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Gone with the wind? - Quantifying wake losses for offshore wind farms and a discussion of mitigation measures

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Europe has set ambitious offshore wind energy targets, aiming for nearly 500 GW of capacity by 2050, with current installations at approximately 35 GW in 2024. Most wind farms are thus yet to be developed and countries with high energy demands but limited maritime space, may be forced to overexploit their domestic wind potential. Currently, some European wind farms exhibit peak power capacity densities exceeding 14 MW/km², while most fall within the 5-6 MW/km² range. Future projections suggest that high power densities will persist in regions with constrained offshore renewable energy potential.
This trend may result in inefficient spacing of wind farms, exacerbating the wake effect, a shading phenomenon which negatively impacts turbine efficiency and the economic viability of future investments. Long term system development studies are thus exposed to the uncertainty regarding future offshore wind capacity factors. The risk is to overestimate the energy yield for existing and future wind farms due to inadequate consideration of cross-border wake effects, potentially affecting turbine performance across jurisdictions.
This work aims to enhance understanding of offshore wake losses within the context of large-scale energy system planning by quantifying the potential generation loss and investigating possible mitigation measures. It argues that production efficiency challenges are interconnected with site identification and transmission corridor designation in heavily utilized maritime spaces. The focus is set on the North Sea, where about 30% of offshore capacity is expected to be concentrated in a single wind corridor by 2050.

This study utilizes the Kinetic Energy Budget of the Atmosphere (KEBA) model to analyze wake losses in offshore wind energy. KEBA is a simplified framework that replicates wind speed reductions by calculating effective wind speeds from sea level to the atmospheric boundary layer (700 m), considering energy inflows and outflows. It incorporates free-flow wind speeds, meteorological parameters, and turbine characteristics to predict wind speed reductions and electricity yields. This input-output approach is applied to three turbine clusters in the exclusive economic zones (EEZ) of the Netherlands, Germany, and Denmark. It thus assesses both domestic wake effects due to local shading as well as cross-border wake accumulation due to the long tail of wake behind a given wind farm. Three scenarios are analyzed: the "Base Case"estimates wake losses based on current plans, while scenario 2 spaces wind farms further apart, and scenario 3 shifts some capacity from Germany to Denmark. The scenarios are tailored to the current offshore development targets of the region for 2050, along with the spatial allocation of the capacity. The model resolution is one box per country EEZ with a temporal resolution of 8760 hours per year. To level out inter-annual weather variability ten representative historical climate years are modelled.
Since the shift in offshore wind generation capacity entails a maritime spatial planning dimension, a complementary GIS analysis is conducted. The purpose is to investigate how the connection corridors and lengths would change among the scenarios and to assess whether the potential gains in production efficiency with reduced wake losses are outweigh by the additional investment need for (longer) cable infrastructure. The GIS analysis employs a cost-minimizing routing algorithm to determine optimal connecting routes for offshore wind farms to shore and has been introduced and validated in previous works.

Wake losses significantly affect the effective wind velocity for downstream wind farms, leading to reductions in full-load hours (FLH) and annual electricity generation yield. They can be witnessed up to 100 km downstream of the wind farms. When comparing FLH under ideal conditions (no wake effects) with simulated wake conditions across three scenarios, the base case with current planning towards 2050 shows an average reduction of 24% in the German Bight, with peaks reaching 30% in Germany. Denmark is affected as well, although it has much lower power densities. The reason is a cross-border accumulation of wake losses which can make up 50% of the total loss.

To mitigate wake losses, spreading wind farms within each Exclusive Economic Zone (EEZ) can reduce power densities, achieving a theoretical limit of approximately 20% reduction in FLH and a potential yield increase of 42 TWh. However, further reductions require effective cross-border cooperation. The redistribution strategy, which involves relocating capacity from the German EEZ to Denmark, can reduce average FLH losses to 16%. Independent of the assessed mitigation scenario, it can be shown that the resulting energy yield saving is disproportionally larger for low wind periods. Since these periods are historically correlated with higher spot market prices compared to high wind periods, the economic efficiency of the wind farm generators would be positively impacted not only by more wind generation but also a higher marginal revenue during these periods. The GIS analysis results confirm for possible cable routes that for the shifting of wind farm capacity across the border slightly longer routes (+7%) would be required. In other words, some of the efficiency gains through a more efficient wind generation is offset by increased material investment costs. The net benefit is, however, still positive.

The chosen methodology proves to be sufficiently accurate when being compared to more complex atmospheric models. It establishes the basis for a possible integration in larger energy system analysis workflows or indeed a model coupling. Further research is identified with respect to an expansion of the analysis scope as well as alternative wake mitigation measures such as overplanting of wind power capacity compared to the grid connection capacity.

Primary author: FLIEGNER, Felix (TU Dresden / 50Hertz)

Co-author: Dr KLEIDON, Axel

Presenter: FLIEGNER, Felix (TU Dresden / 50Hertz)

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