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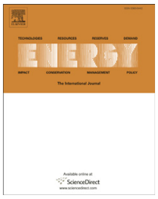

Transmission grid extensions during the build-up of a fully renewable pan-European electricity supply

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ABSTRACT

Spatio-temporal generation patterns for wind and solar photovoltaic power in Europe are used to investigate the future rise in transmission needs with an increasing penetration of the VRES (variable renewable energy sources) on the pan-European electricity system. VRES growth predictions according to the official National Renewable Energy Action Plans of the EU countries are used and extrapolated logistically up to a fully VRES-supplied power system. We find that keeping today's international NTCs (net transfer capacities) fixed over the next forty years reduces the final need for backup energy by 13% when compared to the situation with no NTCs. An overall doubling of today's NTCs will lead to a 26% reduction, and an overall quadrupling to a 33% reduction. The remaining need for backup energy is due to correlations in the generation patterns, and cannot be further reduced by transmission. The main investments in transmission lines are due during the ramp-up of VRES from 15% (as planned for 2020) to 80%. Additionally, our results show how the optimal mix between wind and solar energy shifts from about 70% to 80% wind share as the transmission grid is enhanced. Finally, we exemplify how reinforced transmission affects the import and export opportunities of single countries during the VRES ramp-up.

1. Introduction

In order to reach the 2020 and 2050 CO_2 reduction goals of the European Union, a high share of renewable electricity generation from weather-dependent sources, mainly wind and solar PV power, is inevitable [1]. According to [2], this is both an economically and environmentally viable solution. As opposed to traditional electricity generation from dispatchable power plants, these VRES (variable renewable energy sources) are intermittent. Desirable features of an electricity system with high VRES shares are low needs of storage, transmission and (conventional) backup power, but also minimal excess generation of VRES. Based on the mismatch between weather-determined generation data and historical load, optimal mixes of wind and solar energy with respect to different objectives have been derived [3–5]. Moreover, storage needs on different time scales have been looked at and strong synergies between short-term storage, long-term storage and backup power generation have been discovered [6]. Most recently, the transmission needs of a fully VRES-supplied Europe have been investigated and different grid extension scenarios in order to minimise the need for backup energy were examined [7]. In the spirit of this work, we now proceed to look at not only the fully renewable end-point scenario, but also at possible pathways to it.

As opposed to other grid extension studies such as [5,8–10], we do not follow an overall cost-optimal approach with a simplified transmission paradigm, but focus on *maximum usage and optimal sharing of VRES* at a *minimal transmission* capacity layout. Our results are independent of cost assumptions. At a later stage, our approach can be extended to include an economical evaluation of how a targeted reduction in backup energy can be achieved at a minimal transmission investment. We use the physical DC power flow paradigm together with the most localised equal-time matching of excess-power and deficit-power regions. This yields a lower bound on the total necessary link capacity. It has to be noted that market-driven power transfer will in general lead to more flow. We also do not take the necessary upgrades of the country-internal grids into account. We calculate how much inter-country transmission capacity is needed to reduce the necessary total backup energy by a certain percentage.

We strive to answer the following questions: Which pan-European transmission needs do arise where, and when? How can transmission mitigate backup needs? What are other benefits of reinforced transmission grids, e.g. facilitated trade, and what

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investments are required? The latter two questions have already been addressed in Ref. [7] for a fully renewable end-point scenario. Here, we extend this discussion to the transitional pathways.

The paper is organised in the following way: In Section 2, we describe the load and VRES generation data used in this work, the assumptions made for the growth of VRES installation, and the power flow calculations. Section 3 presents results on the time-dependent reinforcements of the transmission grid during the VRES ramp-up necessary to reduce backup energy by a given amount. It also includes a discussion of the impact of transmission on the optimal mix of wind and solar energy and on the future import and export opportunities of single countries. Section 4 concludes the paper.

2. Data and methodology

2.1. Weather, generation and load data

The weather data set used covers the eight year period 2000–2007 with a temporal resolution of 1 h and a spatial resolution of 47 km × 47 km. Encompassed are the European Union except for the Baltic states. Additionally, Norway, Switzerland, and the Balkans are included. The weather data were converted into wind and solar PV power generation time series for all grid points as described in Ref. [3]. These were further aggregated to country level, ignoring any national transmission bottlenecks.

In addition to weather data, historical load data with hourly resolution were obtained for all countries. They were either downloaded directly from UCTE (Union for the Coordination of the Transmission of Electricity) (now ENTSO-E (European Network of Transmission System Operators for Electricity)) [11] for the same eight year period, or extrapolated from the UCTE data for countries where load data were not available throughout the eight year simulation period. For additional details see Ref. [12]. Finally, the load time series of each country was detrended from an average yearly growth of about 2%.

By combining load and (scaled) VRES power generation, we calculate their hourly mismatch for each country as expressed by Eq. (1) below. When the mismatch is positive, VRES generation is in surplus, i.e. it exceeds the load, and when it is negative, a deficit of VRES generation occurs as compared to the load.

$$\Delta_n(t) = \gamma_n \langle L_n \rangle \left(\alpha_n^{\mathrm{W}} \frac{G_n^{\mathrm{W}}(t)}{\left\langle G_n^{\mathrm{W}} \right\rangle} + \left(1 - \alpha_n^{\mathrm{W}}\right) \frac{G_n^{\mathrm{S}}(t)}{\left\langle G_n^{\mathrm{S}} \right\rangle} \right) - L_n(t), \qquad (1)$$

where L_n is the load at node (country) n, G_n^{W} denotes the corresponding wind and G_n^{S} the solar PV generation time series. The node n's VRES *penetration*, i.e. the ratio between mean VRES generation and load, is denoted γ_n. $0 \le \alpha_n^{\mathrm{W}} \le 1$ is the share of wind in VRES at node n; we also refer to it as the relative *mix* of wind and solar energy. $(1 - \alpha_n^{\mathrm{W}})$ is the corresponding share of solar PV, and $\langle . \rangle$ denotes the time average of a quantity.

The negative part of a country's mismatch may partly be covered by imports from other countries. What is still missing after imports is what has to be covered by the local dispatchable backup system. We term it *balancing*, as it is required to maintain balance between supply and demand in the power system. Here, every form of electricity generation other than VRES is subsumed under balancing.

2.2. Growth of VRES 1990–2050

2.2.1. Overview

In order to model the growth of VRES installation from today's values up to a fully VRES-supplied energy system, we let α_n^{W} and γ_n from Eq. (1) depend smoothly on a reference year. The reference years correspond to real years in the sense that historical penetrations of wind and solar power are made to follow historical values. In a similar fashion, future penetrations are based on official 2020 targets and 2050 assumptions. γ_n and α_n^{W} are obtained by fitting growth curves to historical and targeted penetrations. The year variable of the fit is termed reference year to emphasise that the fit does not exactly pass through neither the historical nor the targeted values.

2.2.2. Historical data and 2020 targets

The historical wind and solar penetrations originate from Eurostat [13] for EU member states as well as Switzerland, Norway, and Croatia, and from the IEA (International Energy Agency) [14] for the other Balkan countries.

The 2020 targets for EU member states are taken from their official National Renewable Energy Action Plans [15]. In the case of Denmark, this target has already been revised because of the strong growth in wind installations, and we consequently use the new target [16]. For Switzerland, the Energy Strategy 2050 of the Swiss government and the corresponding scenario from a consulting firm is employed [17,18]. For Croatia, we use the Croatian energy strategy as officially communicated in Ref. [19]. These figures are also applied to the other Balkan states, since no other data source has been found. For Norway, the 2020 targets are estimates of the independent research organisation SINTEF (Stiftelsen for industriell og teknisk forskning; Foundation for industrial and technical research) [20].

2.2.3. 2050 Targets

For the reference year 2050, we assume a very ambitious end-point scenario by setting the target penetration of VRES to 100% of the average electricity demand for all countries ($\gamma_n = 1$). However, even at this penetration, a backup system of dispatchable power plants is needed to ensure security of supply when the production from VRES does not meet the demand. The minimum balancing energy that must be provided by the backup system was investigated in Refs. [4,6,7], and for a penetration of 100%, it amounts on average to between 15% and 24% of the demand, depending on the strength of the transmission grid. In a fully renewable power system, this energy must be provided by dispatchable renewable technologies such as hydro power and biomass, or from re-dispatch of earlier stored VRES-surplus. In general, conventional fossil and nuclear plants can also be used.

The official goal of the European Union is to reduce CO_2 emissions by 80% before 2050 [21]. It is argued in Ref. [1] that to reach this goal it will be necessary to decarbonise the electricity sector almost completely. The ambitious target of a VRES penetration of 100% ($\gamma_n = 1$) by 2050 is consistent with this goal as the required balancing energy could be provided by a combination of dispatchable renewable resources such as hydro power and biomass, possibly in combination with storage as investigated in Ref. [6]. More conservative end-point scenarios with a lower VRES penetration, e.g. those of [1,9], can easily be encompassed implicitly by shifting the 100% VRES targets to later times, e.g. 2075 or 2100.

It is reasonable to be restrictive in the assumptions on the contribution from non-variable RES (renewable energy sources), which are mainly biomass and hydro power. As summarised in Table 1, growth is severely constrained for both. For biomass, this is firstly because agricultural areas not needed for food production are limited and secondly because it is also commonly used for biofuel and heating. As a result, its contribution to electricity generation is only expected to double during the period 2010–2020, until it covers about 7% of the total (2007) load. In sharp contrast, growth by factors of four to five for the VRES technologies is expected. Concerning hydro power, most of what is feasible is already in use

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