

Analyzing Potential Scarcity Events in a Wind Power-based Electricity System – Case Finland

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Abstract—This study examines possible scarcity situations in the Finnish power system using historical weather data from years 2014–2024. Wind power production is simulated with current capacity level, while other energy production capacities follow up-to-date estimates. No real power shortages have appeared during the period. The study also investigates the frequency and duration of windless frost periods. During the review period, those periods lasted continuously 4.3 hours on average. In the analysis, scarcity in electricity occurs in one year during the review period, with a shortage lasting three hours and an energy deficit of 325.8 MWh. A sensitivity analysis assuming a 1,200 MW transmission line outage reveals shortages averaging 7.7 hours annually, with individual continuous events lasting 2.4 hours. Under baseline conditions the results indicate that electricity sufficiency in Finland is generally adequate, but critical scarcity situations can arise if the system encounters unexpected losses in transmission or production capacity.

Index Terms—electricity generation, Finnish power system, scarcity events, weather conditions, wind power.

I. INTRODUCTION

Carbon neutrality goals and climate change mitigation measures are driving the transition of our electricity system towards the direction where renewable energy sources replace more and more conventional production plants [1]–[3]. As solar power, and especially wind power rapidly increases, our power system is becoming increasingly weather dependent [4]. Accurate forecasts are essential for estimating renewable energy production in real-time and planning the operation of the rest of the power system accordingly. Due to the widespread and rapid penetration of renewable energy, the security of electricity supply has become a critical topic of research and discussion [5]. Concurrently, electricity consumption is projected to grow significantly in the coming years due to electrification of society [6], [7]. The demand for peak power is notably increased for example, by the electrification of heating systems [8]–[10]. The Finnish Government Programme emphasizes that even during windless frost periods there must be adequately electricity available at reasonable prices [11]. Moreover,

the Government Programme aims to promote a balanced mix of weather-dependent production, balancing power, and base load power in electricity production investments, considering both security of supply and overall system costs. The Finnish Government has determined the expected energy deficit in the Finnish electricity system to be a maximum of 1,100 MWh/a and the expected power deficit (LOLE, Loss of Load Expected, h/a) a maximum of 2.1 hours per year [12].

This study concentrates on security of power supply, especially on the physical aspect, that there is sufficient electricity available precisely when needed, and that there are no disruptions in the electricity supply. Other perspectives for the security of power supply include, for example, economic and environmental perspectives. Economic security of power supply pertains to the availability of reasonably priced electricity for consumers, ensuring that demand remains stable [5]. Clean or environmental security of supply, on the other hand, refers to the fact that the electricity supplied reduces dependence on fossil fuels and promotes the development of a carbon-free system.

This study investigates the impact of simulated wind power generation on Finland’s energy balance. The total wind power production in Finland is simulated using historical weather data (wind and temperature observations) over the period from 2014 to 2024, encompassing 11 years of analysis. The simulated wind power generation is compared to the measured electricity consumption in Finland during this period. The study assumes that the wind power capacity installed in Finland in 2024 was the available wind power capacity throughout the review period. The focus is in particular on how the power balance would have behaved in previous years if wind power had been at the current capacity level. Additionally, the assessment of other electricity generation sources to the power balance includes the amounts of other energy production forms reported by the Finnish Energy

Authority for 2024. To note, no real power shortages have appeared in the system during the review period.

A. Literature review

This section reviews previous research that has examined the national security of supply in electricity and the adequacy of the Finnish power system.

Finland's power capacity adequacy during winter peak demand using the EnergyPLAN simulation tool was analyzed in [13]. The paper focused on stress-testing the electricity system by simulating extreme stress factors (e.g., power plant outages, transmission failures), peak demand conditions, and different scenarios to evaluate Finland's ability to maintain energy security under adverse conditions. In the study, a single power plant outage or transmission failure did not cause major supply issues, but multiple simultaneous failures caused scarcity situations. The paper pointed out that Finland relies heavily on electricity imports and the reliance on increased wind power was seen as one future risk.

The impact of a severe drought on Finland's future energy system (2020 and 2030) was studied in [14]. The analysis utilized the EnergyPLAN simulation tool, and the simulations considered electricity demand peaks, energy generation capacity, and the role of electricity imports from the neighboring countries. The study evaluated the Finland's ability to respond to severe hydrological droughts. The results underlined Finland's dependence on cross-border electricity trade in energy security, and reduced investments in nuclear and transmission lead to higher vulnerability.

In [15], the sufficiency of Finland's electricity system resource adequacy in years 2023-2033 was evaluated. They used their own BID3 electricity market model for studying three scenarios: a base scenario and two sensitivity analyses focusing on the availability of the Olkiluoto 3 nuclear power plant. The results revealed that the availability of Olkiluoto 3 is remarkably crucial for maintaining resource adequacy, and the increased demand and variable renewable energy production will challenge resource adequacy.

In [16], the PLEXOS energy market simulation program was used to model and assess the electricity scarcity situations in Finland's low-carbon electricity system. Historical weather years of 1982–2016 were incorporated into the study. The study included two scenarios (2024 and 2030) with projected generation capacities, demand growth, and transmission developments. The results revealed that increasing renewable power generation does not eliminate scarcity risks and Finland may face serious electricity shortages by 2030.

B. Contribution of the study and research questions

The previously discussed studies [13], [14] are starting to become obsolescent. In [16], old historical data (1982-2016)

was used, and the power capacities used in the analysis were based on future projections. In [15], the resource adequacy was evaluated with a consulting company's own market model.

This study provides up-to-date information by simulating wind power production at current capacity levels. Furthermore, the production capacities of other energy sources are based on current data rather than future predictions. The used weather data are observed values from recent history. The primary focus is to assess whether the existing energy production system would have experienced shortages during the past weather years with actual consumption and simulated wind power data. Furthermore, the frequency and duration of windless frost periods are analyzed. Here, frosty times or frost periods are determined as times when the temperature drops to or below zero celcius degrees. The findings of this study serve as a preliminary review, evaluating the necessity and profitability of potential additional reserve capacities and electricity market mechanisms to address scarcity situations.

The research questions are:

1. How many windless frost periods occur annually during the review period?
 - 1.1 What is the average and maximum duration of these windless frost periods each year?
2. To what extent can the current wind power capacity cover the total annual electricity consumption? Will the wind power capacity lead to surplus production?
3. Will there appear scarcity in electricity during the review period?
 - 3.1 If shortages occur, what are their maximum and average durations?
 - 3.2 How will the situation with shortage events change if part of the electricity capacity is lost (the so-called N-1 situation)?

The structure of the rest of the paper is the following: Section II describes the methodology used in the study and the results of the study are presented in Section III. Finally, Section IV concludes the paper.

II. METHODOLOGY

To estimate wind power production in Finland, the production capacity-weighted coordinates for wind power plants were used. This involved calculating the average production capacity-weighted location coordinates of the wind turbines, resulting in a theoretical average center of the wind power production in Finland. The coordinates and capacities of the wind turbines used in the calculation are from 2023, as newer data were not available. During 2024, an additional 1,414 MW of new wind turbines were constructed [17]. The average location coordinates of the wind turbines, weighted by production capacity, have been calculated as follows:

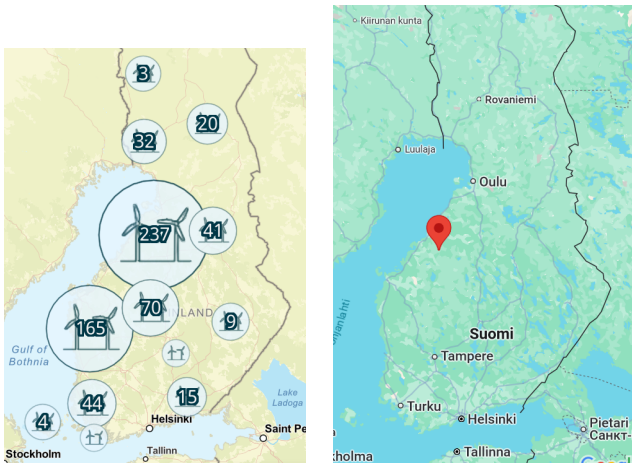
$$\text{Weighted Latitude} = \frac{\sum_{i=1}^n (\text{Latitude}_i \times \text{Capacity}_i)}{\sum_{i=1}^n \text{Capacity}_i} \quad (1)$$

$$\text{Weighted Longitude} = \frac{\sum_{i=1}^n (\text{Longitude}_i \times \text{Capacity}_i)}{\sum_{i=1}^n \text{Capacity}_i}$$

Where:

- Latitude_i and Longitude_i are the coordinates of the i -th wind turbine.
- Capacity_i is the nominal power capacity of the i -th wind turbine.
- n is the total number of wind turbines.

Due to favorable wind conditions on the west coast, the construction of wind turbines in Finland so far has been concentrated there, especially in the areas around the Bay of Bothnia and Northern Quark [18], [19]. Therefore, the average production capacity-weighted location of the constructed wind turbines was estimated to be adequate for the estimation of the total wind power production in whole Finland as the wind conditions can be expected to be quite similar in the wind power-centralized area. However, it should be noted that as the model is based on a single measurement point, there is no dispersion among multiple production points, which results in increased amount of low or zero production hours. If multiple, geographically separated production points were utilized, it would increase the probability that at least one location would generate energy during periods of low wind. However, this is disregarded in the study due to the concentration of constructed wind power for that certain area. The wind speed data used in the calculations were imported from the ERA5 [20], and the data was from the exact calculated location. Wind power plants currently in operation in Finland and the calculated capacity-weighted location for the theoretical center of wind power are presented in Fig. 1.



(a) Wind power plants in Finland [18]. (b) Capacity-weighted average location for wind power in Finland.

Fig. 1. The center of wind power in Finland is in Central Ostrobothnia.

A. Wind power simulation

The estimation of wind power production is based on simulations using historical wind data from years 2014 to 2024. This estimate employs the methodology outlined in the paper [21]. For the sake of simplicity, a specific location has been selected, which represents the capacity-weighted average of the wind turbines in operation in Finland. Wind speed and temperature data for this location were obtained from the ERA5 data library covering the years 2014 to 2024. The research leverages ERA5 reanalysis data, as it offers hourly records with a spatial resolution of approximately 13 km by 28 km in the area of interest [20].

The recorded wind speed data can be converted to wind power P using the Eq. 2 as follows:

$$P = \frac{C_p A \sigma v^3}{2} \quad (2)$$

where:

- P is the power output,
- C_p is the coefficient of performance,
- A is the swept blade area,
- σ is the air density,
- v is the wind speed.

The air density in the power calculation formula is temperature dependent. When incorporating the local temperature data, the air density in the simulation varied between 1.1 and 1.4 kg/m^3 . The simulation used a reference for the capacity of a single turbine of 5.5 MW, reflecting the current average installed turbine size [22]. The turbine model is Enercon EP5 III, with a hub height of 166 m and a blade diameter of 160 m [23], [24], as study [25] determined on their analysis that this turbine model provides the most favorable LCOE and is suitable for whole Finland.

In this study, the coefficient of performance C_p was solved from the power equation. The coefficient of performance for wind power represents the ratio of energy extracted by the turbine to the energy available in the wind stream. Here, the coefficient is smoothed by calculating a running average land and then applying a smoothing spline fit. The turbines are set to operate between their designed cut-in and cut-off wind speeds. The cut-in and cut-off wind speeds of the turbine were selected to 4 and 24 m/s , as representing realistic reference values for many types of turbines [22], [26]. The coefficient of performance was calculated for all wind speeds using the power curve of the wind turbine [24].

The coefficient of performance and production for the reference turbine were calculated on an hourly basis. Subsequently, a power factor ranging from 0 to 1 was derived by dividing the result by the reference turbine's capacity. This

power factor was then multiplied by Finland's total capacity, simulating the whole installed capacity in the country. The total installed wind power capacity in Finland was 8,358.4 MW in 2024.

B. Other power production capacities

While inspecting scarcity situations for the entire electricity system, the value reported by the Finnish Energy Authority for the estimated power production capacity was used to describe the amount of other than wind power production capacity. The capacities reported by the Energy Authority incorporate the estimated availability of various types of power plants, and the estimates are based on historical data. This estimate is an up-to-date assessment of the available capacity during frosty windless days in the winter season of 2024-2025. Consequently, the simulated scenario represents a "worst-case-scenario", necessitating a critical examination of the system's adequacy. Thus, it was assumed in the simulations that all the capacity for hydro, nuclear, and condensing power and the electricity production in CHP plants estimated by the Energy Authority can be utilized in every hour. The data is compiled in Appendix A. The table also represents the capacities of power plants registered in the power plant register. The capacities of backup power plants have not been included in the registered capacities.

III. RESULTS

First, the results of the weather analysis examining the frequency and duration of windless days, frosty days, and windless frosty days are presented. Subsequently, wind power production is analyzed in relation to consumption. Finally, the scarcity situations of the entire electricity system and their continuous durations are evaluated.

A. Frost and windlessness

A correlation study was conducted to examine the relationship between electricity consumption and three temperature measurement points: Oulu Airport, Jyväskylä Airport and Helsinki-Vantaa Airport. These locations were chosen to represent different geographical areas of Finland, specifically the southern, central and northern regions. The study aimed to identify the correlations between the temperatures at these measurement points and the overall electricity consumption in Finland. The findings indicated that the temperature readings from Helsinki-Vantaa Airport exhibited the strongest correlation with electricity consumption, with a coefficient of -0.67. This suggests that as temperatures decrease in southern Finland, electricity consumption tends to increase.

The study conducted a statistical analysis of windless moments and frosty days, both individually and in combination. Frosty times are determined here as times

when the temperature drops to or below zero Celsius degrees. The analysis used the temperature measurements from Helsinki-Vantaa Airport and the wind data from the calculated center of wind power. Over the review period, there was an average of 528 hours of complete windlessness annually, equating to approximately 22 days. Additionally, the average number of frosty hours per year was 2012 (83.8 in days). On average, there were 107 hours per year when the temperature fell below freezing without any wind, which is roughly 4.5 days. However, the variation ranged from 2.4 to 7.9 days during the years. The yearly amounts of windless and frosty hours are gathered in Appendix B.

The continuous periods of frost and windlessness were also examined. The longest continuous windless period averaged 21 hours, while the longest continuous frost period lasted an average of 15.6 days. The continuous period of windlessness and frost lasted longest for 15 hours on average. However, the typical durations were considerably shorter. Generally, a continuous windless period lasted 4.1 hours on average, and the temperature remained continuously freezing for an average of 26.4 hours. The average duration of a windless frost period during the review period was approximately 4.3 hours. The statistics of average durations for windlessness and frost are gathered in Appendix C.

B. Overproduction and a need for other electricity production

During the review period 2014–2024, the average annual electricity consumption in Finland was 81.82 TWh. The wind power production estimated in the study was able to cover an average of 22.18 TWh of the yearly consumption, leaving a need for an average of 59.63 TWh of other electricity production.

On average, there was overproduction of wind power for 15.5 hours per year, resulting in an annual surplus of wind power of 4.07 GWh. This refers to the hours and amount of energy when the total hourly wind power production was greater than the total hourly consumption in Finland at that time. However, most of the time wind power production was not sufficient to cover the total electricity consumption on an hourly basis, and on average there was underproduction of 8,714 hours per year. Appendix D presents the yearly values for load and the amount of load covered by wind power, the need for other production capacities, and the yearly amounts of overproduction of wind power.

The plotted net consumption during the review period, where load is diminished from wind power production, is presented in Fig. 2. The plots above the 0-line represent the surplus production of wind power.

C. Scarcity in the power system

When considering the whole energy production mix, including other estimated energy production capacities and

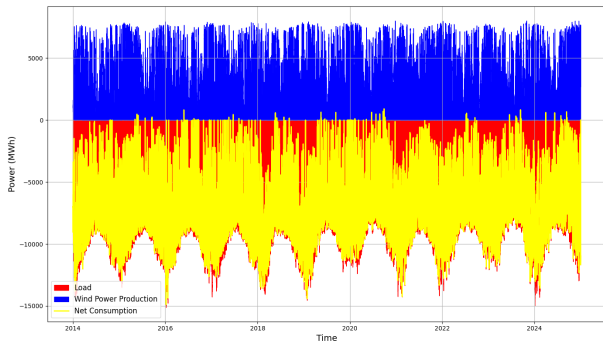


Fig. 2. Load, Wind Power Production, and Net Consumption (= Wind Power Production – Load) in years 2014-2024.

transmission connections to neighboring countries in addition to wind power production, the overall adequacy of the energy system can be assessed relative to power demand. Finland has three transmission connections to neighboring countries: Northern Sweden (1,200 MW), Central Sweden (1,200 MW), and Estonia (1,020 MW).

If the entire estimated available capacity for other energy production produces electricity alongside with the simulated wind power, and all transmission connections are operational, shortages occur in one year, 2016. There are a total of three scarcity hours in that year, which are sequential, resulting in a total power deficit of 325.8 MWh.

D. Sensitivity analysis via N-1 situation

When examining a scenario with transmission connection restrictions, the frequency of shortages increases remarkably. For instance, simulating a situation where a 1,200 MW transmission connection (half of the transmission capacity with Sweden) is unavailable yields to the results presented in Appendix E. While this study uses an interruption in a transmission line as an example reason of power deficit, the resultant power deficit exemplifies a scenario as well in which a major power plant is disconnected from the grid due to maintenance reasons. The average yearly surplus production available for instance for export is 58.4 TWh, but there is also an average of 7.7 hours of shortages per year during the review period. However, it should be noted that in 2016 there were a total of 55 scarcity hours at this capacity, while in several other years, there were no scarcity hours. The average yearly amount of shortage during the review period is 3.95 GWh, with 2016 experiencing a significant shortfall of over 35 GWh.

In Appendix F are gathered the maximum and average lengths of the scarcity periods for the N-1 scenario. The average maximum for the shortage periods was 3.2 hours in the review period. The figure is significantly increased by the value from 2016, when the longest period of scarcity lasted 16 hours in a row. However, on average, the shortage period

lasted 2.4 hours in a row.

IV. CONCLUSION

The temporal adequacy of electrical power and the power balance of the electrical system are timely issues as the share of renewable energy, which can vary rapidly with weather conditions, increases, while electricity consumption rises due to the electrification of the society. In the Nordic countries, windless frosty days pose particular challenges for the electrical system, as electricity consumption tends to increase with intensified frost, but wind power production remains low.

This study investigated electricity scarcity situations in Finland in the period of 2014 to 2024. The analysis utilized historical weather data to simulate wind power production at current capacity levels, and the electricity consumption data was based on historical measurements. Energy Authority's estimates of available capacity was used for other electricity production. Wind power is already a significant part of Finland's energy production mix, as it covers an average of 22.18 TWh, or 27.1% of the total annual consumption, which is 82 TWh annually on average.

Also, the frequency and typical duration of windless frost periods were analyzed in the study. Windless frost periods lasted 4.3 hours continuously on average during the review period. Typically, as frost intensifies, electricity consumption increases in the Nordics, which highlights that when wind power is unavailable due to windless moments, additional energy from other sources is needed.

In scenarios where the current wind power capacity and the estimate of current usable other energy production capacities were utilized, shortages occurred in one year (2016) during the review period. Then, the shortage lasted three hours continuously and the energy deficit was 325.8 MWh. A sensitivity analysis was conducted, where was assumed that one of the transmission lines (1,200 MW) is not in-use. An interruption in transmission connectivity served as an example reason of power deficit. The resultant power deficit could also arise for example from a disconnection of a major power plant from the grid due to maintenance reasons. Under the scenario, shortages occurred on average 7.7 hours per year, with each event lasting 2.4 hours on average. The average annual energy shortage was 3.95 GWh. These values were significantly influenced by the situation in 2016, when record high hourly average power consumption (14.9 GW) was measured during peak winter frosts [27]. The absence of a transmission line led to a 16-hour continuous shortage in the scenario.

The results indicate that with the current production capacity and consumption levels, electricity sufficiency in Finland is generally adequate. However, critical scarcity situations can arise if the system encounters unexpected

losses in transmission or production capacity. Additionally, significant increases in electricity consumption during severe frosts, coupled with weak wind power production, can jeopardize the sufficiency of electricity. The baseline analysis revealed a few hours of scarcity, which could be managed with a storage of few hundreds of megawatt hours of capacity. The findings underscore the importance of investing in energy storage and rapidly adjustable flexible electricity production. This study provides a good estimate of the electricity sufficiency of a wind power-based system using a decade of data. It serves as a preliminary study for subsequent research, which will study the most cost-effective strategies to address possible scarcity situations in the electricity system from both a power system and electricity market perspective.

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APPENDIX A

ESTIMATED POWER PRODUCTION CAPACITY ON A COLD AND WINDLESS DAY AND THE TOTAL CAPACITY IN THE POWER PLANT REGISTER IN MW [28].

Production Form	Estimated Capacity	Capacity in the Power Plant Register
Hydro power	2570	3236
Nuclear power	4220	4369
Condensing power	0	~ 0
CHP, industry	1750	3077
CHP, district heating	2760	3390
Sum	11300	14072

APPENDIX B

THE YEARLY AMOUNTS OF WINDLESS AND FROSTY HOURS.

Year	Windless hours	Frosty hours	Windless and frosty hours
2014	628	1674	115
2015	391	1533	57
2016	686	2117	107
2017	564	1896	139
2018	529	2696	118
2019	498	1759	109
2020	385	1482	59
2021	486	2337	83
2022	609	2347	190
2023	593	2755	138
2024	443	1538	63

APPENDIX C

THE AVERAGE CONTINUOUS DURATIONS FOR WINDLESSNESS AND FROST DURING THE YEARS.

Year	Average duration for continuous windless period (h)	Average duration for continuous frost period (h)	Average duration for continuous windless frost period (h)
2014	4.5	24.3	4.6
2015	3.7	18.5	3.4
2016	4.6	26.5	3.3
2017	4.8	16.8	4.5
2018	3.6	41.5	3.5
2019	3.7	23.5	4.2
2020	3.5	17.6	4.5
2021	4.1	40.3	3.6
2022	5.1	27.3	6.3
2023	3.9	31.7	3.7
2024	4.0	23.0	5.7

APPENDIX D

YEARLY VALUES FOR LOAD, LOAD COVERED BY WIND POWER, NEED FOR OTHER PRODUCTION CAPACITIES, AND YEARLY OVERPRODUCTION OF WIND POWER.

Year	Load (TWh)	Load covered by wind power (TWh)	Need for other capacity (TWh)	Hours of Surplus	Surplus (GWh)
2014	82.48	20.96	61.52	0	0
2015	81.32	24.01	57.31	18	2.88
2016	82.53	19.58	62.95	13	4.65
2017	83.16	21.35	61.81	10	1.65
2018	85.77	21.19	64.58	16	3.52
2019	82.59	22.08	60.51	18	5.6
2020	77.32	23.31	54.01	34	11.79
2021	84.71	24.2	60.51	0	0
2022	79.22	22.11	57.11	15	3.15
2023	78.95	20.03	58.92	23	5.43
2024	81.92	25.19	56.73	24	6.15

APPENDIX E

SURPLUS AND SCARCITY DURING THE YEARS, 1,200 MW OF TRANSMISSION CAPACITY IS INOPERATIVE.

Year	Amount of Surplus (TWh)	Hours of scarcity	Amount of scarcity (GWh)
2014	56.88	8	0.79
2015	61.13	0	0
2016	53.63	55	35.02
2017	56.3	0	0
2018	53.84	3	0.11
2019	56.76	13	4.99
2020	63.38	0	0
2021	57.93	5	2.54
2022	61.32	0	0
2023	59.53	0	0
2024	61.7	1	0.05

APPENDIX F

THE MAXIMUM AND AVERAGE LENGTHS OF CONTINUOUS SCARCITY PERIODS IN HOURS.

Year	Maximum	Average
2014	3	2.67
2015	0	0
2016	16	11
2017	0	0
2018	3	3
2019	7	3.25
2020	0	0
2021	5	5
2022	0	0
2023	0	0
2024	1	1

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