



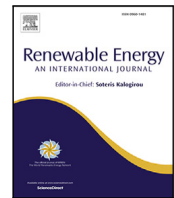
Optimizing wind farm locations for revenue and reduced electricity costs in deregulated electricity markets

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Optimizing wind farm locations for revenue and reduced electricity costs in deregulated electricity markets

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ABSTRACT

With an increasing share of renewable power in the energy mix, planning of new renewable energy production sites becomes increasingly important. Having geographically highly centralized generation leads to overlapping peaks in generation, which are directly seen in the day-ahead markets as increasing electricity price volatility. By analyzing the impact of added generation on day-ahead prices, optimal sites can be identified that maximize investor revenue and societal savings, helping reduce regional disparities in development. This paper uses wind power estimates based on ERA5 global weather data, together with NordPool price data, to evaluate optimal sites for a new wind farm. The paper discusses the value of dispersed generation and co-planning of future wind farm installations. Cannibalization of the day-ahead market price due to centralized generation is addressed, and it is found that additional wind power capacity in high-capacity areas could cannibalize revenue by 9 €/MWh. The results from the applied methodology show that there are areas where it is possible to generate high revenue while simultaneously providing society great benefit in reduced electricity price for energy users in the day ahead-markets of on average 1.1–1.4 €/MWh over the whole year.

1. Introduction

Climate change is one of the major threats of our time. The Paris Agreement aims to limit the increase of average temperature to well below 2 °C [1]. One of the best ways to defossilize and decarbonize an economy is through electrification, which requires investments into new renewable power generation capacity.

The Nordic countries are sparsely populated, having potential for both solar PV and onshore wind power. Typically, solar PV is the lowest-cost source of electricity, closely followed by onshore wind power [2]. Much of the world, especially around the equator, is able to build renewables-based energy systems based on affordable solar PV with grid storage; however, in the Nordic countries, due to polar night and the high likelihood of solar panels being covered with snow, the grid cannot rely on solar power alone. Finland, for instance, is located in the northern part of the EU and belongs to Dfc in the Köppen–Geiger climate classification [3], which indicates the presence of subarctic climatic conditions dominant in the major part of the country. As a result, onshore wind power is the favored source of renewable energy over solar PV. In 2022, Finland and Sweden installed 8% of all new global onshore wind power capacity [4].

According to the Finnish transmission system operator, Fingrid, there were connection requests for over 340 GW of added new renewable generation capacity, of which 200 GW is onshore wind power [5]. At the end of 2023 there was 6900 MW of installed onshore wind power generation capacity connected to the grid, and it is expected to increase to 23 GW in 2030 [5]. At the time of writing this paper in the summer of 2024, the installed capacity of onshore wind power has increased to 7300 MW [6].

Such an increase in the number of new wind farms will have an effect on the grid and energy markets due to overlapping power generation, further amplified by the effect of temperature on power generation [7]. As there is a significant drive to add new wind power generation capacity to the grid, the effects must be evaluated; however, the emphasis should be on prioritizing installations that support the needs of society the most. Future investments should be made to pursue energy security by reducing the effects caused by the intermittency of wind power as well as to reduce the electricity price for consumers, thereby increasing their welfare.

The building of new wind farms is mainly driven by economic considerations. Historically, when the penetration of renewable wind power was low in the energy mix, the most favorable sites were those

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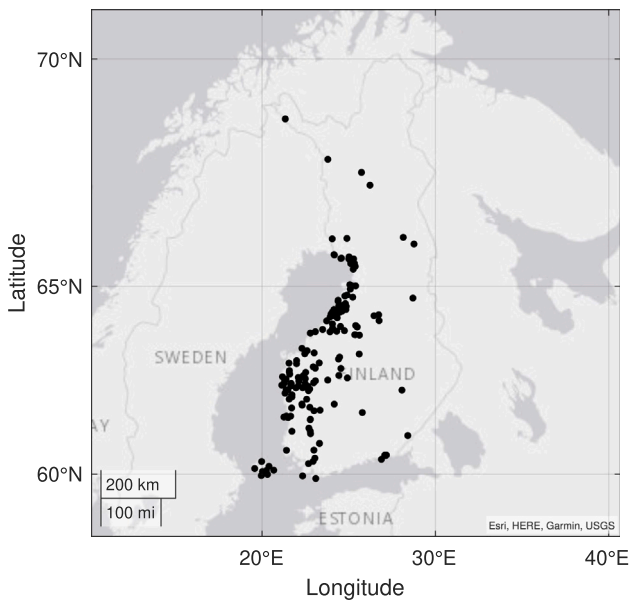


Fig. 1. Locations of installed wind power farms in 2024 in Finland [6].

that generated the most energy. In Finland, this area is the west coast, where most of the currently installed wind farms are located, as seen in Fig. 1. As the penetration of wind power increases, it has more leverage on the day-ahead market prices. After a certain point, highly centralized production can significantly impact the day-ahead market. At times of low wind availability, the day-ahead market prices can increase, and vice versa, even below 0 €/MWh.

The day-ahead electricity price is strongly tied to the balance of wind power supply and heating demand in Finland as it is common for heating to be electrified using a heat pump when located outside the district heating networks. The electricity demand for 2023 for the whole of Finland is illustrated in Fig. 2 plotted against outside temperature from the center of population of Finland. Due to the polar night there generally is virtually no solar power generation during the darkest and coldest months. As a result, in winter, when the electrical loads are the highest, there is a strong dependence on wind power.

To avoid peaks and troughs in power supply, one solution is to have dispersed wind power generation across a larger geographical area. As weather conditions are mostly a local phenomenon that transitions from one place to another, it makes sense to think that having turbines spread over a larger area to catch the weather event, in this case stronger winds, at different times would provide a more base-load like generation profile. Dispersed wind power installation and its effects in Finland have been discussed by Holttinen [8] and Mursu [9].

Holttinen studied the effect of dispersed large-scale wind power generation in the Nordic countries and its related variability [8]. A total of 33 sites were compared using time series data from 2001, and it was concluded that dispersed wind power generation increased base load like power generation and that a greater distance d between two points of wind power generation reduced correlation according to:

$$\rho = e^{-(d/500)} \quad (1)$$

The power profiles from two locations, one from the west and one from the east, are compared in Fig. 3 to highlight the point of Holttinen [8]. The power profiles are from a sample period from the start of the year and stem from the methodology used in this paper which is further discussed in Section 2. It can be seen that the generation of the east and west locations do not align and the wind power can influence the day-ahead prices. It is important to note that the weight of the wind power generation lies disproportionately on the west coast and

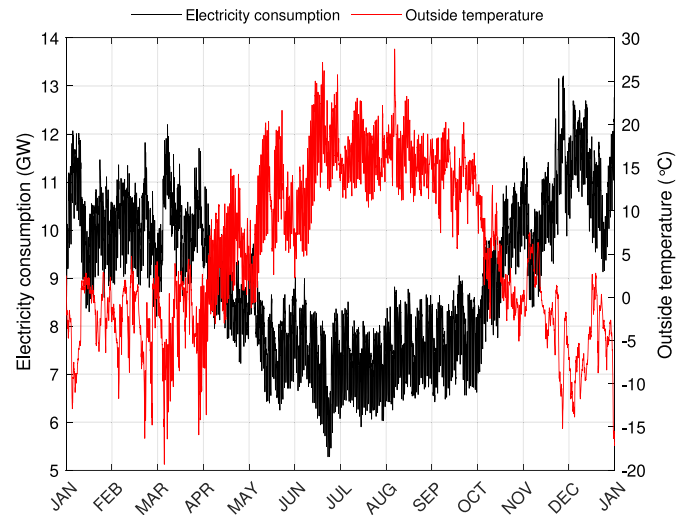


Fig. 2. Electricity consumption of Finland with outside temperature in 2023 [10].

as a result the electricity price will tend to inversely correlate with the generation on the west coast. For added context, the 10 largest cities have been plotted in Fig. 3(a) to showcase the major load centers in relation to the locations of the installed wind power capacity seen in Fig. 1. Still, it is important to note that due to Finland being a single price area without congestion charges (Section 2.4.5), the distance to load centers does not affect the electricity price.

Two locations that are close to each other will often have correlating power generation due to experiencing the same weather front with only a slight delay. As the distance between two locations increases, it is no longer possible to talk about correlation of profiles, as what happens in one location is not directly reflected in the generation profile of the other location at a moment in time. It is not correlation or anti-correlation that is sought, instead, quantifying the temporal shift and change in magnitude of power generation from different weather events coming from different directions which is best done through the analysis of the effects in the day-ahead markets.

Cannibalization of electricity market price is a phenomenon in which a large amount of renewable power is being generated at the same time, leading to downward pressure on the day-ahead market price due to oversupply of power [11]. This can have negative effects on revenue as on average, an investor obtains a lower capture price for the generated electricity because of simultaneous generation from other parties. At the same time, this can lead to large swings in energy price for a consumer. The effect of cannibalization of electricity market price is highly relevant in Finland, where the effects can already be seen despite the fact that there is only one price area over a large surface area [12]. Due to restrictions by the Finnish Defence Forces to not allow the installation of wind turbines near the Russian border, the bulk of wind power capacity is installed on the west coast, where the wind conditions are the most favorable [13]. This is a prime scenario for price cannibalization to occur and to be measured. In 2023, wind power accounted for 18% of the country's total energy. Since the end of 2023, around 600 MW of new capacity (10%) has been installed with a strong growing trend.

Generally, cannibalization of the electricity market price has been recognized to be a growing issue with a higher penetration of renewable energy sources, especially when considering solar PV [11,14–16]. However, in the context of wind power, the topic has not been addressed in such depth. Ajanaku et al. investigated whether wind power can be seen in the wholesale market prices around Pennsylvania with a relatively low wind power penetration of 3% [17]. They observed

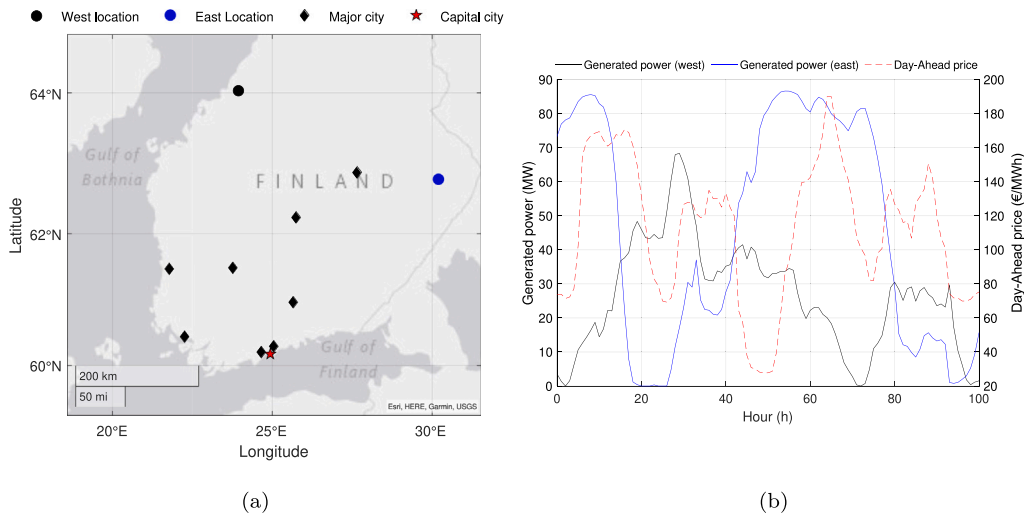


Fig. 3. Comparison of the wind power generation profiles from a location in the west and in the east. The specific location can be seen in Fig. 3(a) together with the 10 largest cities in Finland. Sample power profiles together with the day-ahead price in Fig. 3(b).

that changes in revenue, albeit small, were evident even at such low penetration rates. Reichenberg et al. studied wind power cannibalization of revenue in Germany and ways to combat it to benefit investors through using carbon credits [18]. Prol et al. estimated the effect of curtailment on wind and solar average unit costs [16]. They focused on cannibalization of the market share instead of revenue.

Riaz et al. [19] studied the effect of changing the azimuth angle to catch a better capture price with solar PV in Finland as well as in other countries. They showed that it is possible to design PV systems to catch a better price for the produced electricity at the cost of lower volumes, however, yielding an overall higher revenue. For wind power, it is not as simple as orienting the turbines differently; instead, they have to be geographically located so that they catch more favorable wind conditions. Such research has not been previously performed, likely due to the reasons mentioned in Section 1.2.

Historically, when the share of renewable energy has been low in the energy share, wind farm optimization has largely focused on maximizing electricity output and optimizing turbine control to better handle strong gusts. This has been done by reducing wake effects through optimization of farm layout, such as by Zhang et al. [20]. Papers regarding wake effect measurement methods and results of onshore and offshore wind farms have been compiled in a literature review by Sun et al. [21]. Zhou et al. [22] focus on predicting gusts to better control wind turbines, improving their annual yields while also increasing their reliability. The optimization of wind farm location against electricity markets has not been done before using spatially explicit methods.

The hypothesis of this paper is that through dispersed generation of wind power, there can be significant societal benefit in reducing the consumers' electricity costs by shaving larger price peaks and bringing the average price of electricity down. In addition, there should be some areas where the wind conditions are such that even with an overall lower annual energy yield compared with the best locations, an investor should be able to generate a similar or even higher revenue compared with the currently most favored west-coast locations because of the on-average higher day-ahead market price resulting from lower availability of power in the grid. In that case, the investor would be able to sell electricity at a better price that is less affected by price cannibalization on the west coast. Mursu [9] studied the effect of new wind power capacity in eastern Finland on the electricity system in the year 2022. The study added some wind power generation capacity to the west coast, east and southeastern parts of Finland in different scenarios. The results showed that installing new wind power generation capacity in the south-east could provide better revenue than on the west coast.

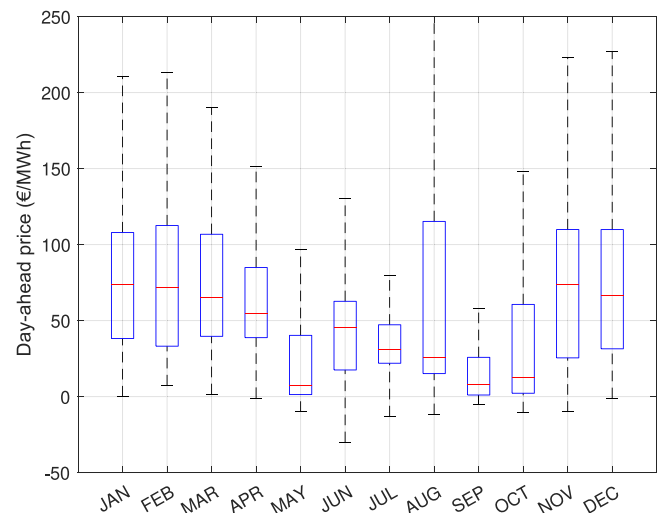


Fig. 4. Day-ahead prices in the price area of Finland in 2023. [23]. The center red line in the box depicts the median. The bottom and top edges of the boxes indicate the 25th and 75th percentiles respectively. The whiskers indicate the most extreme data points that are not considered outliers.

1.1. Aims of the paper

This research seeks to promote the value of strategic planning of the placement of new wind farms to maximize revenue for an investor while also maximizing the societal benefit through reduced electricity prices. The government, municipalities, and investors should work together to benefit everyone.

At the time of writing this paper in 2024, the effect of price cannibalization can be seen in the day-ahead markets. When there is a lot of wind power available, the electricity prices can be 0 €/MWh or even negative fairly consistently, especially in the summer when the need for energy is lower and solar power also contributes to power generation. The price fluctuations in the day-ahead market prices are illustrated in Fig. 4 for the 2023 calendar year [23]. One of the aims of the paper is to quantify the effect of marginal added generation and its effects on the day-ahead market prices, as well as quantify the effect of price cannibalization in different areas.

The results show that while some areas are preferred over others in terms of revenue for investors and reduced electricity costs, no area

should be ignored and all new added wind power capacity benefits society regardless of the location.

1.2. Contribution

It is evident that there is a significant gap in the literature regarding comprehensive understanding of the implications of additional wind power generation on the energy system. To bridge this gap, the main research objective of this paper is articulated as follows:

“What is the effect of dispersed generation on the day-ahead markets?”

To achieve this research objective, the following research questions were formulated:

1. How could dispersed wind power generation lead to reduced electricity costs to consumers?
2. How does the revenue differ based on different locations for the installation of new wind power?
3. To what extent do additional wind power installations affect electricity market prices?

To effectively address these questions, several prerequisites are required:

- A global weather-based wind power model with a temporal resolution which matches that of electricity markets.
- In-depth price area data for both supply and demand, including the merit order of generation.
- A high penetration of wind power in the existing energy mix so that day-ahead market prices experience volatility attributable to renewable energy generation.
- A highly centralized wind power capacity.
- A sufficiently large price area where installation sites are not at a premium. Smaller price areas often lack the flexibility of choice and may need to install wind farms wherever possible.

Based on these considerations, Finland was selected for this study due to its high renewable energy penetration and its position within a dynamic electricity market. In 2023, 31% of all electricity contracts in Finland were spot contracts up from 14% in 2022. This paper proposes and demonstrates a novel methodology that combines global weather data with NordPool electricity market data to assess the effects of price cannibalization from centralized wind power production in Finland. The methodology is applicable globally in regions where such price data are available. The results highlight opportunities to achieve substantial revenue, support the electricity market, provide societal savings on electricity costs, and reduce grid congestion. Additionally, the study shows that dispersed generation can mitigate the intermittency of renewable energy sources.

The authors believe that this paper is the first to fully identify the current state of the electrical system and perform a market study on a whole price area where new turbine capacity should be installed. The methodology proposed by Mursu [9] was further generalized and improved to include the whole of Finland with high accuracy and with a higher temporal resolution of one whole calendar year. One major benefit of the applied methodology is that it can be applied globally as long as the listed data prerequisites are met.

The outline of this paper is as follows: Section 2 describes the methods applied in this paper, followed by Section 3 depicting the results obtained. Section 4 highlights the key-takeaway points, Section 4.1 addressing the limitations of this study. Finally, Section 5 concludes the paper.

2. Methodology

This section discusses the methodology adopted in the paper to evaluate investor revenue and societal benefit through reduced electricity

costs. The research was conducted for the year 2023, as it was the latest full calendar year.

The price area of Finland was chosen for this research due to the large-scale implementation of onshore wind power, which is, due to constraints, highly concentrated on the west coast of the country. As Finland constitutes a single price area, there is also a great opportunity to disperse large-scale generation over a large surface area, unlike continental Europe, where the price areas are relatively small and installation areas are at a premium. In addition, there exists no congestion charges due to the TSO performing what is known as countertrading [24,25], where supply is shifted to a less congested area at a cost to the TSO. This cost is not reflected to either the supplier or the consumer. Overall, Finland experiences very little congestion due to being highly electrified and having strong transmission and distribution networks, which are dimensioned according to peak winter demand for heating and to accommodate electric saunas.

A farm size of 100 MW was chosen due to the ability of being built as a single investment project almost everywhere and it being the mean size of the farms being currently built as seen in Fig. 5.

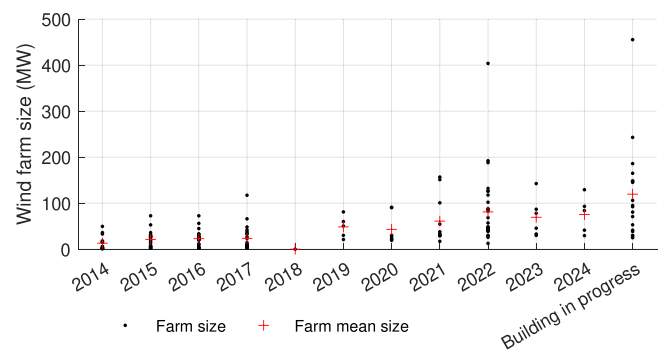


Fig. 5. Distribution of wind farm sizes in Finland.

In this paper, a global weather dataset is used as a basis to a physics-based wind power estimation model for the whole of Finland at an hourly resolution (Section 2.2). Having a global weather based wind power model with a long history of weather data allows for a more general analysis of a whole price area over a longer period of time, which enables research that is not subject to location or time period selection biases. In addition, by employing price data from 2023 the disturbances on energy prices caused by the energy crisis were largely avoided.

The overall methodology applied in this paper can be seen in Fig. 6. Weather based wind power generation is added to the energy supply curves from NordPool. A new market clearing price (MCP) is obtained due to the increased power generation capacity.

2.1. Data

The data used in the research consist of ERA5 weather data (Section 2.1.1) at an hourly resolution, transformed into power generation estimates using an Enercon E-160 EP5 E3 5.5 MW turbine (Section 2.2) [26]. The effect of the additional power supplied to the market was analyzed through hourly supply and demand curves for the Finnish price area provided by NordPool (Section 2.1.2) with the methodology outlined in Section 2.4.1.

2.1.1. ERA5 weather data

The ERA5 dataset is a global weather dataset with hourly resolution and spatial resolution of $0.25^\circ \times 0.25^\circ$, which translates into a resolution of roughly $28 \text{ km} \times 15 \text{ km}$ in Finland, which is the study area in this paper [10].

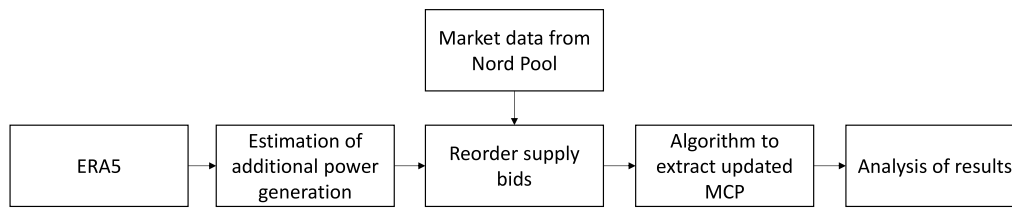


Fig. 6. Overview of methodology.

The ERA5 dataset was chosen for its wide availability. It is especially good in remote areas that do not necessarily have weather stations at a resolution that would make sense due to a low population density. In addition, these areas are more attractive for wind farm installations as they are not located close to habitation centers. The accuracy of ERA5 compared with other global datasets has been evaluated in [27–29] and thus, data validation is not within the scope of this paper.

Biases in the ERA5 data set are recognized to occur at lower wind speeds as seen in the work by Salmelin et al. [7], where the ERA5 wind speeds were compared with mast readings from 100 m elevation obtained from the Finnish Meteorological Institute. The wind speeds were observed to sometimes be overestimated at <5 m/s. However, as the biases were at lower wind speeds, the impact on power generation estimates is minimal due to wind power being proportional to the third power of the wind speed. The bias in the wind speeds was also observed over the Baltic region by Hallgren et al. [30].

2.1.2. NordPool market data

NordPool is the leading power market in Europe, operating in the wholesale electricity market across multiple European countries. Established in 1993, it provides a platform where electricity producers, suppliers, and large consumers can trade electricity in the day-ahead and intraday markets [31].

In this paper, in order to investigate the effect of additional wind power generation in Finland, the supply and demand bids within Finland were employed [32]. The data were acquired from NordPool for the year 2023. Based on these bids, the area price of Finland can be obtained. The methodology for extracting market clearing price based on supply and demand bids is explained in detail in Section 2.4.

2.2. Generating wind power profiles

The wind power profiles for the year 2023 were generated using the methodology displayed in Fig. 7. The methodology has already been used by Salmelin et al. [7]. ERA5 stands at the basis of physics-based estimations of wind power generation together with an E-160 EP5 E3 turbine (5.5 MW) sitting at a 166 m hub height with a 160 m

blade span [26]. The turbine was chosen based on the study conducted by Satymov et al. [33] where they studied the most optimal turbine type globally and found that the Enercon E160 EP5 E3 turbine was the optimal choice for much of the world, including the Finnish price area as a whole, with the lowest levelized cost of electricity (LCOE) in 2035 as well as 2050. The coefficient of performance of the wind turbine, which describes the efficiency of the wind turbine to convert the kinetic energy of wind to electricity, was obtained using a database containing multiple different turbines [34]. The coefficient was estimated in parts from 0 m/s to 26 m/s and smoothed using a running average and finally applying a smoothing spline fit. A better approximation for the coefficient of performance could be achieved if the raw data were made available by the manufacturers; however, this information is often kept confidential.

The turbine selection affects the power generation volumes owing to different turbine characteristics: height, blade length, and performance at different wind speeds. The main objective of the paper is not to dictate at the micro level where individual turbines of a certain type should be installed; instead, the target is to highlight the benefits of dispersed generation and to show that it can be done without losing significant revenue. Some different type of turbine may be better suited for coastal areas where gusting is prevalent, and other locations may benefit from smaller turbines, which are more capable of generating power at lower wind speeds but as shown by Satymov et al. [33], the chosen turbine is well suited for the whole price area.

Additional study has been performed by the authors to complement the present paper, where the effect of turbine selection was estimated on the same key parameters [35]. It was found that the most influential characteristic of turbines was hub height, which should be maximized to obtain the most market benefit together with geographical dispersion of generation. It was initially hypothesized that smaller turbines (around 3 MW) could generate power at lower wind speeds during periods of high electricity prices. However, because power output scales with the cube of wind speed, overall energy production (also annually) remains low. To maximize full-load hours and ensure steadier wind power generation, turbines should primarily be installed with higher hub heights.

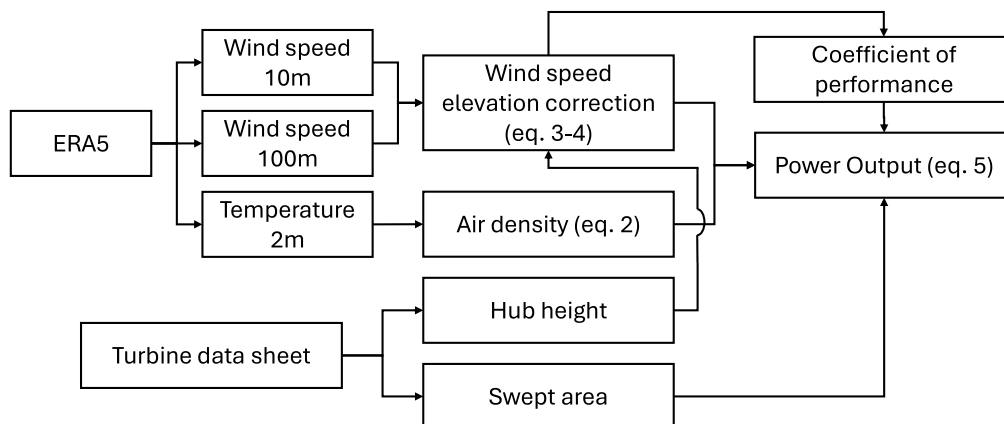


Fig. 7. Formation of the wind power generation profiles at each location.

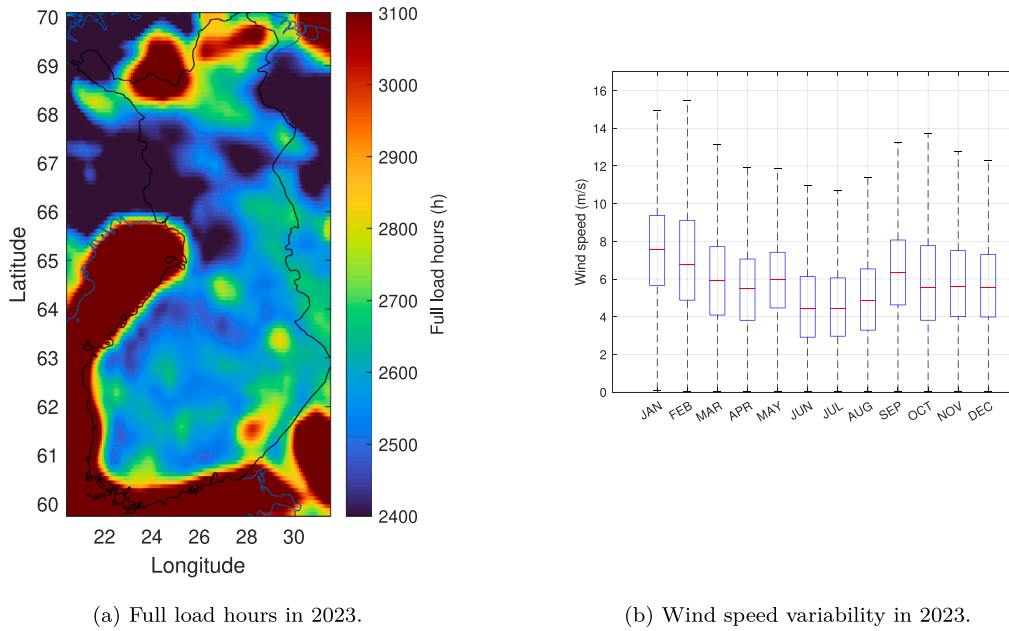


Fig. 8. Full load hours of the different wind farms (8a) using Enercon E-160 EP5 E3 5.5 MW turbine and ERA5 data together with the variability in wind speeds (8b). The center red line in the box depicts the median. The bottom and top edges of the boxes indicate the 25th and 75th percentiles respectively. The whiskers indicate the most extreme data points that are not considered outliers. Data is for Finland for the year 2023.

The air density ρ , which consists of the dry mass of air m , the air pressure p , and the Boltzmann constant k_b , is inversely proportional to temperature T as expressed in:

$$\rho = \frac{mp}{k_b T} \quad (2)$$

The wind speeds v were increased to better simulate the wind speeds at the 166 m hub height, where h corresponds to the respective hub heights according to:

$$v_{166m} = v_{100m} \left(\frac{h_{166m}}{h_{100m}} \right)^\alpha \quad (3)$$

The coefficient α , which is the Hellman coefficient and describes how the surface roughness affects wind speeds, can be calculated with already known wind speeds at different heights using Eq. (4). ERA5 offers wind speeds at 10 m as well as at 100 m, which can be used for the whole geographical area of the study as the α coefficient depends on local conditions:

$$\alpha = \frac{\log\left(\frac{v_{100m}}{v_{10m}}\right)}{\log\left(\frac{h_{100m}}{h_{10m}}\right)} \quad (4)$$

The variables from Eqs. (2)–(4) are combined with the swept surface area A , the coefficient of performance C_p and the wind speed v at hub height to estimate wind power P_{wind} according to the equation:

$$P_{wind} = 0.5 A \rho C_p v_{166m}^3 \quad (5)$$

Uncertainty in the wind power estimates mainly stems from wind speed variability. The ERA5 dataset tends to underestimate wind speeds, especially at lower speeds (Section 2.1.1). Additionally, the hourly resolution does not take into account gusts that can cause the turbine to be shut down. Icing is not considered, which can also affect the accuracy of the model. Despite this, the model is valuable for assessing the market impacts in regions without real wind speed measurements at required heights or existing turbines.

The estimated full load hours are comparable with estimates from VTT (3000–3500 h) from a sample location on the west coast [36]. The rest of the country generally experiences weaker winds, as seen from the Global Wind Atlas [37]. Despite its biases, this method provides consistent wind power generation profiles across Finland, which are mainly driven by local wind availability according to ERA5.

2.3. Wind conditions

Wind conditions are highly affected by seasonal differences in the Nordic countries. During the winter months, the winds tend to be stronger than in the summer. In the summer, the wind power production is 60%–80% while in winter it is 110%–150% of the yearly average [8]. This variation can be observed in Fig. 8(b) for the whole of Finland. When evaluating the generated power, temperature plays a significant role, especially in Finland, where the temperature differences can be over 60 °C between the seasons. This has a direct impact on air density and, as a result, potential power generation, which further amplifies the seasonal differences in power generation [7]. The full load hours can be seen in Fig. 8(a) for the year 2023.

2.4. Algorithm to analyze market data

In order to understand the influence of additional generation in the energy system, a market clearing algorithm that is used in deregulated electricity markets is outlined in this section. The algorithm was developed in Python. The model considers both supply and demand bids, and it incorporates relevant constraints to ensure market feasibility. The overall implementation of this algorithm is described in Section 2.4.5, and a sample graph to illustrate the functioning of the algorithm is depicted in Fig. 9.

2.4.1. Objective function

The day-ahead price is formulated based on a Security-Constrained Economic Dispatch (SCED) model which ensures electricity security while minimizing costs. The objective function of this model (primal problem) provides security of electricity at minimal production costs which is formulated as follows:

$$\max \left(\sum_{i=1}^{N_d} P_i^d Q_i^d - \sum_{j=1}^{N_s} P_j^s Q_j^s \right) \quad (6)$$

where:

- P_i^d and Q_i^d are the bid price and quantity of the i th demand bid, respectively.

- P_j^s and Q_j^s are the bid price and quantity of the j th supply bid, respectively.
- N_d and N_s are the total number of demand and supply bids, respectively.

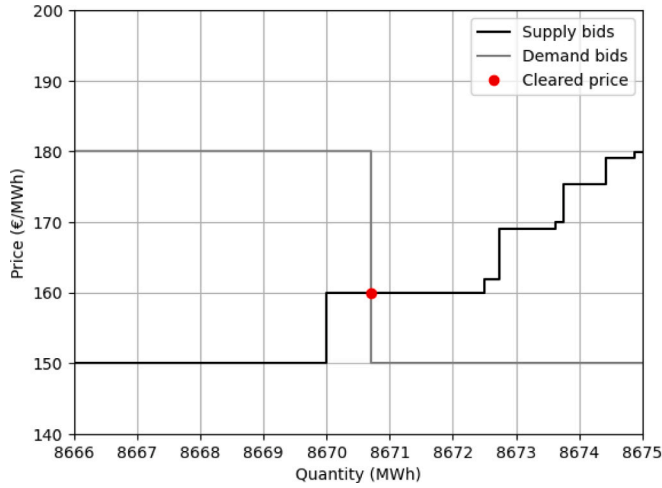


Fig. 9. Sample of the market clearing algorithm and MCP for the whole price area of Finland for a sample hour.

2.4.2. Constraints

The market clearing model is subject to the following constraints:

1. **Supply–Demand Balance:** The sum of electricity produced should be equal to the sum of electricity consumed.

$$\sum_{j=1}^{N_s} Q_j^s = \sum_{i=1}^{N_d} Q_i^d \quad (7)$$

2. **Non-Negativity:** The supply and demand bids should always be positive.

$$Q_i^d \geq 0 \quad \forall i \in \{1, \dots, N_d\} \quad (8)$$

$$Q_j^s \geq 0 \quad \forall j \in \{1, \dots, N_s\} \quad (9)$$

3. **Bid Quantity Limits:** As each supply and demand bid has its maximum limits, all the accepted bids must be within their limits (\bar{Q}_i^d, \bar{Q}_j^s is the maximum limit of i th demand bid and the maximum limit of j th supply bid respectively).

$$0 \leq Q_i^d \leq \bar{Q}_i^d \quad \forall i \in \{1, \dots, N_d\} \quad (10)$$

$$0 \leq Q_j^s \leq \bar{Q}_j^s \quad \forall j \in \{1, \dots, N_s\} \quad (11)$$

4. **Price Limits:** The Market Clearing Price represented as P_{MCP} , should be within the minimum and maximum limits of the market.

$$P_{\min} \leq P_{MCP} \leq P_{\max} \quad (12)$$

The maximum (P_{\max}) and minimum (P_{\min}) price in NordPool in day-ahead market are 4000 and -500 €/MWh respectively.

2.4.3. Dual problem

To derive the MCP, the dual problem is employed in this paper. It offers an alternative perspective on the primal problem by focusing on the constraints rather than on the objective function itself. The dual variable associated with the supply–demand balance constraint plays a key role in determining the MCP. To extract the MCP, a dual variable λ associated with the supply–demand balance constraint is introduced. This dual variable λ represents the marginal value of relaxing the

supply–demand constraint by one unit, which can be interpreted as the MCP.

The Lagrangian (\mathcal{L}) for the primal problem is given by:

$$\mathcal{L} = \sum_{i=1}^{N_d} P_i^d Q_i^d - \sum_{j=1}^{N_s} P_j^s Q_j^s + \lambda \left(\sum_{j=1}^{N_s} Q_j^s - \sum_{i=1}^{N_d} Q_i^d \right) \quad (13)$$

The dual problem is obtained by maximizing the Lagrangian over the primal variables Q_i^d and Q_j^s , and then minimizing it with respect to the dual variable λ :

$$\min_{\lambda} \max_{Q_i^d, Q_j^s} \mathcal{L}(Q_i^d, Q_j^s, \lambda) \quad (14)$$

The optimality conditions for the primal problem require that the derivatives of the Lagrangian with respect to Q_i^d and Q_j^s are zero at the optimal point:

$$\frac{\partial \mathcal{L}}{\partial Q_i^d} = P_i^d - \lambda = 0 \quad \Rightarrow \quad \lambda = P_i^d \quad (15)$$

$$\frac{\partial \mathcal{L}}{\partial Q_j^s} = \lambda - P_j^s = 0 \quad \Rightarrow \quad \lambda = P_j^s \quad (16)$$

Thus, the Market Clearing Price λ is determined by the intersection of the supply and demand curves, where:

$$P_{MCP} = \lambda = P_i^d = P_j^s \quad (17)$$

This means that at the MCP, the dual variable λ equals the bid price for both the marginal (last accepted) demand bid and the marginal (last accepted) supply bid.

The MCP using the dual approach is the value of the dual variable λ that balances the supply and demand in the market. This dual variable represents the price at which the total quantity supplied equals the total quantity demanded. Mathematically, this can be expressed as:

$$P_{MCP} = \lambda^* \quad (18)$$

where λ^* is the optimal solution to the dual problem.

2.4.4. Market clearing algorithm

The market clearing process involves the following steps:

1. **Sort Bids:** Sort supply bids in ascending order of price and demand bids in descending order of price.
2. **Calculate Cumulative Quantities:** Compute the cumulative quantity for both sorted supply and demand bids.
3. **Find Market Clearing Price (MCP):** Identify the price at which the cumulative supply meets or exceeds the cumulative demand, i.e., the optimal solution to the dual problem.
4. **Allocate Quantities:** Allocate the quantities to supply and demand bids based on the MCP, ensuring that the total allocated supply matches the total allocated demand.

An example resulting plot from the market clearing algorithm can be observed in Fig. 9.

2.4.5. Implementation

Market data from NordPool is used in this paper [32]. The supply and demand bids of all energy entities in the day-ahead market for Finland are used for the year 2023. The additional production of electricity through the wind farms would have near-zero operating costs and could be included in the market clearing algorithms at zero cost. The changes in prices before and after the addition of wind power plants are computed and denoted by ΔP . The entire algorithm is implemented in Python using a Gurobi solver.

To simplify the process, cross-border trading is not assumed to take place. Data shows that there has been 0% of the time when Finland has been in a price balance with its neighboring price areas, which indicates that there are cross-border transmission bottlenecks [38]. Furthermore, as the cross-border capacities are already fully utilized and the southern

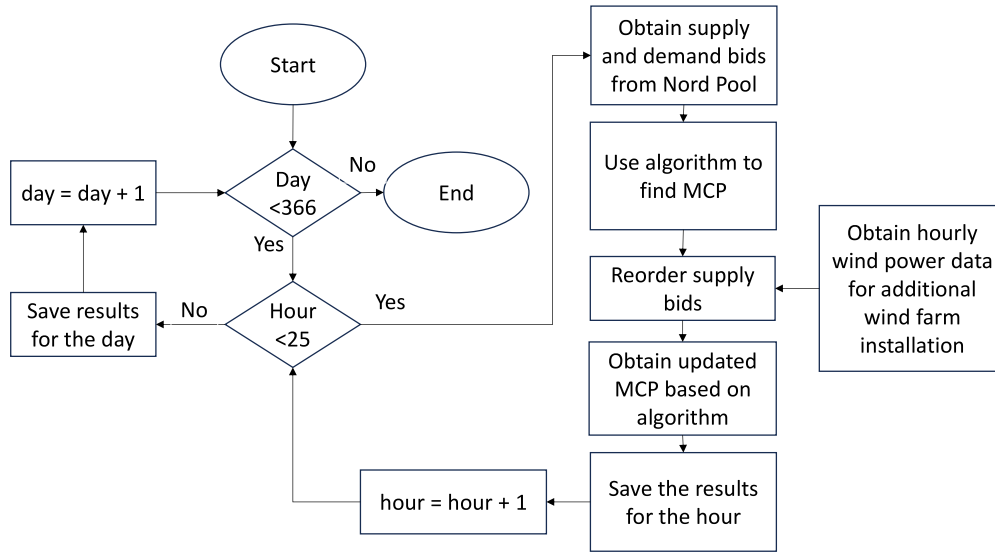


Fig. 10. Process chart of the market analysis.

areas of the NordPool market systematically experience higher prices than either Finland or Sweden, it can be assumed that cross-border flows remain unchanged. Lastly, Finland is highly self-sufficient in terms of electricity consumption, with only 3% of total consumed electricity being imported [39]. The overall process is described in Fig. 10.

Considering a single initial location for the additional wind park installation, as shown in Fig. 10, the price changes are computed on an hourly basis, and the process is repeated over the entire year. The resulting price variations for the specific location are evaluated annually and subsequently re-evaluated for the other locations across Finland. A total of 1890 locations were calculated, of which 1003 fall inside the land borders of Finland.

There are two market design options to deal with transmission network congestion, locational marginal pricing (LMP, aka nodal pricing), in which each network node has separate price including energy, losses, and transmission congestion costs, and zonal pricing, in which larger area (e.g. one county) has uniform price. In Europe, zonal pricing has been chosen as a market design, and the whole of Finland is a single bidding area, thanks to a strong network and no significant congestion within the country.

While grid congestion is becoming ever more relevant, as previously mentioned, there is no market structure in place where costs associated with grid congestion are reflected on the consumer or producer. The TSO performs countertrading [24,25], which shifts power generation to less congested areas. A further study is planned, and thus, a network analysis is not within the scope of this paper, except for acknowledging the growing issue.

If the current existing price area were split into further areas or nodes, it would cause further imbalances and issues in pricing due to the heavy centralized generation, further aggravating cannibalization on the west coast. It could help incentivize the installation of new wind power capacity in other areas; however, it is important to keep in mind the limitations in installing wind power in the north and the east as discussed in Section 1.

3. Results

3.1. Maximizing electricity cost reduction for society

The societal benefit from the added generation is determined as the reduction in the total electricity cost in the day-ahead market

for consumers. The total energy consumed for the year 2023 in the day-ahead markets was 58 TWh. The difference in price (difference between market clearing price before the addition of the new wind power capacity (BW) and after the addition of the new wind power capacity (AW), i.e., $P_{MCP,h}^{BW} - P_{MCP,h}^{AW}$) is multiplied by the new day-ahead market demand ($E_{con,day-ahead}$) at the new capture price to evaluate the societal benefit according to:

$$Societal\ benefit = \sum_{h=1}^{8760} (P_{MCP,h}^{BW} - P_{MCP,h}^{AW}) \cdot E_{con,day-ahead,h} \quad (19)$$

The MCP before the addition of wind power was obtained from the market algorithm described in Section 2.4.4 and verified against the values from the market operator NordPool [40]. This comparison doubled as verification of the functioning of the market algorithm as a whole.

An increase in wind power production due to the merit order of generation, where the cheapest sources of electricity are consumed first, will lead to reduced electricity prices regardless of where the wind farm is installed. The biggest reductions in electricity cost are observed when the power demand is high and the timing of the generation manages to significantly cut a high day-ahead market price. The reductions in electricity costs are illustrated in Fig. 11 in units of M€/a (Million Euro per annum) and €/MWh (Euro per megawatt hour). It is noteworthy that in Fig. 11(b), despite the average reduction in electricity cost per MWh being higher in the center of Finland, other regions may achieve overall higher reductions in electricity cost due to a higher overall supply of energy.

3.2. Maximizing revenue for investors

The areas and their estimated revenue using the new day-ahead market price are seen in Fig. 12. The coastal areas are areas of a high potential revenue as anticipated, mainly driven by the strong winds generating over 15 M€/a in revenue (38.5 €/MWh). The revenue per MWh is lower than in some other areas, but due to volume of generation, the total revenue is higher as seen in Fig. 12(b). The south-east is comparable in terms of revenue due to higher electricity price per MWh (40 €/MWh) generated and the wind conditions being overall only slightly worse than on the coastal regions as seen in Fig. 8(a). It is noteworthy that some areas, especially in the north, are areas where new wind farms may not be readily built due to cultural reasons, national parks, or a lack of connecting infrastructure [41].

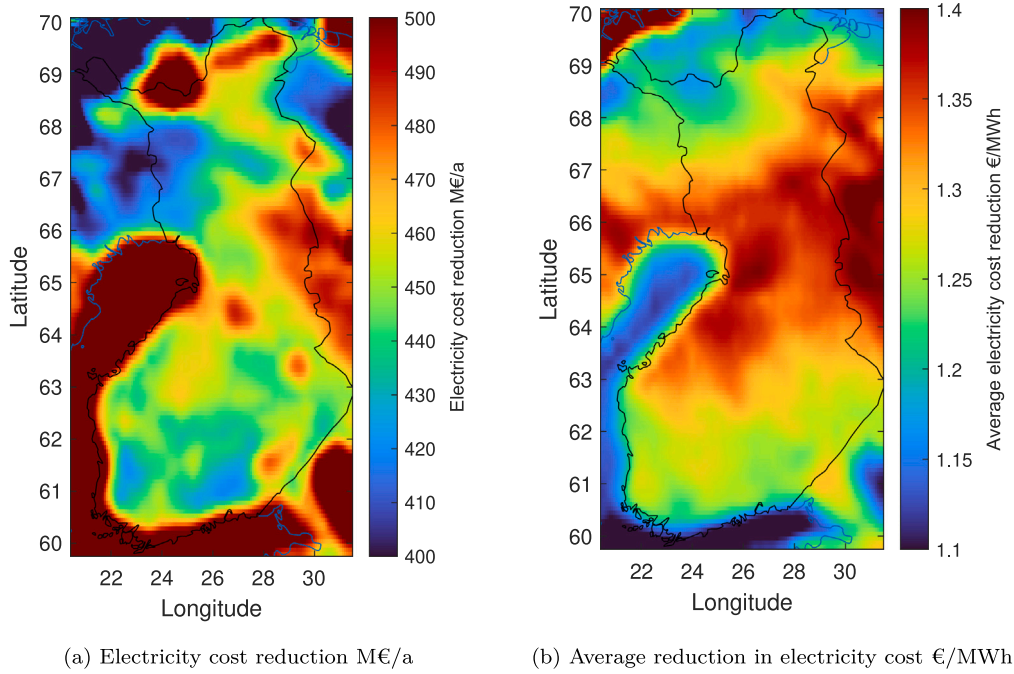


Fig. 11. Quantifying societal benefit through reduction in electricity costs in the day-ahead market.

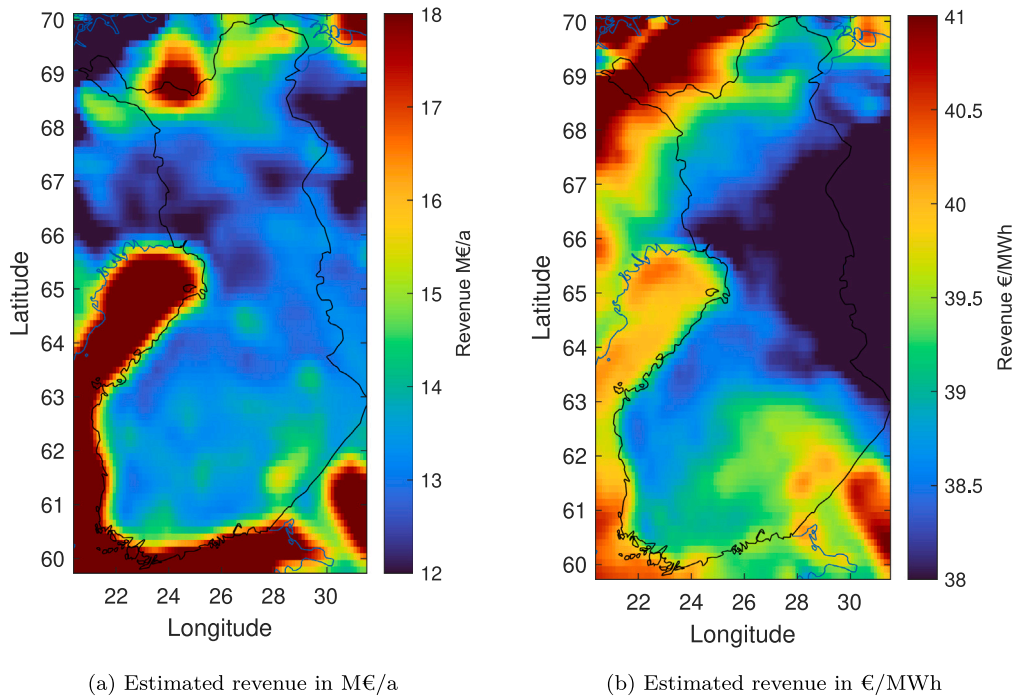


Fig. 12. Estimated revenue for an investor from selling generated wind power in the day-ahead market with a new capture price in 2023.

The best revenue per MWh is obtained in southeastern Finland, as seen in Fig. 12(b). Some areas in the far North obtain similar or better revenue; however, due to aforementioned restrictions new wind power capacity may not be easily built there. Coastal regions offer the highest total revenue due to the higher total generation, as observed in Fig. 12(a). The revenue is comparable between the coastal regions and southeastern Finland; however, due to price cannibalization, especially the west coast may not be as competitive in the future. This is further discussed in Section 3.3.

3.3. Effect of cannibalization on revenue

Cannibalization of the electricity market price is a phenomenon in which the generation from most commonly renewable sources aligns so that there is oversupply of power, leading to a disproportionately lower day-ahead market price. As a result, if additional renewable energy capacity is added to an area that is already generating a lot of renewables-based power, it can cut further into the expected revenue. To combat this effect, the sources of renewable power in an area should

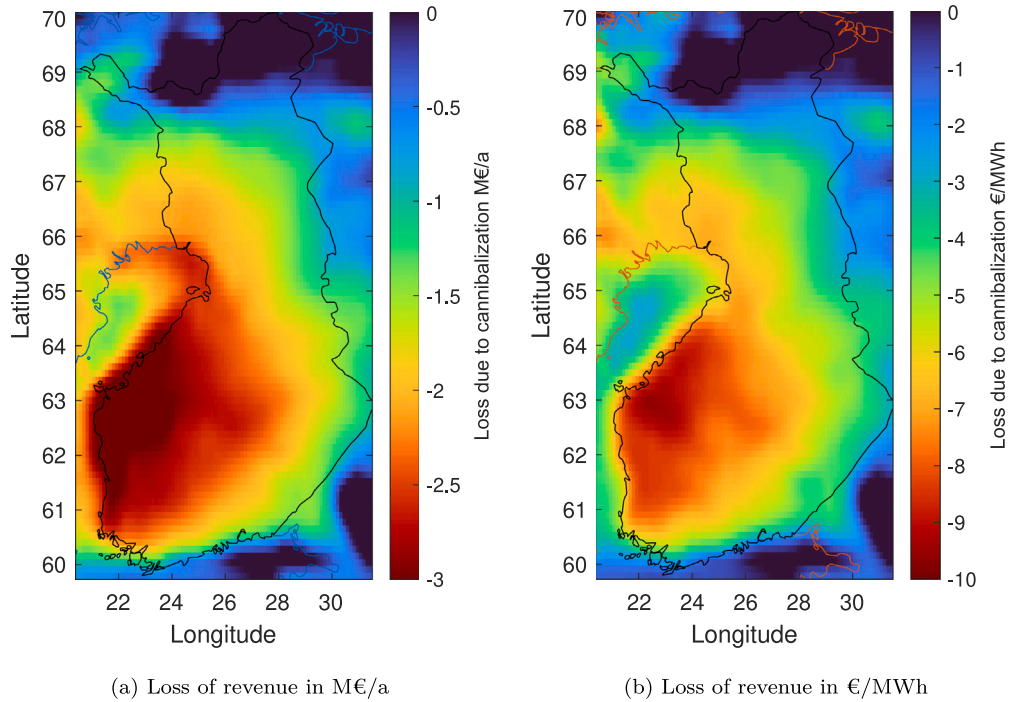


Fig. 13. Comparison of the effects of additional wind power capacity on revenue through cannibalization of electricity market price.

be diversified or installed in other areas with different generation profiles, most commonly at a great geographical distance where possible. The cannibalization effect of additional wind power capacity can be quantified through the effect on revenue in day-ahead markets. The loss in revenue is calculated hourly by comparing the occurred cleared price (P_{MCP}^{BW}) to the new price due to additional generation (P_{MCP}^{AW}) multiplied by the hourly generation (E_{wind}), as expressed by:

$$Loss\ in\ revenue = - \sum_{h=1}^{8760} E_{wind,h} \cdot (P_{MCP,h}^{BW} - P_{MCP,h}^{AW}) \quad (20)$$

The effect of cannibalization is quantified in Fig. 13. It can be seen that the cannibalization effect is stronger on the west coast, where the majority of current wind power is installed. As the distance from the epicenter of generation increases, the losses due to cannibalization also decrease.

The seasonality of the cannibalization is plotted in Fig. 14. The cumulative loss over the year 2023 is plotted for three sample locations: west, east, and north. The highest cannibalization rates can be observed between February and June, which coincides with high electricity prices. Between June and September, the cannibalization rates slow down likely to low electricity prices. As electricity prices start increasing in September, the losses due to cannibalization also increase and continue to the end of the year. The east and north locations follow similar patterns and overall much lower cannibalization rates than the west location, as seen prior in Fig. 13. The west experiences more aggressive increases in losses driven by concentrated simultaneous generation and market saturation, as seen during September and October. All locations are similar in pattern but differ in magnitude with decreasing cannibalization observed at locations further from the west coast.

3.4. Distribution of periods of revenue

The effects on the electricity market from a single new wind farm at a sample location are plotted in Fig. 15. The figure illustrates the hourly reductions in electricity cost, together with the cumulative reductions

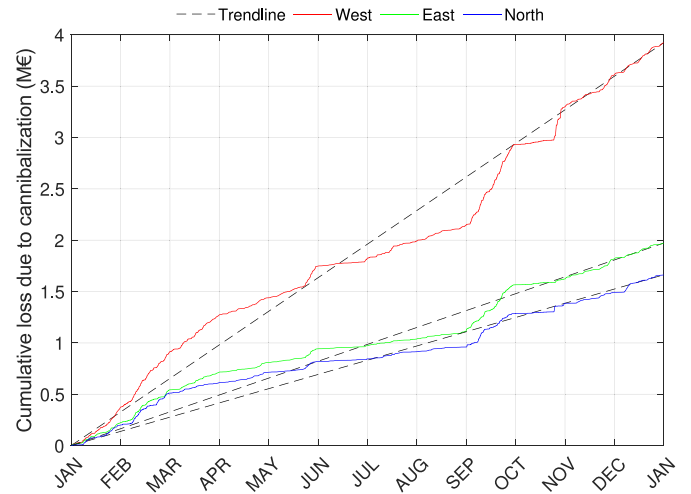


Fig. 14. Cumulative cannibalization of revenue in M€ for the year 2023 for sample locations from the west, east, and the north.

as well as the changes in day-ahead market prices that were caused by the addition of the said wind farm.

Fig. 15 shows that there is no seasonality effect on the timing of the electricity cost reductions obtained, but rather, there are certain periods where the reductions have been significant (from February to March, from September to October and in November). The spikes occurring between September and October can be attributed to the reduced operation of nuclear power in Finland, which resulted in higher electricity price reductions.

At the start of November, a large spike is seen, which can be explained by the beginning of winter when the consumer demand increases and the temperature falls, causing these high price spikes as depicted in Fig. 2. Despite this anomaly in prices, in general, the stream of electricity cost reductions is roughly linear over the year, with a few events of greater contribution.

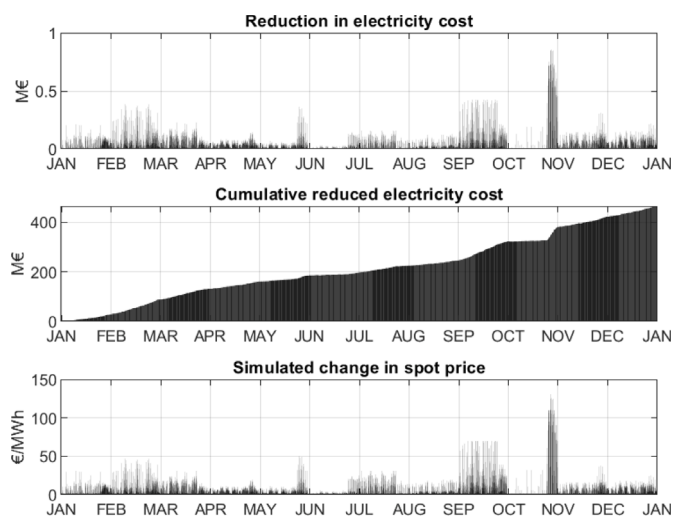


Fig. 15. Distribution of changes in electricity cost and day-ahead market price. The effects are from the effect of the new wind power capacity at a new single sample location.

4. Discussion

Based on the aforementioned results, this paper provides several key takeaway points that are useful to investors, policy-makers, and specialists within the energy industry.

First, this study employs a comprehensive model that integrates an hourly regional weather-based wind power simulation, which is used to assess the impact on the day-ahead market. Specifically, the analysis considers the installation of a 100 MW wind farm at various locations across the country, examining the effects of this additional generation on market dynamics. The methodology proposed in this paper is novel and represents the first of its kind. Moreover, it is readily adaptable for application in other countries, given the availability of relevant data.

Second, the findings of this study underscore the critical importance of dispersed generation within the country. As energy systems continue to develop, proactive planning is essential, since retrofitting solutions can be prohibitively expensive. Regions with high potential for revenue and electricity price reduction should be prioritized for development. Relying heavily on centralized power generation far from load centers necessitates significant investments in the electrical grid. Currently, there is a critical bottleneck in power transmission between northern and southern Finland, which is made worse as more wind power is installed in high-capacity generation areas [38]. Beyond assessing societal electricity cost savings, the present state of the grid must also be taken into account. Locating power generation closer to load centers can alleviate transmission capacity constraints. Singh et al. [42] investigated the challenges of integrating renewable energy sources into the grid, highlighting the limitations of on-grid connections and the advantages of dispersed generation.

Third, this paper highlights the effect of the cannibalization of electricity price with added renewable energy generation within the electricity system. Installing new wind power capacity in areas with already high-capacity causes a higher cannibalization effect. Despite the effect of cannibalization, the revenue on the west coast is high. This is due to only adding marginal new generation (100 MW) compared to the total capacity in the system (7000 MW). This may, however, not be likely for long if new wind power farms are built in the area.

Cannibalization of the day-ahead market electricity prices can have a significant effect on revenue; however, there are ways to counterbalance its effect. The effect of cannibalization has previously been documented by Prol et al. in the State of California and by Reichenberg et al. at a more general level [11,16,18]. Glenk et al. found

that the substantial decrease in life-cycle costs of solar PV outweighs the growing cannibalization effects in California [14]. Similar trends have not been observed for wind power due to significantly higher investment and operational costs. Liebensteiner et al. argued that the effect of carbon pricing can serve as a method to fight the effect of cannibalization in Germany [15]. This means that renewable power producers could compete in the carbon offset markets instead of the electricity markets for the main source of revenue. This can, however, be dangerous from the system perspective, as there may not be great interest in the state of the infrastructure and societal needs from the investors' point of view. Liebensteiner et al. stated that in Germany, a carbon price of 40 €/tCO₂ can offset the cannibalization effect of an RE-intensive system. There can be additional losses in revenue other than cannibalization in specific cases where the system is dominated by intermittent generation and producers can be asked to stop producing during the surplus production hours. Recently, in the Netherlands, residential households have been paid to switch off PV production. One-third of households have solar PV installations simultaneously generating power, which cannibalizes the energy market and stresses the grid [43].

Fourth, there is a significant disparity in development and infrastructure support between different areas. Installing new wind power capacity in eastern Finland could create opportunities and provide essential local support, which is vital for fostering a sustainable future. Moreover, the strategic distribution of infrastructure and power generation across different regions, particularly in eastern Finland, offers substantial socioeconomic benefits. Expanding infrastructure in these areas could generate employment opportunities and attract new industries, leveraging the availability of power and improved infrastructure. Additionally, the eastern region, with its point sources of biogenic CO₂ from pulp and paper mills, could serve as a robust foundation for e-fuels production, further advancing regional development. These considerations emphasize the broader impacts of renewable energy deployment beyond merely increasing energy capacity, highlighting the importance of a balanced and regionally inclusive approach to energy infrastructure development.

Fifth, communication between investors, policy makers and power system operators plays a key role in building a healthy power system, while benefiting society. If wind power installations only continue along the west coast, grid bottlenecks between the west coast and the south will only become more severe, together with increased price volatility. From the perspective of the power system operator, this means more investments in battery energy storage systems and grid reinforcements, which are costly and time consuming. The costs are recuperated through increased distribution costs to the consumer, while still experiencing increased price volatility. The policy maker's role should be to incentivize wind power installations away from the current epicenter. Not only would this make the power system more resilient while providing opportunities where the new installations are built, but it would also reduce the need for additional grid reinforcements on the west coast making best use of the already existing infrastructure, while also reducing price volatility. In the short-term, the addition of individual wind farms is unlikely to overwhelm, however, without proper planning, communication and incentives, price volatility, increased distribution costs, and regional inequality can become a significant problem.

Last but not least, the proximity of the grid plays a major role in determining the profitability and expected return on investment. For example, in the north, due to potentially significant distances to the nearest grid connection point, it may not be economically feasible to build a new farm. A further study is planned to include geospatial data of the landscape and open data on available building areas to evaluate the costs of connecting to the grid. By combining detailed grid connection cost data with information on areas where new wind farms can be built, and considering electricity market effects, individual sites can be ranked according to different key performance indicators. This is further discussed in Section 4.2.

4.1. Limitations

Although this paper provides valuable insights, it has some limitations that should be analyzed. Firstly, this paper does not take into account the present grid infrastructure, which plays a critical role in the deployment and efficiency of renewable energy projects. Currently, a significant number of wind farms are concentrated on the west coast of Finland, largely due to the presence of well-established grid infrastructure and good wind resource conditions. In contrast, the grid infrastructure in the eastern and northern regions of Finland is less developed, limiting the feasibility of large-scale renewable energy projects in these areas. Consequently, the acceptance of energy losses due to cannibalization may be a pragmatic approach, as it circumvents the need for substantial investment in new grid infrastructure.

One potential future approach arising from this paper is to explore the integration of grid infrastructure into the analysis to provide a more comprehensive assessment of renewable energy deployment. Sector integration and coupling can help reduce price fluctuations and can be adopted throughout Finland. Electric boilers for district heating systems can be operated based on day-ahead price, which also offers additional stability in the grid and makes use of low-price hours. Large-scale e-hydrogen production near the sites of generation can act as a flexible electrical load and can further help in the adoption of renewable power. Large-scale electrolyzers have great potential in helping the power balance of the grid due to being able to dynamically operate the plant according to energy availability. Being located near the sites of power generation reduces the stress on the grid as the plants could be even in the GW scale, further supporting the adoption of renewable energy sources of power. Additionally, the potential of battery energy storage systems (BESS) as a solution to grid bottlenecks is also recognized. A BESS could mitigate these constraints by enabling energy storage during periods of low demand and allowing energy trading during peak hours, thereby optimizing grid efficiency. This approach represents a possible brute-force solution to current grid limitations.

Secondly, it is important to note that this study does not delve into the specifics of individual turbine placement or wind farm layouts, as these factors require separate, detailed analysis. The choice of turbine type, especially those designed to withstand gusty conditions, is particularly relevant for coastal regions and should be investigated in further studies. In this paper, the focus is on onshore wind power; however, the results from offshore sites around the Finnish coastline are relevant but only direction-giving and should not be directly compared to onshore sites. Offshore installations tend to be much larger in size and also come with much higher investment costs. A separate study should be made to include investment costs between onshore and offshore sites and compare them to the resulting effects on the day-ahead markets.

This paper employs an area price formulation based on the integration of additional wind power installations within Finland, under the assumption that the generated wind power is primarily traded on the day-ahead market. While it is typically crucial to consider electricity trading across day-ahead, intraday, and reserve markets to maximize revenue [44], this paper deliberately limits its scope. The primary objective is to emphasize the disparity in wind power installations between eastern and western Finland and to underscore the potential benefits of increasing wind power capacity in eastern Finland. Consequently, detailed algorithms and strategies for revenue maximization from the perspective of wind power operators have not been addressed in this study.

While the power estimates have their inherent biases, the results would not change drastically due to the strong dependence on the local wind speeds. For example, cannibalization rates may vary slightly; however, the general trend would remain that additional installation of new onshore wind power capacity on the west coast more aggressively cannibalizes the day-ahead price than locations further from the current installation epicenter.

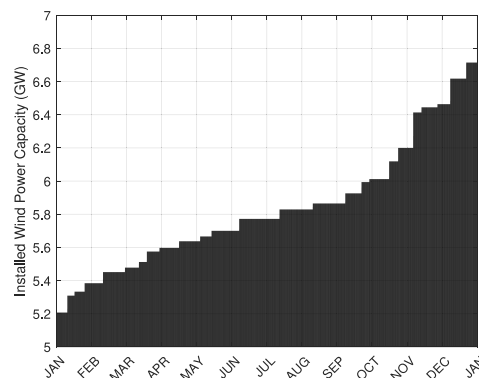


Fig. 16. Installed wind power capacity in Finland in the year 2023 [45].

The rate of installation of new onshore wind power capacity in Finland is one of the highest in the world, despite its relatively low population, adding 4% of global new wind capacity annually [4]. During 2023 alone, many new wind farms were built, and they contributed to the day-ahead markets unevenly at the start and end of the year, as seen in Fig. 16 [45]. The rate at which the situation can change is rapid; however, the importance of co-planning new sites does not reduce with time. On the contrary, it becomes even more important.

In this paper, analyses were limited to a single price area (i.e., the Finnish price area), due to the availability of data. This means that price formation was analyzed based on the bids in the Finnish price area only. This ignores cross-border trading, which would alleviate the volatility impact on the price. However, Finland is a single price area, which differs from similar-sized neighboring countries that have four (Sweden) or even five (Norway) price areas. The impacts on price volatility and cannibalization would have been higher if we had analyzed only one price area in Sweden or Norway. Hence, although cross-border trading was not included, Finland has a high amount of intrazonal energy transmission, which would compensate for the missing cross-border viewpoint.

Lastly, the use of the MCP in this paper is based on the functioning of a deregulated market. However, since Finland is part of NordPool and interconnected with other countries, the changes in the day-ahead price may not exactly match the obtained results. Due to data availability and the complexities involved in formulating the MCP for all interconnected countries, this study focuses solely on the dataset from Finland.

4.2. Future work

Further topics of study are the inclusion of hybrid solar and wind power plants to evaluate their revenue generation potential and how well the different sources complement each other. Future work will also include an analysis of a BESS and whether they can be effectively used to combat the effect of cannibalization of electricity price effectively through appropriate trading algorithms.

In addition, the effect of a large-scale electrolyzer on electricity markets will be studied. How should an electrolyzer be operated to provide the best support to the grid and electricity prices?

Further study is planned to investigate whether it is more costly to invest in new grid infrastructure to include new additional capacity, or to simply accept additional losses caused by cannibalization at the benefit of being able to utilize the already existing infrastructure. The research is performed at higher resolution with the inclusion of different building area restrictions and buffer zones, such as urban and military areas, natural parks, and airports. Additionally, it will take in to account detailed costs of: building the farm, grid connections, power lines and transformers, which have been cost optimized using

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