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ORIGINAL RESEARCH

Effect of temperature on seasonal wind power and energy potential estimates in Nordic climates

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Abstract

A major obstacle standing in the way of full-scale adoption of renewable energy sources is their intermittency and seasonal variability. To better understand the power generation dynamics, the effect of air density due to temperature on power and energy generation figures was modelled. The model uses historical ERA5 data and considers changes in weather patterns in a subarctic climate where seasonal changes are most pronounced. The power generation figures of using a mean and a dynamic air density value were compared and the results show that power generation estimates may be under- and overestimated by on average 5% up to 10% in winter and summer, respectively. This can have implications for the sizing of power transmission infrastructure and energy storage in both on-grid and off-grid applications as well as power availability. The topic is highly relevant in the Nordic countries where roughly 10% of new global added wind capacity is installed annually.

1 | INTRODUCTION

Climate change is one of the major challenges of our time. The world is trying to get rid of its dependence on fossil fuels to reduce greenhouse gas emissions. One of the most effective ways to reduce carbon emissions is through electrification and adoption of renewable energy sources, such as wind and solar. There are sectors that cannot readily be electrified with current energy storage solutions, such as aviation and long-distance cargo shipping amongst many others.

Power-To-X is a value chain that utilizes green electricity from renewable sources to generate green hydrogen. It can be used together with captured carbon dioxide to make carbon-neutral fossil fuel equivalents [1, 2]. The European Union has outlined that after 2027 the energy used in the making of green hydrogen cannot come from already existing energy generation capacity, and as a result, new capacity will have to be built alongside new hydrogen plants [3]. Due to the large projected scale of green hydrogen and Power-To-X projects, together with legislation from the European Union, there is reason to believe that a large number of new installations will be mainly off-grid with possible smaller grid connections to act as a source of flexibility. As a result, it is pertinent to understand local wind generation trends to quantify the amount of variety in generation in order to accordingly scale both on-site energy storages and possible grid connections for efficient operation.

It is expected that in 2023 for the first time over 100 GW of new wind capacity will be installed globally [4]. The Nordic countries are heavily invested in wind power, and despite only having around 3.5% of global population, Finland and Sweden together in 2022 installed 8% of all new global on-shore wind power installation capacity [4].

The Nordic countries are sparsely populated with ample space for on-shore wind. Because of the climate and geographical location, the region cannot rely on solar energy for much of the year. Fingrid, Finland's transmission system operator, states in a report that in 2022 they obtained grid connection requests for 340 GW of renewables generation which consists of 200 GW of wind power, of which 150 GW are on-shore installations [5]. Currently, in 2023, the generation sits at around 11 TWh with a total installed capacity of 6200 MW which is expected to grow to 23 GW in 2030 [5]. Finland's electricity consumption in 2022 was 82 TWh [6].

The vast amount of available potential available in the Nordic countries combined with hydropower suggests that a scenario where the Nordic countries become net exporters of energy into mainland Europe is plausible through Power-To-X processes.

As the air density is linearly inversely proportional to air temperature, the consistent seasonal shifts in both temperature and wind conditions provide a strong hypothesis for the inclusion of dynamic air density in power generation estimates. It would provide better understanding of the amount of energy and power available and help in decision making of required infrastructure to support large scale wind installations.

There are three main reasons why it is important to consider peak power when modelling system infrastructure. Firstly, the capacities of transmission lines and transformers are designed according to peak power in order to guarantee supply at all times. Secondly, the supply of power needs to match demand at all times. With seasonal shifts in wind speeds and air densities, the amount of power and energy can vary significantly. Together with the rapid growth in investments of on-shore wind, the absolute amounts of energy and power can vary greatly as seen from the results of this study. Thirdly, the network losses due to high peak power need to be estimated and understood as what they mean to the operation of the grid as the losses scale non-linearly with transferred current.

From the perspective of an energy retailer, the power generation estimates and their associated uncertainties must be known in order to minimize risks in the electricity markets. Increased uncertainty in power availability leads to increased electricity reserves to guarantee that the demand for electricity is met. Increased electricity reserves increase system costs which is reflected to the consumers as on average increased electricity prices. This is becoming more and more relevant when considering large-price areas with significant wind power generation potential such as Finland.

1.1 | The Nordic climate

Subarctic land regions can only be found in the Northern Hemisphere between 50°N and 70°N. Subarctic climates are characterized by long cold winters with short warm to cool summers. The average temperature for the year lies between 0°C and 10°C. In Finland, during an average year, the temperature difference between summer and winter can be over 50°C. The main element in the variability is the sun or the lack of it. Due to being far from the equator, the incoming irradiation is relatively low or even non-existent within the Arctic Circle. During winter, solar energy generation is often not considered due to low hours, low intensity, and the possibility of the panels being covered by snow.

As a result, subarctic regions require mixed generation between wind and solar in order to meet energy demand by renewable means throughout the year. The temperature difference is mentioned as it has a direct relation to air density, meaning that comparable wind speeds between summer and winter will not have the same kinetic energy, which will lead to inaccurate seasonal power generation estimates. Out of the roughly 15 million people that live in the Arctic, subarctic, and boreal regions of the world, one third live in Finland, which makes the topic highly relevant to the Finnish economy [7].

1.2 | Challenges with renewable power in Finland

While solar power has quickly become a very attractive source of renewable energy with rapidly declining costs and ease of installation, it does not perform at its full capacity due to seasonal changes experienced by Finland and other subarctic regions. During summer the production is stable through the long summer days, however, during winter the generation drops to virtually zero due to low or non-existent irradiation in addition to the possibility of the panels being covered in snow. As a result, seasonal storage of energy would be required, which tends to be expensive or alternatively be able to rely on mostly wind power to meet energy needs during the whole year.

Wind energy is a volatile energy resource both in terms of power quantity and timing. It is equally important to understand how much energy is being generated over a certain time frame as it is to understand the generation profile of when the energy is being generated. As more wind power capacity is being installed, the effect on the power system becomes greater. The timing and quantity of generation affects transformers, transmission lines and also demand through demand response which all in turn influence the reliability of the grid. The grid has to be appropriately sized, and modelling plays an important role in understanding what kinds of seasonal loads are to be expected in the future. Through modelling, recommendations can be made on where new installations should be prioritized to optimally utilize already existing grid infrastructure and reduce peaks and troughs to achieve a more base-load-like generation profile from wind.

1.3 | Previous research and research novelty

The effect of air density on wind energy generation has been considered previously mainly due to elevation from sea level [8, 9]. The effect of average temperature increase on wind generation has been evaluated by Miguel et al. [10]. The effect of absolute high temperatures has been studied by Al-Khayat et al. [11].

Ulazia et al. [12] consider the effect of seasonal changes of air density on a global level during the four seasons and gauge the effect on total energy generation numbers. Their results highlight the expected differences in generation averaged over periods of three months which does not focus on peak current loads and durations in those time frames nor differences in wind conditions between the seasons. While they identify that temperature does have an effect on the energy generation seasonally, it does not comment on the peak powers and their effect on the attached grid over a longer time period. This is further discussed in Section 4.3.

It is important to note that this paper does not seek to predict future weather conditions or short-term wind power production. Instead, the focus is on time series analysis which relates to the long-term planning of the energy system. The ERA5 dataset provides a robust global weather data set with a long history (more in Section 2), which can be utilized in the creation of long detailed time series which are important for assessing the performance of future new power generation capacity, especially in an off-grid context. Temperature dependent air density could be utilized as an additional variable in improved forecasting models. Li et al. (2023) discuss the pros and cons of different forecasting methods and propose the use of machine and reinforcement learning together with large data sets of weather data in ultra-short-term forecasting of wind power generation [13]. This is useful for predicting loads on the grid to enable better control of the system. Robust state estimators can help mitigate data-related uncertainties, resulting in models less dependent on parameter choices as outlined by Chen et al. (2015) [14]. Combining these methods are highly relevant in building a full operation model including complex control dynamics. Such empirical models are data-intensive and thus well-suited to very specific problems, but they differ fundamentally from the physics-driven model applied in this work for highlighting the effect of air density on power values.

The added value of the present study comes from demonstrating the interannual differences in the air density due to temperature, which is the main contributor to the change in the air density. When modelling energy systems in the future, both on grid and off grid, the wind generation should take into account the temperature trends at each location individually in order to gauge loads on the networks, as discussed in the introduction. In the past, the addition of new renewable energy generation capacity has been straight-forward due to low overall penetration of renewable energy in the energy mix. However, with increasing shares of renewable energy, periods of over- and undersupply are becoming more prominent. The seasonal differences in wind speeds (Section 4.3) are significant leading to swings in power generation further amplified by the change in air density. The effect is global where seasonal variations in temperature are observed, however, has not been previously documented at this resolution.

When considering a national grid or an off-grid network, the short-term delivery of power and energy play an important role and need to be understood for effective dynamic operation. Weather is dynamic and intermittent, and therefore, it is also pertinent to study the differences in generation at an hourly resolution over many years to better understand wind generation dynamics and the requirements for energy storages or supporting solar power generation. As much as the grid is stressed by moments of oversupply, the consumers are stressed in times of undersupply. This is highly relevant in a country where energy supply is said to double by 2030 [5] mainly driven by wind power installations as outlined in the introduction.

The results highlight the importance of using local air density distributions for estimating wind power. Often when browsing literature, one may notice that a constant 1.225 kg/m^3 is often used [15, 16]. The different air density distributions for reference locations used in the study are discussed in Section 4.2 and as can be seen, there can be significant deviations from what is often considered a standard air density value. The locations chosen for the analysis for this paper display a range of roughly 1.1 to 1.4 kg/m^3. In some wind intermittency risk as well as grid impact analysis the direct impact of air density on power availability has been excluded altogether [17, 18].

In much of the world, the seasonal temperature difference is too low for the variance in air density to significantly affect the seasonal generation. In addition, in many locations where significant enough temperature differences do occur, either the population density or economic cost have not made large-capacity wind installations relevant, such as Northern Canada or Russia, where alternative energy sources are available. Globally, solar is foreseen to provide the lowest cost of energy and dominate the energy generation sector in a lot of the world [19], however, due to extreme seasonal shifts solar and short-term battery solutions cannot solely be relied on in subarctic climates.

2 | DATA

Several locations in both Europe and Finland were chosen to both provide context and highlight the value of the research for the Nordic countries. A period of eight years (2015–2022) was used to evaluate the differences in energy and power generation that exist during the years when comparing variable and constant air density. The ERA5 dataset was chosen for the wind speed and temperature data. More about the selection in Section 2.1.

Figure 1 depicts the different steps to obtain a final power output reading from the model. Some assumptions have been made regarding the parameters used in the analysis.

2.1 | ERA5 reanalysis

One of the main challenges with weather forecasting and modelling is the availability of data across many years and locations, especially across borders. Countries may have publicly available data that is accurate, but due to different approaches and different data-keeping methods, combining these data sets can be a challenge. The sources of data also tend to be found near population centres which are not always suitable sites for new wind turbine installations. The ERA5 reanalysis data set is attractive as it covers these points.

ERA5 is an atmospheric model provided by the Copernicus Climate Exchange Service and the European Union that utilizes data assimilation to generate a high-resolution model of the atmosphere on the hourly scale [20]. ERA5 is an attractive dataset as it is free and open-source, thus easily accessible. The dataset covers the whole globe and as a result, is a great candidate for wind potential modelling as the results can be applied anywhere. The data come with 0.25° resolution which equates to a roughly 13 km × 28 km grid between the 60° and 70° longitudes.

ERA5 wind speed reanalysis data has been compared with other data sets, mainly MERRA-2, and has been generally found to be more accurate in wind speed modelling applications [20–22]. As the comparison of data sets has been already performed, rather than comparing all the available data sets with each other the ERA5 measurements were validated to our area

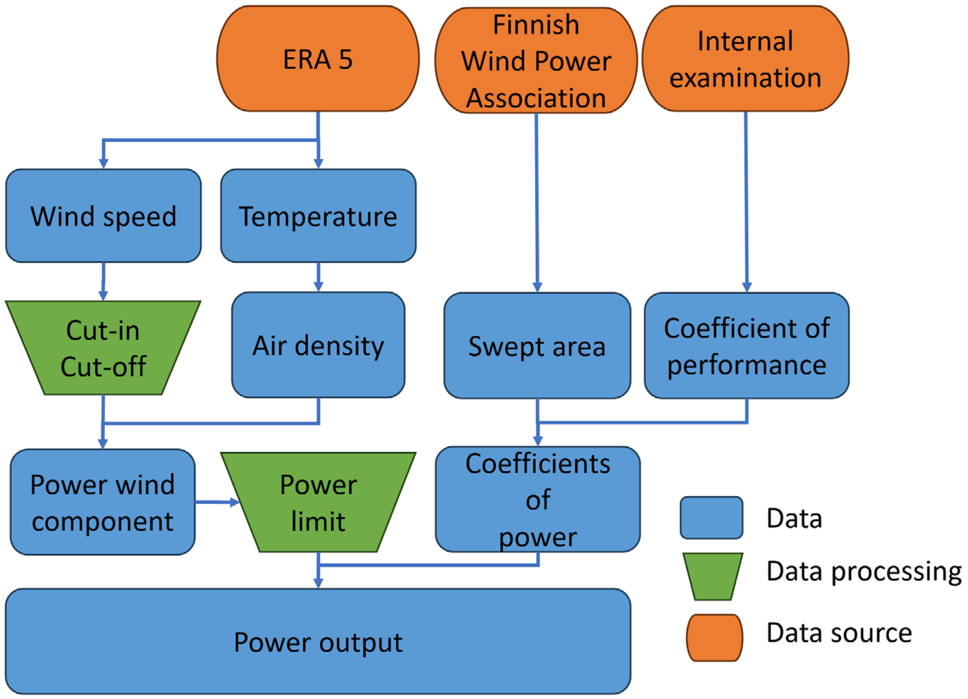

FIGURE 1 Representation of data and analysis method.

and climate of study. The aim of the comparison is twofold. Firstly, to establish that the ERA5 wind data does indeed match well with the wind speed data provided by the Finnish meteorological institute (FMI). Secondly, to showcase challenges in data in making numerical analysis of complex phenomena that are heavily parameter and data-reliant. The focus is on showcasing trends and their expected seasonal amplitudes rather than making specific predictions. Data kindly provided by FMI was used in the comparison.

2.2 | Finnish Meteorological Institute LiDAR measurements

Finnish Meteorological Institute (FMI) utilizes wind speeds retrieved from Doppler LiDAR measurements as part of the Finnish remote sensing network [23] operated by FMI. At Kuopio and Sodankylä measurements were carried out with Halo Photonics Stream Line Pro Doppler LiDAR. At the Helsinki location a Halo Photonics Stream Line XR Doppler LiDARwas deployed. The Halo Photonics Stream Line XR is a fully scanning 1.5 μm fibre-optic doppler LiDAR [24], while for the Pro version scanning is limited to elevation angles > 70° due to not having any moving parts on the outside.

The Stream Line Pro Doppler LiDARs were configured with a velocity azimuth display (VAD) scan at 75 elevation angle every 10 min at Sodankylä and every 15 min at Kuopio. The Doppler LiDARs at Helsinki was configured with 70° elevation angle VAD scans every 15 min. Data from 101 m from Kuopio and Sodankylä in addition to data from 98 m in Helsinki was provided. Horizontal wind speed and direction were retrieved from the VAD scans following Browning et al. [25]. Previously, winds retrieved from Halo Doppler LiDARs have been shown to compare well with anemometer observations [26] and have been utilized also to evaluate reanalysis performance over Baltic Sea [27].

The locations for comparison in Finland were selected based on the availability of wind measurement data from approximately 100 m height from FMI. With the variety of the weather conditions of the selected locations, understanding can be built of how the ERA5 dataset operates in subarctic climates of different types in the context of wind power generation.

2.3 | Reference locations in Europe

The temperature and air densities of six different locations in Europe were compared. Four locations found in Continental Europe and one in the North of the United Kingdom were chosen as reference locations to provide context for the research. The locations were selected to provide a holistic view of different locations where wind farms are already installed in Europe and contrasted to Pyhäjoki (FI) around where most of the currently installed wind capacity can be found in Finland. The locations are followed by their respective 2-letter country code.

Orkney (UK) is famous for its wind energy generation and has recently made a lot of headlines as the renewable energy island. In Schleswig-Holstein (DE) Germany's largest on-land farm can be found right at the border with Denmark. Sevilla (ES) was specifically chosen to represent a warmer climate while having adequate wind resources. Munich (DE) was chosen to represent data points more in-land while still remaining in a zone of adequate wind energy resources. Bretagne (FR) was also selected because of its favourable wind conditions. The exact

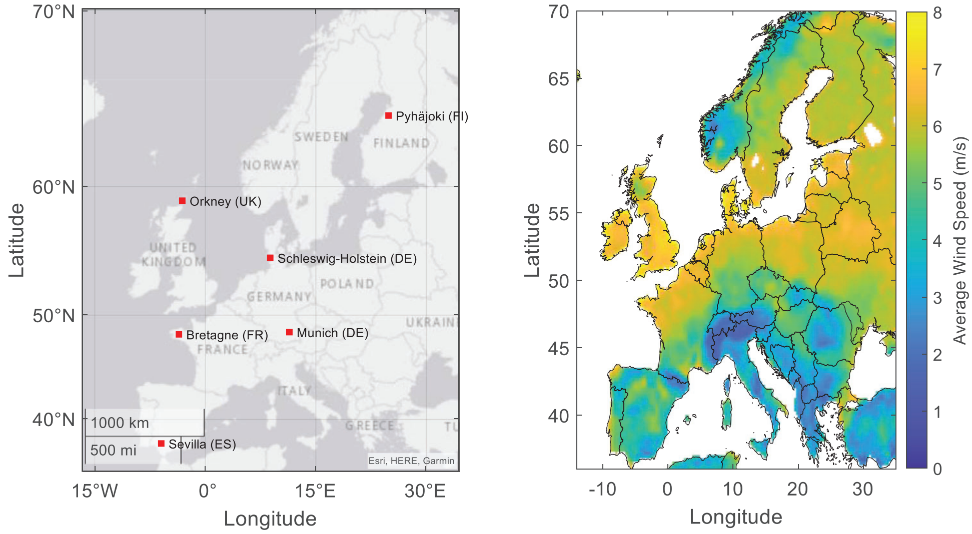

FIGURE 2 Exact locations of the European reference cases (left) and average wind speeds in Europe between 2015 and 2022 (right) [28]. The names of the locations are followed by their respective 2-letter country code.

locations can be seen in Figure 2 together with average wind speeds of the locations between 2015–2022.

3 | METHOD AND PARAMETERS

The current trend with wind turbine installations is to build bigger and taller. Currently, the mean installation size of turbines is around 5.5 MW [29], however, the bulk of new planned installations are 7 MW installations [30]. The model uses an approximation of what a typical 6 MW turbine could look like while still focusing on highlighting the effect of the air density on power generation by simplifying some parameters.

For simplicity, the theoretical kinetic energy contents of the wind using wind speed data measured at 100 m as well as temperature data measured at 2 m are used. The exact temperature at hub height is tough to estimate, however, the surface temperature should act as a reliable proxy of the changes occurring at hub height in the long term as in the short term the experienced temperature depends on the angle of the incoming wind.

The coefficient of performance for wind turbines describes the ratio of energy extracted by the turbine relative to energy contained by the wind stream. Exact values for the coefficient of performance are difficult to obtain from open literature especially for newer turbines as they are often only known by the wind turbine developers. For this work, an average power coefficient was estimated from a database containing several turbines [31]. The power coefficient was estimated in segments for wind speeds ranging from 0 to 26 m/s. The coefficient is smoothed by calculating a running average land then applying a smoothing spline fit. This approach can be thought to give a better approximation for larger geographic areas where multiple different turbine types have been employed. Even better approximation could be obtained if the exact type of turbine were known with certainty and calculated separately, but this is a level of detail that was deemed out of scope for this work.

Wind turbines are designed to operate between a certain range determined by the cut-in and cut-off wind speeds. The cut-in and cut-off wind speeds of the turbine were set at 4 and 24 m/s, respectively as they represent realistic reference values for many types of turbines in our power range [29, 30]. The generation capacity of the turbine was capped at 6 MW. It is important to note that the amount of generated energy is highly theoretical and it is expected that there are additional losses present.

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

The density of air σ consists of four parameters: air pressure p, dry mass of air m, the Boltzmann constant k_b and the temperature of the air in degrees Kelvin T as seen in Equation (1).

$$P = \frac{C_p A \sigma v^3}{2} = \frac{C_p A m p v^3}{2 k_b T} \tag{2}$$

The energy generation P from a wind turbine depends on the wind speed v, swept blade area A, air density σ and the turbine coefficient of performance C_p. The cut-in and above the cut-off speeds are taken into account in the coefficient of performance. The power values above 6 MW were rounded down to 6 MW. The effect of icing is not considered in this paper. The power equation can be seen in Equation (2).

Two sets of power generation values were calculated with different air densities: constant and variable based on ERA5 data and Equation (2). The constant set utilizes a constant air density value obtained for each location from the mean of the 8 year data set. The constant set is used as the reference. The variable set utilizes a temperature data series from 2 m in an hourly resolution to continuously estimate the air density to match the wind speed time series.

3.1 | Limitations

As per with any model there are limitations linked to the study. Firstly, the resolution of ERA5 is limited to $0.25° \times 0.25°$ which covers a region of roughly 13 km × 28 km. The wind conditions between two neighbouring areas can be different due to geographical features directing air currents differently. Surface roughness also plays a role in how wind currents behave. As a result, the results of each location are not absolute as the turbines may be installed geographically close by to the ERA5 data source location but may be hidden behind some significant geographical feature which may alter wind patterns. The research does not take a stance on where to install new wind turbines and seeks to simply highlight the effect of the climate on power generation numbers.

Secondly, there are no reliable data sources of temperature from 100 m elevation. A dataset from already existing wind turbine farms with temperature readings from the top of the turbines could be used for further study. Many wind farms are however reluctant to provide such data. The ERA5 dataset that relies on pressure levels is able to provide temperature data from pressure levels that would equate to hub height elevations but due to varying surface elevation levels, it can be hard to make sure the pressure levels match real hub height at a specific location. Temperature data from 2 m height acts as a good enough of a proxy for this research to highlight the effect of temperature on power generation. A challenge with this is that the temperature at hub height depends on the vertical direction of the wind column. At higher elevations, the air tends to be cooler, while closer to the surface the air tends to be warmer. Exact measurement data from the desired hub height would be required which is a challenge in itself.

Thirdly, the wind speed resolution is at an hourly level which is enough for total energy generation estimates. However, due to the poor resolution system balancing within the hour cannot be studied. Gusting is also ignored which may in some cases lead to the shutting generation of the turbines, especially in the coastal areas which affect the total generation of a turbine over time.

Fourthly, ERA5 data is reanalysed data and is not real measured data. The data was compared with measured data from FMI to validate the data set for Finland. A long-term comparison of the data is not within the scope of this paper and has been performed prior over the Baltic Sea [15, 16]. Some samples were analysed to try and observe biases in the data.

Overall, the main challenge in building a time series power estimation based on weather data is the susceptibility to parameter choice. Wind farm operators do not openly share their generation values and thus the output of a model may not be perfectly verified. The role of this paper is simply to highlight the effect a dynamic temperature-dependent air density can have on the results of a model. Work is ongoing to build a full power estimation model and will be the topic for a future publication where model implementation of all of the factors mentioned above will be discussed in detail.

Lastly, this research aims to provide groundwork for further research into the most favourable regions for wind farm installations while considering the effect on the transmission infrastructure and power potential. The overall trend of wind turbines is that they are growing larger and taller but at the time of writing not much information on for example the power curves of 6 MW turbines are available. The coefficients of performance are often kept a secret by manufacturers and are hard to obtain for newer models. Some assumptions had to be made regarding the coefficient which was discussed in Section 3.

4 | RESULTS

In this section, the ERA5 reanalysis data is validated for Finland with a comparison made with the LiDAR measurements from FMI. It is followed by an overview of the air densities present in the reference locations as well as in Finland. Finally, the differences in power generation are visualized and in the case of Finland quantified and discussed.

4.1 | Evaluating ERA5 in Finland

The locations in Finland were chosen for two main reasons. In addition to having concrete measurement data from FMI to use as a comparison, these locations offer a wide view of the different weather conditions experienced in Finland. It is worth noting that the distance between Helsinki and Sodankylä is over 800 km.

Helsinki is located in the very South of Finland right at the border of the Subarctic and warm summer humid continental climate zones. On average, it is much warmer than the rest of the country together with other coastal areas in the South and South-West.

The other locations are all found in the Subarctic. Pyhäjoki is located in the North-Ostrobothnia region which is home to the majority of currently installed wind capacity in Finland. The region has favourable coastal wind conditions, low population density as well as easy installation sites. Kuopio is located inland in the northern parts of the Lake District providing insight on more continental weather patterns. Sodankylä in the north is located in the region with the most installation potential and often experiences Arctic winds and extremely cold conditions. The exact locations can be seen in Figure 3a.

In Figure 3b–d, some samples were taken from different locations to firstly show the coherence of the ERA5 data and measured wind speed data by FMI at nearby locations. Secondly, to showcase some challenges with the data. Low-level jets are tricky and are known to cause lower-than-expected values in models [22]. Both MERRA-2 and ERA5 are known to have small negative biases at lower wind speeds in the range of 1–2 m/s [32] which can be observed in Figure 3b.

In sample (d) from Sodankylä, while the average wind speeds match well when dealing with time resolutions of 1 h, a lot of information about gusting is lost on its effect on total power generation. In some cases, the gusting could be enough to vouch for a turbine or farm to be turned off to avoid damaging the turbines which would dramatically affect total generation numbers

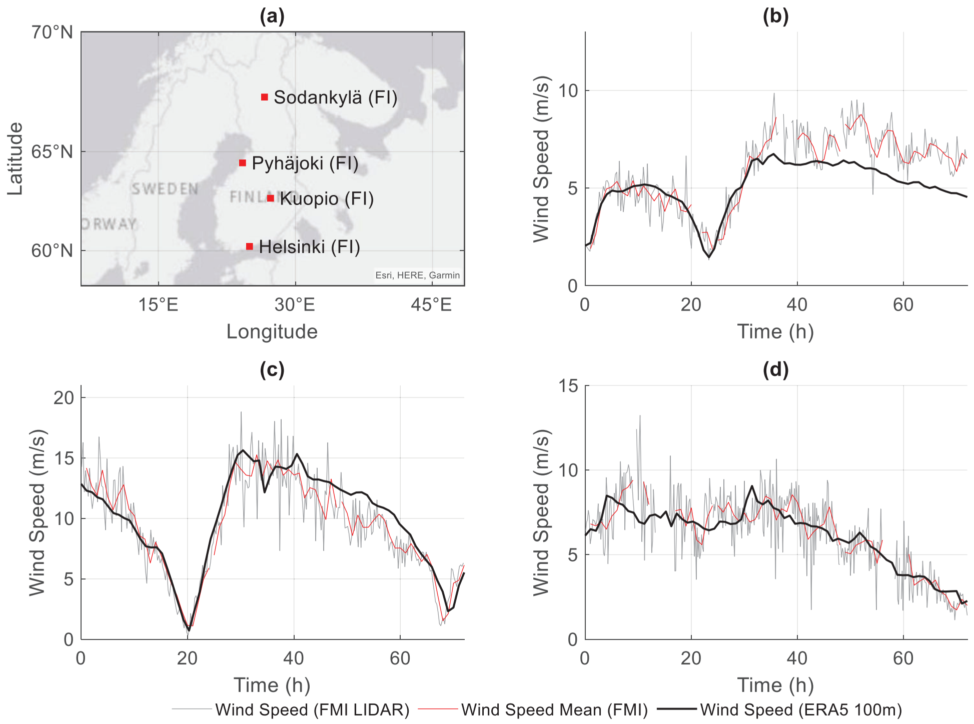

FIGURE 3 Exact locations of selected comparison points in Finland (a) with three sets of wind speed samples from FMI compared with ERA5 wind speed data (b–d).

especially on the system level. The effect of gusting on national energy generation is a topic for further research.

4.2 | Reference locations

The different air density distributions for all of the reference locations from 2015 to 2022 are seen in Figure 4. The larger the temperature difference during the years is, the larger the span of the distribution.

Orkney, as it is surrounded by the sea, experiences less temperature variation during the year and as a result, the air density distribution will be sharper than elsewhere. Sevilla is on average much warmer than the other locations and as a result the distribution is shifted greatly to the left. This has an immediate effect on energy generation compared to other locations with cooler climates and similar wind speeds. Bretagne has a similar distribution shape as Sevilla but is shifted to the right due to a cooler climate. As we go geographically northward the distribution starts to spread as the temperature differences increase during the year. What is interesting to observe in the Schleswig-Holstein and Pyhäjoki figures is that a clear double peak is present. The trough of the peaks is found at the air density which corresponds to 0°C. They are also the only two locations where temperatures consistently can be found below freezing. While there is temporal symmetry in the distributions due to the imbalance in the measured wind speeds between seasons (discussed in Section 4.2) the lower density air during the higher wind speed months amplifies the generation further. Opposite is observed in the summer months when wind speeds tend to be lower, the effect of lower air density further amplifies the difference.

Figure 5 depicts the intra-annual difference at all of the reference locations. In every location during the winter months the estimated wind generation is underestimated while during the summer months the generation is overestimated when using a constant air density as opposed to a variable air density. The difference between the estimates is more pronounced in locations where the temperature difference between seasons is broader.

Figure S1 provides insight into the inter-annual differences in the longer term. In locations that experience a more extreme temperature range as a result may have larger differences in generation between years.

What is worth noting is that while the percentage difference between locations may be small, in a place like Orkney, due to the massive amount of available wind resources a smaller percentage difference in air density may still lead to a larger swing in absolute wind power generation. While the focus of the work is to highlight the effect of temperature on peak power in subarctic climates, this also has implications for the rest of Europe where all of the locations except Orkney reach 5% misevaluation of power in both ways.

4.3 | Finland

The different air density distributions for the reference cases in Finland are seen in Figure 6. The distributions are wide, rang-

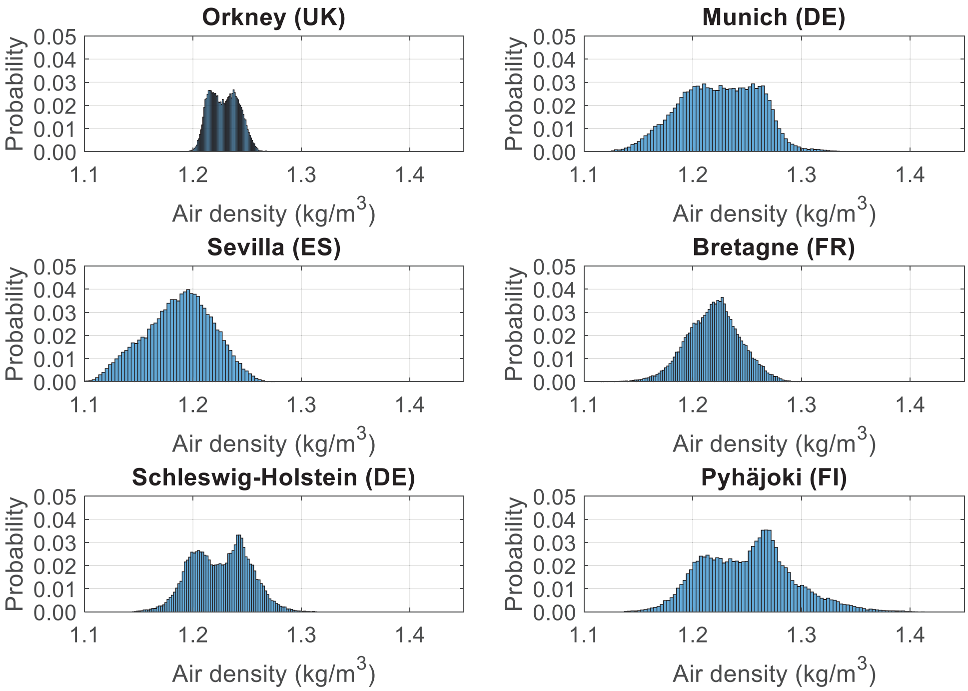

FIGURE 4 Air density comparison of the reference locations (2015–2022).

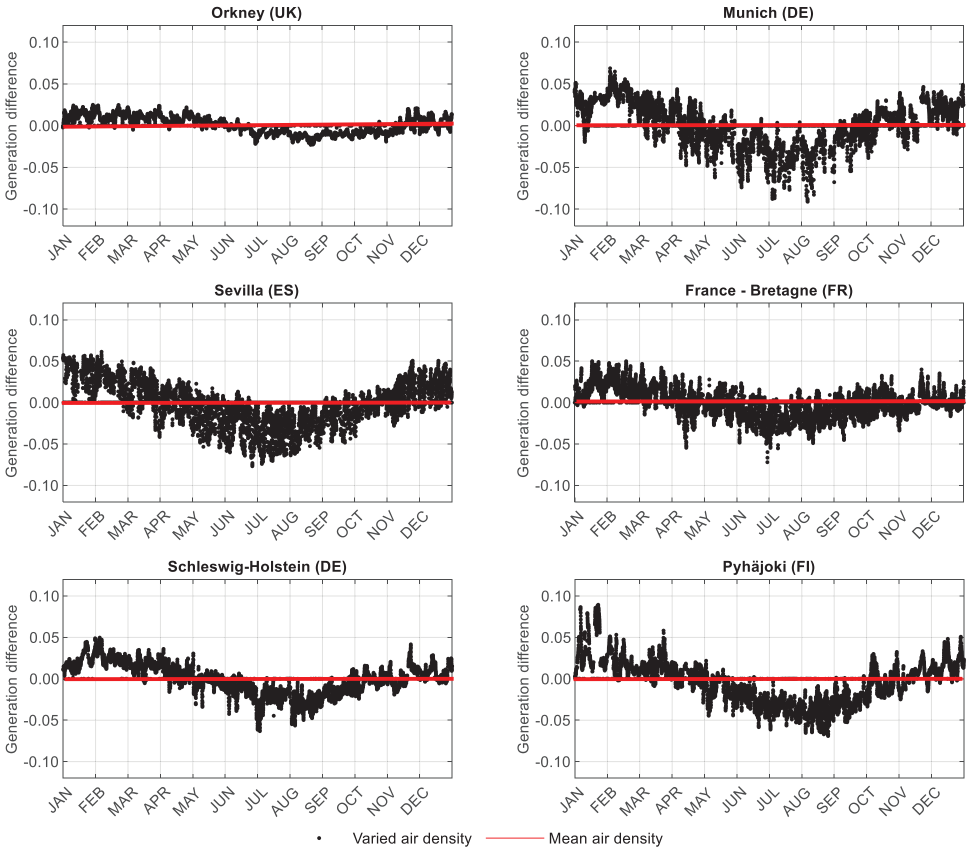

FIGURE 5 Comparison of energy generation between using a mean value for air density and varied air density dependent on temperature for one sample year for the reference locations (2015).

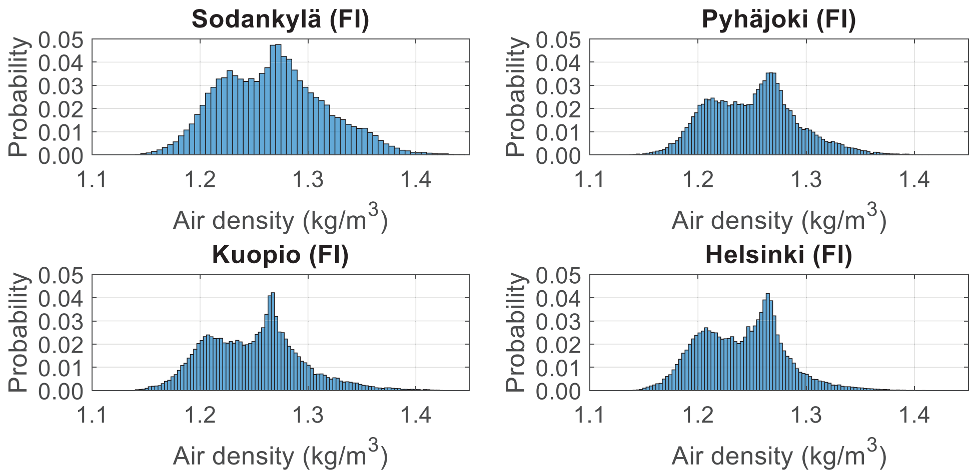

FIGURE 6 Air density comparison of locations in Finland (2015–2022).

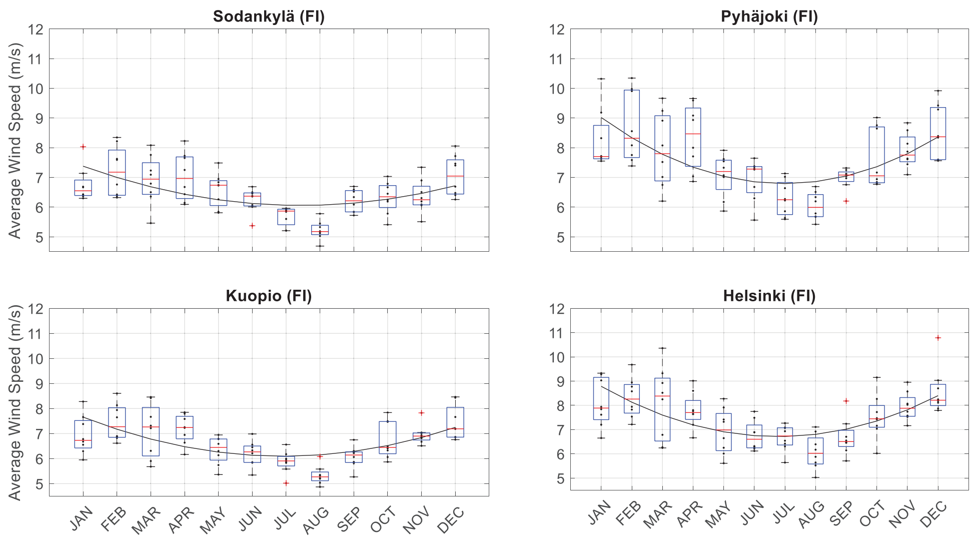

FIGURE 7 Wind speed comparison between locations in Finland (2015–2022). The red centre line denotes the median value (50th percentile), while the blue box contains the 25th to 75th percentiles of the dataset. The black whiskers mark the 5th and 95th percentiles, and values beyond these upper and lower bounds are considered outliers, marked with red dots.

ing from as low as 1.14 to 1.42. Sodankylä is, on average, the coldest location, and as a result, experiences the widest distribution of densities. Although Pyhäjoki is located marginally more North than Kuopio, it is located near the sea, which has a damping effect on the extremes. As a result, Kuopio's distribution is marginally wider due to experiencing more continental weather patterns. Helsinki is the southernmost location, and the distribution is also the narrowest; however, still wider than any of the reference locations.

In Figure 7, the average wind speeds between different months are compared between the four reference locations in Finland. The data consists of data from eight different years and what can be seen is that systematically the winter months have better wind conditions than during the summer. The largest fluctuation between years is also observed during the winter months.

The intra-annual differences in generation between the two power sets are observed in Figure 8. The start of the year experiences large swings in temperatures that can be observed in all four locations and highlights the effect of temperature on power generation.

Years can differ greatly as seen in Figure S2. The winter of 2020 was milder than others and as a result the difference in the generation also differs less than in the other years. This highlights the fact that there is variation between the years and estimates should not be made on the windiness or temperature distributions of a single year. As with the reference locations, the whole eight years were studied to display that the phenomenon is not simply occurring in a single year.

Table 1 shows the monthly breakdown of all of the locations in Finland for the whole 8 year timeframe used in the analysis. The percentage values are obtained from comparing

TABLE 1 Numerical values of the locations of Finland comparing the monthly generation difference between power calculations using a variable and mean air density. The mean difference refers to the monthly average difference over all of the eight years used in the study. Max refers to the maximum observed difference which is interpreted as by how many percentage units during an individual hour the generation would have been underestimated by. Min refers to minimum difference which is read as the largest overestimation of power generation. The colour of the cells ranges from blue to red where blue depicts underestimation while red depicts overestimation of power by respective percentage.

	Sodankylä (FI)			Pyhäjoki (FI)			Kuopio (FI)			Helsinki (FI)		
	Mean (%)	Max (%)	Min (%)	Mean (%)	Max (%)	Min (%)	Mean (%)	Max (%)	Min (%)	Mean (%)	Max (%)	Min (%)
January	4.5	12.4	0.0	3.4	9.0	0.0	3.2	9.4	0.0	2.5	7.2	0.0
February	2.5	8.1	−0.1	1.8	6.0	−0.2	2.0	7.6	−0.4	2.1	6.6	0.0
March	1.0	7.2	−2.1	1.3	5.3	−0.9	1.4	6.4	−1.4	1.7	5.9	−0.6
April	−0.1	2.9	−2.4	0.2	1.9	−2.9	0.3	3.3	−2.3	0.4	2.7	−1.9
May	−1.6	1.8	−6.9	−1.1	1.4	−4.5	−1.3	1.1	−4.6	−0.9	2.1	−4.0
June	−2.3	0.0	−7.4	−1.8	0.2	−5.0	−2.1	0.0	−6.5	−2.0	0.0	−5.2
July	−2.8	0.0	−6.6	−2.4	0.0	−6.0	−2.1	0.0	−7.9	−2.5	0.0	−7.2
August	−2.5	0.0	−8.5	−3.0	0.0	−6.7	−2.4	0.0	−6.6	−2.2	0.0	−6.3
September	−2.4	0.0	−7.1	−2.1	0.3	−5.2	−1.8	0.0	−4.6	−1.9	0.6	−4.2
October	−0.1	2.4	−2.7	−0.5	2.5	−3.3	−0.3	2.5	−3.2	0.3	3.4	−3.4
November	0.9	6.4	−1.6	0.2	3.1	−2.5	0.4	2.7	−2.1	0.4	3.5	−2.2
December	2.7	9.2	−0.2	1.3	5.5	−0.5	1.2	4.1	−1.3	1.1	5.5	−1.3
Average	0.4			0.0			0.1			0.1		

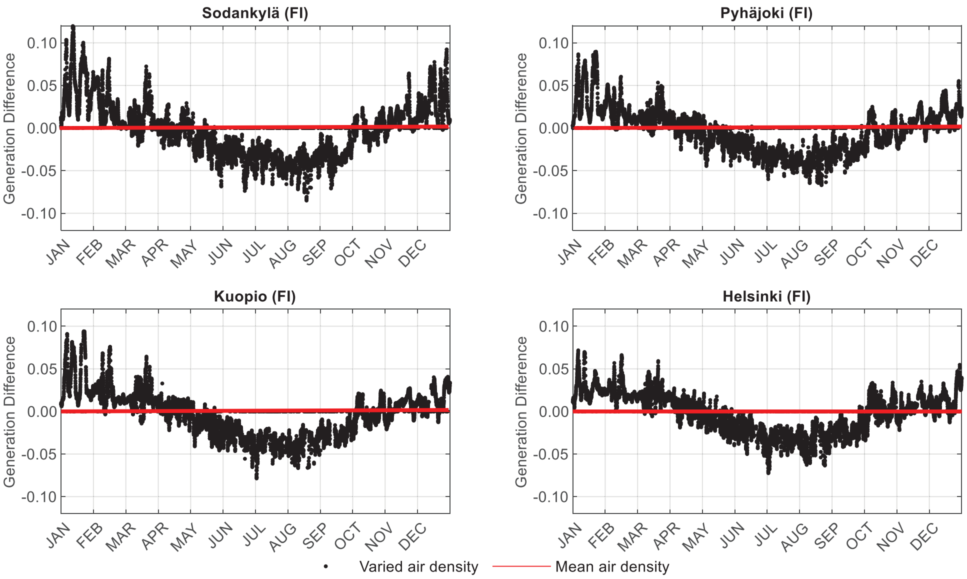

FIGURE 8 Comparison of energy generation between using a mean value for air density and varied air density dependent on temperature for one sample year for the locations found in Finland (2015).

the power values using the variable air density value with the constant mean. These values are of interest to us as previously mentioned as the design of grids and transmission lines are made with the maximum power transmission values in mind. While the number of hours where the maximum differences are obtained reduce quickly, they provide insight into required infrastructure considerations to withstand said loads on the grid. As anticipated, on the annual level the differences even out. In all four locations of Finland an energy generation increase of less than 0.5% is seen on the annual level.

The locations in Finland experience much greater difference than the reference locations during the year as seen in Figure 9. Around 20% of the time the generation is over or underestimated by over 5% with peaks of around 12%. Around 20% of the time it does not matter which air density is used as they will yield similar results either due to the wind speeds being below the cut-in speed or due to the air densities matching mostly in spring and autumn.

Due to the transformers and grid connections being sized for the maximum output of a wind farm, at the wind farm level no changes may be required to deal with the effect of increased air density on wind power generation. However, when looking at the grid as a whole, larger areas may reach the rated output of a wind farm simultaneously. This can lead to curtailment of power due to grid side limitations. Possible solutions to combat this is to have a battery buffer at the site of generation which is capable of absorbing some generation during times of high supply and over time releasing that power back into the grid in times of low generation which comes with additional costs. On the other hand, the output from the storage system could be timed to obtain a better price for the generated power on the electricity markets.

It is likely that in the future we will see completely off-grid industrial sites that generate their own power. In applications where a constant feed of power is required, the understanding of seasonal variance, power and energy availability is crucial for operation. Energy storages play an important role but also an expensive role.

5 | CONCLUSIONS

With an increased share of renewable energy sources powering the grids, it is important to understand not only the total energy generation from a site over the period of a year but also the timing of when the power is available. In subarctic climates where the temperature has a great effect on the air density, we have to take this into account when estimating the power generation seasonally. This should be combined with work on estimating the effect of dispersed generation to have as constant of a base load as possible from dispersing the generation from a single weather event.

There is a great incentive from the electrical system perspective to keep the number of peaks in power generation but also consumption as low as possible to reduce system-level losses. One of the big challenges of the future of national grids is how to deal with the intermittency from renewable energy sources.

The differences in generation of all of the locations considered were highlighted in Figure 9. The locations in Finland all can be found experiencing much greater swings in generation than the reference locations more in the south. In Finland, it can be seen that around 10% of the time the summer is overestimated by more than 5% and up to around 13%. In winter, a similar result is seen that for roughly 10% of the time the energy generation is underestimated by 5% to 13%. Only around 20% of the time there is practically no difference between using a fixed and a variable air density value. These are likely times of low or no production. On the annual level it can be seen that

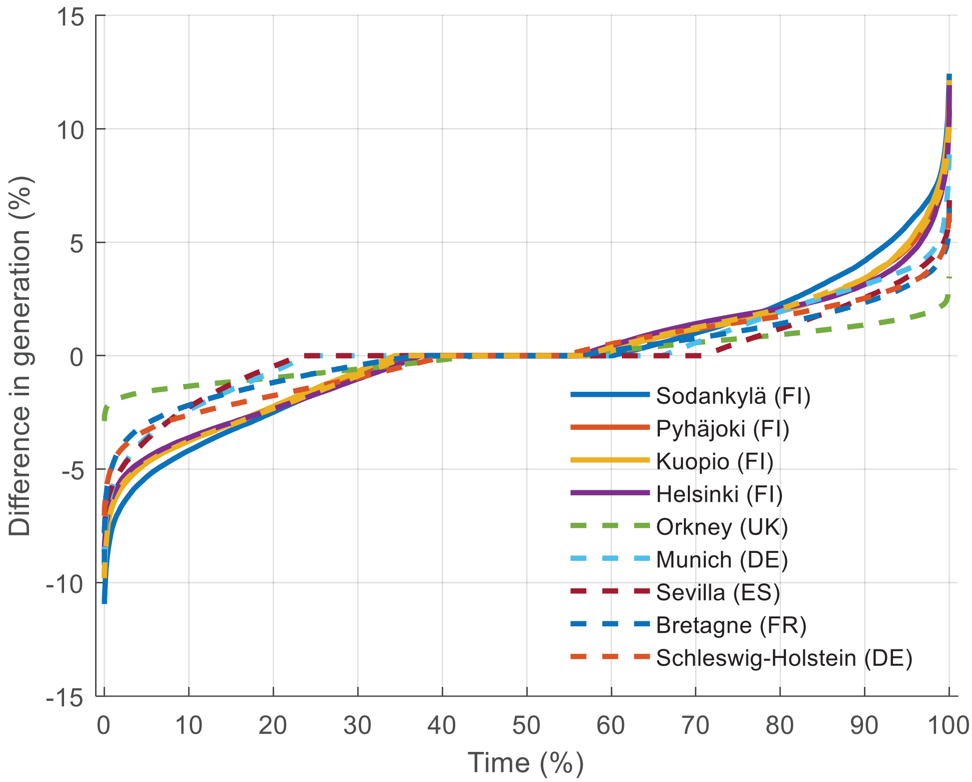

FIGURE 9 Generation difference curve between the locations in Finland (continuous) and the reference locations (dotted) (2015–2022).

due to the symmetry of gross numbers of generated energy, a fixed air density using the mean of air density distribution can be used.

When applied on the national level a 10% difference in generation is highly significant in managing and operating the grid. It would be a significant financial blow if the grid were oversized or undersized by the 10% that was estimated. Historically renewable sources of energy have only played a small role in the total generation of grids but that is changing. As outlined in the introduction, massive investments are made especially into wind power and in a near future where wind energy dominates the energy share, these swings will not go unnoticed.

The output of an individual wind farm is capped at the nominal capacity of the farm meaning that on the farm level, no changes may be required if the energy generation is different from anticipated. However, on the network side investments must be made to handle larger swings in power generation. Storages in the form of both electricity and heat play a large part in efficient operation when looking at the greater system, especially off-grid. The system itself must also adopt ways to utilize power flexibly when it is available through demand response. Hydrogen production could be a valid flexible way to regulate the grid and also act as a variable large load at the sites of generation.

Further investments must be made on the network planning side to reduce the stress on long-distance power lines. Planning should be made to evaluate other sites than on the West Coast in order to have a more baseload-like generation profile.

The main message of this work is that the inclusion of variable air density due to temperature is relevant in most places of the world but even more so in subarctic regions where the differences in temperature are much greater between seasons. While the results may not be relevant from the perspective of how much energy is produced annually it is highly relevant in the sizing of electricity grids and when considering energy storage to combat the intermittent nature of wind power generation both in the shorter term as well as between seasons.

5.1 | Future work

Air density plays an important role in the estimation of wind energy and power generation. The next steps focus on estimating the value of dispersed energy generation from the system and market perspective. Currently most of the installed capacity can be found in a single geographical area due to numerous limitations. As a result, wind power generation is rather homogenous in nature. With dispersed generation it is expected that the times of high energy prices can be reduced. An aim would be to evaluate the best sites for investments to provide balance for the grid from the electricity market perspective. The inclusion of the seasonal shifts studied in this paper will play a significant role in the evaluation of the best sites.

With the current trend of increased average temperatures with extreme weather events becoming more common, it would be of interest to study the effect of weather pattern trend on power generation and timing from wind in the long term over a specific geographical area.

AUTHOR CONTRIBUTIONS

Salmelin Markus: Conceptualization; data curation; formal analysis; investigation; visualization; writing—original draft; writing—review and editing. **Karjunen Hannu**: Methodology; resources; supervision. **Lassila Jukka**: Methodology; supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the authors on request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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