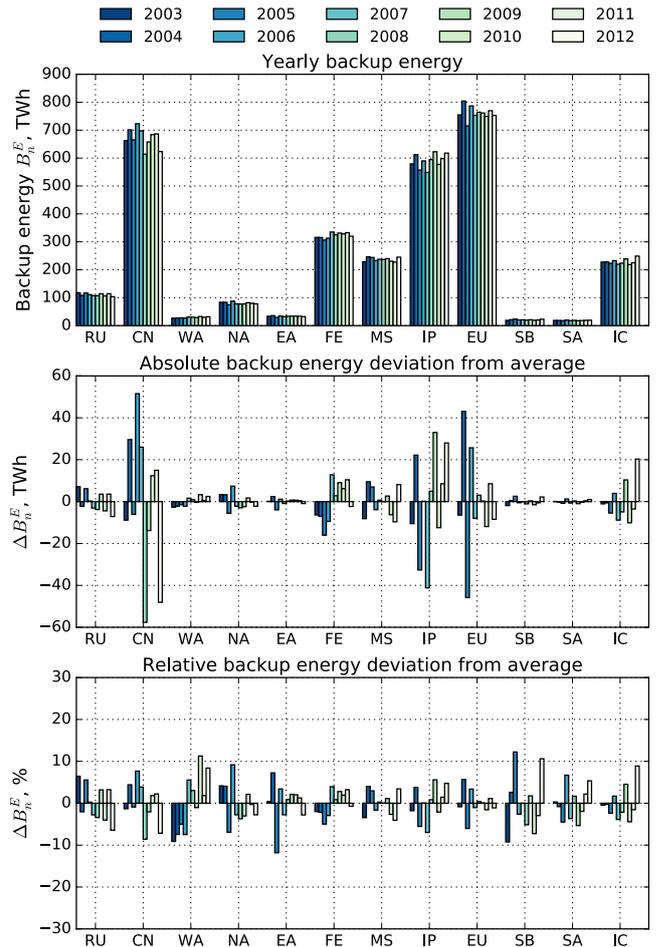The total renewable generation of each region in the following sections is calculated with power mixes resulting from optimal β_n^{opt}.

Figure 4. Yearly backup energy need and its deviation from 10-year average $\Delta B_n^C = \langle B_n^C \rangle - B_n^C$ for the isolated regions with $\alpha = 1$.

4   Afro-Eurasia

The next step is to investigate the impact of the smoothing effect on the need for backup energy in the supergrid. The yearly variation of the backup energy need of the single regions is shown in Fig. 4 for isolated regions and Fig. 5, if all of them are connected. While yearly patterns of the deviation from average are similar in both cases, relative differences increase in case of the supergrid. The main reason for this is overall decrease of the backup need in the grid, and therefore – the average backup, by around 50 %. Absolute deviations stay within the same range as in the case of isolated nodes, while relative deviation increases because of the lower average.

Yet not all nodes see backup deviation change proportional to overall backup reduction. This is the result of linking nodes through the transmission grid. In case of isolated regions the excess renewable power is not shared with other nodes. Therefore, nodes with comparably high demand have to balance it with their local resources. When nodes partici-
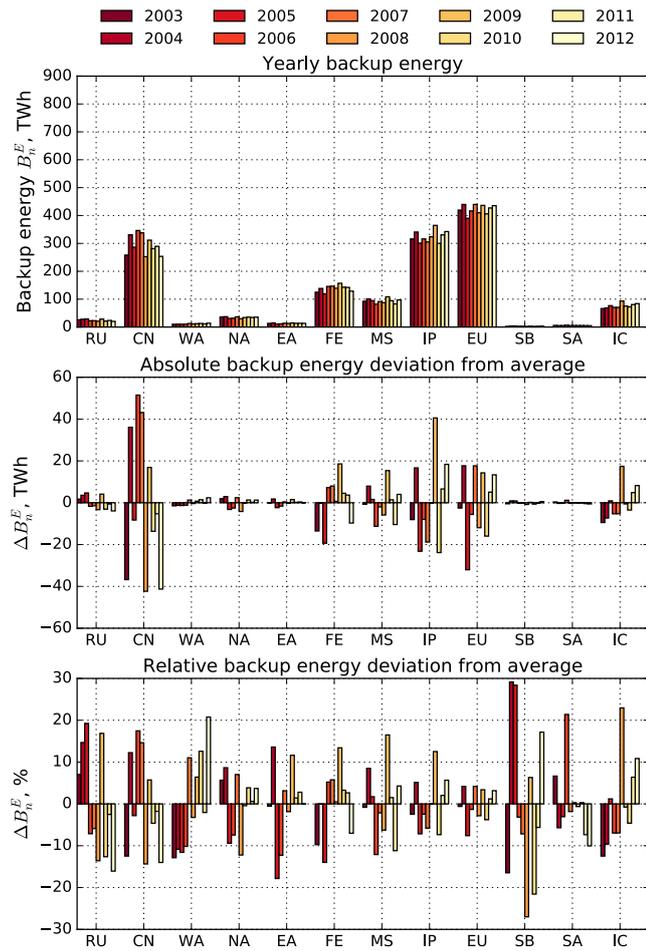
Figure 5. Yearly backup energy need and its deviation from 10-year average $\Delta B_n^C = \langle B_n^C \rangle - B_n^C$ for Afro-Eurasian grid with $\alpha = 1$.

Table 3. Transmission grid setups. While all regions are always present in the simulation, some of them are not connected to a grid. Node to node links correspond to topology suggested in Fig. 1

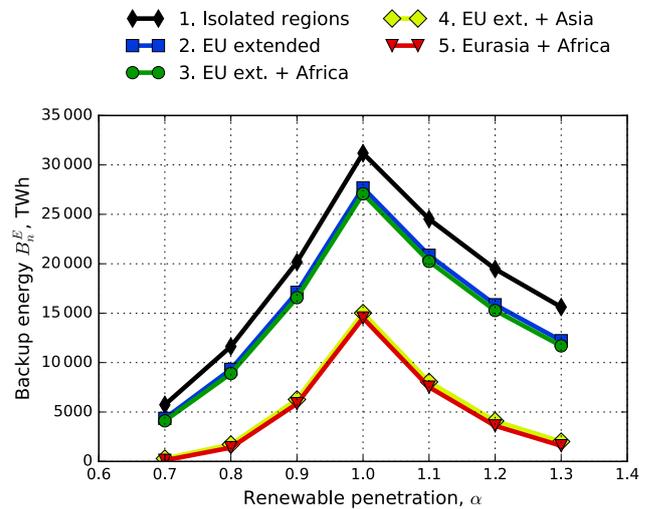| Grid setup ID	Linked regions	Isolated regions
1. Isolated regions	None	All
2. EU extended	EU, RU, NA, MS	SB, IP, CN, IC, FE, WA, EA, SA
3. EU ext. + Africa	EU, RU, NA, MS, WA, EA, SA	SB, IP, CN, IC, FE
4. EU ext. + Asia	EU, RU, NA, MS, SB, IP, CN, IC, FE	WA, EA, SA
5. Eurasia + Africa	All	None

Figure 6. Need for backup energy for different grid toplogies in dependency of the renewable penetration.

pate in power exchange, excess renewable power is used to balance the demand throughout the grid.

In addition, the reduction for backup energy need is higher, if the year is favourable for wind and solar power generation. Hence, relative yearly differences are additionally emphasized in the grid due to different weather years. For some nodes, backup energy requirements of consecutive years vary by 40–50 %. This comparison emphasizes the importance of considering more than a single weather year to obtain reliable results in renewable power system analysis.

The total 10-year need for backup energy in dependency of the renewable penetration α for several transmission grid setups (Table 3) is investigated by linking different groups of Eurasian and African nodes. The global renewable penetration is defined similarly to Eq. (14) through global generation and load averages, where distribution is assumed to be homogeneous, i.e. $\alpha_n = \alpha$ for all nodes.

The different setups allow to explore, how the need for backup energy is effected as more regions are connected through the transmission grid. If all Afro-Eurasian nodes are

connected, a reduction by around 50 % is observed compared to isolated regions for $\alpha = 1$ (Fig. 6).

The decrease is mainly caused by the interconnection between Europe and Asia, whereas adding the connection between Europe and Africa has only a small beneficial effect, as seen by comparing setups 2–3 and 4–5. The maximum backup reduction is reached when all regions are linked into the intercontinental Afro-Eurasian grid (setup 5). The much smaller benefits from linking Europe and Africa compared to Europe and Asia are, besides the lesser spatial extent, most likely caused by high correlation of solar feed-in in Europe and Africa as they belong to similar longitudes.

5 Eurasia

It is shown in the previous section that major benefits stem from the extension of the European power grid to the east, i.e., Asia. Therefore, we investigate this option further and compute a different set of grid configurations. We start

with isolated regions and then link regions one by one from west to east. The first simulated grid contains only the link between EU + RU, the second comprises a triangle EU + RU + MS, and so on until all Eurasian regions are connected. Figure 7 shows the need for backup energy, backup capacity and transmission capacity in dependency of the grid extension. The transmission capacity is summed up for all links containing a corresponding node.

It can be observed that connecting RU, IP and CN causes the biggest decrease in the need for backup energy and backup capacity for the European Union (EU). This is likely caused by the fact that they are modelled as having a similar average load and generation due to the projected size of their economies in 2050.

However, extending the transmission network to the east comes at the price of a large need for transmission capacities. Comparing EU + RU to the case of entire Eurasia shows transmission capacities to grow for Europe by a factor of 7. It is notable, that transmission needs increase for all nodes with the grid extension, except for MS, which sees a small decrease after the node CN is connected. Possessing a very high demand, the CN node redirects power flows to itself, thus slightly relieving the power exchange through MS.

6 Discussion, summary and conclusions

In this work, we have investigated a pan-continental supergrid. Technologically, such a supergrid would most likely depend on high-voltage direct-current (HVDC) transmission systems. Components of such systems mostly already exist today. However, because converters, cables, and other components for HVDC are more expensive than those for AC as of today, they are economically inefficient for short connections, but HVDC systems become advantageous over long distances because of favourable features, such as easy transfer of power between grids that are operating at different frequencies.

The greatest obstacle for a global supergrid seems to be a fair cost-allocation mechanism. Even on the country level, costs for different system components and their allocation to consumers and generators is the subject of regular dispute. However, the advantages of such global grid, including the ones presented in this paper, can make future research and efforts promoting global cooperation on renewable energy generation and exchange appear meaningful.

A straightforward extension of this work would be to include storage options in the calculations. (Bogdanov et al., 2015) have found for a similar Eurasian grid that HVDC transmission leads to a cut-off of storage utilization and decrease the need for primary generation capacities.

In our calculations it was shown that such a grid has the potential to reduce the need for backup energy by up to one half by transmitting energy surpluses via long distances to cover energy deficits. This is a comparable number as
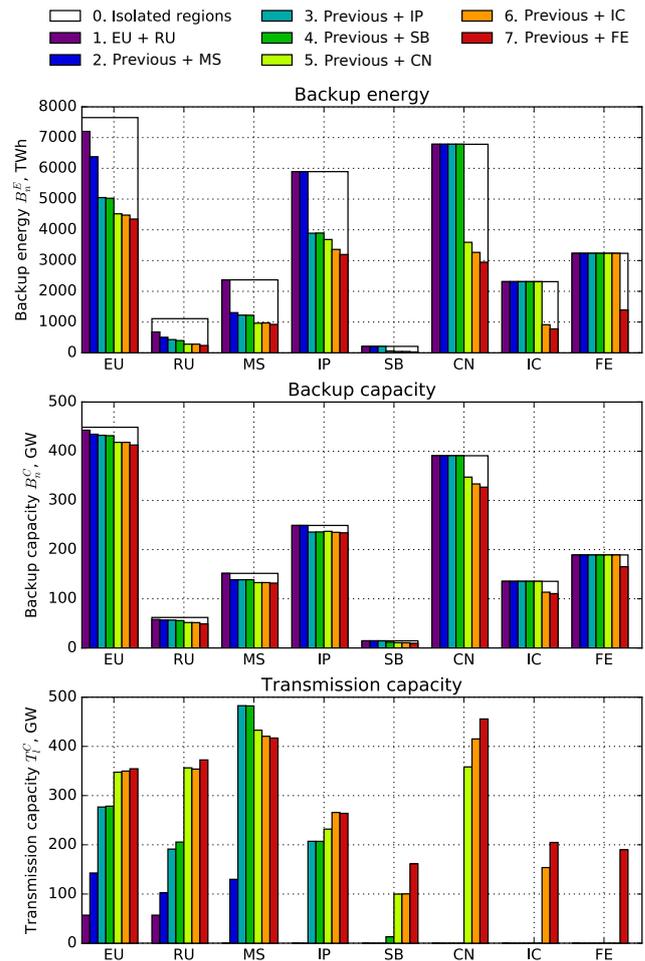

Figure 7. Need for backup energy, backup capacity and transmission capacity of the Eurasian regions in dependency of the grid expansion from west to east, $\alpha = 1$. The node labels are listed in the order of connection to a grid.

found by other studies. (Dahl et al., 2017) found the need for backup energy decrease from 18 to 10 % of the total consumption if Europe, Russia, North-Africa and the Middle East are connected.

Besides, the importance of using multiple weather years to obtain reliable results in the modelling of renewable energy systems was substantiated by the observed yearly variation within the 10-year period.

It can be concluded that a pan-continental Eurasian power grid has the potential to reduce fluctuations on the generation side and consequently the need for dispatchable backup power to a large degree.

Data availability. Data on generation and load per node is publicly available (Krutova et al., 2017). The only exception is the load time series for the EU node, which was produced within the project

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