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Transmission needs across a fully renewable European power system

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ABSTRACT

The residual load and excess power generation of 30 European countries with a 100% penetration of variable renewable energy sources are explored in order to quantify the benefit of power transmission between countries. Estimates are based on extensive weather data, which allows for modelling of hourly mismatches between the demand and renewable generation from wind and solar photovoltaics. For separated countries, balancing is required to cover around 24% of the total annual electricity consumption. This number can be reduced down to 15% once all countries are networked together with unconstrained interconnectors. The reduction represents the maximum possible benefit of transmission for the countries. The total Net Transfer Capacity of the unconstrained interconnectors is roughly 11.5 times larger than current values. However, constrained interconnector capacities 5.7 times larger than the current values are found to provide 98% of the maximum possible benefit of transmission. This motivates a detailed investigation of several constrained transmission capacity layouts to determine the export and import capabilities of countries participating in a fully renewable European electricity system.

1. Introduction

The sustainability of the world's energy supply is strongly dependent on the successful integration of renewable sources. Variable Renewable Energy Sources (VRES), such as wind and solar energy, promise to be key elements in future energy systems [1–5]. The nature of VRES makes them hard to integrate into an electrical system that was built on more or less predictable loads with dispatchable generation. In small penetrations, the variations can be absorbed without much consequence, but will be harder to ignore in a future, highly renewable, macro energy system. The spatio-temporal dispersion of the weather patterns that define the output of wind and solar energy will lead to fluctuating mismatches between regional demand for and generation of electricity. This will give rise to new challenges for countries with a high penetration of VRES, such as the need for back-up conventional balancing, flexible demand, dispatchable renewable sources such as hydroelectric reservoirs or biomass, increased transmission capacities to neighbouring regions and energy storage [2,4]. In order to understand and to design the future energy systems with dominant shares of VRES, we need to let the weather decide.

For the optimal integration of VRES in future 100% renewable electricity systems, one wishes to make as much use as possible of renewables while minimizing the need for conventional balancing, both in the installed power capacity required and the energy expended [6]. Additionally, we wish to minimize the need for storage [7,8] and transmission capacities [9,10]. In determining lower bounds on the need for storage and transmission, the synergies between these factors and the need for balancing must be well understood [11,12]. In this article, we focus on determining the synergy between transmission and balancing.

There is a conflict between the need for maximizing the integration of fluctuating VRES and minimizing the expansion of the transmission system. Several studies have assessed the need for a larger transmission network [4,13–15]. Despite the planned investments in grid strength, the European Network of Transmission System Operators for Electricity (ENTSO-E) has identified 100 bottlenecks in their network development plan [16], with 80% of them due to integration of renewables. By looking at characteristic weather patterns and possible wind and solar power generation across Europe, potential transmission between regions has been estimated. This has been done for Germany [17], and with an economic approach for Europe [9,12]. A similar study has looked at regional aggregation and transmission in the United States [18]. Estimates on the size of an ideal transmission grid are large, such as

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20 GW for the link between France and Spain [15], which is over 15 times larger than the current interconnector capacity.

Starting from the same large weather database as presented in Refs. [7,8,11], we estimate the potential output of wind and solar photovoltaic energy for any given country in a 30-node representation of Europe. In Section 2, we introduce a model which calculates the local mismatches between VRES generation and load in this set of interconnected countries, and which distributes the excess generation in a way that maximizes the use of renewables. An efficient usage of renewables also minimizes the need for balancing energy E coming from conventional dispatchable resources. Section 2 also explains how this optimal distribution of VRES excess generation can be found by performing a novel generalization of DC power flow calculations with constrained interconnectors. It also determines the interplay between installed transmission capacity and the benefit coming from transmission. In Section 3, the DC power flow model is applied to the case of a future, 100% renewable Europe. A minimum E that each country can attain through an optimal mix of wind and solar is found, and then compared to that of a fully connected, unconstrained Europe. The total E resulting from this unconstrained flow leads to the maximum benefit of transmission, when countries can make the most use of the renewable excess generation of their neighbours. By applying the constrained DC power flow calculation we find a precise relation between the installed transmission capacity and the required total balancing energy E. Section 4 discusses the limits to import and export capabilities, and the reduction of conventional power capacities. The conclusion is presented in Section 5.

2. Methodology

The following is a method to determine power flows in a power system with a large amount of VRES generation, and the benefit they bring by reducing the need for balancing. Power flow calculations are detailed for unconstrained and constrained cases.

2.1. Definitions

For a node n representing a country, the hourly VRES generation and the electrical load will generally not be equal. The hourly mismatch between the load L_n and the combined output of wind G_n^W and solar G_n^S generation in a 100% renewable system is defined as [7]

$$\Delta_n(t) = \left(\alpha_n^W \frac{G_n^W(t)}{\left\langle G_n^W(t)\right\rangle} + \left(1-\alpha_n^W\right)\frac{G_n^S(t)}{\left\langle G_n^S(t)\right\rangle}\right)\cdot\langle L_n(t)\rangle - L_n(t). \tag{1}$$

Here, t represents the hourly timestep and α_n^W the wind share at node n. Time-averaged means are denoted by $\langle . \rangle$. The VRES generation is normalized to its mean and scaled to the mean value of the load. Under this scaling, VRES generate as much energy, on average, as is consumed by the load. The mean of the mismatch $\langle \Delta_n \rangle = 0$, but, due to the fluctuations of the generation and the load, $\Delta_n(t)$ will almost always be either positive in case of excess generation or negative in case of deficit generation.

The negative part of the mismatch defines the positive-valued residual load of a country,

$$\Delta_n^-(t) = \max\{-\Delta_n(t), 0\}, \tag{2}$$

which needs to be balanced by other dispatchable generation sources. The positive part of the mismatch is positive-valued excess power

$$\Delta_n^+(t) = \max\{\Delta_n(t), 0\}, \tag{3}$$

which must either be exported or curtailed. The time averages of (2) and (3) are identical, $\langle \Delta_n^- \rangle = \langle \Delta_n^+ \rangle$.

2.2. Unconstrained DC power flow

Assuming that the nodes are connected by links, the transmission of energy would follow Kirchhoff's rules for electric flow. Given a directed graph consisting of N nodes and L links with zero global mismatch, that is

$$\sum_{n=1}^{N} \Delta_n = 0, \tag{4}$$

the DC approximation to the full AC power flow [19] unambiguously defines the flow between two neighbouring nodes n and m as

$$F_{n\to m} = b_{nm}(\delta_n - \delta_m), \tag{5}$$

where b_{nm} is the susceptance of the connecting link and δ_n and δ_m are the voltage phase angles of the connected nodes n and m, respectively. The relative phase angles thus determine the potential flow between all nodes in the graph, and can be found by solving the system of N equations

$$\Delta_n = \sum_{n=1}^{N} B_{n,m}\delta_m. \tag{6}$$

The elements of the susceptance matrix B are defined by

$$B_{n,m} = \begin{cases} -b_{nm} & \text{if} \quad n \neq m \\ \sum_{m\neq n}^{N} b_{nm} & \text{if} \quad n = m \end{cases} \tag{7}$$

The DC approximation defined by (4), (5), and (6) is valid as long as the network is in steady state, the resistances of the links can be neglected and no significant voltage phase shifts occur between the nodes [20]. Another consequence of the zero-resistance assumption is that the susceptances do not depend on the length of the links and can be uniformly chosen to be equal to one. This means that the $N \times N$ matrix B becomes exactly identical to the matrix product of the $N \times L$ incidence matrix K,

$$B = K \cdot K^{\mathrm{T}}, \tag{8}$$

where K is

$$K_{n,l} = \begin{cases} 1 & \text{if link } l \text{ starts at node } n, \\ -1 & \text{if link } l \text{ ends at node } n, \\ 0 & \text{otherwise.} \end{cases} \tag{9}$$

Equations (5) and (6) can then be expressed as

$$F = K^{\mathrm{T}} \cdot \delta \tag{10}$$

and

$$\Delta = K \cdot K^{\mathrm{T}} \cdot \delta = K \cdot F. \tag{11}$$

The last equation expresses local flow conservation at each node.

The power flows (5) resulting from the DC power flow equations (4) and (6) can also be derived from the constrained quadratic mimization objective