What can transmission do for a fully renewable Europe?

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Abstract. Our research is centred around the question how to best integrate the variable renewable energy sources (VRES), wind power and solar photovoltaics, into the European electricity grid. The future electricity supply will be based to a large extend on these fluctuating resources. We have conducted a study, extrapolating national historical and targeted wind and solar power penetrations in Europe up to 100% VRES [1, 2]. A high share of VRES means large fluctuations in the generation, causing overproduction and deficits. One way to reduce such mismatches is power transmission spatially smoothing out the fluctuations. This has the potential to reduce the remaining shortages by sharing the surplus production of others. We find that shortages can at maximum be reduced by 40% in the hypothetical case of unlimited transmission capacities across all of Europe. A more realistic extension of the transmission grid, roughly quadrupling today’s installation, turns out to be sufficient to harvest 90% of this potential benefit. Finally, the import and export of single countries is investigated. We conclude that a country’s load size as well as its position in the network are the determining factors for its import/export opportunities.

1 Motivation

The ambitious goal of the European Union to reduce green house gases, in particular CO₂ by 80% by 2050 [3], entails a shift to almost completely CO₂-free electricity generation in the same time horizon [4]. A large part of this renewable generation will come from the variable renewable energy sources (VRES) wind and solar PV. Due to their intermittent nature, their integration into the power system poses a considerable challenge. To this end, various measures have been proposed and to some extend also tested or implemented: Energy storage systems, demand-side management (DSM)/Smart Grid technologies, or coupling to the other energy sectors, heating/cooling and transportation (via electrical heating/cooling, electric vehicles, or fuel generation from electricity and vice versa), all have the potential to shift load and/or generation in time, thus reducing the mismatch between the two. Another path to follow to reduce the mismatch between load and generation is its spatial distribution over larger areas, i.e. power transmission. Wind power production, for example, has been shown to decorrelate over the range of ~1000 km for the cases of the US East Coast [5] and Sweden [6]. Such spatial smoothing has the potential to yield a more even generation output, and hence a better chance to match it to the load. In this proceedings, we assess the potential of transmission from a purely technical point of view. We investigate what transmission is able to do as well as what it cannot do. Economics are not taken into account. Furthermore, we look for efficient ways of enhancing the transmission grid and develop a tentative roadmap of which links should be reinforced and when, and we explore the effects of such an enhanced transmission grid on the trade opportunities of single countries. Parts of these results have been published in [1, 2]. Here, we present additional discussion of the factors that influence a country’s import and export opportunities, and show the time development of the distributions of the mismatch between load and renewable generation. The latter reveal that transmission is particularly well-suited to reduce the occurrence of small mismatch events, but the mitigation of large mismatches remains a major challenge, even when an upgraded transmission grid is available.

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2 Data and methodology

2.1 Weather and generation

In this paper, we use the same weather and generation data that have been described at this conference in the talk "Weather-driven modelling of future renewable power systems" by G. B. Andresen et. al. Therefore, we only repeat the essentials of our Weather-Driven Renewable Energy System Modelling (WDRESM). At the core lie generation data for wind and solar PV power which are calculated based on real weather data of eight years with hourly resolution. They are aggregated to country level and normalized by their mean, yielding $W_n(t)$ (wind time series for country $n$) and $S_n(t)$ (solar time series for country $n$). Load data $L_n(t)$ were obtained for the same eight years, in hourly resolution as well. The key ingredient to all further modelling is the mismatch between generation and load:

$$\Delta_n(t) = \gamma_n \left( \alpha_n W_n(t) + (1 - \alpha_n) S_n(t) \right) \cdot \langle L_n \rangle - L_n(t)$$

(1)

In this formula, the factor $\gamma_n$ scales the average generation from the two variable renewable sources (VRES) to a desired fraction of the load, so we can model different penetrations of wind and solar power, and $\alpha_n$ is the relative share in wind in VRES. $\langle \cdot \rangle$ denotes the time average of a quantity. If this mismatch is positive, it means that surplus generation occurs which can be exported to other countries or used domestically in other energy sectors. If it is negative, generation is insufficient and the electrical load has to be covered from other sources or shifted to other times.

2.2 Logistic fit

In order to have a tangible scaling of the renewable penetration from the medium-sized percentage seen today to a scenario where mean load equals mean VRES generation, we extrapolate logistically from historical values through the 2020 EU targets [7] to a hypothetical 2050 target of an on average 100% VRES-supplied European electricity system. This still includes balancing from dispatchable sources. For details of the data as well as the logistic fit, see [2]. An example is shown in Fig. 1.

![Logistic fit of wind power penetration (a) and solar power penetration (b) for the example case of Denmark. The historical values originate from eurostat [8], the 2020 targets from the National Renewable Energy Action Plan [7], and the 2050 target is a hypothetical scenario in which the average wind and solar power generation equals the average load.](image)

2.3 Power transmission between countries

In our power transmission model, each country forms a node in a network. In the case at hand, we investigate the European countries. The topology of the network can be seen in Fig. 4. The power
transmission framework has been developed and tested as published in [1, 2]. It consists of a generalized DC power flow. For a stable electricity grid, the full AC equations can be well approximated linearly, yielding a system that is mathematically completely analogous to DC power flow [9]. One formulation of this is the following: Given a mismatch vector, $(\Delta_n)_{n=1..N}$, find a flow vector $(F_l)_{l=1..L}$ along the $L$ links of the network that solves

$$\Delta_n - (KF)_n = 0 \quad \text{(cover deficits with surpluses)}$$

$$\min \sum_l F_l^2 \quad \text{(minimize transmission dissipation)}$$

where $F_l$ is the power flow along link $l$ and $K$ is the incidence matrix,

$$K_{nl} = \begin{cases} 
1 & \text{if link } l \text{ starts at node } n \\
-1 & \text{if link } l \text{ ends at node } n \\
0 & \text{else}
\end{cases}$$

This has two drawbacks that make it seem unattractive for our application: It only has a solution if $\sum_n \Delta_n = 0$, and it does not allow to take limits on the flow due to finite line capacities into account. We therefore generalize it in two ways: First, we allow for residual surpluses and deficits. The latter have to be covered from other sources. We call those “balancing”, since they balance the system, $B_n(t)$. We minimize their usage such that VRES are always preferred. Second, we include the constraints on the flows in the two resulting minimizations:

1st step: $\min \sum_n (\Delta_n - (KF)_n)_- = \min \sum_n B_n \rightarrow B_{\min}$ \text{(minimize back-up power)}

subject to: $h_- \leq F_l \leq h_l$

2nd step: $\min \sum_l F_l^2$

subject to: $h_- \leq F_l \leq h_l$, $\sum_n B_n = B_{\min}$

Here, $(x)_- = \max\{0, -x\}$ denotes the negative part of a quantity $x$. This optimization problem is proven to be convex and can hence be handled with standard techniques.

As a last remark, we observe that this flow paradigm leads to power flow only transporting VRES surplus production from one country to another, where it either covers VRES deficits or replaces balancing. Trade with conventional power, balancing in our terminology, does not take place. This follows from Eq. 5: Producing the balancing energy for one country in another and then transferring it leads to more flow while keeping the total amount of balancing constant. Minimizing the flow means localising the balancing at those nodes that actually see a deficit.

3 Transmission

3.1 Benefit of transmission

The benefit of transmission of a certain line capacity layout is formulated as a percentage of reduction in balancing energy relative to what is achievable with transmission. Denote a given line capacity layout, i.e. a set of line capacities, by $CL_{this} = (h_{\pm l}^{(this)})_{l=1..L}$. Under the fixed flow paradigm defined above, this gives rise to a well-defined corresponding total balancing energy needed, $B_{\text{tot}}(CL_{this}) = \sum_n \sum_l B_n(t)$. For unconstrained transmission, $CL_{\text{unconstrained}}$, as well as for no transmission, $CL_{\text{zero}}$, the total balancing energy is calculated. The difference between those two is the maximal balancing energy reduction achievable by transmission. The benefit of $CL_{this}$ is now defined as the balancing energy reduction resulting from going from $CL_{\text{zero}}$ to $CL_{this}$, normalized by the maximal possible reduction.

$$\beta_{\text{this}} = \frac{B_{\text{tot}}(CL_{\text{zero}}) - B_{\text{tot}}(CL_{\text{this}})}{B_{\text{tot}}(CL_{\text{zero}}) - B_{\text{tot}}(CL_{\text{unconstrained}})}$$

Fixing the benefit of transmission amounts to fixing the total balancing energy.
3.2 Build-up of the transmission grid

An obvious question to ask, given a transmission grid topology, is how to extend it in the most efficient way. If we had a certain investment (in terms of additional MW in line capacity), how should it be distributed among the links to obtain the highest possible benefit of transmission? We have tested several build-up scenarios, as described in [1], for the case of $\gamma_n = 1 \forall n$ in Eq. (1), i.e. VRES generation average equalling load average, and a wind/solar mix $\alpha^W_n$ that makes their generation follow the load in the closest possible way, for details on this, see [1]. The first (blue curve in Fig. 2a) is an upscaling of the line capacities present today.

\[ h^{(1)}_l = b \cdot h^{\text{today}}_l \forall l \]  

(7)

For the second (red curve in Fig. 2a), we calculate the flows resulting from removing the flow constraint from the two minimizations (4), (5). A capacity layout is then constructed by taking quantiles $Q$ of the distributions of these unconstrained flows:

\[ h^{(2)}_l = \text{Quantile}_Q(\{F_l(t)\}_{t=1..T}) \forall l \]  

(8)

The third (green curve in Fig. 2a) is a simplification of the second: Instead of taking different quantiles, only the 99% quantiles are used and scaled down. This yields similar capacities as compared to the second approach.

\[ h^{(3)}_l = b \cdot \text{Quantile}^{99\%}(\{F_l(t)\}_{t=1..T}) \forall l \]  

(9)

The most successful interpolation scheme of the three under consideration are the quantile capacities, the second method described above, as can be seen in Fig. 2a. This will be used as a standard for the rest of this proceedings.

When looking at the performance of the different transmission enhancement schemes (Fig. 2), we see that transmission can, at best, reduce the residual need for balancing by about 40%, from 24% of the load to 15% of the load, but not more. The rest has to be dealt with by other measures, such as DSM or coupling to other energy sectors, no matter how strong the transmission grid.

![Figure 2: Left: Normalized total balancing energy as a function of transmission strength. The vertical dashed line indicates the total installed capacity in winter 2010/2011, as reported by [10]. The horizontal dashed line is the asymptotic limit for strong transmission grids. Notice how the balancing energy can be reduced by 40% by transmission. The different curves correspond to different distributions of capacity across the single lines, see Sec. 3.2 for details. Right: Balancing energy ("deficit", shown in blue) and surplus ("excess", shown in green) energy for single countries, for different transmission layouts: Zero transmission, today’s (winter 2010/2011) line capacities, 99% quantiles of the unconstrained flow, and an intermediate layout halfway between today’s and the 99% quantile layout. Right panel taken from [1].](image-url)
Figure 3: Growth of wind as well as solar installations for the single countries for wind (a) and solar PV (b), and the line investment per five-year interval necessary to keep the line capacities at a level of 90% benefit of transmission, panel (c).

Figure 4: Growth of the European transmission network necessary to provide a 90% benefit of transmission throughout the years. Shown are snapshots of 2010, 2020, 2030, and 2050. Line style and thickness indicates its transmission capacity, but node sizes and line lengths are not to scale. The VRES gross share $\gamma_n$ is colour-coded for each of the nodes $n$, from red ($\gamma_n = 0.0$) through yellow ($\gamma_n = 0.5$) to green ($\gamma_n = 1.0$).
3.3 Line build-up in time

In the previous section, a scenario has been examined where VRES installations provide already (on average) as much as what is consumed, while the lines are build up. To make the model more realistic, we now turn to a scenario where the lines are build in parallel to the VRES installations. The VRES build-up is assumed to follow the logistic growth discussed in Sec. 2.2. The line capacities are chosen as quantiles of the unconstrained capacities of the fully renewable 2050 scenario, such that a 90% benefit of transmission is maintained throughout the years. In our model, the build-up in wind installations takes place mainly between 2015 and 2035, and solar PV installations follow with a delay of about five years, see Fig. 3a and b. Correspondingly, the line build-up necessary to keep the benefit of transmission at 90% is highest between 2020 and 2035, see Fig. 3c. The line capacities are summed over all links and normalized by the total installations we have today. Overall, they have to be quadrupled as compared to today’s values over the course of the years. The development of the single lines as well as the nodes is shown in Fig. 4. It is seen that in particular, the weak link between Spain and France as well as between Great Britain and continental Europe are dramatically reinforced, while the grid in the South-East remains relatively weak.

3.4 Import and Export

From the single countries’ perspectives, it is also interesting to see how they fare in the international power trade. Keep in mind that we only use power flow to distribute VRES excess from one country to the other; conventional generation is not transported (Sec. 2.3). As is already seen in Fig. 2b, the different countries do not have equal import and export opportunities. Some can reduce their relative surplus as well as their relative deficits more than others. We find that there are in general three factors that have an influence on the fraction of surplus that can be covered by imports/exports: Firstly, size matters. While the relative deficits of e.g. Germany and Denmark are comparable, the absolute values are not. This means that big Germany has far worse chances of covering its deficit by imports, while small Denmark encounters relatively few problems. The same holds mutatis mutandis for exports. The second factor is the time of transition. As a proxy, we use here the year in which the gross penetration $\gamma$ reaches 50%. Early adopters, such as Denmark or Spain, face an export boom in the beginning when they see surplus production while others do not. Since our power distribution favours VRES whenever possible, this surplus production can almost certainly be exported to other countries where it replaces balancing. The third factor is the position of the country in the network, whether it is central or peripheral. This is due to the flow minimization we perform, see Eq. (5). Since flow to or from a central country comes with shorter paths, on average, it is preferred. Therefore, central countries have slightly better import and export opportunities than peripheral ones. The correlations between the exported fraction of the surplus and these three factors are shown in Fig. 5.

![Figure 5: Correlation across all countries between exported surplus fraction and (a) betweenness centrality, a widely used measure from the theory of complex networks of how central a node is, (b) load size, and (c) transition time.](image-url)
Figure 6: Distribution of the load (red), distribution of the mismatch between renewable generation and load before power sharing takes place (yellow), after sharing takes place with today’s line capacities (green), and after sharing takes place with the 90% benefit of transmission line capacities (blue), for the years 2030 (a) and 2050 (b), for Denmark. The dashed lines indicate the 99% quantile of the residual deficit. For clarity, the peak at zero is not shown here. Some of the lines cover each other.

Figure 7: Distribution of the load (red), distribution of the mismatch between renewable generation and load before power sharing takes place (yellow), after sharing takes place with today’s line capacities (green), and after sharing takes place with the 90% benefit of transmission line capacities (blue), for the years 2030 (a) and 2050 (b), for Spain. The dashed lines indicate the 99% quantile of the residual deficit. For clarity, the peak at zero is not shown here. Some of the lines cover each other.
These findings are illustrated when looking at mismatch histograms, Figs. 6, 7, and 8. For the influence of load size, compare the situation in Germany and Denmark in 2050, 6b and 8b. The mismatch before sharing renewables (yellow curves) is comparable, since it is normalized by the mean load in both cases. After sharing with the strong 90% benefit of transmission capacity layout (blue curves), Denmark’s residual mismatch is much smaller than the German one. The correlation between load size and fraction of the surplus that can be exported (Fig. 5b) shows that this is not just an accident, but a general trend.

The effect of position in the network is well illustrated when comparing Spain (Fig. 7b) and Denmark (Fig. 6b), and looking again at mismatch before (yellow) and after sharing with the strong transmission layout (blue). Again, we see that Spain’s reduction is smaller than Denmark’s. The early export boom in Denmark and Spain can be guessed from the almost complete elimination of the surplus production tail by exports in 2030 (Fig. 6a and 7a). For more details and alternative illustrations, see [2].

There are other general observations from the mismatch histograms, Fig. 6-8. One is that transmission is able to reduce the bulk of the mismatch, roughly the region between $-1$ times the average load and $+1$ times the average load. Here, enhanced transmission clearly leads to fewer mismatch events. However, the tails of the distributions are almost unaffected. This corresponds to a reduction of mismatch energy by transmission (which we calculated above to be at most 40% of the total mismatch energy in a fully renewable scenario), but not so much of the “mismatch power capacity”. From these plots, it seems that large surplus as well as large deficit events hit Europe more or less synchronously, thus preventing the countries from smoothing the mismatch out by distributing it geographically. Ongoing research indicates that this effect can be mitigated to some extend by sharing not only VRES generation, but also balancing and surplus energy. A radical approach of ”complete sharing” is able to reduce the high quantiles of balancing from about 100% of the average load to about 80% of the average load, see Fig. 8 and the corresponding discussion in [1].

The other observation to be made is that the transmission grid as it is is highly inhomogeneous. While it does not make much of a difference for Denmark whether we have the line capacities seen today or the 90% benefit of transmission layout, for Spain this is the crucial difference between being able to participate in European trade or not (compare the green and the blue curves in Fig. 6b and Fig. 7b).
4 Conclusions

According to our analysis, transmission can reduce the balancing energy by up to 40%, in particular by decreasing the bulk of the mismatch between generation and load. On the other hand, transmission cannot take care of the remaining 60% balancing energy, and equivalently the corresponding 60% surplus (for the fully renewable end-point scenario). As for the power capacities of balancing and alternative usage/curtailment, transmission (with a different flow paradigm than presented here) is at best able to reduce them by about 20% of the average load.

If a reinforced transmission grid is to be build, we recommend to follow the quantile capacity interpolation method. This enables Europe to gain 90% of the potential benefit of transmission while roughly quadrupling today’s transmission capacities. This build-up is comparable to what has been seen over the past decade [10].

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