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

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ABSTRACT

The global share of renewable energy sources in the electricity mix has increased substantially, with the rate of installation continuing to accelerate. Geographical diversification of renewable generation can lead to a more balanced generation profile, thereby contributing to price stability despite the intermittent nature of supply. The issue of revenue cannibalization among renewable energy sources has become increasingly relevant with centralized renewable power generation. The proposed methodology examines the impact of incremental addition of solar photovoltaic capacity, with power profiles modeled based on ERA5 weather data, on present day-ahead electricity markets. This is achieved by the manipulation of day-ahead bid curves from NordPool to establish a new day-ahead market price caused by the addition of 100 MW_p of solar photovoltaic capacity at different geographical locations. The findings indicate that the regions most effective in reducing electricity prices are not necessarily those with the highest energy production; rather, the temporal coherence of generation with bulk renewable output plays a crucial role in determining market effects, especially in the Nordic countries with significant seasonal variations. Electricity cost reductions of 18 M€/a were observed with the highest price cannibalization rates of 13 €/MWh. The results highlight the importance of considering generation patterns, not only capacity, when assessing the impact of renewable energy integration.

1. Introduction

The European Union (EU) has set goals to decarbonize national energy systems by 2050 with initiatives such as RePowerEU [1]. The goals are in line with the Paris Agreement [2], in which it is outlined that global warming should be kept below +2 °C. Furthermore, Finland has an accelerated target of being climate-neutral by 2035 [3]. This can be primarily achieved through the adoption of renewable sources of energy and the direct electrification of other energy sectors.

Wind and solar power are the two main renewable energy sources that have experienced substantial global growth. Some regions, such as the Nordic countries, may not rely on solar photovoltaics (PV) as their main source of renewable power due to seasonal changes in power availability. Nevertheless, due to its low cost and complementary generation profile, solar power can support wind power (Section 6.1). Generally, a renewable-energy-based system is prone to power generation intermittency. Thus, it is important to diversify the electricity mix, either through geographical dispersal or technological diversification [4,5].

As investments into renewable power sources grow, the need for system-level planning increases. The “lowest-hanging fruits” in terms of location should be prioritized; however, how these are defined may vary. For instance, a site can be best in terms of land use, grid connection availability, proximity to load points, a lower overall stress on the grid, generation potential, or generation-demand profile coherence. All of these factors have associated costs or potential for savings.

One way to examine the benefit or cost of new renewable power generation capacity is through the proxy of the day-ahead electricity market. If the electricity price is low, it is likely that there is an abundance of renewable power available in the grid, and vice versa. By adding simulated power generation from different geographical locations to the supply bid of the day-ahead market, a new market clearing price (MCP) can be evaluated. The monthly day-ahead market prices and their variance for the year 2023 are illustrated in Fig. 1.

The hypothesis is that due to different areas having different generation profiles and susceptibility to clouds and snow, some areas should stand out and help stabilize electricity prices more than others. The

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Nomenclature

AOI	Angle of Incidence
AS	After solar
BESS	Battery Energy Storage System
BHI	Beam Horizontal Irradiance
BS	Before solar
DC	Direct Current
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
DSO	Distribution System Operator
ECMWF	European Centre for Medium-Range Weather Forecasts
EU	European Union
E	East
FLH	Full Load Hours
GHI	Global Horizontal Irradiance
LCOE	Levelized Cost of Electricity
LMP	Locational Marginal Pricing
LPM	Levelized Profit Margins
LROE	Levelized Revenue of Electricity
MCP	Market Clearing Price
N	North
POA	Plane of Array
PVPMC	PVPerformance Modelling Collaborative
PV	Photovoltaic
SCED	Security-Constrained Economic Dispatch
SSRD	Surface Solar Radiation Downwards
TSO	Transmission System Operator

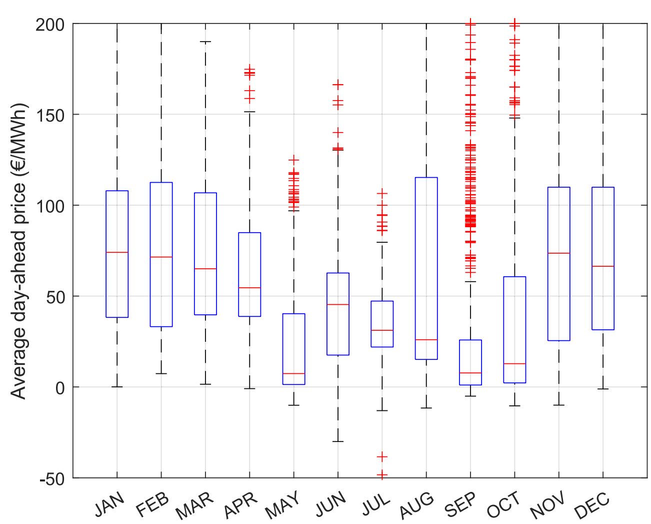


Fig. 1. Day-ahead price variation in Finland in 2023 [6]. The center red line in the boxes depicts the median. The bottom and top edges of the boxes indicate the 25th and 75th percentiles, respectively. The whiskers indicate the most extreme data points that are not considered outliers. The red crosses indicate outliers in the data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

southwestern areas could have more opportunities to provide electricity when the day-ahead market prices are higher in the winter months. As most of the daylight hours of the northern areas are during the summer months when the day-ahead prices are relatively low, they could have less benefit. Hence, the aim of the study is to quantify the market impact of different regions and identify the areas with the greatest potential benefit in the day-ahead, especially since the Finnish day-ahead market is growing at a fast pace. In 2023, the demand for electricity in the day-ahead market was 58 TWh, with 31% of retail contracts being day-ahead (spot) contracts, up from 14% in 2022 [7].

1.1. Objectives of the paper

The objective of the paper is to develop a method for studying day-ahead market effects of new solar PV farm installations while quantifying cannibalization, revenue and societal benefit. A further objective is to identify areas that are less prone to cannibalization and promote areas where a high level of revenue can be obtained while providing reduced electricity prices for society.

To that end, the paper seeks to answer the following research questions:

- What is the effect of additional solar power capacity on day-ahead prices?
- How could dispersed solar PV generation lead to reduced electricity costs for consumers?
- How does revenue differ based on location?
- Which areas show signs of price cannibalization from additional solar generation capacity? And, to what extent?

1.2. Scientific contribution

The scientific contribution of this paper lies in the methodology applied to analyze the benefit of new solar PV farm installations spread over a large geographical area with high temporal and spatial resolution. The study takes into account the effect of snow on solar PV power generation, which significantly affects solar power generation under Nordic weather conditions. The results provide insights into the electricity market and allow for better energy system planning and reduction of day-ahead market prices, thus providing welfare for consumers while maintaining revenue levels to drive investments.

Overall, price cannibalization is a known phenomenon studied in literature. However, no other works have been identified where spatially explicit methods were utilized to study cannibalization effects on the scale of a large price area or country.

2. Literature review

Cannibalization of the day-ahead electricity market price is a phenomenon in which a large amount of overlapping renewable power generation leads to a downward pressure on the day-ahead market price due to the oversupply of power [8]. The reduction in day-ahead market prices leads to a reduced revenue for a producer, which could disincentivize investments.

Existing cannibalization studies are based on regions or countries with a high solar power generation potential [8–11], such as California or Spain. Prol et al. [8] studied the cannibalization effect of both wind and solar power in the Californian wholesale markets. They concluded that increasing solar and wind penetration in the power system undermines their unit revenues, more so at high solar and wind penetration and low consumption levels. In addition, Prol et al. [11] studied the dynamics of renewable energy curtailment in California. They found that Variable Renewable Energy (VRE) curtailment increases exponentially at lower levels of load.

Glenk et al. [9] introduced the concept of Levelized Profit Margins (LPM), defined as the difference between Levelized Revenue of Electricity (LROE) and Levelized Cost of Electricity (LCOE). The study was conducted for California and Texas, and it was found that the cost of solar panels decreases at a faster rate than the losses due to the increase in cannibalization in California. It is important to note that the study was based on 2019 data, and since then, a significant change has occurred in the power system with a surge in solar panel installations and different Battery Energy Storage Systems (BESS).

A cannibalization study combining all renewable sources in the Baltic countries was conducted by Kozlovas et al. [12], showing that the increase in renewable energy sources will halve the electricity prices. They estimated that electricity price reductions of 5.5–17 €/MWh could be reached in Lithuania by 2033.

As for wind power, price cannibalization has been identified in [5, 13–15]. However, it is not within the scope of this paper, but can support a system-wide perspective and promote discourse on the topic of electricity price cannibalization.

One way to reduce the cannibalization effect is to shift and smoothen solar PV production peaks over the daylight hours. Riaz et al. [16] varied the panel azimuth and tilt to influence the timing of peak generation in Finland. An east-facing panel array was found to capture more of the morning sun than a west-facing array, which targets the evening rays, which could be a point of further study and collaboration in future research. Integration of large-scale vertical bi-facial solar PV in Europe was discussed by Szabo et al. [17]. They proposed the use of vertical bi-facial solar PV to improve the distribution of power generation to better meet the morning and evening demand.

Regulations and policies play a crucial role in the adoption of solar PV as well as the mitigation or exacerbation of the cannibalization effect. In the Netherlands, net metering, scheduled to end in 2027, has significantly incentivized solar power uptake [18], which has led to approximately 500 negative price hours in 2024 [19]. Due to the periodic oversupply, solar PV installations have been forced to be switched off [20]. A new fee has been introduced for prosumers for the surplus energy fed into the grid [21,22].

A literature review regarding merit order and cannibalization was conducted by Johanndeiter et al. [23]. They showed that in the Spanish markets, many solar producers generate power at a non-zero marginal cost due to participating in arbitrage in different markets, as cannibalization of a specific market can eat away the required revenue for economic operation.

The present paper examines the cannibalization effect of solar power within a highly centralized, wind-power-dominated electricity system. Unlike solar-dominated systems, such as those in California or Spain, where the peak electricity demand typically coincides with the peak solar generation and elevated cooling loads, this system experiences peak demand during periods when solar generation is minimal or nonexistent.

3. Background

This section briefly describes the case study region, Finland, used to demonstrate the developed methodology. The current state of the power system and the energy mix are discussed in Section 3.1. The solar resources are discussed in Section 3.2.

3.1. Finnish power system

In 2023, wind power covered 14% of the total energy demand, while solar PV covered <1%. These numbers have grown to 23.9% and 1.5%, respectively in 2025. The intermittency of renewable sources of power can already be seen in the day-ahead market, as discussed in Salmelin et al. [13]. The incredibly fast rate of the adoption of especially onshore wind power can clearly be observed in the energy share.

Currently, a large proportion of wind power is highly centralized on the west coast of Finland [24]. The eastern parts of the country have not experienced as much development due to the military constraints from the Finnish Defence Forces [25]. As a result, the eastern parts of Finland have a significant opportunity to connect large-scale solar farms to the already present grid infrastructure. The largest planned solar farm in Finland to date [26], reaching 250 MW_p of generation, is planned at a single site in the southeastern region. Using data aggregated from the distribution system operators (DSO), small-scale rooftop installations are most common in urban areas, with the southwestern parts of the country having the highest installed capacity in addition to the capital city in the south [27]. The share of rooftop solar PV accounted for 75%–80% of all solar PV generation in 2023 [28].

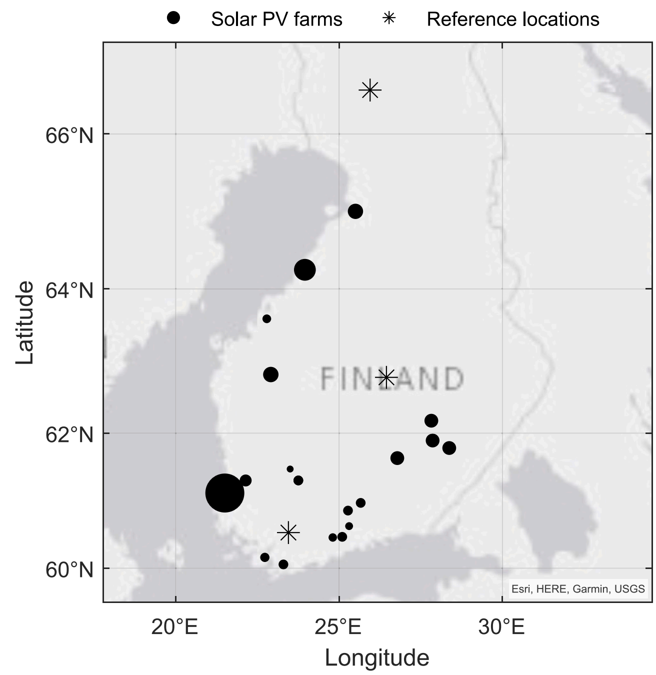


Fig. 2. Peak capacity of installed solar farms >1 MW_p in 2024 [29]. In addition, there are three reference locations: northern, central, and southern, which are discussed in later sections of the paper.

The analysis of the results is carried out in the context of wind power dominance in the renewable energy mix in the grid, and thus, wind power is able to influence the day-ahead market prices due to the difference in installed generation capacities.

Solar PV installations are often found on rooftops or as larger-scale commercial or industrial installations. In 2024, 1 GW_p of installed solar capacity was reached with 24 sites of over 1 MW_p and under 5 MW_p, with two outliers of 10 MW_p and 32 MW_p sites being operational. The rest of the installed capacity consists of smaller-scale installations mainly scattered around population centers; however, covering 75%–80% of all solar PV energy [28]. The installation sites of the >1 MW_p farms are illustrated in Fig. 2.

The geographical site where the large-scale solar farms are installed will have an effect on day-ahead prices. Different areas will have varying levels of cloud coverage, snow, and most importantly, irradiation. The solar conditions are discussed further in Section 3.2.

3.2. Solar conditions

In the Nordic countries, solar PV cannot be the main source of electricity due to significant seasonal variations in solar power availability as seen in Fig. 3. The average capacity factor for the sample location is low and practically nonexistent from November to March.

Nevertheless, solar PV has been identified as a viable source of electricity, as seen in the growth trend reported by Fingrid [30]. According to Fingrid, there have been connection inquiries for over 400 GW of renewable generation capacity [30]. Fingrid estimates that over 55 GW of renewable power will be connected to the grid by 2035. By 2030, 9 GW_p of solar PV capacity is expected [30] to be connected to the grid. For reference, the current winter peak demand of electricity

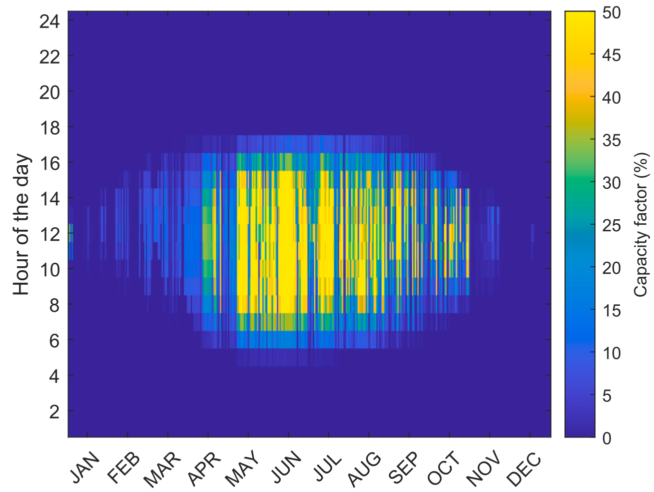


Fig. 3. Sample solar power capacity factor from the northern reference location in 2023. Because of the low general irradiance, note the corresponding scale of the capacity factor.

for Finland was expected to be around 14.4 GW in 2024 [31]. Wind power experiences seasonal variations, and solar power can effectively complement those variations well, as seen in Fig. 4.

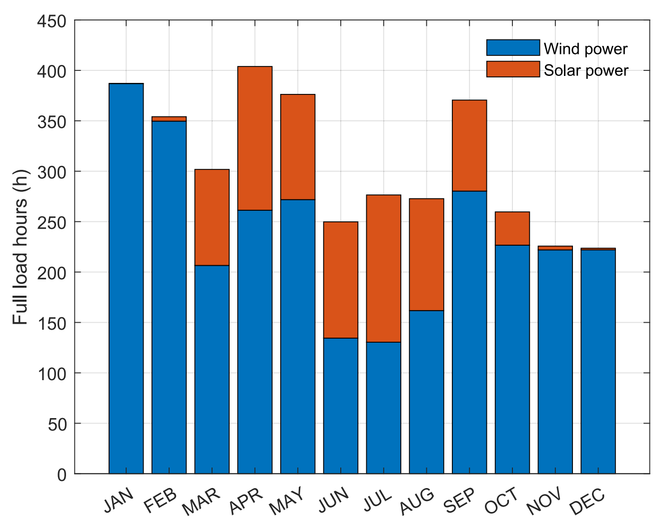


Fig. 4. Sample wind and solar power estimates for the year 2023 from a single sample location in central Finland. Installed 100 units of wind and solar power for a total of 200 units of renewable power generation capacity. The specific location will influence the level of complementarity; however, the seasonal support will still remain.

The solar conditions in Finland experience some of the largest swings in the world. In winter, the polar night dominates and panels may be covered in snow, leading to virtually no generation for often months at a time. In the summer, the opposite is true: the days are long, and sunshine hours are plentiful. Thus, the reliance on solar power is very low; however, due to the low cost of solar PV, the installation rates have been high, especially in homes and businesses. The low cost and the outstanding ability to compensate for seasonal fluctuations in wind power generation make solar power a viable option. The solar variance is plotted in Fig. 5. In April, when the ground is usually still covered in snow and the temperatures are low, the panels receive a great level of direct and indirect irradiation through reflections from snow and ice. In addition, due to the low temperatures, the efficiency of the panels is improved. As a result, in some years, the full load hours (FLHs) in April can be comparable with, if not even better than those in July. Once the snow has melted and the average temperatures increase in May, the FLHs decrease and peak again around July. In January and December, the days are short and often very cloudy, and thus, the FLHs are practically nonexistent.

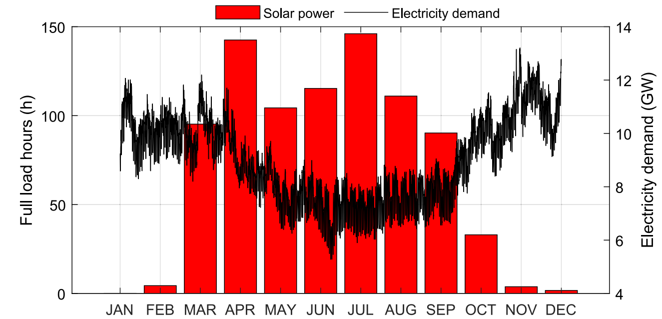


Fig. 5. Seasonality of solar power in Finland from a sample location plotted against the electricity demand in 2023.

The greatest FLHs are generally found in the southwest and along coastlines; however, the situation may vary between years, as the snow cover of the panels and cloudiness in a specific year can significantly influence the FLHs. At higher latitudes, the solar irradiation is lower. As the distance from the coast increases, the annual FLH levels generally decrease. The FLHs for the whole country are shown in Fig. 6.

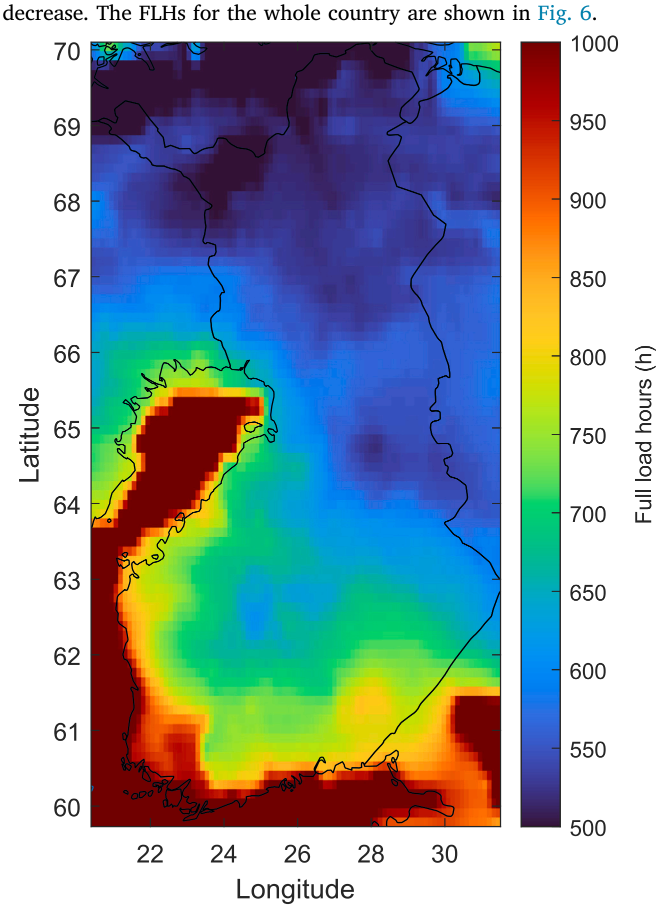


Fig. 6. Full load hours (FLHs) of solar power in Finland in 2023 when considering the effect of snow on solar panels.

4. Method and data

The methodology used in this paper is the same as that applied by Salmelin et al. [13], where a similar study was performed for wind power in Finland. The scientific value of this paper lies in the interpretation of the results for new solar PV installations in a wind-power-dominated system.

First, solar PV power generation profiles from south-facing arrays at 45° tilt angle were generated using the methodology explained in

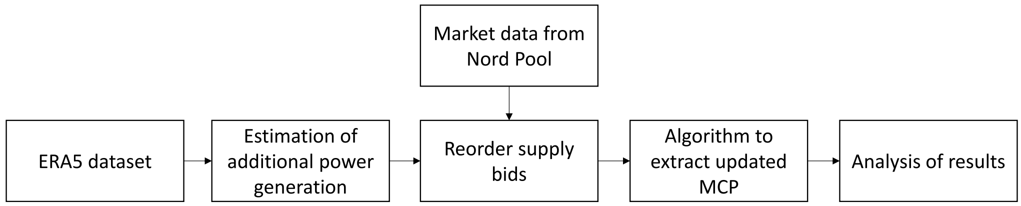


Fig. 7. Summarized general process graph, where MCP stands for market clearing price.

Section 4.1. Such profiles have previously been used in [32,33]. South facing arrays were chosen to maximize the annual yield and to isolate the tendencies of local weathern patterns on power generation. The additional power generation is then added to the supply bids from NordPool [34] using the algorithm fully described in [13], but also in Section 4.3, to obtain a new MCP. Lastly, the effects on day-ahead market prices are analyzed. A summary of the method is presented in Fig. 7.

The year 2023 was chosen so that the results would be comparable with the previous study for wind power [13].

4.1. Solar model for solar power

The potential for solar PV power generation is evaluated using the ERA5 reanalysis dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF) [35]. Hourly meteorological variables, such as temperature, wind speed components, surface pressure, and surface solar radiation downward (SSRD), are available in the ERA5 dataset at a spatial resolution of 0.25°. The main input of the SSRD is used to estimate PV power generation. It includes both direct and diffuse solar radiation and is typically provided as Global Horizontal Irradiance (GHI).

However, for accurate modeling of tilted PV panels, knowledge of the beam (direct) and diffuse components of solar irradiance is required. The PVPerformance Modeling Collaborative (PVPMC) provides an open-source tool for calculating Direct Normal Irradiance (DNI) and the solar zenith and azimuth angles, which are used to calculate the incident solar radiation [36]. The following formula is used to calculate the Beam Horizontal Irradiance (BHI):

$$\mathrm{BHI} = \mathrm{DNI} \times \cos(\theta_z) \tag{1}$$

where θ_z represents the solar zenith angle. Diffuse Horizontal Irradiance (DHI) is obtained from the Global Horizontal Irradiance (GHI) and the BHI.

The Angle of Incidence (AOI), which significantly influences PV reflection losses, is computed as:

$$\mathrm{AOI} = \arccos\left(\cos(\theta_z)\cos(\beta) + \sin(\theta_z)\sin(\beta)\cos(\gamma_s - \gamma)\right) \tag{2}$$

where β is the tilt angle, γ_s is the solar azimuth, and γ is the PV array azimuth. The work used the Hay and Davies transposition model [37] and also Klucher's studies [38] to estimate the beam and diffuse plane of array (POA) irradiances. The reflected irradiance on the plane of array can be computed using the isotropic sky model, originally formulated by Liu and Jordan [39], which considers ground-reflected radiation on inclined surfaces. The ground albedo, showing the reflectivity of the surface, is assumed to be an empirical constant of 0.2 for PV applications, based on studies such as Duffie and Beckman [40]. By calculating the components, the total plane of array irradiance is calculated by summing the beam, diffuse, and reflected irradiance components of the plane of array.

The module temperature T_{mod} needed for the power model is estimated using an empirical model [41] that incorporates the ERA5 air temperature and wind speed data:

$$T_{\mathrm{mod}} = T_{\mathrm{amb}} + \frac{G_{\mathrm{POA}}}{U_0 + U_1 \cdot WS_{\mathrm{mod}}} \tag{3}$$

where U_0 and U_1 are heat transfer coefficients, and WS_{mod} is the module-level wind speed.

The study uses the solar power model created by Huld et al. [42] to estimate DC power output, which accounts for both temperature and irradiance effects:

$$P_{\mathrm{DC}} = G'\mathrm{eff} \cdot \eta\mathrm{rel}(G'\mathrm{eff}, T'\mathrm{mod}) \cdot P_{\mathrm{STC}} \tag{4}$$

Furthermore, reflection losses are incorporated into the model using the Martin and Ruiz approach [43].

4.2. NordPool electricity market data

NordPool, founded in 1993, is the primary power market in Europe, facilitating wholesale electricity trade across various European countries. It serves as a trading platform for electricity producers, suppliers, and major consumers in both day-ahead and intraday markets [44].

To assess the impact of additional solar PV power generation in Finland, this study used supply and demand bid data specific to Finland and the price area of Finland, sourced from NordPool for the year 2023 [34]. These bids were used to calculate the area price for Finland. The process of determining the market clearing price based on these bids is detailed in Section 4.3.

4.3. Algorithm for market analysis

This section presents an overview of the algorithm designed to simulate the market clearing processes; the algorithm is commonly used in liberalized electricity markets to study the effects of additional electricity generation on the system. The algorithm is developed in Python with Gurobi as the solver, assuming no cross-border trade. The model takes into account both supply and demand bids, applying necessary constraints to maintain market viability to obtain a market-cleared price as illustrated in Fig. 8. As verification, the original market clearing price was obtained using the proposed methodology and compared with the actual market-cleared price before obtaining a new MCP with the added solar PV power generation.

This study employs NordPool data, analyzing supply and demand bids in the day-ahead market in Finland for 2023 [34]. The day-ahead price is generated using a Security-Constrained Economic Dispatch (SCED) model, which secures supply while minimizing costs. The overall process flow is illustrated in Fig. 9. A more detailed explanation of the modeling can be found in [13].

The objective function for the market clearing process is defined as:

$$\max\left(\sum_{i=1}^{N_d} P_i^d Q_i^d - \sum_{j=1}^{N_s} P_j^s Q_j^s\right) \tag{5}$$

where:

- P_i^d and Q_i^d are the bid price and quantity of the ith demand bid, respectively.
- P_j^s and Q_j^s are the bid price and quantity of the jth supply bid, respectively.
- N_d and N_s are the total number of demand and supply bids, respectively.

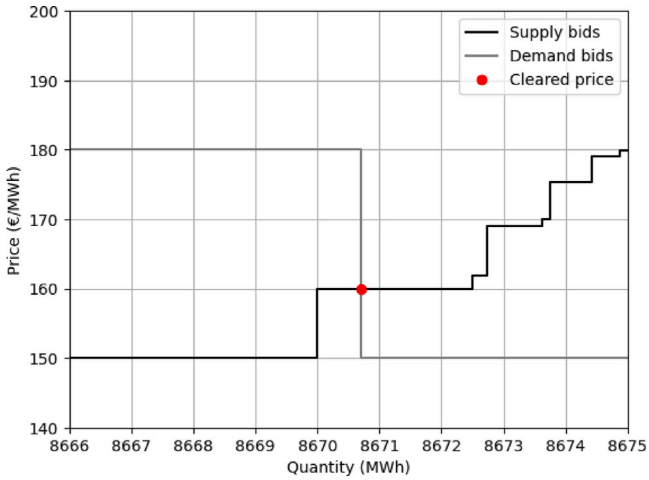


Fig. 8. Illustrative output of the market clearing algorithm and the market clearing price (MCP) for a sample hour in Finland.

The following constraints are applied to the market clearing model:

1. **Supply–Demand Balance:** The sum of the produced electricity should equal the amount of the consumed electricity.
2. **Non-Negativity:** The quantity of supply and demand bids must be positive, but the bids could be negative.
3. **Bid Quantity Limits:** Accepted bids must be within their accepted limits.
4. **Price Limits:** The MCP should be within the minimum (−500 €/MWh) and maximum (4000 €/MWh) limits of the market.

Solar PV power generation, assumed to have negligible operating costs, is introduced into the algorithm at zero marginal cost, and the resulting price changes ΔP are computed.

The algorithm assesses price impacts by simulating solar PV installation at a single location, iterating the process hourly throughout the year, and repeating for 1890 potential locations, of which 1003 fall within the land borders of Finland.

4.4. Other considerations

A 100 MW_p solar farm was chosen due to the convenient installation size and the solar farm being large enough for the peak power to influence the day-ahead markets. A 100 MW_p farm can conveniently be installed and attached to most already existing substations without requiring additional grid-side investments. The installed capacity is the same as in [13] for the case of wind power, which makes the results directly comparable. While the FLH of a solar farm is much lower than that of a wind farm, the peak power remains the same, which is often the factor according to which the transmission capacity is sized.

The present study uses zonal pricing in which a larger area, for example, a large region or a country, has the same electricity price, which is the case in Finland and Europe as a whole. Finland is a single bidding area owing to its strong grid and no significant congestion issues within the country. Another option would be to model the market through locational marginal pricing (LMP, aka nodal pricing), where larger areas are divided into nodes with individual electricity pricing and transmission congestion costs. As there are no congestion considerations and the existing market is already zonal, it is not within the scope of this paper to model the market with LMP.

Congestion charges were not considered due to there being no market mechanism to address congestion. In Finland, which is a single price area, the TSO performs countertrading, where production is shifted from a grid-congested area to a less congested area at the expense of the TSO, leading to reduced congestion. These costs from countertrading are not reflected directly in market pricing [45,46].

In addition, further dividing the current price area into smaller areas or nodes would lead to increased cannibalization rates and price fluctuations on the west coast, further aggravating the current situation. Larger price areas with more varied generation decentralized can reduce price fluctuations; however, this would require a strong transmission network.

Cross-border electricity transmission was not considered in this paper for the following reasons. Firstly, the power generated from a 100 MW_p solar PV farm is considered a marginal addition to the market with an average capacity factor of 10%–25% [47]. Secondly, there have been 0% of hours where the electricity prices in the price area of Finland have been in balance with its neighboring countries [48]. Thus, due to the existence of price differences between zones, the cross-border transmission capacity has already been fully utilized. Therefore, any additional power generation in the market will most likely stay

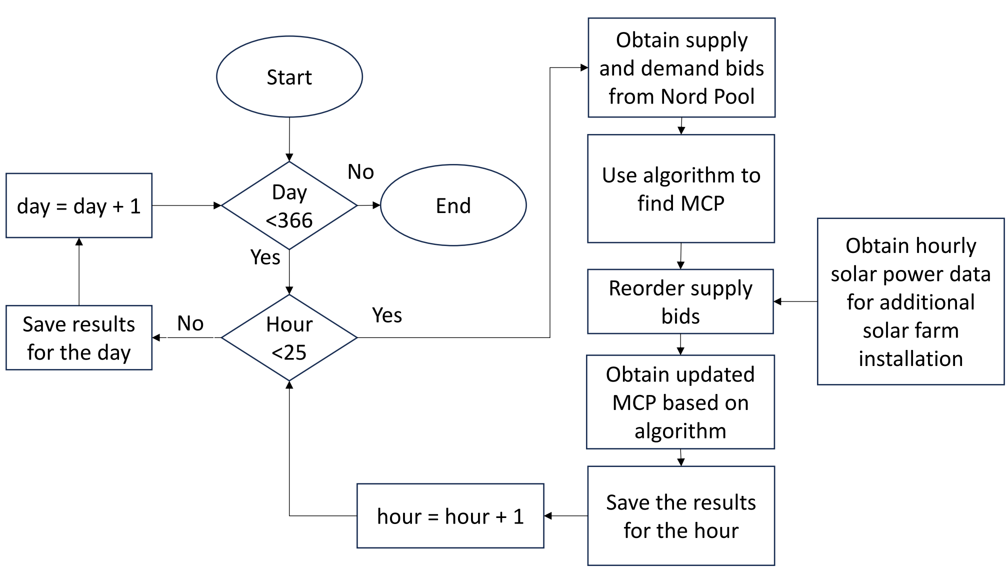


Fig. 9. Flow diagram of the market analysis procedure, where MCP stands for the market clearing price.

in Finland. Finally, on an annual level, Finland is also highly self-sufficient, only importing 3% of final consumed electricity [49]. The inclusion of cross-border trading does not overall influence the result due to the cross-border capacity already being saturated.

As this study is the first to employ spatially explicit methods to assess the market impacts of new solar PV capacity, there are no directly comparable prior works. Nevertheless, the validity of the results is supported by the aforementioned key considerations. Specifically, the marginal increase in power generation capacity compared to system size, the existence of a single price area, the absence of congestion charges, the minimal influence of cross-border transmission on market outcomes, and Finland's high degree of energy self-sufficiency collectively provide strong justification for the robustness of the findings.

5. Results

The results are analyzed in this section with the main focus on societal benefit (Section 5.1), revenue (Section 5.2), and cannibalization (Section 5.3).

5.1. Maximizing electricity cost reduction for society

The societal benefit is defined in this paper as the benefit that all the other participants in the day-ahead market gain through reduced electricity costs from the new generation capacity, which is calculated by multiplying the electricity consumption of the day-ahead market hourly ($E_{con,day-ahead,h}$) by the change in the day-ahead market price before ($P^{BS}_{MCP,h}$) and after ($P^{AS}_{MCP,h}$) the addition of the new solar PV power generation:

$$Societal\ benefit = \sum_{h=1}^{8760} (P^{BS}_{MCP,h} - P^{AS}_{MCP,h}) \cdot E_{con,day-ahead,h} \tag{6}$$

The reduction in electricity costs according to Eq. (6) is depicted in Fig. 10. It can be seen that the greatest reductions in electricity costs can be observed in the southern half of the country.

In the southwest, there is an area where the power generation is seen to have a proportionally smaller effect on the electricity prices than the neighboring areas, despite having better irradiation conditions, as seen in Fig. 6. This could be attributed to the hours of generation taking place at generally more stable periods of time, where the additional generation does not significantly affect the market clearing price. Other southern areas are able to generate power at a more crucial time when a marginal increase in power affects the MCP more. The north does not have a strong ability to influence the market price. The hotspots in the south are scattered and seemingly do not follow a specific trend that could be tied to factors other than climatic. A peculiar transition area is seen on the south coast (24E, 60.5N), where the reduction in electricity cost jumps from a much lower value to the highest of the price area in the west-to-east direction. The area to the west of this transition line experiences the most FLHs in the year, and the hypothesis for a lower cost reduction rate for the whole calendar year is that for much of the year it is the only region that is able to produce a significant amount of power when the electricity prices are high. The solar PV generation from other regions does not overlap with this generation, leading to a lower overall price reduction in the said power generation. Other regions, still in the general south, may only be able to generate solar power at the same time as other installed capacity. This leads to overlapping power generation from multiple sources, resulting in more likely reductions in the electricity price. Still, solar power has a limited ability to influence the electricity price on this scale compared to wind power.

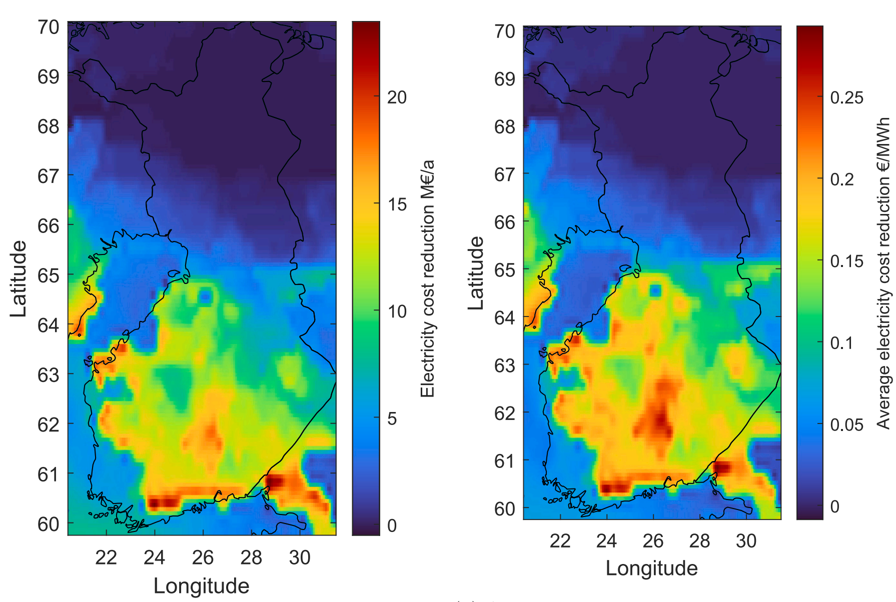
While the overall average reduction in electricity price is small, because the price reduction is applied to all consumers in the day-ahead market with the annual energy consumption of 58 TWh, the reduction in price indicates total cost reductions of several millions of euros, even up to around 18 M€/a, for the market participants.

5.2. Maximizing revenue for investors

The revenue in the day-ahead markets is obtained by multiplying the new MCP ($P_{MCP,h}$) by the amount of electricity produced hourly ($E_{prod,h}$) according to:

$$Revenue = \sum_{h=1}^{8760} P_{MCP,h} \cdot E_{prod,h} \tag{7}$$

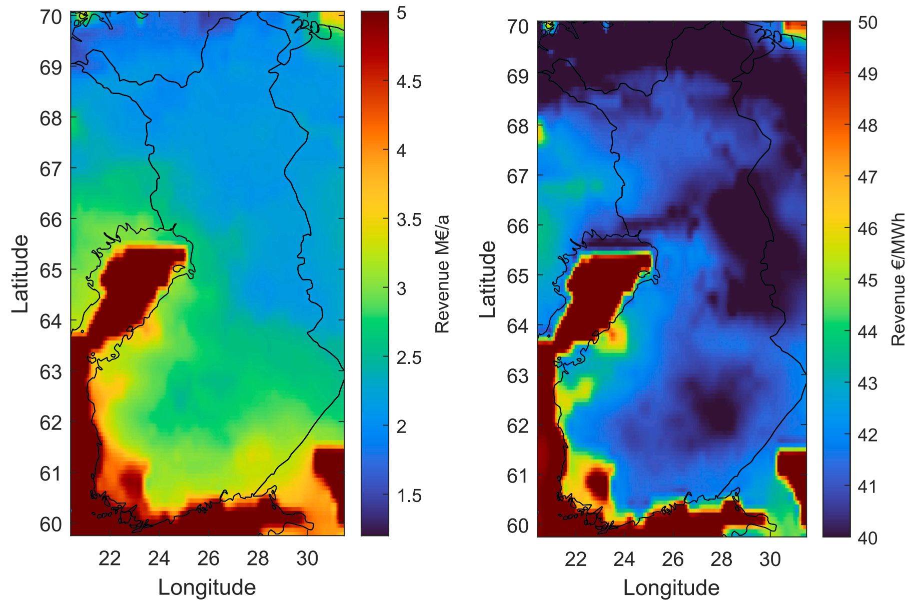
The revenue is mapped in Fig. 11. The areas of highest revenue are the coastal areas in the southwest. The best price for the unit of energy produced over the whole year is also obtained in the southwest. Overall, most of the country can be considered homogeneous in terms



(a) Electricity cost reduction M€/a

(b) Average reduction in electricity cost per unit energy produced €/MWh

Fig. 10. Quantifying societal benefit through reduction in electricity costs in the day-ahead market.



(a) Revenue M€/a (b) Revenue €/MWh

Fig. 11. Comparison of the effects of additional wind power capacity on revenue through cannibalization of electricity market price.

of revenue (€/MWh) with the exception of the southwest. Fig. 11(a) indicates that the southwestern and some of the west coast regions are able to generate solar power during times when day-ahead prices are higher than in the rest of the price area.

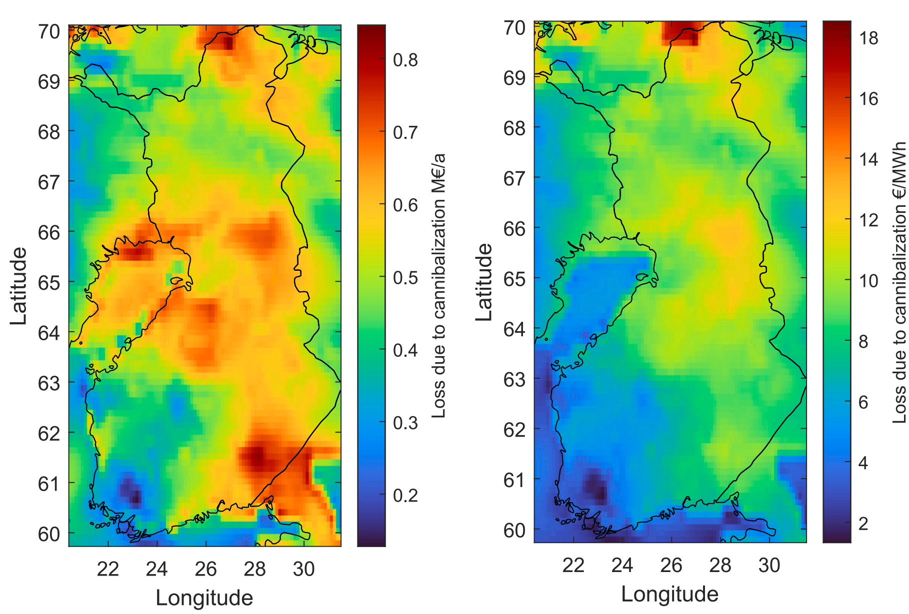
The area of higher revenue in the southwest differs from the areas of the highest benefit observed previously in Section 5.1. This is likely due to the effect of the timing of the generation. If the generation occurs at a time when the market prices are already low in summer and price cannibalization further lowers the market price, it requires significant generation to provide noticeable revenue. If a location is able to produce electricity when market prices are on average much higher in spring and autumn, they may have a better opportunity to produce much higher revenue. A seasonal analysis is performed in Section 5.4.

5.3. *Effect of cannibalization on revenue*

The effect of cannibalization is defined as the sum of the hourly change in the day-ahead market clearing price (MCP) before ($P^{BS}_{MCP,h}$) and after ($P^{AS}_{MCP,h}$) the addition of new solar PV capacity multiplied by the solar production of the said hour ($E_{solar,h}$):

$$Loss\ in\ revenue = -\sum_{h=1}^{8760} E_{solar,h} \cdot (P^{BS}_{MCP,h} - P^{AS}_{MCP,h}) \tag{8}$$

The loss in revenue due to added generation is presented in Fig. 12. A surprising result is that the greatest level of cannibalization is not observed in the southwest, where the solar conditions are the best. It is also the area of the country that is the most densely populated and



(a) Loss of revenue in M€/a (b) Loss of revenue in €/MWh

Fig. 12. Comparison of the effects of additional solar power capacity on revenue through cannibalization of electricity market price.

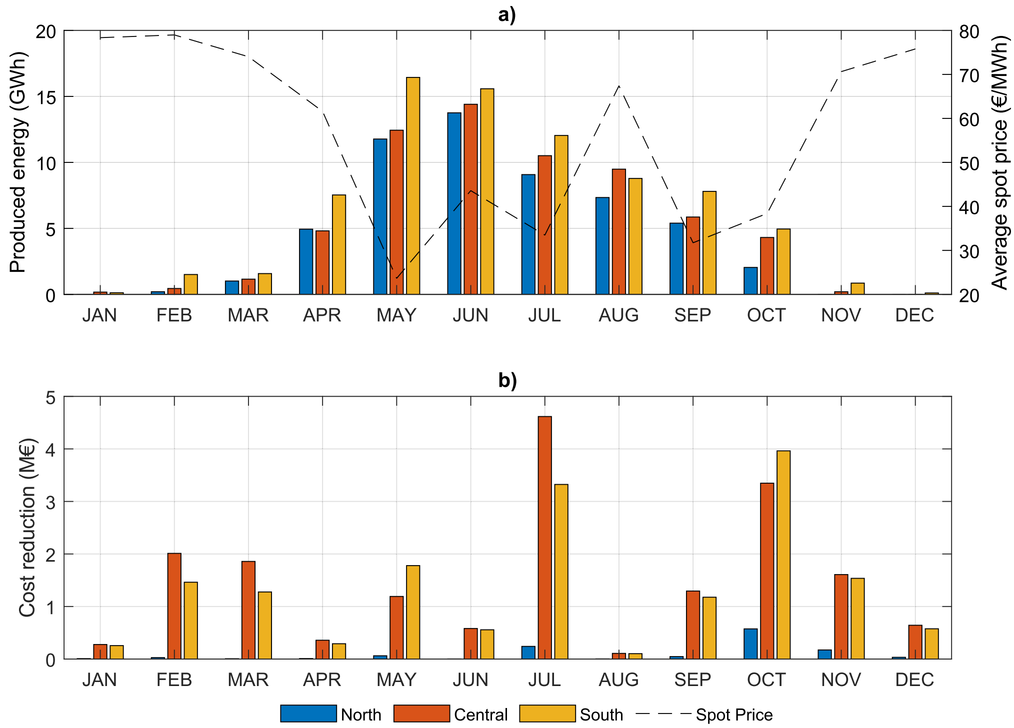


Fig. 13. Monthly price reduction in three sample locations in 2023: northern, central, and southern. The exact locations are seen in Fig. 2. In (a) the total amount of energy generated in 2023 are compared monthly together with the average spot price. In (b) the potential for cost reductions are highlighted.

where most of the rooftop solar should be found. Regional installation figures, however, are not readily available for comparison.

Large-scale solar installations are only now emerging in Finland. There is no clear overlap with the already existing large-scale solar installations displayed in Fig. 2.

The southwest experiences overall the lowest loss due to cannibalization despite having the best sunshine hours. The result is counter-intuitive, as one would expect the sunniest areas to already have the most solar capacity installed, as supported by [27], leading to a more dramatic change in price. There are two main hypotheses to explain this.

First, the solar PV capacity of the area is mostly installed on rooftops, which is seen as a reduction in demand instead of increased regional supply. As seen in Fig. 2, there are no major solar farms installed in the region, which supports this hypothesis.

Second, the rest of the country produces most of its power and energy during summer when sunshine hours are abundant, even at night in the north. With the lower demand for power and much of the country no longer having snow on the panels, the whole price area is able to generate power at once, cannibalizing the final day-ahead price more profoundly. The southwestern area is also the area of Finland with the least snow coverage and usually the first area to clear of snow after a long winter. Thus, it is able to produce solar power for some time decoupled from the generation from the rest of the country, when the electricity prices are higher.

5.4. Seasonal breakdown

Solar irradiation in the Nordic countries is highly seasonal, as shown in Fig. 5. In contrast to the average day-ahead price in Fig. 13a, the northern areas are at a disadvantage, as their power generation window is very narrow during the summer months, when the day-ahead market prices are already low on average. The southwestern areas benefit from much less snow and the ability to generate some power during high day-ahead prices, especially in the springtime.

The hourly effect of the additional solar PV power generation is analyzed in Fig. 14. It is observed that the peak price reductions occur between the hours of 9 a.m. and 1 p.m. Against the original hypothesis, the northern location, despite having irradiation available in the summer months during most hours of the day, does not experi-

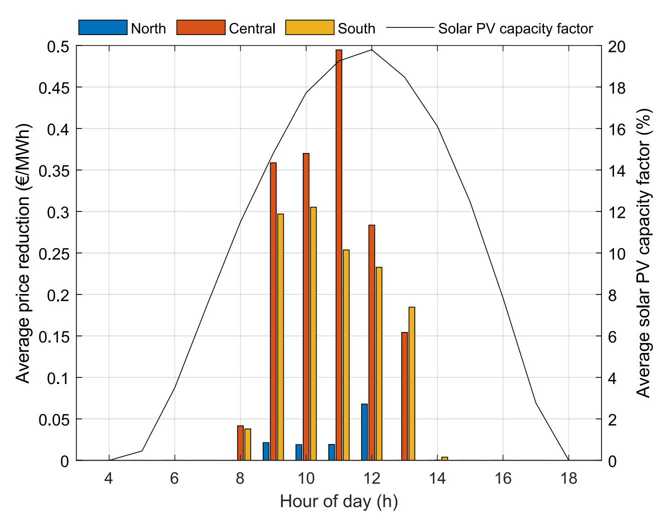


Fig. 14. Hourly average electricity cost over the whole year of 2023 contrasted with the average capacity factors and electricity demand levels. The exact locations are seen in Fig. 2.

ence any price reduction opportunities during what is considered the conventional night period (due to the midnight sun). The benefit of the northern location is low in comparison with the central and southern locations. The peak price reduction is observed at hours 10–11. In winter, when the electricity price is highest, the demand profile is dominated by electrical heating in the form of heat pumps. The demand profile is strongly correlated with outside temperatures and thus may not be cyclical in nature, unlike other significant loads in a household.

The southern and central parts have a much better opportunity to influence the day-ahead market prices than the north. In Fig. 15, the areas that have no opportunity to influence the market prices even for a single hour in the whole year are shown in black. Installations further north have a lower influence from the additional generation due to lower FLHs in the year, and the production aligning almost exclusively to the summer months when the electricity prices are lower.

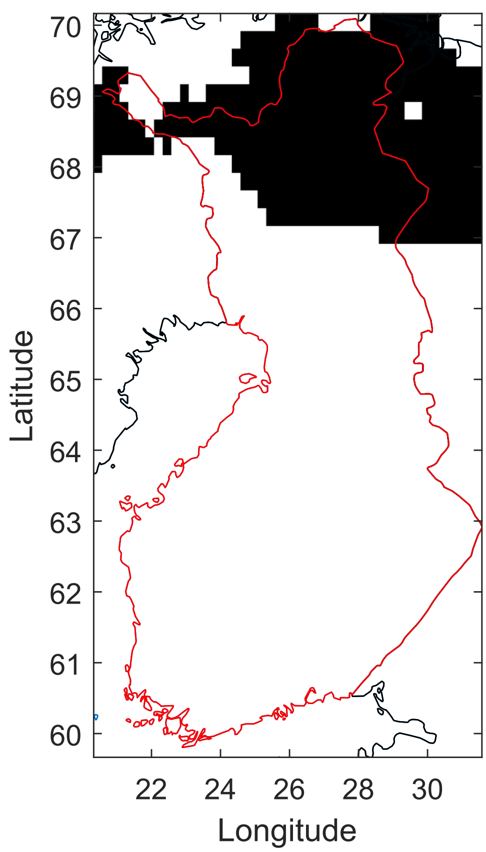


Fig. 15. Areas colored in black where the solar PV generation does not have any effect on market prices in 2023. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5.5. *Effect of snow and annual variability*

Weather conditions vary between years, and thus, the results also vary. Cloud coverage, snow on solar panels, and wind power availability all affect the outcomes of this paper [50].

When considering the day-ahead markets, the solar PV generation can have a great impact in the spring period. In Finland in the springtime, the thick, dense layers of snow take a significant amount of time to melt. The snow can improve power generation by increasing reflections while effectively cooling panels, leading to overclocked power generation, often above the rated capacities, of the panels at a time of year when the electricity demand is still relatively high. Snow or the lack of it can have a significant influence on the generation. The annual variations at a sample location in central Finland are illustrated in Fig. 16.

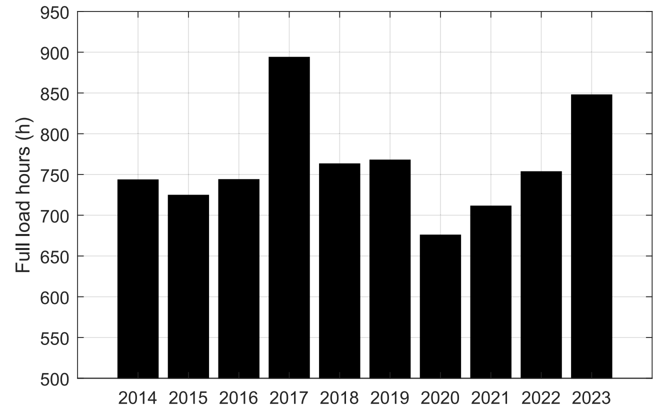


Fig. 16. Example of annual variance of solar PV power generation for a sample location in central Finland. Snow, clouds, and latitude will inevitably influence the full load hours, and thus, the values may vary greatly depending on the selection of location.

6. Discussion

The installed solar PV capacity can take many forms, either as rooftop solar installations or larger commercial sites. Due to the resolution of the data, the end result can be a mix. In this model, south-facing solar PV with a 45-degree tilt angle was used. The solar PV power generation profile can be affected in many ways, for example, through changing the azimuth angle to capture more irradiation in the morning hours by facing the panel east or alternatively west to cover more of the evening demand, as highlighted in [16]. The panel angle also has an effect on the seasonal effectiveness. A steeper panel angle is more beneficial in winter, with the additional benefit of the panel being able to better release snow from the panel. In addition, even in summer, the panel tilt angle is relatively high, around 60°, due to the installation latitude. Solar PV in Finland is overall still in a very minor role compared to wind power. As a result, the role of solar PV has been to maximize electricity generation. Thus, a south-facing farm was selected.

Having 100 MW_p of purely south-facing panels can realistically be achieved only from planned industrial sites. From an energy system perspective, having the capacity installed on rooftops behind loads and with varying orientation would benefit the grid the most, as a proportion of the generated power is first consumed at the site of generation, and due to the scattered orientation of the panels, the peak generation power is lower than if the panels were all facing south. It is common for sites to also employ east–west-facing panels; however, in the northern latitudes, this is not as feasible as the sun tracks low in the sky, and much of the radiation potential would be lost. This is more common and more beneficial closer to the equator.

The results are fascinating. From the perspective of an investor, the areas with the highest solar PV potential are the areas that provide the highest level of revenue. Counterintuitively, these areas also are the areas that lead to least price cannibalization of revenue, which further supports investments in the area. The southwest is also close to load centers, which frees capacity on the main north–south transmission lines. From the societal perspective, the areas that would bring most benefit to the whole price area are scattered generally in the south of Finland with no clear pattern with some marginally better areas. There is generally a very low overlap with the areas that would bring most revenue to an investor and the areas that affect the electricity price for the rest of the consumers in the day-ahead markets. This means that in order to attract investments in the areas that would contribute to higher cost reductions, other incentives would be required, such as lower grid connection costs due to the already existing infrastructure with available connection and transmission capacity.

6.1. Solar PV as a supporter of wind power

While solar PV alone does not seem to have a significant effect on the day-ahead market, it should not be ignored. Due to the complementary nature of solar power, it should be installed alongside wind power to make use of the already existing infrastructure, thereby reducing investment costs [51]. A more geographically dispersed generation capacity provides the best support for the day-ahead market and its customers. As the penetration of renewable power increases in the energy share, there is not only a higher need to balance power, but also energy.

One of the motives for rooftop solar PV is to reduce distribution costs. The ability to produce your own power cuts a significant proportion of the total cost of energy for a regular consumer. This can be an effective cost reduction in the range of 40 €/MWh [52] while excluding related taxes, in addition to omitting the cost of the energy itself.

A benefit of solar PV over wind power is that smaller units can be dispersed across larger geographical areas on rooftops. However, with larger installations around larger population centers, as in the southwest, it can become problematic with time. As large-scale renewable sources of power require significant investments in the common grid infrastructure, in the future, it is likely that while the energy cost components remain low, the distribution cost component will increase.

Solar power can benefit from installations in the eastern parts of Finland, as there are available grid connection spots not taken by wind power. Already built areas should be prioritized, such as rooftops, fields, and out-of-use peat harvesting areas. This reduces the ecological footprint of a new solar PV farm installation. Currently, the cannibalization rates are not significant in comparison with wind power; however, areas that would benefit society can be observed. The greatest benefit, still, is the reduction in distribution costs if the solar capacity is installed behind a load where the distribution grid is not used.

6.2. Limitations

The current day-ahead market analysis does not consider changes in cross-border trade for two reasons. Firstly, the self-consumption rate of energy in Finland is high, with only 3% of all electricity being imported in 2024 [53]. Secondly, the change in electricity supply, due to the added solar PV capacity, is relatively marginal in nature compared to the power system size. As a result, the uncertainty in the model is low, especially when considering the capacity factor of solar power.

In this paper, only one solar panel configuration was considered: 45° south-facing. This was done to isolate the effect of geographical dispersion on solar PV production and its impact on the day-ahead market.

Finally, the proximity to existing grid connection points was not considered in this study. In turn, the investment costs required to utilize existing connection points or build new ones were also not included in the present analysis.

6.3. Future work

Based on the aforementioned limitations, there is potential for studying the effect of locally optimizing panel tilt and azimuth against the day-ahead electricity market. Further study is also planned to estimate grid connection costs throughout the country. Especially in the north, distances to the nearest grid connection points can be long with significant impacts on total investment costs. Additionally, the inclusion of geographical obstacles at higher resolution is required.

Moreover, the impact of BESS and trading algorithms on the financial viability of renewable power capacity additions in areas with high cannibalization rates can be investigated. These areas are often characterized by their proximity to existing grid connections. In addition, analysis of hybrid power plants combining wind and solar power generation capacity behind common grid infrastructure is planned.

7. Conclusion

This study evaluated the day-ahead market effects of a new 100 MW_p solar PV farm in different geographical locations within the single price area of Finland. This was performed by the manipulation of bid curves from NordPool. Revenue, cannibalization, and societal benefit were calculated, which provide insights into the most optimal sites to build new solar PV farms.

The level of revenue ranges between 40–48 €/MWh across Finland. From the consumer perspective, energy cost savings of up to 18 M€/a (equivalent to 0.25 €/MWh) were observed. The low price reductions can be attributed to the bulk of the generation occurring during summer months. These months are characterized by significantly lower demand compared with winter months, leading to relatively lower electricity prices which, in turn, dampen cost savings from additional solar PV capacities. From the supplier perspective, the same phenomenon results in high cannibalization rates of up to 13 €/MWh.

Regional differences are highlighted at both annual and seasonal levels. The south has greater potential to influence day-ahead market prices and also provide higher revenue due to higher energy yield. The highest cannibalization rates were observed in inland locations, which do not have much opportunity to generate electricity in the winter months due to low irradiation levels and snow coverage.

The area with the highest energy yield also experienced the lowest cannibalization rates over the whole year. In addition, it was observed that solar power generation was best able to reduce electricity prices during hours between 8–13.

While large-scale solar PV installations support the day-ahead market, the most significant savings come from prosumer solar installations partially mitigating distribution costs, which can be higher than the electricity price from the day-ahead market. To maximize welfare and energy savings, solar installations of any size should primarily be installed behind loads, and any surplus power should be sold within the technical limits of the grid connection and the power system. Due to the Finnish climate conditions, solar power plays only a supporting role, increasing self-sufficiency, while wind power is used to supply the bulk of renewable energy to households and industry year round.

CRediT authorship contribution statement

Markus Salmelin: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Araavind Sridhar:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Nashmin Hosseinpour:** Writing – original draft, Methodology, Data curation. **Samuli Honkapuro:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Jukka Lassila:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Large Language Models (LLMs) in order to improve readability and language of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare to have no known competing interests. Funding sources for the research are listed in the Acknowledgements.

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Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request. However, the market data used in this study were obtained from NordPool and are subject to licensing agreements. As such, these data cannot be shared publicly, however, can be obtained from [34].

References

[1] European Commission, REPowerEU: A plan to rapidly reduce dependence on russian fossil fuels and fast-forward the green transition, 2022, https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131, (Accessed 18 May 2022).
[2] UNFCCC, The Paris agreement, International treaty on climate change, 2015.
[3] State Treasury Republic of Finland, Carbon neutral finland 2035, 2024, https://www.treasuryfinland.fi/investor-relations/sustainability-and-finnish-government-bonds/carbon-neutral-finland-2035/, (Accessed 11 November 2024).
[4] H. Holttinen, Hourly wind power variations in the Nordic countries, Wind. Energy: An Int. J. Prog. Appl. Wind. Power Convers. Technol. 8 (2) (2005) 173–195.
[5] J. Mursu, Itä-Suomen Tuulivoima Energiajärjestelmässä, LUT-University, 2023, In Finnish. https://urn.fi/URN:NBN:fi-fe2023052447444.
[6] Nordpool, Day ahead prices, 2024, https://www.nordpoolgroup.com/en/market-data12/Dayahead/Area-Prices/FI/Hourly/?view=table, (Accessed 21 August 2024).
[7] Energy Authority, National report on the state electricity and gas markets in finland to the European Union agency for the cooperation of energy regulators and to the European Commission year, 2025, https://energiavirasto.fi/documents/11120570/13026619/National+Report+on+electrcity+and+gas+markets+in+2023+in+Finland.pdf/64cf6db3-0995-bdd1-21d6-795daf7df53e/National+Report+on+electrcity+and+gas+markets+in+2023+in+Finland.pdf?t=1720680024410, (Accessed 14 April 2025).
[8] J.L. Prol, K.W. Steininger, D. Zilberman, The cannibalization effect of wind and solar in the California wholesale electricity market, Energy Econ. 85 (2020) 104552.
[9] G. Glenk, S. Reichelstein, The economic dynamics of competing power generation sources, Renew. Sustain. Energy Rev. 168 (2022) 112758.
[10] M. Liebensteiner, F. Naumann, Can carbon pricing counteract renewable energies' cannibalization problem? Energy Econ. 115 (2022) 106345.
[11] J.L. Prol, D. Zilberman, No alarms and no surprises: Dynamics of renewable energy curtailment in California, Energy Econ. 126 (2023) 106974.
[12] P. Kozlovas, S. Gudzius, A. Jonaitis, I. Konstantinaviciute, V. Bobinaite, S. Gudziute, G. Giedraitis, Price cannibalization effect on long-term electricity prices and profitability of renewables in the baltic states, Sustain. 16 (15) (2024) 6562.
[13] M. Salmelin, A. Sridhar, H. Karjunen, S. Honkapuro, J. Lassila, Optimizing wind farm locations for revenue and reduced electricity costs in deregulated electricity markets, 2025, http://dx.doi.org/10.2139/ssrn.5234276, submitted for publication. Available at SSRN as preprint.
[14] B.A. Ajanaku, A.R. Collins, Does it matter when the wind blows? Differential impacts of wind generation on the pjm wholesale electricity market, Electr. J. 36 (6) (2023) 107303.
[15] L. Reichenberg, T. Ekholm, T. Boomsma, Revenue and risk of variable renewable electricity investment: The cannibalization effect under high market penetration, Energy 284 (2023) 128419.
[16] N. Riaz, S. Repo, Comparative analysis of revenue generation from different photovoltaic panel orientations in wholesale electricity markets, in: 2024 20th International Conference on the European Energy Market, EEM, IEEE, 2024, pp. 1–7.
[17] L. Szabo, M. Moner-Girona, A. Jäger-Waldau, I. Kougias, A. Mezosi, F. Fahl, S. Szabo, Impacts of large-scale deployment of vertical bifacial photovoltaics on European electricity market dynamics, Nat. Commun. 15 (1) (2024) 6681.
[18] GridX, Net metering, 2025, https://www.gridx.ai/knowledge/what-is-net-metering-in-the-netherlands-salderingsregeling, (Accessed 2 February 2025).
[19] PV Magazine, Netherlands posts more negative energy prices, 2024, https://www.pv-magazine.com/2024/08/16/netherlands-posts-more-negative-energy-prices/, (Accessed 18 November 2024).
[20] DutchNews, Zeeland home owners are being paid to turn off solar panels, 2024, https://www.dutchnews.nl/2024/08/zeeland-home-owners-are-being-paid-to-turn-off-solar-panels/, (Accessed 18 November 2024).
[21] Balkan Green Energy News, Dutch prosumers must pay fees to feed surplus electricity to grid, 2024, https://balkangreenenergynews.com/dutch-prosumers-must-pay-fees-to-feed-surplus-electricity-to-grid/, (Accessed 18 November 2024).
[22] PV Magazine, Netherlands approves grid fees for rooftop pv system owners, 2024, https://www.pv-magazine.com/2024/05/10/netherlands-approves-grid-fees-for-rooftop-pv-system-owners/, (Accessed 18 November 2024).
[23] S. Johanndeiter, V. Bertsch, Bidding zero? an analysis of solar power plants' price bids in the electricity day-ahead market, Appl. Energy 371 (2024) 123672.
[24] Finnish Wind Power Association, Operating and dismantled wind turbines, 2024, https://tuulivoimayhdistys.fi/en/wind-power-in-finland/wind-power-in-production-and-dismantled, (Accessed 21 August 2024).
[25] Finnish Defence Forces, Guidelines for observing the defence forces' activities in wind power building, 2024, https://puolustusvoimat.fi/en/wind-farm-consultation-process, (Accessed 21 August 2024).
[26] Forus, Konnunsuo solar park, 2024, In Finnish, https://www.forus.fi/fi/konnunsuo/, (Accessed 11 November 2024).
[27] Energy Authority of Finland, Technical indicators of electricity grid operation 2022, 2024, In Finnish, https://energiavirasto.fi/verkkotoiminnan-julkaisut, (Accessed 13 November 2024).
[28] Yle, Suomeen nousee aurinkopaneelipeltoja sellaista vauhtia, että asiantuntija nostaa esille jo uhkia, 2024, In Finnish, https://yle.fi/a/74-20021701, (Accessed 15 November 2024).
[29] Motiva, energiavirasto, aurinkosähkövoimalat, 2024, In Finnish, https://aurinkosahkovoimalat.fi/?plantStatus=19%29, (Accessed 11 November 2024).
[30] Fingrid, Sähkön tuotannon ja kulutuksen kehitysnäkymät, 2024, In Finnish, https://www.fingrid.fi/globalassets/dokumentit/fi/tiedotteet/ajankohtaista/sahkon-tuotannon-ja-kulutuksen-kehitysnakymat-q3-2024-fingrid.pdf, (Accessed 15 November 2024).
[31] Fingrid, The adequacy of electricity in the coming winter looks good, 2024, In Finnish, https://www.fingrid.fi/en/news/news/2023/the-adequacy-of-electricity-in-the-coming-winter-looks-good/, (Accessed 15 November 2024).
[32] E. Inkeri, H. Enayatizadeh, J. Hyypiä, T. Tynjälä, H. Karjunen, N. Hosseinpour, Uncertainty analysis for power-to-methanol plant regarding economic and flexibility parameters, in: International Renewable Energy Storage and Systems Conference, IRES 2023, Atlantis Press, 2024, pp. 72–85.
[33] V. Eloranta, E. Inkeri, M. Ropo, V. Sihvonen, A. Jaatinen-Värri, M. Luoranen, M. Salmelin, N. Hosseinpour, A. Grönman, Probabilistic optimization of a Nordic smart local energy system: Cost and emission insights from 2020 to 2023, IET Gener. Transm. Distrib. 19 (1) (2025) e70037.
[34] NordPool, Aggregated day-ahead bidding curves, 2025, https://www.nordpoolgroup.com/en/services/power-market-data-services/aggregatedbiddingcurves/, (Accessed 8 January 2025).
[35] H. Hersbach, B. Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers, et al., The era5 global reanalysis, Q. J. R. Meteorol. Soc. 146 (730) (2020) 1999–2049.
[36] J.S. Stein, W.F. Holmgren, J. Forbess, C.W. Hansen, Pvlib: Open source photovoltaic performance modeling functions for matlab and python, in: 2016 IEEE 43rd Photovoltaic Specialists Conference, PVSC, IEEE, 2016, pp. 3425–3430.
[37] J. Hay, J. Davies, Calculations of the Solar Radiation Incident on an Inclined Surface 1980: Proceedings of First Canadian Solar Radiation Data Workshop, Vol. 5972, Canadian Atmospheric Environment Service, Canada.
[38] T.M. Klucher, Evaluation of models to predict insolation on tilted surfaces, Sol. Energy 23 (2) (1979) 111–114.
[39] B.Y. Liu, R.C. Jordan, The long-term average performance of flat-plate solar-energy collectors: with design data for the US, Its outlying possessions and Canada, Sol. Energy 7 (2) (1963) 53–74.
[40] J.A. Duffie, W.A. Beckman, Solar Engineering of Thermal Processes, Wiley New York, 1980.
[41] D. Faiman, Assessing the outdoor operating temperature of photovoltaic modules, Prog. Photovolt., Res. Appl. 16 (4) (2008) 307–315.
[42] T. Huld, G. Friesen, A. Skoczek, R.P. Kenny, T. Sample, M. Field, E.D. Dunlop, A power-rating model for crystalline silicon pv modules, Sol. Energy Mater. Sol. Cells 95 (12) (2011) 3359–3369.
[43] N. Martin, J. Ruiz, Calculation of the pv modules angular losses under field conditions by means of an analytical model, Sol. Energy Mater. Sol. Cells 70 (1) (2001) 25–38.
[44] Nord pool overview, 2024, https://www.nordpoolgroup.com, (Accessed 14 September 2024).
[45] Fingrid, Countertrade, 2025, https://www.fingrid.fi/en/electricity-market/market-integration/tilastoja-sahkomarkkinoiden-yhtenaisyydesta/countertrade/, (Accessed 4 June 2025).
[46] European Union Agency for the Cooperation of Energy Regulators, Redispatching and countertrading, 2025, https://www.acer.europa.eu/electricity/market-rules/capacity-allocation-and-congestion-management/redispatching-and-countertrading, (Accessed 4 June 2025).

[47] L. Moraes, C. Bussar, P. Stoecker, K. Jacqué, M. Chang, D. Sauer, Comparison of long-term wind and photovoltaic power capacity factor datasets with open-license, Appl. Energy 225 (2018) 209–220, http://dx.doi.org/10.1016/j.apenergy.2018.04.109, URL https://linkinghub.elsevier.com/retrieve/pii/S0306261918306767.

[48] Fingrid, Matching of bid areas, 2025, In Finnish, https://www.fingrid.fi/sahkomarkkinat/markkinoiden-yhtenaisyys/tilastoja-sahkomarkkinoiden-yhtenaisyydesta/tarjousalueiden-yhtenaisyys/#2022, (Accessed 4 June 2025).

[49] Statistics Finland, Supplies and total consumption of electricity, 1960–2024, 2024, https://pxdata.stat.fi/PxWeb/pxweb/en/StatFin/StatFin__ehk/statfin_ehk_pxt_12sv.px, (Accessed 19June 2025).

[50] Finnish Meteorological Institute, Snow statistics, permanent snow layer dates, 2024, In Finnish, https://www.ilmatieteenlaitos.fi/lumitilastot, (Accessed 13 November 2024) aetag=
.

[51] N. Ghorbani, M. Salmelin, J. Haakana, O. Räisänen, N. Nortamo, N. Hosseinpour, D. Bogdanov, J. Haapaniemi, J. Lassila, Assessing the financial viability of pv integration and grid expansion for wind farms, 2024, Manuscript submitted for publication.

[52] Helen Electricity Network, Distribution prices and terms of contract, 2025, https://www.helensahkoverkko.fi/en/contact-information/customer-service/distribution-prices, (Accessed 17 April 2025).

[53] Statistics Finland, Energy supply and consumption, 2025, https://pxdata.stat.fi/PxWeb/pxweb/en/StatFin/StatFin__ehk/statfin_ehk_pxt_12vp.px/table/tableViewLayout1/, (Accessed 17 April 2025).