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Trading rights to consume wind in presence of farm-farm interactions

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Introduction

The total installed offshore wind power capacity worldwide amounted to 56 GW in 2021 of which more than 50% was in Europe.[1] Specifically, the North Sea region hosts the vast majority of the European offshore wind power capacity. Figure 1 shows the operational wind farms and development zones for future wind farms. Belgium, Denmark, Germany, and the Netherlands plan to deploy together 150 GW of offshore wind in the North Sea by 2050 compared to 15 GW in 2021.[1,2]

Due to the limited availability of space, current wind farm clusters in the North Sea are close to one another. As a result, wakes behind upstream farms reduce the available energy at a location downstream, which leads to a reduced power output of the downstream wind farms.[3,4] This behavior is often visible in satellite images and large-eddy simulation studies, where wakes extending up to 70 km downwind of large-scale wind farms have been observed.[4,5] Besides, different wind farms could be part of different market zones, meaning that the produced power could be valued differently in electricity markets. In this

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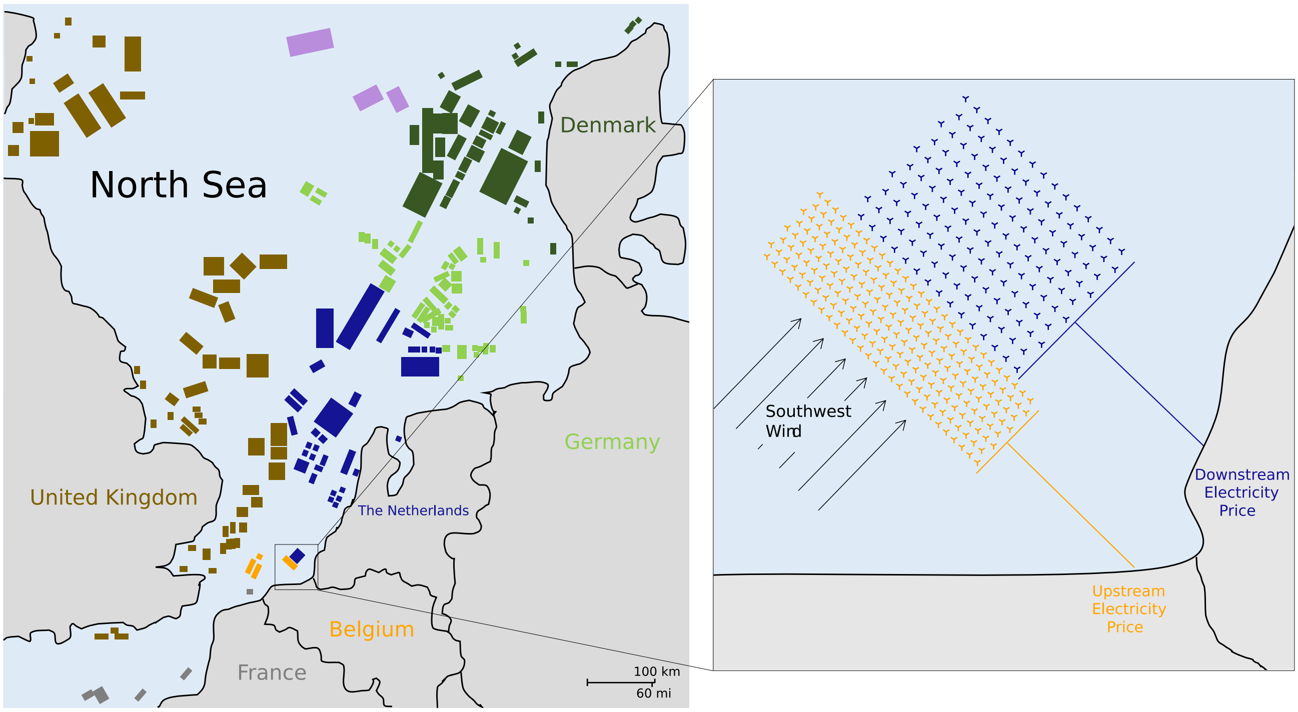

Figure 1. Many (future) wind farms in the North Sea lay close to each other
The upstream wind farm naturally possesses the rights to consume the wind. When trading these rights, the upstream wind farm extracts less power from the wind while the downstream wind farm extracts more.

contribution, we reveal the potential for trading rights to consume wind between farms in which the upstream wind farm is de-rated to enhance the available energy at a downstream location. This poses novel opportunities when neighboring groups of wind farms are competing with each other in the electricity market, especially when they face different electricity prices. Bilaterally trading the rights to consume wind can lead to increased profitability of both the upstream and downstream wind farms. This paper is the first to address this opportunity.

The situation today

We take the neighboring Belgian ("Belwind," "Belwind DEMO," "Thorntonbank," "Northwind," "Nobelwind," "Rentel," "Nother," "Northwester 2," and "SeaMade") and Dutch ("NoordzeeWind," "Prinses Amaliawindpark," "Gemini," "Borssele 1 & 2," "Borssele 3 & 4," and "Borssele 5") offshore wind farm clusters as an example. The Belgian wind farm typically is the upstream farm due to a dominant southwest wind direction. We value electric energy at day-ahead wholesale electricity prices because they come from the power exchange with the largest traded volumes. Note that other valuations, e.g., based on intra-day or real-time prices, are also possible depending on the bidding strategy of the specific wind farms. The temporal granularity is hourly, and the spatial granularity is, in Europe, determined by bidding zones. Most bidding zone borders align with national borders meaning that the Belgian and Dutch clusters may face a different electricity price in the day-ahead market. Under a business-as-usual scenario, each wind farm maximizes its own revenue by maximizing its own wind power output regardless of the impact on the power output of its neighboring wind farm. Wind farms usually have different owners so that, without the option to trade rights to consume wind, they do not co-optimize their actions.

Modeling farm-farm interactions

We use the fictitious layout displayed in Figure 1 in our wind power simulation model, which consists of 224 and 150 IEA 10 MW turbines[6] for the Belgian and Dutch clusters, respectively. The number of turbines and spacing between turbines are selected so that the power density of the wind farms matches the real layout.

The wakes generated by single turbines merge into a single farm wake. To model this phenomenon, we adopt the analytical wake model developed by Lanzilao and Meyers,[7] which shows a good trade-off between computational cost and model accuracy. The model provides a power curve per wind farm, which expresses the power output with varying control parameter C_{up}. The control parameter C_{up} is a proxy for how much power the upstream wind farm extracts

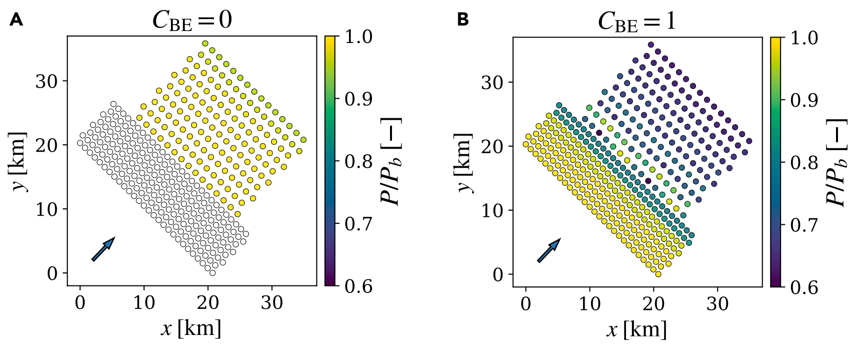

Figure 2. Power output for each wind turbine in the Belgian and Dutch wind farm on August 6, 2021, at 03:00 UTC for two cases with a different control of the Belgian (upstream) farm

On the one hand, the wind velocity at the Dutch farm is unperturbed by the Belgian farm if the control parameter C_{BE} equals zero. On the other hand, there is a clear wake effect, i.e., reduced power output in the Dutch (downstream) farm, visible if the control parameter C_{BE} is 1. Results are normalized with the power $P_b = 10$ MW obtained with the background wind speed $U_b =$ 12.3 m/s.

from the wind ranging from zero (no power output) to 1 (maximal power output at the given wind conditions). The atmospheric conditions, i.e., turbulence intensity and wind speed measured at hub height, serve as an input to the wind power simulation model. We perform the simulation for every hour of the year 2021 using real-world atmospheric conditions. We refer to the supplemental information for more details about the model formulation and wind farm layout.

We take the atmospheric conditions on August 6, 2021, at 03:00 UTC as an illustration. At this time stamp, the price difference between both countries is 52.64 €/MWh (4.45 €/MWh in Belgium and 57.09 €/MWh in the Netherlands). The Belgian wind farm is located upstream (C_{up} = C_{BE}). Figure 2 shows the power output of the individual wind turbines if the control parameter C_{BE} equals either zero or 1. While the wind velocity at the Dutch farm is unperturbed by the Belgian farm in one case, there is a clear wake effect visible in the latter case.

Increasing the profitability of upstream and downstream wind farms

Trading rights to consume wind involves a mechanism in which the upstream wind farm extracts less power from the available wind than what is technically possible. This enables downstream wind farms to extract more energy and subsequently sell more electricity than would otherwise have been the case. The total revenue for both wind farms, however, could be either higher or lower depending on the electricity prices in the different bidding zones. If the downstream farm's electricity price is higher than the upstream farm's, then the total revenue could be higher using this mechanism. In other words, the increase in revenue of the downstream wind farm is larger than the decrease in revenue of the upstream wind farm. The upstream wind farm is willing to participate in this mechanism when it receives a remuneration from the downstream wind farm that amounts to at least its decrease in revenues. As a result, the upstream wind farm sells part of its rights to consume wind to the downstream wind farm.

Under business-as-usual, i.e., without trading the rights to consume wind, the Belgian wind farm will set its control parameter C_{BE} to 1 to reach a maximal revenue of €9,403 (see Figure 3A) and maximal power output of 2,113 MW (see Figure 3B). This implies a Dutch revenue of €60,788 and a Dutch power output of 1,065 MW. When maximizing the total revenue, however, the control parameter C_{BE} equals 0, leading to a Belgian revenue of €0 and a Dutch revenue of €84,954. In that case, the rights to consume wind are sold to the Dutch wind farm. The Belgian wind farm will only sell the rights if it receives a remuneration of at least €9,403 in order to make up for its loss of revenue from the day-ahead electricity market. The Dutch wind farm will be willing to pay up to €24,166 (€84,954 minus €60,788) for the rights to consume wind. As a result, the price for the rights to consume wind will lay between €9,403 and €24,166 so that both wind farms are better off compared to business-as-usual. The price should be determined in a bilateral contract. The combined revenue for both wind farms, however, will increase by 21.03% from €70,191 to €84,954 during this specific hour.

The financial incentives for trading rights to consume wind are here

The main drivers to increase the revenues of both the upstream and downstream clusters are the electricity prices that both farms face. A large price difference allows for arbitrage if the highest price is found in the zone of the downstream wind farm. Whether prices of zones converge or not depends on the commercial transmission capacity between the zones. If the commercial transmission capacity for cross-border electricity trade is fully used, a price difference occurs. In the case of the Belgian and Dutch wind farms, the price difference in 2021 ranged from 0 €/MWh up to 216 €/MWh and was smaller than 5 €/MWh in 70% of the hours, between 5 €/MWh and 20 €/MWh in 17% of the hours, and larger than 20 €/MWh in 13% of the hours.[8] In that regard, trading rights to consume wind can be seen as arbitrage between the low-price zone and the high-price zone.

We simulate the power output and potential revenue increases as a result of

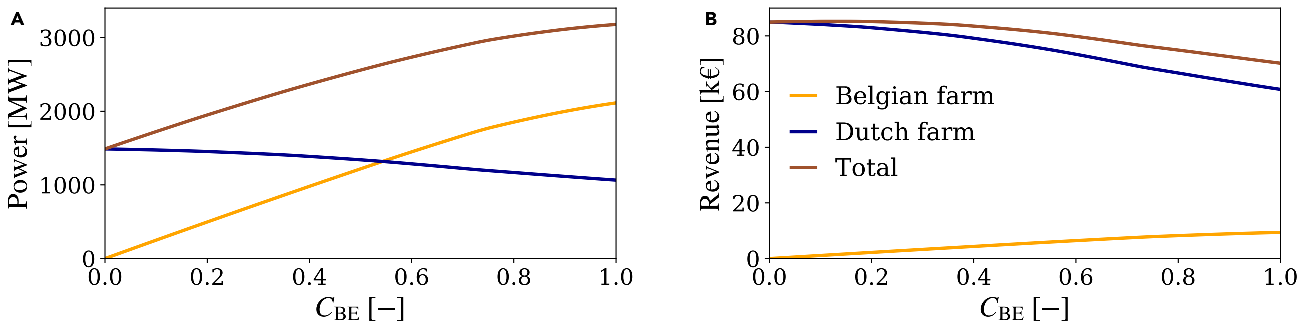

Figure 3. Power and revenue

(A) Power and (B) revenue of the Belgian and Dutch wind farms on August 6, 2021, at 03:00 UTC with varying control parameter C_{BE} of the Belgian (upstream) farm.

trading rights to consume wind for all 8,760 h of 2021. The Belgian farm is the upstream one for 63% of the time. During 37% of the year 2021, there has been an opportunity to pursue trading rights to consume wind leading to increased revenues for both the Belgian and Dutch farms. The revenue from the day-ahead electricity market would, on a yearly basis, have decreased by 0.27% for the Belgian farm and increased by 0.87% for the Dutch one. Correcting for the minimum remuneration for the right to consume wind (i.e., the compensation for the Belgian farm, paid by the Dutch farm), the Dutch farm's revenues increase by at most 0.46%. Note that this is the revenue gain across all hours in the year 2021, but there exist specific hours with much larger gains (up to a combined revenue gain of 52.23% in a single hour). The exact distribution of the combined revenue gain (0.18%) depends on the negotiated prices for the rights to consume wind.

While the relative revenue increase for each wind farm across the entire year is less than 1%, the relative profit increase from the day-ahead market is higher. We estimate the profit increase for the Dutch wind farm to be 7.32% at maximum. This is based on a back-of-the-envelope calculation assuming an investment cost of 2,400 €/kW and a lifetime of 30 years, implying a yearly depreciation of 120 M€ for the Dutch wind farm. Ignoring the cost of capital, the yearly profit of the Dutch wind farm could increase from 16.26 M€ (136.26 M€ minus 120 M€) to 17.45 M€ (137.45 M€ minus 120 M€). We remark that these gains cannot be extrapolated to other farms in the North Sea. In fact, results are heavily dependent on the layout of the farm and the geographical landscape, which influences the atmospheric state, as well as on the electricity price differentials between the electricity market zones in which these wind farms are active.

Prospects

The potential of trading rights to consume wind is not limited to the case of the Belgian and Dutch neighboring clusters. In fact, with many offshore wind farm zones being developed, farm-farm interactions will increase in the North Sea, the US East Coast, and other regions. Increased revenues imply that less financial support is needed to build offshore wind farms leading to an accelerated growth of renewable energy capacity. Moreover, arbitrage through trading rights to consume wind leads to decreased volatility and, hence, financial risks for wind farm owners.

The impact of trading rights to consume wind is expected to increase as electricity differentials between market zones become higher and more frequent. This may be driven by increased spatial granularity of on- and offshore bidding zones, which are the subject of an ongoing political debate,[9] and the expected strong increase of variable renewable energy sources.[10] Note that many regions (e.g., some regions in the US, New Zealand, Singapore, and Mexico) already have nodal electricity markets implying that each node in the power system can face a different electricity price.

Trading rights to consume wind can serve as a tool for policy makers to deal with the technical, legal, and political challenges of determining the location of new offshore wind farms. Specifically, it allows them to cope with a sub-optimal siting of wind power plants. Besides, it serves as an alternative to additional transmission capacity between two market zones. The latter guarantees to maintain the same level of total wind power output but comes with large investment costs as opposed to trading the rights to consume wind.

Despite the potential of trading the rights to consume wind, regulatory gaps exist.[11] There are no legal frameworks that recognize wind farm wakes, lowering resources for wind farms in a neighboring country. There should be incentives for countries to cooperate. Trading rights to consume wind could play a key role in the integration of offshore wind generation capacity in power systems and could unlock many opportunities. These regulatory and legislative initiatives could draw from the rich experience that exists on regulating other cross-border, financial markets.

This paper applies a very simple wind farm control strategy. Future research should focus on more advanced techniques, for instance with the use of an optimization framework to find the optimal turbine thrust set-points of the upwind farm given a certain level of derating. Moreover, more accurate flow solvers should be adopted to investigate farm-farm interactions, such as linear wind farm flow models or large-eddy simulation solvers, at the expense of an increase in computational costs. Finally, more effort should be spent on better defining the legal implications of trading the rights to consume wind.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2023.05.015.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. WFO (2022). Capacity of offshore wind turbines in operation and under construction in 2021, by country (in megawatts). https://www.statista.com/statistics/264264/capacity-of-offshore-wind-power-plants-worldwide-2010/.
2. Wind Europe (2022). North Sea offshore wind to help repower the EU. https://windeurope.org/newsroom/press-releases/north-sea-offshore-wind-to-help-repower-the-eu/.
3. Munters, W., Adiloglu, B., Buckingham, S., and Beeck, J.v. (2022). Wake impact of constructing a new offshore wind farm zone on an existing downwind cluster: a case study of the belgian princess elisabeth zone using floris. J. Phys, Conf. Ser. *2265*, 022049.
4. Maas, O., and Raasch, S. (2022). Wake properties and power output of very large wind farms for different meteorological conditions and turbine spacings: A large-eddy simulation case study for the german bight. Wind Energ. Sci. *7*, 715–739.
5. Hasager, C., Vincent, P., Badger, J., Badger, M., Di Bella, A., Peña, A., Husson, R., and Volker, P. (2015). Using satellite SAR to characterize the wind flow around offshore wind farms. Energies *8*, 5413–5439.
6. Bortolotti, P., Tarrés, H.C., Dykes, K., Merz, K., Sethuraman, L., Verelst, D., and Zahle, F. (2019). IEA Wind Task 37 on Systems Engineering in Wind Energy - WP2.1 Reference Wind Turbines (NREL).
7. Lanzilao, L., and Meyers, J. (2022). A new wake-merging method for wind-farm power prediction in the presence of heterogeneous background velocity fields. Wind Energy *25*, 237–259.
8. ENTSO-E. (2022). Transparency Platform. https://transparency.entsoe.eu/.
9. European Commission (2020). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: An EU Strategy to Harness the Potential of Offshore Renewable Energy for a Climate Neutral Future. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A741%3AFIN.
10. Collins, S., Deane, P., Ó Gallachóir, B., Pfenninger, S., and Staffell, I. (2018). Impacts of inter-annual wind and solar variations on the european power system. Joule *2*, 2076–2090.
11. Finseraas, E., Herrera Anchustegui, I., Cheynet, E., Guillermo Gebhardt, C., and Reuder, J. (2022). Gone with the wind? Wind farm-induced wakes and regulatory gaps. https://doi.org/10.2139/ssrn.4294614.