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Research article

Renewable energy analysis for 2023 and estimate for 2030 in Finland

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Abstract: In this study, we examined Finland's renewable energy landscape in 2023 and provided an extrapolated estimate for 2030 using hourly data and capacity projections. The method applied 2023 hourly capacity factors to 2030 installed capacity and consumption estimates provided by Fingrid to simulate future production and consumption patterns. In 2023, wind and solar power comprised 19% of electricity production but were projected to supply over 50% by 2030. However, due to the intermittency of these sources, the model estimated that Finland will remain electricity-negative for 61% of the hours in 2030, with an annual deficit of 10 TWh. Electricity price data from Nord Pool was also analyzed, showing a modest inverse correlation between wind production and market price. The analysis revealed significant seasonal variability, with winter deficits and summer surpluses closely associated with wind availability. Nuclear and hydropower remain critical for baseload and grid balancing, whereas storage technologies and flexible demand are necessary to close the gap. We conclude that under the current development trajectories, Finland is unlikely to achieve full electricity self-sufficiency by 2030 and will continue to rely on imports during low-production periods. These findings highlight the importance of diversifying renewable generation, improving capacity factors, and investing in energy storage to support Finland's 2035 carbon neutrality target.

Keywords: renewable energy; wind power; solar energy; energy transition; Finland; capacity factor

1. Introduction

The global shift toward renewable energy sources has become a central strategy for addressing climate change, ensuring energy security, and fostering economic resilience [1]. Finland demonstrates this transition with its ambitious goal of achieving carbon neutrality by 2035 [2]. To achieve this target, Finland must continue decarbonizing its electricity sector while electrifying other sectors, such as transport, heating, and industry. This will require a substantial increase in renewable electricity generation, particularly wind and solar power, alongside the deployment of energy storage solutions and hydrogen technologies. Maintaining a low emission factor while meeting rising electricity demand is critical to ensure that sector coupling contributes positively to the overall carbon neutrality goal [3].

The transition is essential not only for reducing carbon emissions but also for enhancing energy independence and economic stability [4]. By utilizing advancements in renewable energy technologies and integrating innovative solutions, Finland aims to optimize energy efficiency and grid reliability [2]. The shift toward renewables also aligns with broader European climate goals, reinforcing Finland's commitment to a sustainable and resilient energy system [5].

The Finnish government has laid a robust foundation for the green transition by prioritizing renewable energy investments, phasing out fossil fuels, and implementing progressive energy policies, such as the Carbon Neutral Finland 2035 strategy [2]. With abundant natural resources, Finland has rapidly adopted wind, solar, hydro, and nuclear power while striving for a balanced energy mix to meet growing demands and sustainability targets [6].

While numerous national and international reports provide projections for renewable energy development, few studies offer high-resolution data-driven analyses that compare real-world hourly production and consumption patterns with forward-looking estimates. The literature often relies on average capacity factors or aggregated annual values, which obscure the temporal variability and operational challenges associated with intermittent renewable sources such as wind and solar [7,8]. Furthermore, country-level analyses rarely combine historical hourly data with future capacity projections to estimate the temporal distribution of electricity surpluses and deficits.

In the Finnish context, although policy targets are well documented [2,9–11], there remains a lack of research that critically examines whether the projected capabilities, particularly for wind and solar, translate into reliable energy supply patterns across different seasons. This gap is particularly significant given Finland's climatic conditions, with high heating demands in winter and relatively low solar potential. By using actual hourly capacity factor data from 2023 and extrapolating it to 2030 scenarios, this study fills a methodological and analytical void in the renewable energy literature. It provides not only an estimate of future production but also a dynamic picture of when deficits are likely to occur, thereby highlighting the operational constraints that must be addressed to ensure energy reliability and autonomy in the coming decades.

We aim to provide a high-resolution analysis of Finland's electricity system in 2023 and estimate the system's balance and sustainability by 2030. By combining hourly production and consumption data with capacity projections, we evaluated the characteristics of various energy sources, the distribution of electricity surplus and deficit, and the impact of intermittency on system reliability. The goal was to assess whether the current development trajectories are sufficient to achieve

Finland's 2035 carbon neutrality target and to identify the structural and technological changes required to reach electricity self-sufficiency.

Using a quantitative approach, we synthesized historical data, extrapolative methods, and literature reviews to offer insights into Finland's energy evolution. We also highlighted the nation's challenges and opportunities in moving toward an energy mix increasingly dominated by renewable energy.

With our findings we aimed to provide a comprehensive overview of Finland's renewable energy trajectory by examining its production capabilities, consumption patterns, regulatory impacts, and technological advancements. Moreover, by juxtaposing the 2023 data with the 2030 projections, we identified critical pathways to achieve energy sustainability and independence while addressing potential gaps in the strategies.

2. Research background

2.1. Green transition and renewable energy

Unsustainable energy and land use, including over a century of heavy fossil fuel burning, have led to a 1.1 °C increase in temperature over the last 150 years. Current estimates show that we may reach a rise of 2 °C by the end of this century. Moreover, limiting the human effect on Earth requires net-zero CO_2 emissions [12]. The use of renewable energy is pivotal for achieving carbon neutrality, and nuclear and renewable energy sources have been shown to reduce environmental degradation when used together in a balanced energy mix [13]. Estimates show that by 2025, renewables will surpass coal as the number one source of electricity globally. Solar PV is estimated to surpass coal by 2027, becoming the single largest source of electricity [14].

European cities have shown great commitment to the green transition policies set by the EU, with Finland ranking 2nd in adapting green policies and strategies in cities [15]. In addition to mitigating climate change, green transition policies could also contribute to short- and long-term economic growth and job creation [16]. Economic growth, financial development, and income inequality have been found to consistently increase renewable energy consumption [17].

Another driver of green transition and green investments is the major impact of the COVID-19 pandemic and the Russia-Ukraine War [18].

The large-scale implementation of renewable energy production methods also involves challenges. Wind and solar power are intermittent by nature, with the highest wind power intermittency in winter [19,20]. The intermittent nature of renewable energy sources requires flexibility in the energy consumption sector [8]. The intermittency challenges can also be addressed with energy storage solutions, some of which are fully mature while others are in early development, such as fuel cell technologies [21].

The increase in renewable energy poses some challenges to the energy grid, with challenges in maintaining grid frequency and concerns about grid capacity [22]. The green transition also poses some social challenges, with concerns about safety, pollution, and the visual impact of new technologies [23].

2.2. *Policy and regulatory framework for renewable energy*

2.2.1. Europe

The European Union has implemented multiple green energy policies and directives to achieve a sustainable energy transition and combat climate change. The policies relevant to renewable energy and green hydrogen are as follows: The European Green Deal aims to make Europe the first climate-neutral continent by 2050. The "Fit for 55" package in the European Green Deal aims to reduce greenhouse emissions by 55% by 2030 compared to 1990 levels [5].

The Energy Efficiency Directive (EED) aims to reduce energy consumption by improving energy efficiency across the European Union [24]. The emission trading system and effort-sharing regulation aim to reduce greenhouse gas emissions from multiple sources, such as manufacturing industries, the power sector, and heating of buildings [25,26]. The Just Transition Mechanism (JTM) is a tool established to ensure a fair transition to a climate-neutral economy. Its purpose is to alleviate the socioeconomic impact of the transition, especially in the most affected regions. It focuses on addressing the regions, industries, and workers who would face the greatest challenges through three pillars, totaling up to €55 billion over the period 2021–2027 [27].

Perhaps the most important policy regarding renewable energy is the Renewable Energy Directive (RED, revised as RED II in 2018 and RED III in 2023), which aims to promote the share of renewable energy in all sectors of the EU. RED II set a renewable energy target of 32% for 2030, which was increased to 42.5% with the introduction of RED III. RED III also introduced goals for biofuels and Renewable Fuels of Non-Biologic Origin (RFNBOs), for which the combined share needs to be 5.5% of the energy supplied to the transport sector in 2030, of which the share of RFNBOs needs to be 1% [28].

2.2.2. Finland

Additionally, in line with the directions and strategies set by the EU, Finland has set additional national goals, strategies, and laws to combat climate change. Carbon Neutral Finland is a government program that aims for a carbon-neutral Finland by 2035, followed by carbon negativity [2]. For reference, the emission factor for electricity production in Finland in 2023 was 38 gCO_2/kWh [29]. The goal is to reduce carbon emissions by 95% by 2050, compared to 1990 levels. This is achieved by phasing out fossil fuels and increasing renewable electricity sources, promoting non-combustion-based heating, enhancing system integration, and developing a national hydrogen strategy, including increasing electrolysis capacity to 1000 MW by 2030 [2]. The roadmap to fossil-free transport requires the emissions of the transport sector to be halved in 2030, compared to 2005 levels. By 2050, the transport sector should be entirely fossil-free. The strategy includes three phases, by which the government aims to promote carbon-neutral transport. These phases introduce subsidies, incentives, and requirements to increase the use of biogas, e-fuels, electric vehicles, and other low-carbon modes of transport [11]. Additionally, EU directives and strategies must be implemented at the national level.

2.2.3. History of renewable energy in Finland

The first hydroelectric power plant in Finland was the Keskiputous power plant, built in Tampere in 1891 [30], and the newest is the Kuhankoski power plant, built in 2023 [31]. Due to environmental and nature conservation reasons, it is unlikely that new hydropower plants will be built in Finland [32].

The first wind turbine in Finland was a 300 kW test facility built in Inkoo by Imatran Voima in 1986 [33]. Wind power capacity has been increasing since, with the number of turbines, capacity factor, and turbine height increasing steadily [34].

Similarly, the first solar power plant in Finland was a test facility built in Inkoo by Imatran Voima in 1989 [35]. Similar to wind power, solar power production capacity has greatly increased, especially in the 2020s. For example, in 2022, the solar power production capacity doubled [36].

Wood burning has also been a central energy source for decades [37]. In 2000, peat was decided to be considered a non-renewable energy source [38].

From 2011 to 2017, the Finnish government implemented a feed-in tariff system for new wind power installations, guaranteeing a minimum price of €83.50 per MWh. The guarantee was valid for 12 years from the commissioning of the wind turbines [39]. After the termination of the system, multiple wind farms have been built, and further developments continue, indicating that wind power remains a lucrative and profitable investment, even without government support.

2.3. Capacity factor of renewable energy methods

Capacity factor is a metric used to represent the average energy output of a power generation system in relation to its maximum potential power-generating capacity. Capacity factor can be used for any power generation method; however, this study focuses on the capacity factors of renewable energy power generation methods, specifically wind and solar energy. The capacity factor can be measured at the level of a single generator unit, power generation park, or geographical area, as well as for any chosen period.

The capacity factor of a wind turbine is dependent on its geographical location, with offshore generators commonly having higher capacity factors than onshore generators [40,41]. For wind power, 35% is used as a common value among decision-makers; however, in reality, the capacity factors may be much lower [7].

Over the years, improvements in wind power turbine technology have increased the average capacity factors of wind turbines. This has been achieved by lengthening the turbine blades and implementing blade pitch control. These features enable wind turbines to operate at a higher rate at lower wind speeds [42].

Kalmikov [43] states that 30% is a typical value for an economically viable wind turbine, while the regions with the best wind resources can reach numbers up to 50%. Boccard [7] states that in a literature review of 26 studies, the capacity factors averaged a rather high 37%. In their own research, they measured an average capacity factor of 21% in European countries in 2009.

The capacity factor of a photovoltaic power plant is highly susceptible to geographical factors, seasonal changes, and weather fluctuations [44].

The capacity factors of solar power plants do not decrease significantly with age [45].

3. Research methodology

3.1. Research process, method and data

Chapter 2 provides the conceptual, technological, and regulatory framework that forms the basis for this study, offering essential context on the drivers of the green transition, the structure of renewable energy policies, and the operational characteristics of different energy sources. Building on this foundation, the following chapter outlines the methodology, data sources, and techniques used to examine the 2023 energy data and estimates for 2030.

In this quantitative study, we used historical data and extrapolative forecasting methods to estimate energy production values for 2030.

Moreover, we used data from multiple reliable sources to ensure the robustness of the analysis. The primary source of hourly electricity production and consumption data was the open data portal provided by Fingrid, the Finnish national transmission system operator [46]. Data was collected, summarized, and key indicators were extracted. The data was provided in 15- to 60-minute intervals, and hourly averages were calculated to provide a suitable estimate of the total energy production for the review periods.

In addition to historical datasets, we incorporated forward-looking insights from Fingrid's Q3 2024 report, which outlines the projected trends in electricity generation and consumption in the future [47]. Fingrid made this estimate based on the total number of power grid connection inquiries, and these estimates were further utilized.

The key indicators used to measure the performance of the energy system are the ratio of energy positive vs. negative hours, the number of negative and positive hours in succession, and the net total of energy surplus or deficit, defined as the difference between electricity production and consumption. These KPIs were chosen to evaluate the temporal balance and volatility of the energy system, highlighting the intermittency of renewable sources and the need for balancing solutions.

Figure 1 summarizes the research process.

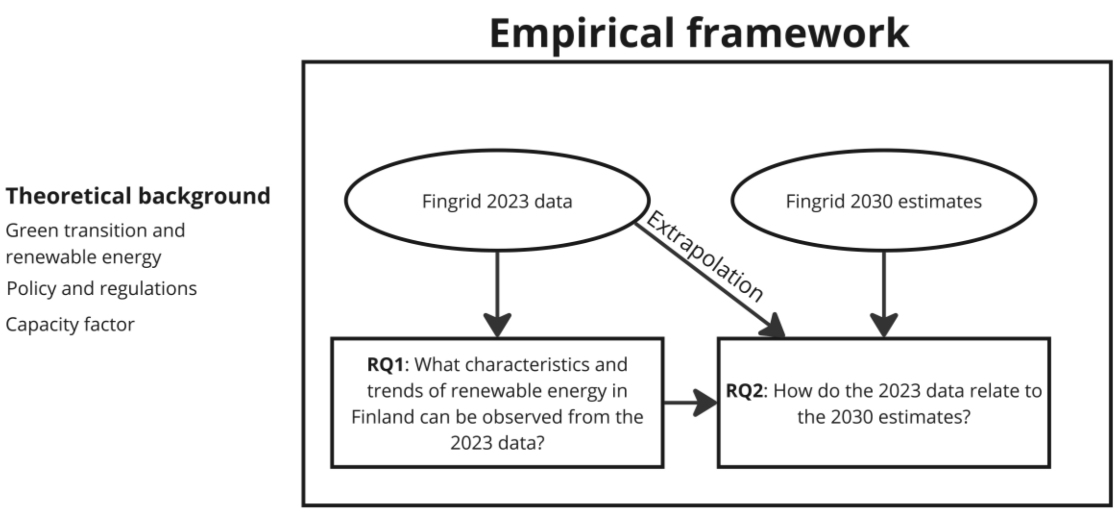

Figure 1. Research process.

3.2. Extrapolative forecasting

Extrapolative forecasting is a forecasting method in which the future is predicted by extrapolating a historical trend.

The estimation for 2030 was made using a combination of Fingrid's future total capacity estimates and 2023 wind and solar power data. 2023 data was used to calculate the hourly capacity factors for each power-generating method, and using the 2030 total capacity estimates, an hourly estimation was calculated. The estimation assumed that the hourly capacity factors for wind and solar power in 2030 will match the 2023 values. The formula for calculating the production estimate for hour n in 2030 is as follows:

$$P_n = CF_n * TC_n$$

where P_n is the hourly production estimate for hour n in 2030, CF_n is the capacity factor measured for hour n in 2023 and TC_n is the total production capacity estimate for hour n in 2030.

The estimate for hourly electricity consumption was derived similarly. The hourly consumption values from 2023 were scaled up using the ratio of the total consumption in 2030 and 2023. The 2023 total consumption was calculated from the hourly values and verified from the end-of-year report by Fingrid. For the 2030 total consumption, the Fingrid estimate was used. The formula is as follows:

$$C_{n,2030} = C_{n,2023} * \frac{C\_total_{2030}}{C\_total_{2023}}$$

where $C_{n,2030}$ is the consumption estimate for hour n in 2030, $C_{n,2023}$ is the recorded consumption for hour n in 2023, C_total_{2030} is the estimated total consumption for 2030, as stated by Fingrid and C_total_{2023} is the recorded total consumption for 2023.

No average capacity factors were assumed in this extrapolative model. Instead, the actual hourly capacity factors from 2023 were directly applied to the 2030 capacity values.

3.3. Annual production and consumption totals

Annual totals were obtained from two different sources. The first method involved obtaining data directly from the reports of the Finnish national statistical institution Tilastokeskus (Statistics Finland). The second method involved calculating the totals from the Fingrid production statistics. Fingrid provides power production statistics at varying time intervals. The data for hydro and nuclear power production was provided at 3-minute intervals, whereas the data for solar power production was provided only at 1-hour intervals. The data for wind power production was provided both at 3-minute and 1-hour intervals. The total production and consumption were provided at 1-hour intervals.

For the calculations, the hydro and nuclear power data were converted into hourly intervals by averaging the values within each hour. Fingrid data had some gaps, and for some hours, the data was missing. In these cases, the hourly value was estimated to be the value of the previous hour.

Thus, an hourly value was derived for each measure. The annual total value is calculated as:

$$V_{total} = \sum_{n=1}^{8760} P_n$$

where V_{total} is the value for the annual total, P_n is the hourly value and 8760 is the number of hours in a year.

3.4. Method for calculating electricity prices

Values for the hourly electricity prices in sector FI were downloaded from the Nord Pool Data Portal. The hourly price values were used to calculate the average price for the year, and daily average prices were used to create a daily average chart. From the data, the maximum and minimum price values were also gathered. The Nord Pool data was complete and contained exactly 8760 data points, one for each hour of the year. These values were used to examine the volatility and seasonal variation in electricity pricing over the year.

3.5. Data validation, error analysis, and pre-processing

To ensure the accuracy of the calculated energy values, the results derived from Fingrid were validated against official statistics published by Tilastokeskus. Absolute and relative errors were computed for each energy production method and for the total energy production and consumption using standard error calculation methods [48]. In cases where data was missing, missing values were assigned using the value from the previous hour. This forward-filling method preserves the time continuity. Four hourly values were missing for each production type: hydropower, solar, nuclear, and wind. Therefore, the effect of forward-filling on the KPIs can be considered negligible. The absolute and relative errors were calculated as follows:

$$Absolute\ error = \left|V_{Fingrid} - V_{Tilastokeskus}\right|$$

$$Relative\ error = \frac{\left|V_{Fingrid} - V_{Tilastokeskus}\right|}{V_{Tilastokeskus}} * 100\%$$

Data obtained from Fingrid varied in resolution, with data reported in 3-minute, 15-minute and 1-hour intervals depending on the measured value. All data series were resampled to hourly values using arithmetic mean aggregation to ensure a uniform granularity. Outliers, such as negative prices, were identified. For instance, the Nord Pool price dataset showed extreme values attributed to market anomalies, which were retained for transparency but were annotated in the results.

3.6. Regression analysis

To explore the relationship between electricity production and market price dynamics in Finland, a simple linear regression analysis was employed. This analysis aimed to identify whether variations in electricity production have an observable effect on electricity prices.

The regression model used is as follows:

$$y = \beta_0 + \beta_1 x + \varepsilon$$

where:

- y is the daily average electricity price.
- x is the daily average production.
- β_0 and β_1 are the intercept and slope.
- ε is the error term.

The regressions were conducted using the trendline tool of Microsoft Excel. The coefficient of determination (R2) was used to assess the model fit. While regression captures general trends, price formation in electricity markets is influenced by many factors; therefore, the analysis is primarily an exploratory tool.

3.7. Methodological limitations

We assumed constant diurnal and seasonal variation patterns when estimating future hourly production and consumption. Structural changes, such as the integration of offshore wind, energy storage technologies, or major shifts in demand-side behavior, were not explicitly modeled. Additionally, data gaps and simplifications, such as forward filling missing values or averaging over intervals, may introduce small errors in hourly estimates. Additionally, forward-filling may introduce bias during periods of high variability, such as sudden weather-driven shifts in production.

Nonetheless, this approach provides a transparent and robust framework for scenario-based planning and comparison of historical and projected energy trends in Finland.

3.8. Software and tools used

All data processing, analysis, and visualization tasks in this study were conducted using Microsoft Excel. Raw data files were downloaded in CSV format from the Fingrid open data portal and Nord Pool market data portal using a standard web browser. These files were imported into Excel for further processing.

Excel was used to resample the time-series data to an hourly resolution, calculate capacity factors, perform extrapolative forecasting, compute error metrics, and generate visualizations. Key performance indicators, such as energy-positive and energy-negative hours, were also derived using Excel.

This approach ensured a transparent and reproducible workflow, enabling the seamless integration of all datasets into a single environment. Given the modest dataset size, Excel was sufficient for performing the necessary aggregations, extrapolations, and statistical analyses required for this study. Excel was selected because of the authors' strong proficiency with the platform.

4. Results

4.1. Analysis of 2023 electricity production

The total energy production in Finland in 2023, as reported by Tilastokeskus, was 78.0 TWh. The same number calculated from the hourly production amounts reported by Fingrid was 77.5 TWh, resulting in an absolute error of 0.5 TWh and relative error of 0.6%. The difference in numbers can be explained by the error generated by interpolating the hourly values. Fingrid reported that instantaneous values were incorrectly reported instead of averages for the hourly values, which can lead to an interpolation error. A similar error was observed in the production method-level calculations. These are shown in Table 1. Solar energy had the largest relative error of 34%. This can be explained by the estimation-based methodology used by Fingrid. First, the total installed capacity is estimated based on data submitted by local electricity grid companies to the Energy Authority (Energiavirasto). Second, the location of solar installations was only roughly estimated based on the operating area of each reporting grid company, not the precise location of the panels. Third, the actual production was modeled using these two factors and nationwide weather forecasts. Therefore, the reported hourly solar power values are not direct measures but the result of multiple-layered estimations, introducing considerable uncertainty. The estimation-based nature of the 2023 solar data introduced uncertainty into extrapolations for 2030. However, this uncertainty was not explicitly accounted for in our analysis.

Table 1. Power production values.

Production method	Calculated value (TWh)	Reported value (TWh)	Absolute error (TWh)	Relative error
Total production	77.53	78.00	0.47	0.60%
Wind energy	14.03	14.47	0.44	3.07%
Nuclear energy	32.67	32.74	0.07	0.20%
Hydro energy	14.34	15.02	0.69	5%
Solar energy	0.864	0.647	0.22	34%

4.1.1. KPIs of wind electricity production

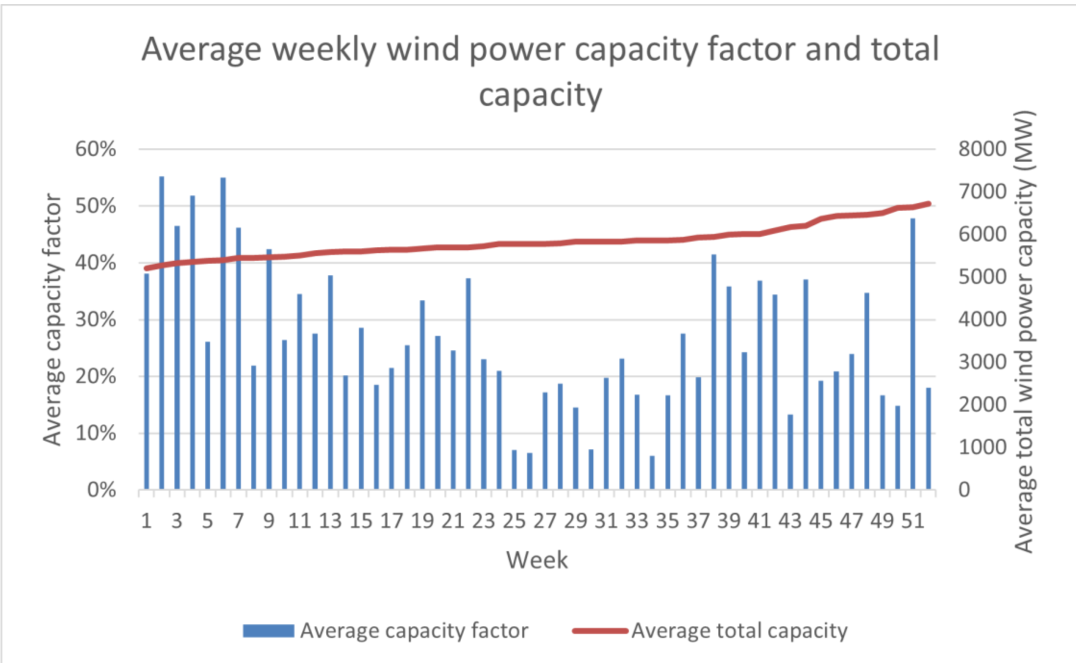

Figure 2. Average weekly wind power capacity factor and total capacity.

The average capacity factor of wind electricity production in 2023 was 27%. The highest amount measured was 88% on February 8th at 21–22, when the total wind power production was 4734 MW. The lowest amount was 0%. The wind power capacity grew by 1508 MW or 29% over the course of the year, from 5207 MW to 6715 MW.

From the weekly average capacity factors, a seasonal pattern was observed, where there was a slight decrease in the capacity factor during the summer weeks. This seasonal trend is shown in Figure 2.

4.1.2. KPIs of solar electricity production

The average capacity factor of solar power production in 2023 was 12.8%. The highest value of 85% was measured on June 6th, when the total solar energy production was 621 MW. The total solar energy capacity grew from 606 MW to 1018 MW, for a total growth of 412 MW or 68%. An obvious seasonal pattern could be observed from the weekly capacity factor averages, as shown in Figure 3.

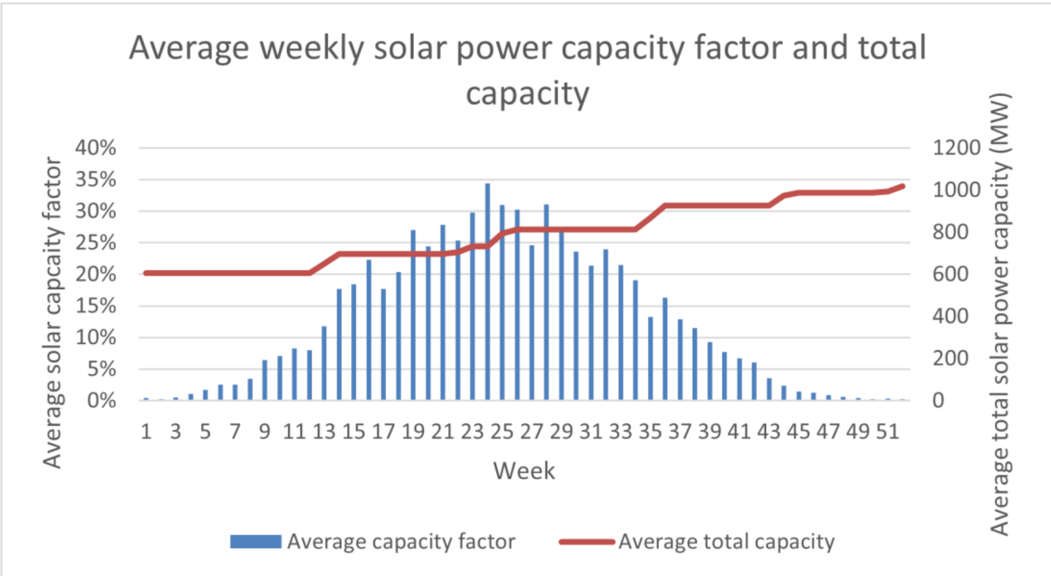

Figure 3. Average weekly solar power capacity factor and total capacity.

4.1.3. KPIs of hydroelectricity production

The total capacity for hydroelectricity production in Finland was 3190 MW, which remained constant throughout the year. The highest total hydropower production was measured at 2601.5 MW on the 30th of October, and the lowest was 429.17 MW on the 13th of June. The average capacity factor for hydropower was 51%; however, due to the regulating nature of hydropower, this number was not comparable to the capacity factors of wind and solar power. Figure 4 shows the stable total capacity and weekly average capacity factors of hydropower.

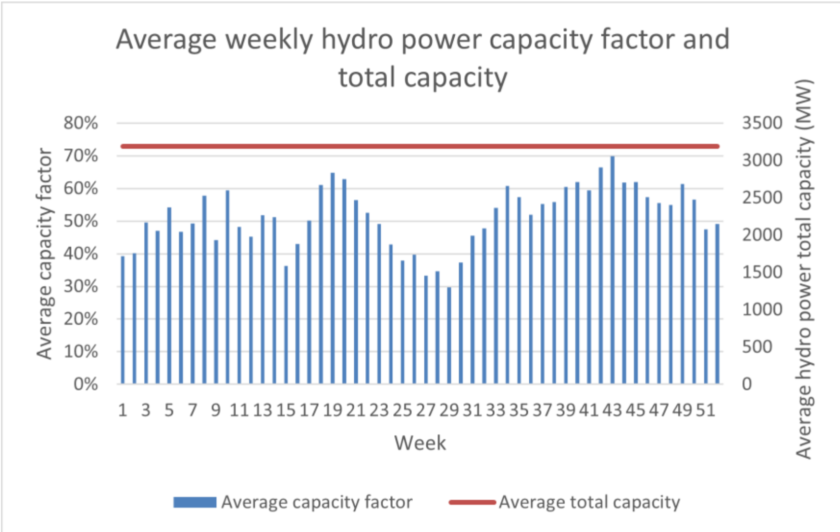

Figure 4. Average weekly hydropower capacity factor and total capacity.

4.1.4. KPIs of nuclear electricity production

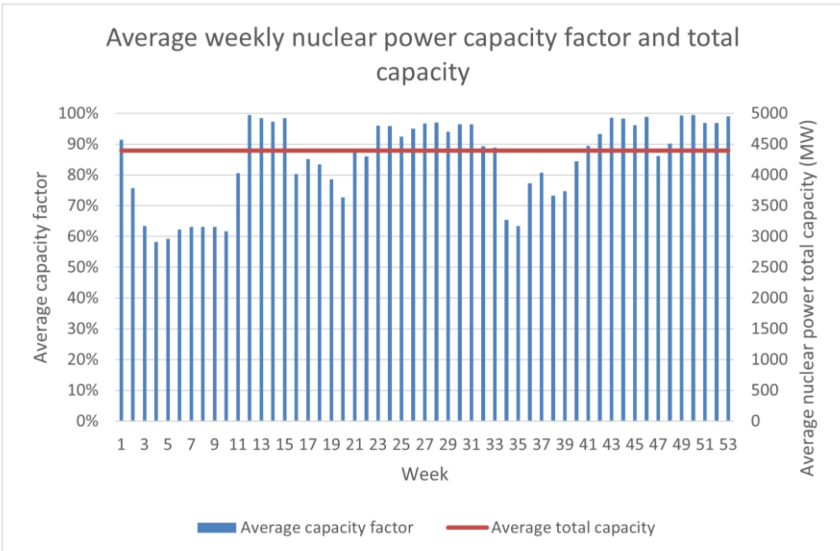

Figure 5. Average weekly nuclear power capacity factor and total capacity.

The average capacity factor of nuclear power was 85% for the year. Nuclear power plants operated at 99% or more of their total capacity 18% of the time. The lower capacity factor during the first weeks of the year could be partly explained by the ongoing commissioning of the Olkiluoto 3 reactor, which was fully commissioned on April 16th. Figure 5 shows the total capacity and weekly average capacity factors of nuclear power.

4.2. Analysis of 2023 electricity consumption

The total energy consumption, as reported by Tilastokeskus, was 79.69 TWh, and the same number calculated from the Fingrid values was 79.41 TWh, thus having an absolute error of 0.26 TWh and a relative error of 0.32%. The lowest consumption was 5675 MW, recorded on June 21st, and the highest was 13300 MW, recorded on November 27th. Households and agriculture were the largest power-consuming sectors, accounting for 24.1 TWh, or 30.3% of the total electricity consumption. Table 2 presents the annual electricity consumption by sector in TWh and as a share of total consumption.

Table 2. Annual electricity consumption by sector.

Sector	Total annual electricity consumption (TWh)	% of total consumption
Forest industry	14.357	18.0%
Metal industry	6.381	8.0%
Chemical industry	7.976	10.0%
Other industries	4.786	6.0%
Households and agriculture	24.141	30.3%
Services and public consumption	19.211	24.1%
Transmission and distribution losses	2.817	3.5%

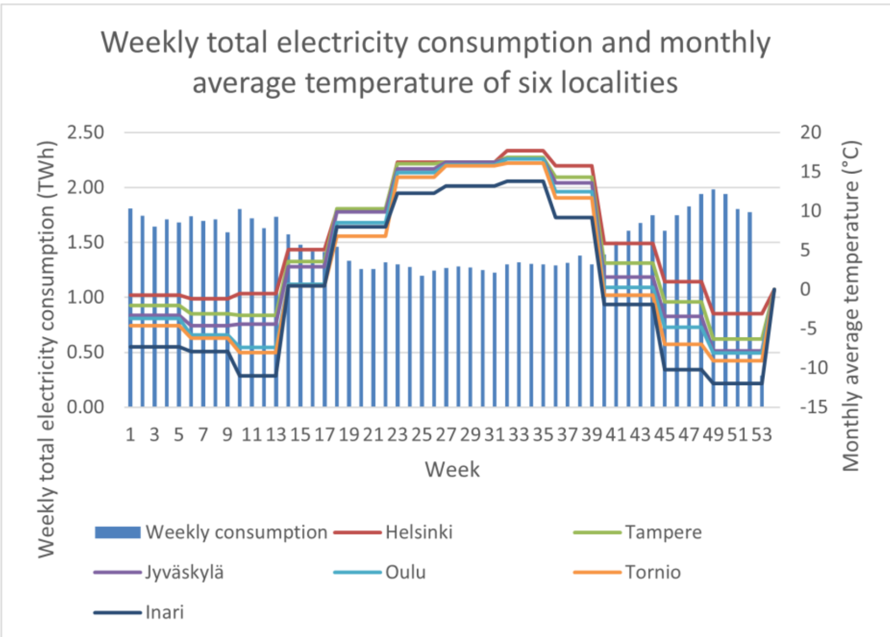

Figure 6. Weekly total electricity consumption and monthly average temperature of six localities.

Electricity consumption has a seasonal pattern, with summer weeks having lower consumption than winter weeks. Building heating accounted for 28% of the total energy consumption for the year, and although not all heating was performed using electricity, the impact of cold temperatures on electricity consumption was evident, as shown in Figure 6.

4.3. Analysis of the difference between production and consumption

The electricity deficit for 2023, as reported by Tilastokeskus, was 1.72 TWh. The calculated yearly totals were 77.53 for production and 79.41 for consumption, leading to a net deficit of 1.88 TWh for the year. A third value for the annual deficit was calculated from the Fingrid data for net export and import in 3-minute intervals, and using this data, an annual deficit of 1.53 TWh was calculated.

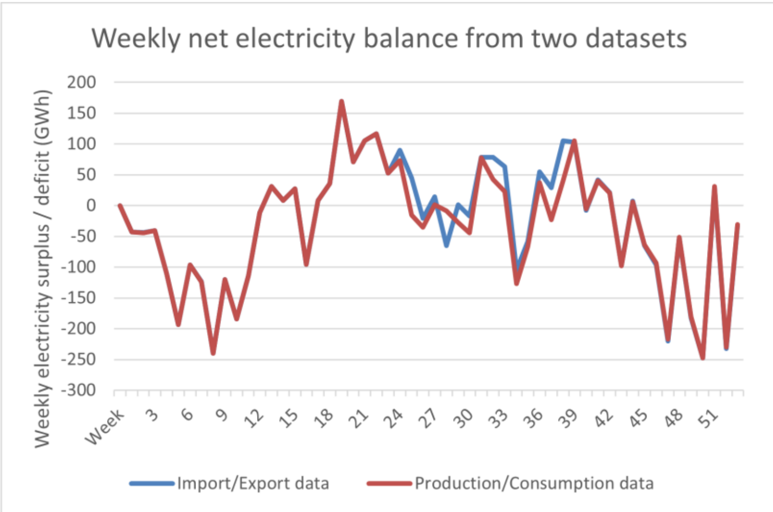

Figure 7. Weekly net electricity balance from two datasets.

Figure 7 illustrates that the data from the two datasets overlap during most weeks, with minor differences observed. The largest energy deficit occurred in week 50, when a net total of 247 GWh of electricity was imported. The largest energy surplus occurred during week 19, when 169 GWh of electricity was exported. In total, of the 8760 hours of the year, 3336 (38%) were net positive, meaning that electricity production exceeded consumption. A total of 5421 (62%) hours were net negative, while 3 hours were neutral, with production equaling consumption.

The longest consecutive series of negative hours was 226 h, whereas the longest series of positive hours was 146 h.

4.4. Analysis of electricity price in Finland

The average price of electricity was €56.47/MWh in sector FI. This was lower than that in most European energy sectors, as shown in Table 3. The highest price was €777.18/MWh, which occurred on November 21st. The lowest price was −€500/MWh, which occurred on November 24th. The low price was a direct result of an internal system error, which artificially lowered electricity prices [49].

Figure 8 shows a slight seasonal pattern in electricity prices. The price was lower in the warm summer months and higher during the colder months.

Table 3. Average electricity prices in European energy sectors.

Energy sector	Average price (€/MWh)
NO4 (Norway)	29.95
NO3 (Norway)	38.55
SE1 (Sweden)	39.97
SE2 (Sweden)	39.98
SE3 (Sweden)	51.70
FI (Finland)	**56.47**
SE4 (Sweden)	64.88
NO1 (Norway)	66.95
NO5 (Norway)	67.05
NO2 (Norway)	79.45
DK2 (Denmark)	81.25
DK1 (Denmark)	86.83
EE (Estonia)	90.79
LV (Latvia)	93.89
LT (Lithuania)	94.44
GER (Germany)	95.18
NL (Netherlands)	95.82
FR (France)	96.86
BE (Belgium)	97.27
AT (Austria)	102.14
PL (Poland)	111.65

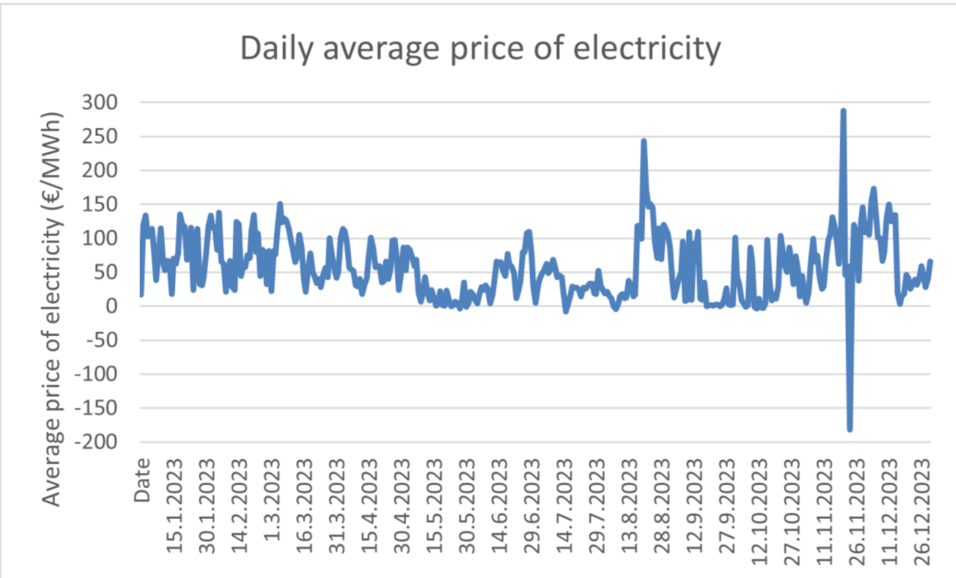

Figure 8. Daily average price of electricity.

4.4.1. Effect of electricity production on electricity price

Figure 9 illustrates the relationship between the daily average wind electricity production and daily average electricity price in Finland. The regression shows a negative slope, indicating that higher wind power production was generally associated with lower electricity prices. This aligned with expectations, as wind power is a low-marginal-cost energy source that can reduce reliance on more expensive production methods. The coefficient of determination R^2 for this regression was 0.149, suggesting a modest inverse correlation, although other factors mostly affect prices. Omitting the outlier hours mentioned in Section 4.4 increased the R^2 value to 0.153, slightly strengthening the observed correlation between wind power production and electricity price.

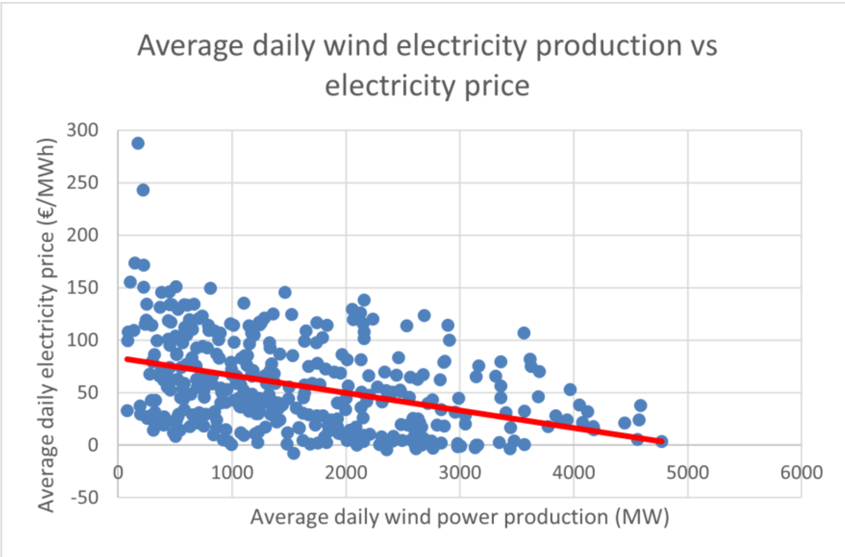

Figure 9. Average daily wind electricity production vs electricity price.

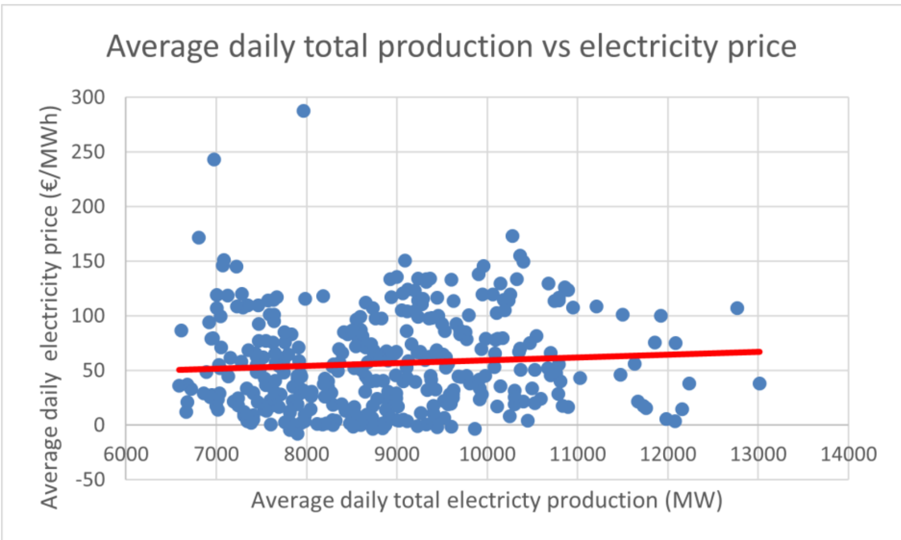

Figure 10. Average daily total production vs electricity price.

Figure 10 presents the regression between total electricity production and electricity price. Here, the fitted linear regression line shows a slightly positive slope, indicating that prices tended to increase with higher total production. While counterintuitive, the result could be explained by market behavior: During high-demand periods, when cheap renewable sources were exhausted, more expensive electricity-generating methods were utilized, leading to higher prices. However, the relationship was weak, as reflected in the very low R^2 value of 0.005, indicating that total production explained very little of the variance in electricity prices on a daily scale. When the outlier hours were omitted, the R^2 value increased to 0.008.

These regressions show the complex interplay between renewable energy availability and market pricing. While wind power availability had a clearer inverse influence on price, total production was a poor predictor of price movements because of multiple confounding factors.

4.5. Estimates for annual totals for 2030

Fingrid has released estimates of the total electricity production and consumption for 2030. They estimated the total electricity consumption to be 125 TWh. The total electricity consumption for industries was estimated to be 69 TWh, which was nearly equal to the total electricity consumption of all sectors in 2023.

Fingrid has also created estimates for electricity production by production method. The estimated wind electricity production was 60 TWh, and solar electricity production was 10 TWh, with other generation methods remaining close to their 2023 values.

Table 4. Comparison of Finland's electricity production and consumption in 2023 vs. estimated in 2030.

Category	2023 (TWh)	2030 (TWh)	Change
Total production	78.0	131	68%
Total consumption	79.7	125	57%
Wind power	14.5	60	315%
Nuclear power	32.7	34	4%
Hydropower	15.0	14	−7%
Solar power	0.6	10	1446%
Thermal power	15.1	13	−14%

The estimated increase in total production of solar and wind power, shown in Table 4, was not equal to their respective estimated installed capacity increase, shown in Table 5. Fingrid may have estimated a higher capacity factor for the wind turbines and solar panels in 2030, thus increasing their total power production. This led to a higher increase in total production compared with the average capacity factor. From these values, we could derive that Fingrid used an average capacity factor of 38% for the total wind power production estimate and a value of 13% for the total solar power production estimate.

Table 5. Average installed generation capacity for wind and solar power in 2023 and 2030.

Generation source	2023 (MW)	2030 (MW)	Change
Average wind capacity	5833.8	18000	209%
Average solar capacity	788.7	9000	1041%

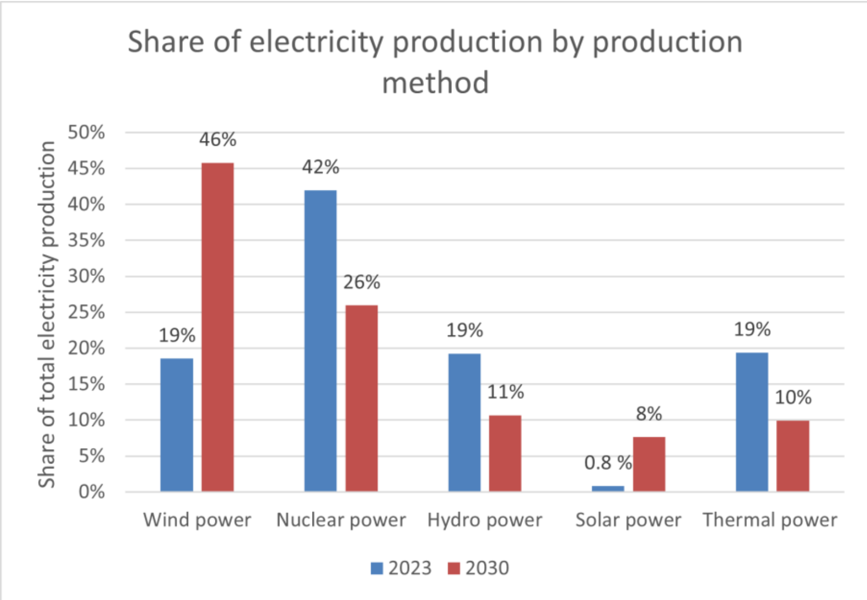

Figure 11. Share of electricity production by production method in 2023 and 2030.

The estimated increases in total wind and solar power production led to a vastly different distribution of electricity production in 2030, with wind power accounting for 49% of the total annual electricity production. In this estimate, weather-dependent power generation methods, wind and solar power, would add up to 53% of the total production, compared to 19% in 2023. Figure 11 presents the annual share of total electricity produced by power generation method in 2023 and in 2030.

4.6. Estimates for hourly values for 2030

Using the methods explained in Chapter 3, an hourly estimate for electricity production was derived using the Fingrid 2030 estimates for total capacity and the 2023 hourly capacity factor values. An estimate for hourly electricity consumption was derived from the annual total consumption estimate for 2030 and the hourly consumption values for 2023.

Figure 12 shows the estimation of average weekly wind electricity production, solar electricity production, total electricity production, and total electricity consumption. Wind power accounted for over 50% of the total production, and the effect of wind power was visible in the total production graph. Solar power generation was also slightly visible in the total production graph.

Figure 13 shows the weekly average electricity surplus or deficit. This was also strongly related to the wind power produced. The cold winter weeks were expected to have large electricity deficits, whereas the summer months were expected to have a surplus of electricity. However, 61% of the year was estimated to be in deficit.

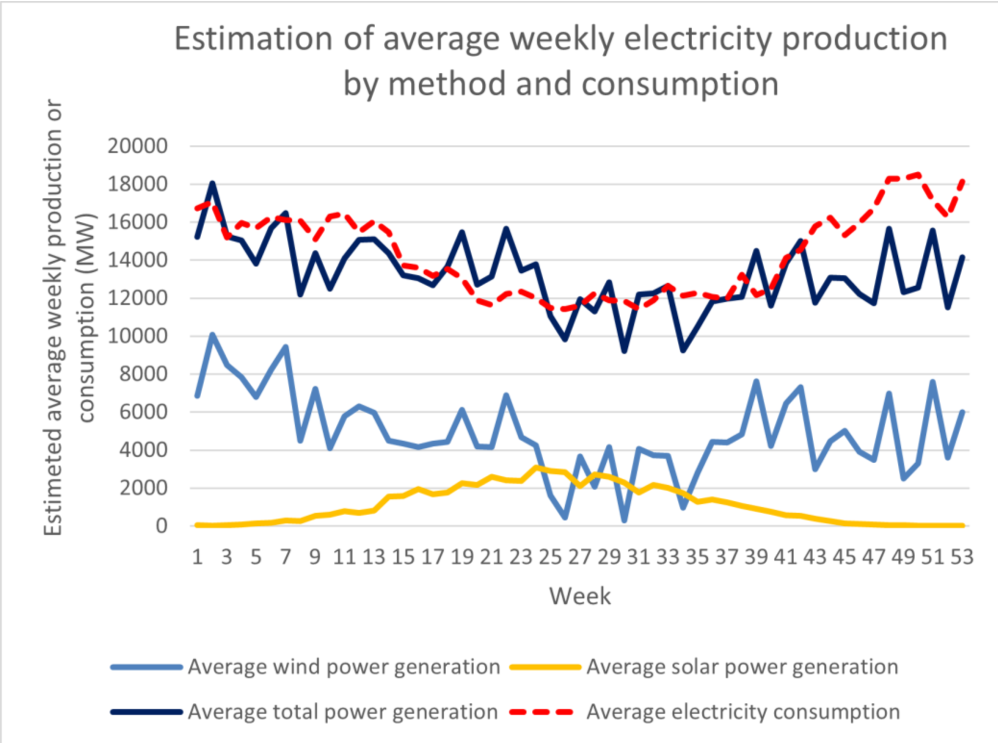

Figure 12. Estimation of average weekly electricity production by method and consumption.

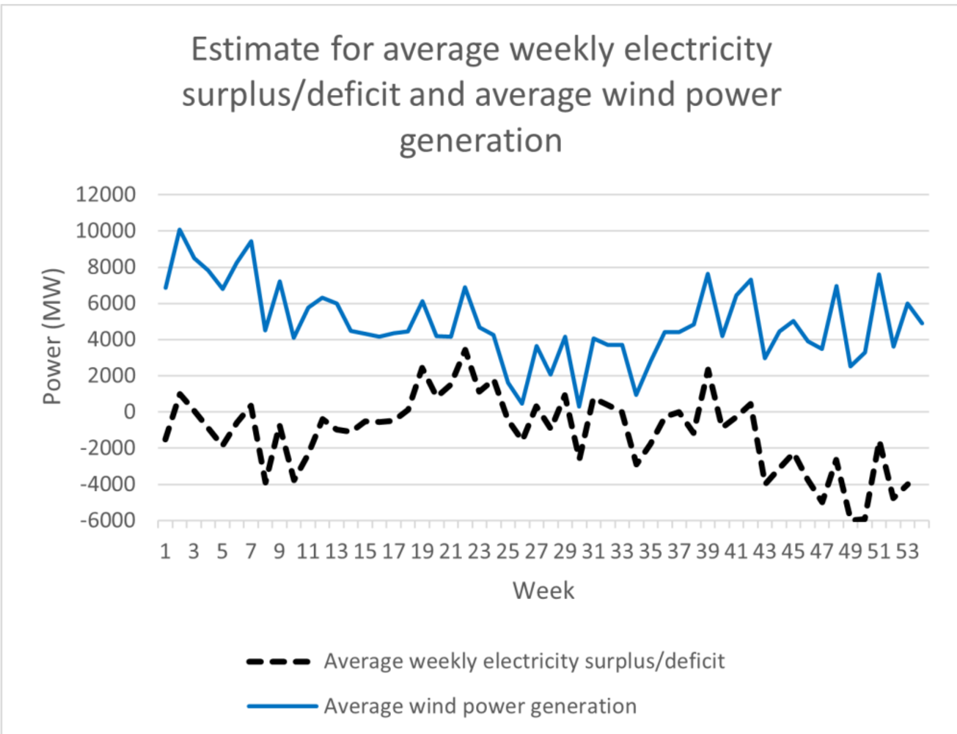

Figure 13. Estimate for average weekly electricity surplus/deficit and wind power generation.

The total electricity produced was estimated to be only 116 TWh, which was 15 TWh less than the Fingrid estimate of 131 TWh. This difference could be mostly explained by the smaller amount of wind power generated. Fingrid estimated a total of 60 TWh of wind power to be generated, where the calculated value based on 2023 numbers was 43 TWh, leading to a difference of 17 TWh. This difference, in turn, was explained by the higher average capacity used in the Fingrid estimation. The average capacity factor for 2023 was 27%, and Fingrid's estimate for 2030 was 38%.

When these differences were considered, the estimate for the total annual power generated was below the total consumption, with a total deficit of 10 TWh. Of the hours, 39% were estimated to be electricity-positive, whereas 61% were negative. The amount of surplus electricity generated during the positive hours was estimated to be 9.5 TWh, and the amount of electricity deficit during the negative hours was estimated to be −18.7 TWh.

5. Discussion

We examined Finland's electricity production and consumption patterns in 2023 and explored how these patterns are expected to evolve by 2030. The analysis of 2023 power production, consumption, and pricing data revealed key insights into the nation's energy characteristics and trends. Additionally, contextualizing the 2023 data within the framework of future projections provides valuable perspectives on the evolution of Finland's renewable energy landscape and the anticipated energy profile for 2030.

5.1. Characteristics of production methods in 2023

To understand the current characteristics of Finland's electricity system, the 2023 data was analyzed by production method, with each method evaluated based on five key characteristics: Price correlation, seasonality, total capacity, average capacity factor, and flexibility.

Wind, solar, and nuclear power exhibited a slight negative correlation with price, indicating that prices tended to decrease as production increased. Because these are all relatively low-cost production methods, the correlation is likely to be causal. In contrast, hydropower production and price were positively correlated. This suggests that higher hydropower production may correspond to periods of increased demand or constrained supply from other energy sources, as hydropower is often used as a regulating power source.

Wind and solar power exhibited noticeable seasonal variations, whereas neither hydropower nor nuclear power showed significant seasonal patterns. The seasonal variability of wind and solar power is primarily driven by weather conditions: Wind power production tends to peak during the colder months when wind speeds are higher, whereas solar power production is naturally higher during the summer because of longer daylight hours and increased solar intensity. In contrast, hydropower output is often regulated to meet demand rather than being influenced by seasonal weather changes. Similarly, nuclear power is used as a baseload energy source, maintaining steady production throughout the year, regardless of weather conditions.

The total capacity of Finland's power production methods saw notable developments in 2023. Wind power capacity increased by 29% over the course of 2023, measured from the capacity on

January 1st to that on December 31st, reflecting continued investment in renewable energy and the expanding role of wind energy as a key energy source. Solar power capacity experienced an even more significant rise, increasing by 68% over the course of 2023. A major milestone in nuclear energy was the full commissioning of the Olkiluoto 3 reactor in April, which significantly boosted Finland's nuclear power capacity and enhanced its role as a baseload energy source. In contrast, the capacity of hydropower remained stable, and although possible new locations for new hydroelectric plants have been recognized, the construction of additional plants is unlikely because of environmental and nature conservation reasons [32].

The average capacity varied significantly among the different production methods, reflecting their operational characteristics and reliance on external conditions. The average capacity factor for wind power was 27% in 2023. This value represents the variability of wind resources, which depends on weather conditions and geographical factors. Notably, Finland's wind capacity factor (27%) is slightly above the EU average for onshore wind (24%) [50]. Solar power had an average capacity factor of 13%. Despite its lower capacity factor, the rapid growth of installed capacity highlights its potential as a complementary renewable energy source during sunnier months when wind power generation is lower. Hydropower achieved a capacity factor of 51%, reflecting its ability to operate more consistently. However, because hydropower is less influenced by weather conditions and is actively managed to meet demand, direct comparisons with other production methods are not entirely appropriate. The capacity factor of nuclear power was 85%. This highlights its importance as a consistent baseload energy source that is unaffected by weather conditions. As the operation of Olkiluoto 3 stabilizes, an even higher capacity factor of nuclear power can be expected.

The flexibility of the production methods varies significantly. Hydropower stands out as the most flexible electricity source, capable of rapidly adjusting its output to meet fluctuations, matching demand, and compensating for the variability of other sources. This makes hydropower an essential tool for large-scale grid balancing. Wind power production is dictated by wind availability; therefore, the maximum production is dictated by the weather. However, discussions about a capacity mechanism in Finland are ongoing, possibly leading to some wind power capacity being left for grid balancing purposes in the future. Solar power exhibits low flexibility because its production follows daily and seasonal sunlight patterns. Although nuclear power is reliable, it is largely inflexible in real-time operations. It functions as a baseload energy source, providing a consistent and steady output with a limited ability to adjust production in response to immediate changes.

Table 6 summarizes the key characteristics of electricity production methods in Finland in 2023.

Table 6. Summary of characteristics of electricity production methods in 2023.

Production method	Correlation on price	Seasonality	Total capacity	Average capacity factor	Flexibility
Wind	Negative	Slightly winter centered	Increase of 29%	27%	Low/Market-related
Solar	Negative	Heavily summer centered	Increase of 68%	13%	Low
Hydro	Positive	No notable seasonality	No changes	51%	High
Nuclear	Negative	No notable seasonality	Commissioning of OL3	85%	Low

5.2. Characteristics of total production, consumption, and electricity prices in 2023

Additionally, the total production, consumption, and electricity prices were analyzed. In 2023, electricity consumption and production exhibited slight seasonal variations, with lower levels observed during the summer months. Consumption was higher during the colder periods due to increased heating demands, reflecting the influence of Finland's temperature variations on electricity usage.

Electricity prices followed a similar seasonal trend, with slightly lower prices during warm summer months. The most significant price peaks were observed during the winter months. These price spikes were likely driven by heightened demand during colder periods and the need for additional energy imports or more expensive production methods. The highest electricity price, recorded at €777.18/MWh on November 21st, was likely influenced by the combination of low wind power production and operational malfunction of Olkiluoto 3 on that day.

The low R^2 values observed in the regression analyses (0.15 for wind power and 0.005 for total electricity production) indicate that electricity price variation is influenced by factors beyond production levels. While an inverse relationship exists between wind power and price, the weak overall fit suggests that other factors play a significant role in price formation. In the future, researchers could explore nonlinear or multivariable models that incorporate additional variables to better capture the price-setting mechanisms in the Nordic electricity market.

Interestingly, electricity prices were positively correlated with total electricity production. This counterintuitive trend can be attributed to the activation of high-cost production methods during periods of high demand and constrained supply from lower-cost electricity sources.

5.3. Estimates for 2030

To estimate Finland's energy balance in 2030, capacity projections from Fingrid were used to extrapolate the hourly production and consumption values based on 2023 patterns. The calculated estimates for Finland's electricity production differ significantly from those provided by Fingrid, with the primary divergence arising from the capacity factor used to estimate wind power production. Fingrid uses a value of 38%, leading to more optimistic production estimates than the calculated values, which use a value of 27%. However, advancements in wind turbine technology, along with the increasing adoption of offshore wind farms, are expected to contribute to a higher capacity factor, making the likely capacity factor in 2030 higher than that observed in 2023.

Finland is expected to increasingly rely on wind and solar power, both of which are intermittent energy sources. Consequently, the total electricity production graph closely mirrors the wind production graph, given that wind is projected to become the dominant energy source by 2030. Seasonal variations are evident, with lower wind production compensated by higher solar power generation during the summer months.

The intermittency of these renewable sources poses significant challenges. During periods of low wind production, net power often becomes negative, highlighting the need for energy storage solutions. Energy storage systems are crucial for mitigating the effects of production variability in renewable-dominated grids. Pumped hydro storage has reached maturity in Finland, and new installations are unlikely to occur because of geographical constraints. Battery energy storage systems (BESS) offer greater deployment flexibility and are well suited for short-duration balancing but are expensive at the grid scale. Hydrogen storage holds promise for long-duration storage; however, storage infrastructure, electrolyzer capacity challenges, and low round-trip efficiency raise questions about its feasibility. Nevertheless, the expected increase in electricity storage deployment would reduce the number and duration of electricity-negative hours projected for 2030.

Based on the dynamic hourly modeling presented in this study, Finland is unlikely to achieve full electricity self-sufficiency by 2030, despite the significant planned capacity expansions. This is primarily because the growth in new electricity production capacity, especially from wind and solar, is insufficient to meet the projected increase in electricity consumption, particularly during periods of low renewable output. The analysis estimates that 61% of the year would be electricity-negative, and a net annual electricity deficit of 10 TWh is projected using the current capacity factor assumptions. This indicates that under the current development trajectories, Finland may not fully meet the electricity sector's 2035 carbon neutrality target.

The extrapolation to 2030 assumes that the hourly capacity factors will remain identical to those observed in 2023. This assumption simplifies the modeling process but does not account for expected technological and geographical developments, such as the increasing share of offshore wind farms and advancements in wind power technology and turbine size. Consequently, the model may overestimate production variability and underestimate the average efficiency of wind turbines in 2030, leading to an underestimation of electricity-positive hours.

6. Conclusions

We examined the status of renewable energy in Finland as of 2023 and estimated its development by 2030, focusing on production, capacity, and sustainability. The analysis evaluates wind, solar, hydro, and nuclear energy while considering the challenges posed by intermittency and energy deficits.

The transition to renewable energy is imperative for Finland to achieve its climate targets and gain energy independence. However, this transition poses challenges in integrating intermittent energy sources, such as wind and solar, into the national grid while ensuring a constant supply and economic feasibility.

Our analysis reveals that renewable energy, particularly wind and solar power, will play a pivotal role in Finland's future energy landscape. Wind energy is expected to become the dominant energy source by 2030, with significant growth in its capacity and production. Although solar energy is limited by seasonal factors, it is set to expand significantly.

Addressing the projected electricity deficit will require a diversified system design. Although offshore wind could improve capacity factors, future wind power expansion is increasingly constrained by environmental impact assessments and municipal-level zoning responsibilities. Additionally, the proposed extensions to protective zones around wind turbines may further limit the number of suitable areas. Given these constraints, Finland's strategy should prioritize energy storage and demand-side flexibility to reduce the mismatch between production and consumption and improve the hourly balance.

Hydro and nuclear power will continue to provide essential stability, with nuclear power acting as a reliable baseload and hydro as a flexible balancing tool. However, the projected increase in electricity consumption by 2030 highlights the importance of improving production efficiency and exploring innovative energy-storage solutions.

In the future, researchers should focus on the integration and optimization of Finland's electricity and gas grid, ensuring seamless connectivity to support the increasing share of renewable energy and emerging technologies, such as hydrogen production. A key area is the utilization of green electricity for hydrogen generation, which can be used directly or further processed into advanced fuels and materials. Additionally, advancements in energy storage systems, such as battery technologies, pumped hydro, and hydrogen storage, are essential to address the challenges posed by the increasing share of intermittent energy sources. Future studies could also consider a scenario-based sensitivity analysis for capacity factors, to account for anticipated technological and geographical improvements and their potential impact on production variability and grid stability.

Use of AI tools declaration

No Generative-AI tools were used in the creation of this article.

Assistive-AI tools (LanguageTool and PaperPal) were used for language refinement and grammar improvement.

The authors take full responsibility for the contents of the article.

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Conflict of interest

All authors declare no conflicts of interest in this paper.

Author contributions

Conceptualization: J.S. and P.T.; methodology: J.S., P.T. and M.H.; validation: J.S., P.T., H.H., and M.H.; investigation: J.S. and P.T.; writing—original draft: J.S. and P.T.; writing—review & editing: J.S., P.T., H.H., and M.H.; supervision: P.T. and H.H.; project administration: P.T.

All authors have read and agreed to the published version of the manuscript.

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