Effect of wind turbine selection in newly built wind farms in decentralized electricity markets

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***Abstract*—As energy systems are transitioning to renewable sources of power, planning of the locations of new renewable energy generation is in an increasingly important role. A renewable power based system is characterized by intermittent supply of power, which is reflected on the day-ahead market prices of electricity. By geographically dispersing renewable power generation capacity, it is less likely that the power generation from different sites significantly overlap. By using wind power estimates based on global ERA5 weather data, it is possible to evaluate the effect of new additional wind power generation capacity in different geographical areas. By modifying day-ahead market bid curves to include newly added generation from the building of a new 100 MW wind farm, the effects of the additional wind power capacity on the day-ahead electricity prices can be quantified. This paper studies the effects of five different wind turbines, with total 100 MW of installed capacity, at different locations on the day-ahead electricity markets with focus on revenue, cannibalization of the day-ahead electricity price, and societal benefit in electricity price reduction.**

***Index Terms*—Wind Power, Electricity Markets, Cannibalization, Renewable Energy, Carbon neutral, ERA5**

I. INTRODUCTION

Climate goals from the Paris Agreement [1] and RePowerEU [2] have accelerated the adoption of renewable sources of power. Finland and the Nordic countries have adopted wind power as the main renewable source of power and are on the forefront of the green energy transition. Fingrid, the national transmission system operator in mainland Finland, has received grid connection requests for over 400 GW of renewable power of which the majority is onshore wind power [3]. The Finnish electricity markets are considered the most volatile in Europe with 721 h of negative price hours and 170 h of zero cost energy in 2024 [4]. Continuing the rapid adoption pace of onshore wind power, price fluctuations will only increase if the installation sites remain mostly on the west coast of Finland [5] where most electricity production potential lies.

With better system planning, different sites can be identified which best complement current power production. The sites are characterized by a temporal phase shift in the timing of the power generation, better covering times of lower system power generation and reducing the periods simultaneous power generation from several sites. Identifying these sites can reduce price fluctuations, reduce uncertainty and also allow for more renewable power generation to be connected to the power system.

Previous research [6], which this paper is based on, shows that decentralizing wind power generation offered great benefits in the day-ahead market and reduced the effects of price cannibalization in a highly centralized system. It was observed that building a new 100 MW wind farm, where most current farms already exist on the west coast, could cannibalize revenue by as much as 9 €/MWh compared to around 3 €/MWh closer to the eastern border. To obtain biggest average price reduction, the central northern areas offered the best effect in units of €/MWh price reduction. This previous study was performed with a single turbine type, an Enercon EP5 III. According to [7], this specific turbine is well suited for the whole country and offered the lowest levelized cost of electricity (LCOE).

This paper focuses on expanding previous research to include multiple turbines with focus on the following: revenue, electricity price cannibalization, and societal benefit through electricity price reduction as well as answering the following research questions:

- How does wind turbine selection affect the results on the day-ahead markets?
- What are the effect of hub height and turbine size on the day-ahead markets?
- How can wind turbine selection be optimized? What are the most favorable characteristics?

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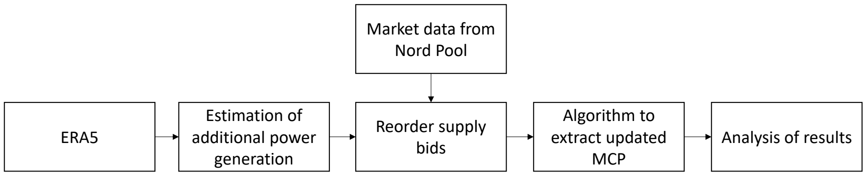

Fig. 1. Summarized methodology.

The method and data are explained in Section II, assessment criteria in Section II-C and the results finally analyzed in Section III.

II. METHODOLOGY AND DATA SETS

To evaluate the effect of wind turbine selection on the day-ahead markets, a 100 MW farm is installed in a total of 1860 locations around Finland, of which 1003 fall within its land borders. It is important to note that Finland has one price area, which coincides with its land borders. Each of the locations has location specific wind power generation profile based on global ERA5 reanalysis weather data [8] (Section II-B). The location wind speeds are turned into power generation profiles using methodology first explained in [9] and further developed to include changes to wind speed according to hub height in [6]. Analyzed hourly, the new wind power generation is added to the day-ahead bid curves obtained from Nord Pool for the year 2023 [10]. From the new supply bid with additional supply, a new market clearing price (MCP) is calculated. This is performed hourly, for all 1860 locations, for all five turbine types. The overall methodology is explained in depth in [6]. The methodology is summarized in Fig. 1. Some of the data used can be found in Table I.

TABLE I
DESCRIPTION AND SOURCES OF DIFFERENT DATA USED IN THIS PAPER.

Data Source	Data Description	Reference
Salmelin et al.	Python algorithm for bid curve analysis	[6]
Copernicus	ERA5 reanalysis weather data	[8]
Nord Pool	Supply and demand bids for Finland price area 2023	[10]
Nord Pool	Occured day-ahead market price	[11]

A. *Wind turbine selection*

A wide range of different turbines of different sizes optimized for different conditions were selected. Naturally, when comparing individual turbines, larger turbines will have a greater effect on the electricity markets due to supplying more power. To counter-balance this a total of 100 MW of generation for each turbine type is considered, which is the average size of new farms being built in Finland. The turbines and their main characteristics can be found in Table II. The coefficients of performance for each turbine can be seen in Fig. 2, how they are obtained is explained in Section II-B.

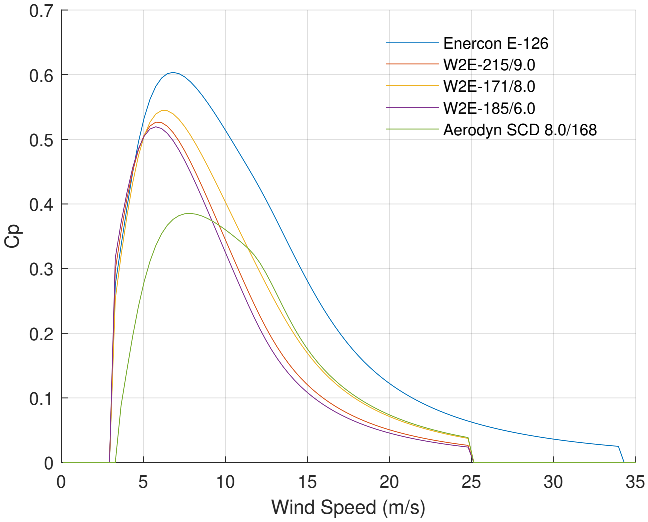

Fig. 2. The coefficients of performances of the different turbines

The coefficients of performance (Cp) were estimated based on power curves obtained from [12]–[16]. A smoothing spline fit was used to obtain the coefficient of performance at different wind speeds. The full load hours (FLH) for the reference turbine Enercon EP5 E3 can be seen in Fig. 3. The

TABLE II
CHARACTERISTICS OF THE TURBINES USED IN THIS PAPER, *INCLUDING SEA AREAS

Turbine model	Capacity	Hub-height	Blade length	Cut-in speed	Cut-off speed	*Average FLH	Reference
1. Enercon E-126	7.58 MW	135 m	127 m	3 m/s	34 m/s	1929 h	[12]
2. W2E-215/9.0	9 MW	170 m	215 m	3 m/s	25 m/s	3576 h	[13]
3. W2E-171/8.0	8 MW	160 m	171 m	3 m/s	25 m/s	2853 h	[14]
4. W2E-185/6.0	6 MW	160 m	185 m	3 m/s	25 m/s	3693 h	[15]
5. Aerodyn SCD 8.0/168	8 MW	110 m	168 m	3.5 m/s	25 m/s	2130 h	[16]

figure highlights some of the regional differences that can be found in wind resources. The average FLHs for the different turbines can be seen in Table II. For simplicity, in this paper the turbines are referred by number 1 to 5 according to the order in the table starting from the top.

B. Wind Power

The wind power estimates for each wind turbine are based on ERA5 meteorological reanalysis data [8] which has been converted to wind power estimates using methodology applied in [6], [9].

First, the air density (ρ) is calculated, which is dependent on the dry mass of the air (m), air pressure (p), Boltzmann constant (k_b) and outside temperature (T) according to [9]:

$$\rho = \frac{mp}{k_b T} \tag{1}$$

In order to calculate the wind speed at hub height, must surface roughness (α) first be calculated using wind speed (v) measurements from 10m and 100m according to:

$$\alpha = \frac{log(\frac{v_{100m}}{v_{10m}})}{log(\frac{h_{100m}}{h_{10m}})} \tag{2}$$

The wind speed at hub height is calculated using the surface roughness, which describes the surface's effect on wind speeds at different elevations, from Eq. 2:

$$v_{hub-height} = v_{100m} \left(\frac{h_{hub-height}}{h_{100m}} \right)^{\alpha} \tag{3}$$

To obtain a wind power estimate, Eqs. 1-3 are combined together with the Cp corresponding to the respective turbine type (Section II-A) and characteristics of the turbine (Table II):

$$P_{wind} = 0.5 A \rho C_p v^3_{hub-height} \tag{4}$$

The wind power estimates for the reference turbine can be seen in 3. The figure highlights the regional differences in wind resources. While some areas have better overall wind conditions and are able to yield more energy over the year, the working hypothesis is that some areas with lower annual yield can be better at reducing electricity prices and reducing cannibalization effects due to less overlapping supply of power from the west coast. The heat maps of the FLHs of the different turbines in this study can be found in Appendix A.

C. Assessment criteria

The performance of the turbines are evaluated based on three different criteria: revenue (Eq. 5) , cannibalization of electricity price (Eq. 6), and average electricity price reduction (Eq. 7).

Revenue is an important factor as it drives investments. Without significant revenue, a specific site simply will not be built without government support. There are two components to maximizing revenue at each location: amount of energy generated (E_{wind}) and the cleared market price ($p_{MCP,h}$) at the hour of generation. To maximize revenue, must both of these be high:

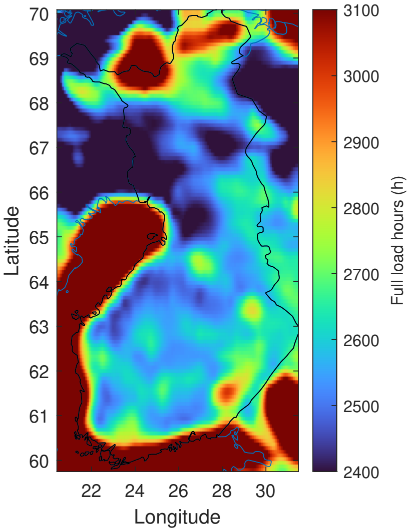

Fig. 3. Sample FLH figure showcasing the regional differences in full load hours in 2023 with the reference Enercon EP5 III turbine [17].

$$Revenue = \sum_{h=1}^{8760} E_{wind,h} \cdot p_{MCP,h} \tag{5}$$

Cannibalization of revenue is an unwanted effect of the electricity price dropping due to downward pressure of the additional power generation, reducing revenue. The higher the cannibalization rate, due to overlapping power generation from other renewable sources, the clearer of a sign that that there is too much centralized generation. Hypothesis is that by dispersing generation can a higher MCP be obtained leading to higher revenue despite lower overall power generation from being able to sell electricity at time of better price. Price cannibalization is defined as:

$$Loss\ in\ revenue = -\sum_{h=1}^{8760} E_{wind,h} \cdot (p^{BW}_{MCP,h} - p^{AW}_{MCP,h}) \tag{6}$$

The societal benefit is defined as the overall lowering of electricity prices for the rest of the day-ahead market participants, which often are regular consumers. The best locations for a new wind farm are the ones where the largest price peaks are reduced due to power generation during those times. By installing power generation away from the west coast, the hypothesis is that they should be able to generate some power during otherwise low power generation, providing steadier supply of power into the power system. The societal benefit as a result is defined as the change in electricity price before (BW) and after (AW) the addition of the new wind power multiplied by the energy consumption of the day-ahead market ($E_{con,da}$):

$$Societal\ benefit = \sum_{h=1}^{8760} (p_{MCP,h}^{BW} - p_{MCP,h}^{AW}) \cdot E_{con,da,h} \quad (7)$$

III. RESULTS

The five different wind turbines were compared according to criteria outlined in Section II-C. For Sections 5–III-C, the results for turbine 3 are highlighted due to clarity of results and being able to well highlight regional differences. The result graphs for all assessment criteria, for all of the turbines can be found in the Appendix. The analysis according to the assessment criteria are performed in absolute units of M€/a and relative units M€/MWh.

A. Revenue

The revenue from each turbine are analyzed and compiled in Appendix B and C. The total revenue is highly dependent on the amount of energy generated. The higher the FLH of the farm is, the more revenue should the farm obtain as seen in Appendix B tying to Appendix A. In Appendix C the electricity is mostly sold at between 45 and 55 €/MWh.

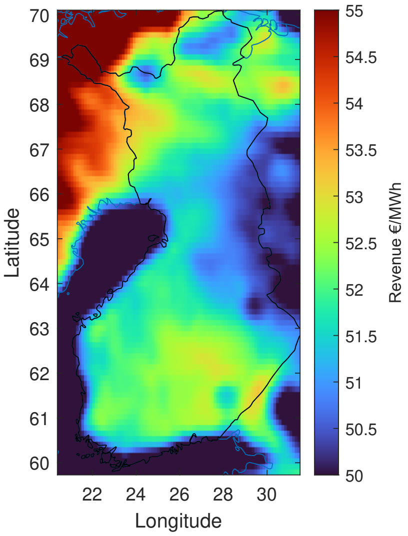

Fig. 4. Average revenue for turbine 3 in units of €/MWh.

According to the hypothesis, areas with weaker wind conditions can, in some cases, bring better revenue if the power generation does not overlap with the rest of the centralized power generation. The reference area being the west coast, most of the inland areas, especially in the south east, are able to yield a better market price than the west coast where most of the wind power capacity is currently installed. A similar trend is seen with the other turbines. However, total revenue still dominates on the coastal regions.

B. Cannibalization

The effect of cannibalization are studied in Appendix D and E. In previous research in [6], the strongest cannibalization was observed on the west coast, which coincides with the results of this set of turbines. There is some variety in the expansion of the stronger cannibalization areas to the more inland areas which are linked to the timing of power generation of the turbine types. Even when relatively close to the national epicenter of power generation, if the turbine is designed to generated power under different conditions as the already installed capacity, can the cannibalization effect be weaker. If the installed turbine type has strong overlap in characteristics to the already installed turbines, will the cannibalization effect also be stronger. The hypothesis is that turbine 1 and 5, due to their low hub height at 135 m and 110 m respectively, are not able to collect strong enough winds that they're better designed for and are stuck at lower wind speeds for which older installed capacity are designed for, leading to a high overlap in generation amplifying the electricity price cannibalization effect. Turbines 2–4 have significantly higher hub heights being able to harvest winds that are out of reach from most currently installed turbines leading to a unique generation profile, different from most currently installed capacity leading to weaker price cannibalization. The relative cannibalization rate of turbine 3 is displayed in Fig. 6.

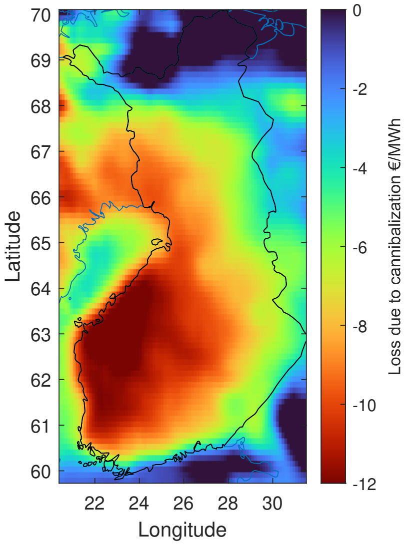

Fig. 5. Cannibalization of day-ahead electricity price for turbine 3.

C. Societal benefit

The societal benefit is arguably the most important criteria of the three, as it disproportionally influences a large number of market participants. A small change in electricity price will have significant effect. The difference in scales becomes apparent when comparing values in Appendix B and F.

Generally, the areas that reduces the electricity price the most should be prioritized. There are two main ways a farm can have significant effect on the rest of society. Either the wind power farm is able to reduce the number of high price hours while there is significant load present in the system or it is able to consistently reduce the price, through a consistent generation profile. In this analysis, both of these are ways are aggregated into a single figures. Deeper analysis on this was conducted for a single turbine type in [6].

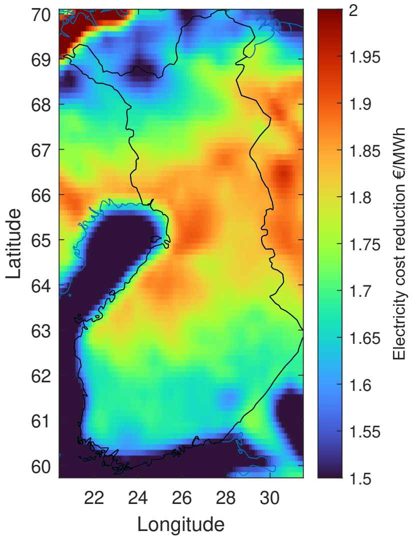

Fig. 6. Average price reduction of the electricity price in the day-ahead electricity market in €/MWh for turbine 3.

IV. Discussion and Conclusions

As the investment costs in the turbines and different associated costs with grid connections and possible transformers were not considered, the results do not comment on which turbines should be chosen for each area in a definitive manner and the final turbine selection for each area should be studied case specifically. The effect on the electricity price is simple in nature, however, is justified in the case of a marginal power change in the system where the remaining market mechanism remain mostly the same. The peak power of 100 MW is rarely achieved with average capacity factor being less than 50 %. Detailed case studies on turbine type should be made with societal benefit in mind when the final location decision for a new park is made. A network analysis is planned to optimize wind turbine type regionally according to local wind conditions to include investment costs of turbines and grid connection costs to evaluate a final LCOE and market benefit elaborating on the work of Satymov et al. [7].

The hub height has the most significant effect on all compared metrics and highlights the need for new turbines, even at lower capacity, to be installed higher. Turbine 4, despite only being a 6 MW turbine, in a farm configuration outperformed the taller turbines 1 and 5, with 7.85 MW and 8 MW respective capacities. A brief comparison of main characteristics is performed in Fig. 7. It can be seen that turbines with a relatively high hub height and long blades also have the highest FLH. The turbine capacity does not correlate with the full load hours.

If a turbine is optimized for lower wind speeds it may have better chance to target wind speeds during a time of overall lower wind power availability. In a highly centralized wind power dominated system, day-ahead electricity price is strongly linked to wind power generation. If all wind turbines were large, optimized for maximum power generation, optimized for higher wind speeds, may the total amount of electricity generated and as a result revenue be higher than with smaller turbines, however, during periods of overall weaker wind conditions may the electricity prices be high due to overall less efficient power generation. A healthy power system consists of geographically dispersed power generation with a variety of wind turbines targeting both stronger and weaker winds. Homogeneous geographical installation of turbines of similar characteristics is likely to lead to significantly overlapping power generation spikes, which lead to fluctuations in the day-ahead prices.

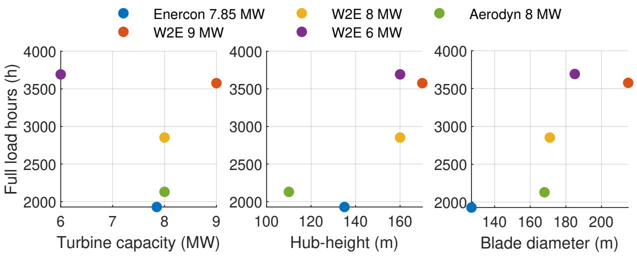

Fig. 7. Comparing correlation between turbine capacity, hub height and blade diameter on full load hours of the turbines. Points in the top right corners are considered better.

The results of this study, while performed with onshore turbines, from the sea areas are relevant as offshore wind power generation would still be connected to the mainland markets. With offshore turbines more generation is expected due to larger size and ease of installation compared with installation of equivalent onshore turbines.

The effect of price cannibalization is the strongest on the west coast where most of the installed wind power capacity lies. By altering wind turbines, the cannibalization can be reduced by producing at a different profile than most of the already existing turbines despite being installed in the same areas. In absolute terms the revenue. The effect of turbine selection on the societal benefits of reducing electricity prices

The main conclusion is that it is possible to affect the day-ahead markets and cannibalization and minimize their respective effects through wind turbine selection. However, what seems to be most important is to disperse generation away from areas with already highly centralized power generation. In addition, taller turbines be preferred. Lower capacity turbines can be better than larger capacity turbines if the hub heights are higher.

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APPENDIX

Appendix A

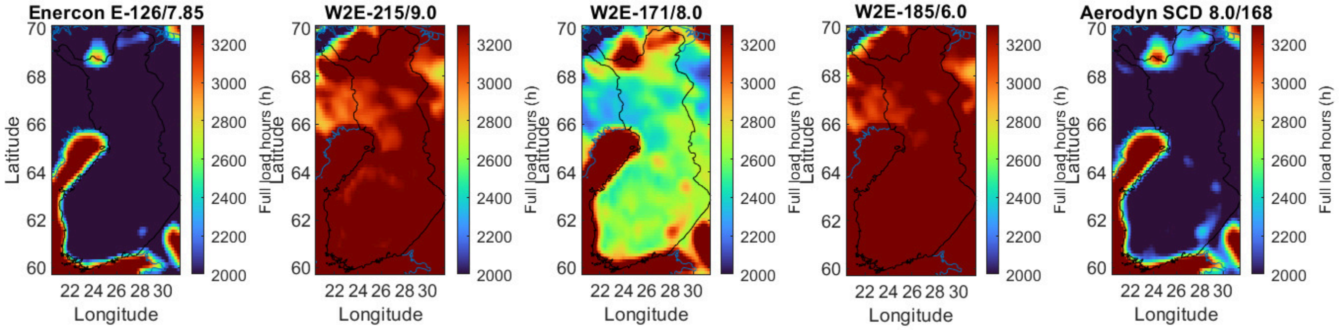


Fig. 8. Full load hours of the different turbines.

Appendix B

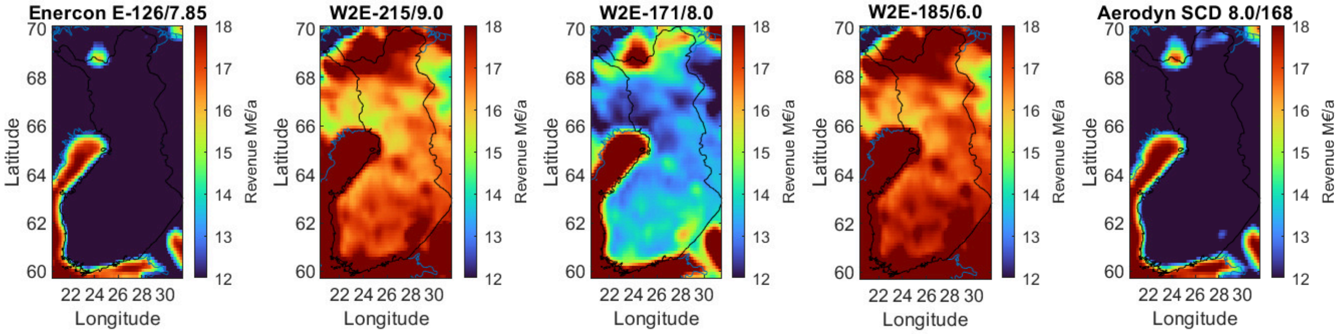


Fig. 9. Revenue in units of M€/a

Appendix C

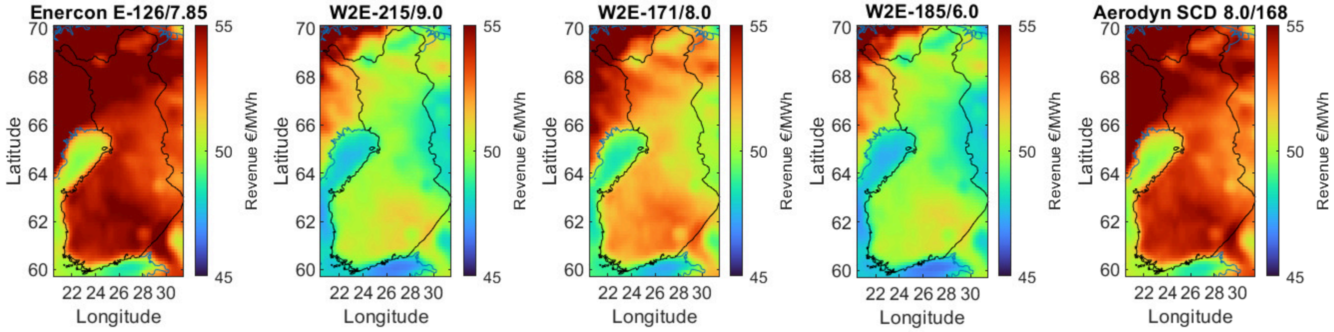


Fig. 10. Revenue in units of €/MWh

Appendix D

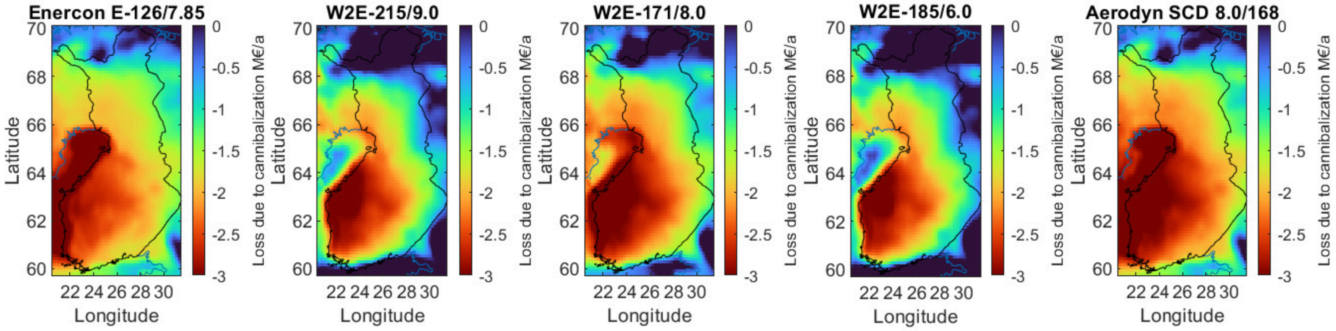


Fig. 11. Cannibalization of day-ahead price in units of M€/a

Appendix E

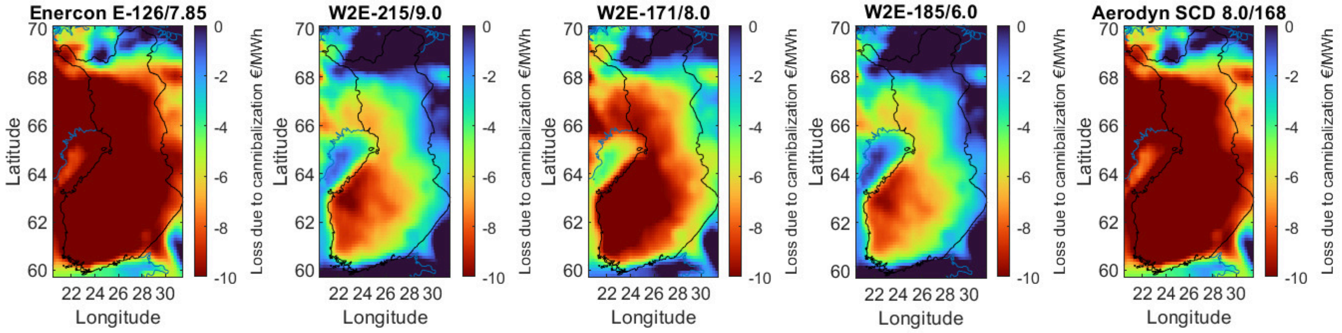


Fig. 12. Cannibalization of day-ahead price in units of €/MWh.

Appendix F

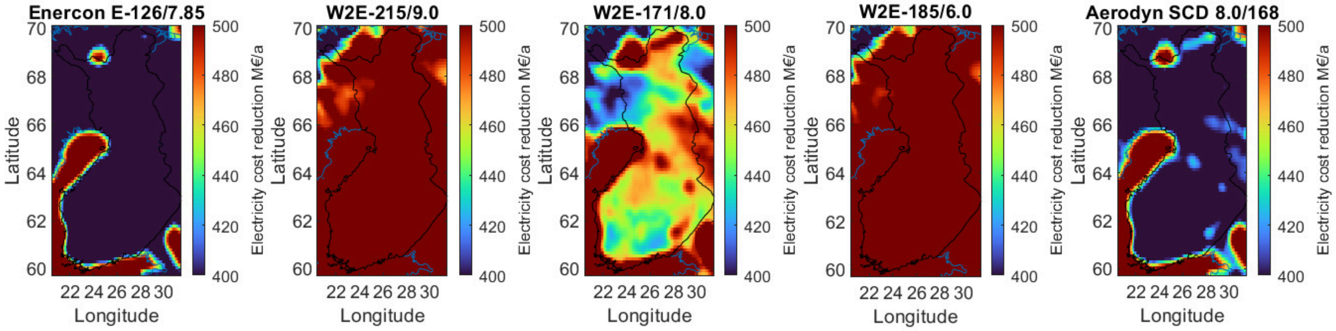
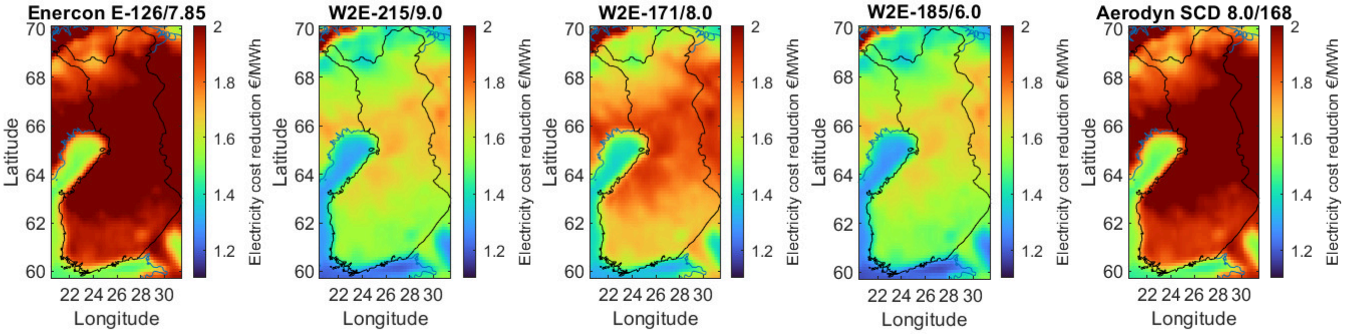


Fig. 13. Societal benefit as average reduction of day-ahead price in units of M€/a.

Appendix G


Enercon E-126/7.85

W2E-215/9.0

W2E-171/8.0

W2E-185/6.0

Aerodyn SCD 8.0/168

Fig. 14. Societal benefit as average reduction of day-ahead price in units of €/MWh.