Benefits of spatial integration and deployment coordination: optimal allocation of wind capacity in China, Europe and the USA

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Overview

Renewable energy sources are set to become the main component of decarbonized electricity systems. However, due to their variability, integration cost may hamper their diffusion due to the increasing difficulty of managing higher shares of intermittent resources. Spatial integration softens volatility by integrating regions with opposite generation patterns and deployment coordination amongst countries allows them to make the most of this complementarity. We calculate the optimal allocation of wind capacity in China, Europe and the USA to achieve the maximum possible average capacity factor (CF) per unit of volatility (defined as the capacity factor standard deviation: SD). By optimizing the CF-SD trade-off we can build an efficient frontier of portfolios (understood as shares of installed capacity per country) that yield the minimum possible SD for each given level of CF. Once we have the efficient frontier, we can derive the optimal portfolio as the one that maximizes the Sharpe ratio, i.e. yields the maximum average CF per unit of SD.

We calculate efficient frontier and optimal portfolios for different configurations. Departing from the autarky situation of all individual Chinese provinces, European countrieas and USA states, we design configuration at different levels: (1) Power regions, (2) Economic regions, (3) Continental and (4) intercontinental configurations to assess how increasing the spatial coverage of a configuration improves the average capacity factor and reduces volatility.

Methods

We apply modern portfolio theory to assess the CF-SD trade-off of wind generation in Europe. We use hourly wind capacity factor data for each Chinese province, European country and USA state during 30 years provided by Staffell and Pfenninger (2016)[1]. The problem consists in minimizing the portfolio SD (σ_p) for every attainable average CF according to eq. (1):

$$min(\sigma_p) = min\left(\sqrt{\sum_{i=1}^{n} x_i^2\sigma_i^2 + \sum_{i=1}^{n}\sum_{j=1}^{n} x_i x_j p_{ij}\sigma_i\sigma_j}\right) \qquad (1)$$

where the first added is the sum of variances (σ_i^2) times the squared shares of wind installed capacity in each country (x_i^2) and the second addend is the covariance of hourly CF between countries, with (p_{ij}) as their respective correlation. This minimization is subject to a non-negativity constraint (i.e. all shares must be positive or zero: $x_i \in \mathbb{R} \geq 0$), and a "full investment" constraint (i.e. the sum of shares must equal one, $\sum x_i = 1$)

Results

We apply modern portfolio theory to assess the CF-SD trade-off of wind generation in Europe. We use hourly wind capacity

Our results show, on the one hand, the optimal allocation of wind capacity in China, Europe and the USA (see, e.g. European optimal allocation in the left panel of Fig. 1). On the other hand, we can assess the benefits of spatial integration and deployment coordination. Fig. 1 right panel shows the probability of low wind events (defined as percentage of hours with less than 10% capacity factor) for each of the European countries, for each of the two main European electricity markets (Nord Pool and Epex Spot) if they had the optimal wind allocation, and finally of Europe as a whole.

[1] Data freely available at renewables.ninja.

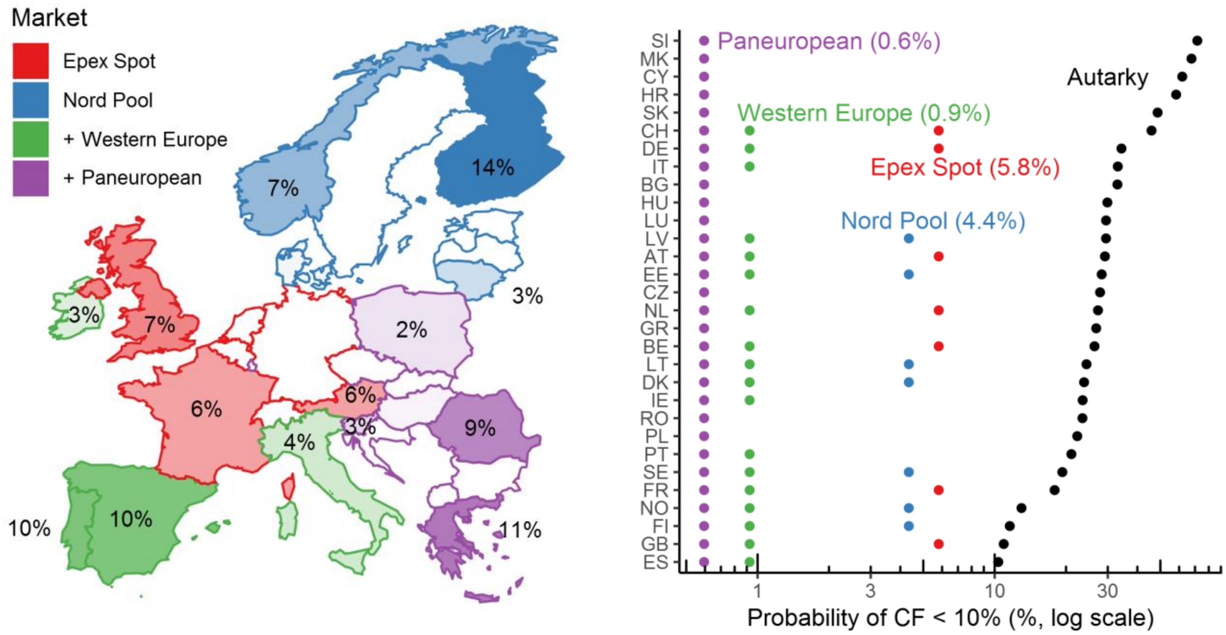

Figure 1. Benefits of spatial aggregation and deployment coordination: Left: optimal wind capacity in Europe. Right: probability of low wind events in autarky (black) or with the optimal wind allocation in the Epex Spot market (red), Nord Pool (blue), Western Europe (green) and Paneuropean (purple).

Conclusions

Since SD is scale-dependent on the level of CF, the increasing average CF provided by better technologies and locations entails that spatial integration and wind deployment coordination will be increasingly important in the future to allow the high penetration of variable renewables at the minimum possible cost. We show how modern portfolio theory can be applied to derive optimal portfolios of country shares of wind installed capacity that minimize the total SD for every level of average CF. Spatial integration and deployment coordination at regional, continental and even intercontinental levels would bring significant benefits in terms of lower volatility and lower probability of low generation events on one hand, and in terms of higher average capacity factors on the other hand. This would contain integration costs derived from variability and reduce aggregate wind levelized and system cost per unit of electricity generated.

References

Staffell, I., & Pfenninger, S. (2016). Using bias-corrected reanalysis to simulate current and future wind power output. *Energy*, *114*, 1224–1239. https://doi.org/10.1016/j.energy.2016.08.068