Future Potential Impact of Wind Energy in Sweden's bidding area SE3

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Abstract

This research addresses the potential for increasing wind power in Sweden's bidding area SE3. Sweden currently faces an energy imbalance, with larger production in the north and high demand in the south. Four bidding areas were introduced to incentivize energy production in the south. SE3, the largest bidding area, represents 60% of total demand. Using Seasonal Auto-Regressive Integrated Moving Average (SARIMA), historic data analysis from 2007 to 2022 is forecasted to a medium long-term future of 2035. Forecasting the observed trends reveals a potential supply deficit even under minimum demand growth scenarios made in literature. Closure of nuclear plants contributes to the shortfall, and the increasing trend in solar and wind power falls short. To study the impact wind power can have, the monthly wind patterns are analyzed, and used to calculate the power potential of different turbine capacities. Offshore areas show the highest potential for increasing wind power capacity in SE3. Economic factors, like payback time, are considered. The research concludes that there is technically and economically viable potential for wind power capacity to address the demand-supply gap by 2035. However, it depends on permitted areas, excluding built areas, UNESCO sites, and fishing routes. Future research should further explore these restrictions and address the seasonal variability in wind power to improve the understanding of the potential for wind power in the SE3 bidding area.

1 Introduction

Swedish electricity generation has historically been reliant on nuclear and hydro power and produces very little emissions. However, Swedish nuclear power is being phased out, and it is uncertain how many reactors will be operational after 2040 (SWEA, 2021; IEA, 2019). An expansion of wind power can replace fossil fuels and nuclear power and thus contributes positively to the environmental quality goals (Energimyndigheten, 2018; SWEA, 2021). These goals follow from the Energy Agreement formed by the parliament in 2016 and got adopted in 2018 (IEA, 2019). It states that the energy policy in Sweden should combine ecological sustainability, competitiveness and security of supply (IEA, 2019). Regarding electricity, Sweden must have a network with high security of supply and low environmental impact and offer electricity at competitive prices (IEA, 2019; Statens Energimyndighet, 2022). Relative environmental targets that result from the agreement are (IEA, 2019; Råberger & Vingmarker, 2019; Statens Energimyndighet, 2022): net zero emissions by 2045 and negative thereafter, 63% lower greenhouse gas emissions by 2030 compared to 1990, energy use must be 50% more efficient in 2030 compared to 2005, and a 100% renewable electricity production by 2040 (excluding nuclear energy). The Energy Agreement states that Sweden must have a network with high security of supply and low environmental impact and offer electricity at competitive prices (IEA, 2019; Statens Energimyndighet, 2022).Increasing the amount of wind power contributes to creating a more resilient and secure energy network because of the spatial distribution of power plants and would also meet the urgent power demand in southern Sweden (SWEA, 2022). However, at the same time, the increased share of renewables in the power grid raises concerns about security due to the intermittent characteristics in the availability of wind and solar energy (Gawel et al., 2017). Sweden is subdivided into four bidding areas, SE1-4 (Svenska Kraftnät, 2022). Even though Sweden is producing most of its energy within its borders, southern areas SE3 and SE4 have a relative energy deficit compared to the northern areas SE1 and SE2 (Armelius, 2022; IEA, 2019). The difference in price between the bidding areas was introduced in 2011 to encourage an increase in power production capacity in the southern areas (IEA, 2019). SE3 is the largest energy consumer, as it contains the largest share of the population and industry with cities such as Stockholm and Göteborg (Svenska Kraftnät, 2007-2022; Svenska Kraftnät, 2021; Back, 2020). The Swedish wind energy agency (SWEA) estimates an increase from 30TWh in 2020 to 60TWh with a capacity of 18.5GW in 2030 and 120TWh with a capacity of 33.3GW in 2040 (SWEA, 2021). The overall objective of this report is to analyze historical electricity consumption and production data, study wind patterns, determine payback times for turbines, and assess the potential for wind power to meet future demand. The goal is to create a tool for evaluating feasible wind farm locations and assessing the impact on the supply-demand balance in the SE3 area. The research aims to contribute to higher electrical independence, lower consumer prices, and a better understanding of wind power's role in the energy mix (SWEA, 2022). This is done with the aim of answering the question: *How complementary can wind power be in the SE3 bidding area?*

2 Methodology

To be able to understand the impact wind power can have in the SE3 area, multiple parameters need to be studied. Historic energy data in SE3 needs to be understood before setting future demand scenarios. This data is obtained from the Transmission System Operator (TSO) Svenska Kraftnät and completed using the imbalance settlement services from eSett. Analysis of past trends, combined with literature on supply and demand changes, enables estimations of future supply-demand gaps. Forecasting models, such as the seasonal auto-regressive integrated moving average (SARIMA), will be employed to establish scenarios based on historic patterns. Assuming a linear increase in electricity demand and a stable share of Sweden's total consumption in SE3 of 60%, minimum and maximum demand growth scenarios will be considered. Next to this, wind data analysis using weather station data around SE3 will assess the potential of wind power to address power production deficiencies and achieve climate goals. The study will calculate turbine payback time based on power generation capacity, considering both onshore and offshore locations. Gaussian process regression will be used to fill gaps between weather stations and create a comprehensive wind speed map for SE3. Surface roughness lengths extracted from the Global Wind Atlas will be used to convert wind speed measurements from weather stations to turbine height (Badger et al., 2023). The grid density obtained from the surface roughness length data results in cells being approximately 1 by 1.5 kilometres. Considering current and future turbine capacities, the research assumes an onshore capacity increase from 3.5 MW to 15 MW and offshore capacity increase from 12.5 MW to 25 MW for calculations in 2035 (SWEA, 2021). Evaluating power calculations for different turbine capacities will aid in identifying suitable locations. The impact on the grid will be assessed based on the payback time of each turbine, with cost being a determining factor for installation and grid integration. To assess the payback time, the historic day-ahead electricity prices will be observed, which is obtained from European Network of Transmission System Operators for Electricity (ENTSO-E) (ENTSO-E, 2023). The electricity price observed will be used to set a value for the electricity price when calculating the payback times. This will not be forecasted due to the large variability and dependencies in the electricity price determination.

2.1 Wind power calculations

To be able to comprehend the wind speeds attributes, understanding the wind speed dependency of turbines is crucial. The theoretical energy that can be harvested from wind can be determined using (Boyle, 1996; Shu & Jesson, 2021):

$$P = \frac{1}{2} A \rho u^3 \tag{1}$$

Where P is the energy, A the swept area of the rotor, ρ the air density and u the wind speed. The unpredictability of wind characteristics has resulted in a probability distribution that describes the variation of wind speed at a location, indicating the likelihood of a wind speed to occur at a location (Shu & Jesson, 2021; Burton et al., 2011). The two-parameter Weibull distribution is most commonly used to perform the wind energy assessment and capture the skewness of the wind speed distribution (Shu & Jesson, 2021; Burton et al., 2011). The Weibull distribution is a function of wind speed $f(u)$;

$$f(u) = \left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} \exp\left[-\left(\frac{u}{c}\right)^{k}\right] \qquad (u > 0; k, c > 0) \tag{2}$$

The function is further described by a scale parameter (c (m/s)), which establishes the horizontal axis scale of the wind distribution and a dimensionless shape parameter (k), describing the width of the distribution. c is thus linked to the wind speeds at a site, or elevation. Meaning, determining the ratio in speed at different altitudes can help to determine the c parameter at another altitude once it is calculated at an elevation. This leads to a shift in the probability density function described by the Weibull distribution, but the shape of the function, described by k would not change. The probability of a turbine being able to operate in the area can be determined using (2), and can be written as (Shu & Jesson, 2021):

$$p(u) = \exp\left[-\left(\frac{u_c}{c}\right)^{k}\right] - \exp\left[-\left(\frac{u_f}{c}\right)^{k}\right] \qquad (u_c < u < u_f) \tag{3}$$

With the cut-in wind speed (u_c), the cutoff wind speed (u_f). The total energy a turbine produces over a certain time can be calculated by:

$$E = \sum_{0}^{i} (P_i \cdot p_i \cdot dv_i \cdot t) \tag{4}$$

where P_i is the power at a wind speed, p_i is the probability of that wind speed occurring according to the Weibull distribution, dv_i is the interval of the wind speeds in the power curve from the turbine and t is the time over which the turbine runs. Which in turn can be used to determine the capacity factor (CF) of the turbine. This describes the ratio of measured energy a turbine produced to its rated energy over a year.

2.2 Research boundaries

The Swedish electricity grid faces barriers in electrification related to generation, system adequacy, demand, and grid infrastructure (DNV, 2021). In the SE3 area, the lack of local generation and available grid pose significant challenges, along with lengthy planning and permitting processes for new projects and grid upgrades (Armelius, 2022; DNV, 2021). The intermittent behaviour of renewable sources like wind and solar adds pressure to system adequacy, highlighting the need for storage and grid flexibility (DNV, 2021). However, this research does not specifically address storage implementation or the use of battery electric vehicles for grid balancing. Factors such as population growth, economic development, technological advancements, and political decisions impact electricity demand but are not individually addressed in this study. Demand forecasts from the literature, representing minimum and maximum growth scenarios, will be considered in conjunction with supply forecasts using SARIMA. The research focuses on providing technologically feasible results that account for seasonal changes and contribute to addressing the power production gap with wind power. The study does not consider the influence of political decisions, public opinions, or other external factors. Limitations on possible wind turbine sites such as jurisdictional and natural factors, as well as stakeholder influence are not fully examined. Economic indicators, specifically the payback time, are considered in determining turbine feasibility, while grid parameters are not included. Increasing north-to-south transmission capacity to utilize wind energy in northern areas is an alternative to reduce SE3's self-supply requirements.

3 Results and Discussion

Following the methods on the data gathered different results are obtained. The historical data is transformed and visualized after which the production sources are forecasted. Data from weather stations are transformed to show the general wind direction over the region and the average monthly wind speeds. This in turn can be used to calculate the power a turbine can produce in the area, after which the payback time for a turbine can be calculated. The results obtained from the forecasting can be compared with the technical potentially available wind power with a reasonable payback time to learn about the role wind power can play in SE3.

3.1 Electricity demand and supply

The data from 2007 to 2022 is used to observe the historic behaviour in demand and supply. The behaviour in the different supply sources is forecasted using SARIMA in order to keep the trend. The trend observed in demand will be compared with different demand scenarios in 2035 obtained from literature. Combining these forecasted results gives an insight in the future demand and supply of the SE3 area for the different scenarios and when following the current trends in power supply.

3.1.1 Historic demand and supply

The annual consumption from 2007 to 2022 is visualized in Fig. 1. The average annual consumption during this time period is found to be 83.3 TWh. The stability in consumption can be explained by trends counteracting each other; in the 1980s and 1990s the demand increased by a growth in electric heating, but the shift to efficient heat pumps stopped the growth in electricity demand, and also the electrification of the industry has been counteracted by increasing efficiencies (IEA, 2019).

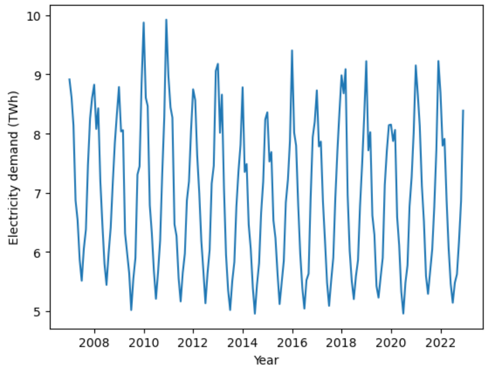

Figure 1. The total monthly consumption in SE3 from 2007 to 2022.

Fig. 2 shows how the demand is met by the different types of power production sources.

Nuclear power is seen to form the large base in the region and gets supplemented by hydro power to make up the vast majority of the power production. Thermal power can be seen to mostly add in production during the winter months. The increase in wind power can be observed, whereas the increase in solar power is still to small too be visible. The reduction in production from nuclear power is the result of the decommissioning of nuclear power plants in 2020. The forecasting

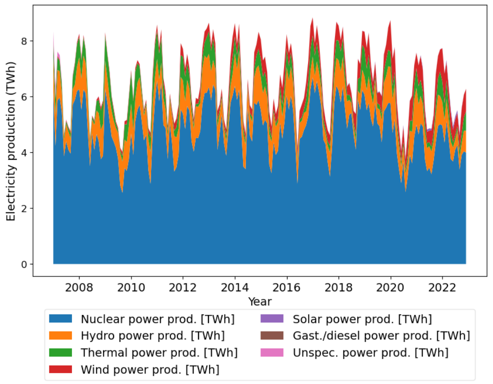

Figure 2. Total monthly electricity production by source in SE3 from 2007 to 2022.

of nuclear power assumes a continuation in production based on the capacity from 2020 onwards. Hydro and thermal power have been a stable source throughout these years and are assumed to stay stable when forecasting these sources. The observed solar power production shows an exponential growth up to 2022. The forecast follows a linear increase, which is in line with the expectation of the total installed power from 2023 to 2030 for the whole of Sweden (JB Sustainable Approach AB, 2019). This linear growth is assumed to continue to 2035. The wind power production has a linear increase, which is continued.

3.1.2 *Forecasting demand and supply*

The supply is forecasted using SARIMA based on the trends observed and explained in Section 3.1.1. To be able to adjust the demand growth to the different scenarios, the demand from Fig. 1 is represented by a sine wave. The seasonal variability in consumption is assumed to stay the same. Assuming a linear growth in consumption, the largest growth is mentioned to be +2.5 TWh/year (DNV, 2021). A minimum growth is found to be +0.1 TWh/year (Bruce et al., 2019). This growth is based on the whole of Sweden, combining these growths with the assumption that the SE3 area consumes about 60% of the total energy, the 2035 demand scenarios are presented in Table 1. Creating a mean demand from these scenarios and adding a deviation from the mean to the different scenarios allows for a comparison between the demand scenarios. The SARIMA forecasting results have been added together to show a total monthly supply up to 2035. How the demand and supply forecasting results compare is shown in Fig. 3.

Table 1. The total electricity demand in SE3 based on different scenarios in 2035.

Scenario	SE3 demand in 2035
Minimum	81.2 TWh
Maximum	117.2 TWh

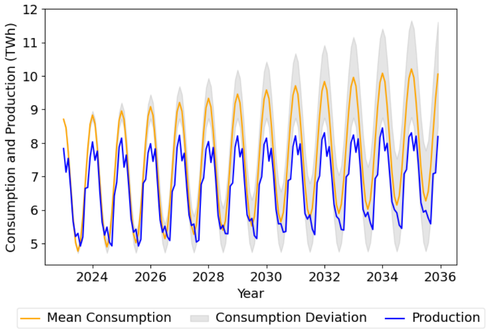

Figure 3. Visualization of the total forecasted power supply and a minimum and maximum demand growth scenario to the year 2035.

From Fig. 3 it can be observed that initially the total monthly supply can match the total monthly demand during the summer months, when the demand is lower compared to the colder winter months. This power shortage during winter months continues, but decreases with an increases supply. The growing supply does not match the mean in growing demand and is increasing more than the supply, increasing the scenarios in which there would be shortages. During high demand periods, the current trends in supply will result in shortages for all scenarios. The forecasting of future demand scenarios relies on literature, each with its own boundary assumptions. The minimum demand value found is lower than the mean historic demand from 2007 to 2022. To maintain current demand levels with the expected electrification of multiple sectors, significant efficiency improvements would be required. The paper justifies this assumption based on expected demand savings in the housing and services sector. For production forecasting, SARIMA models are used, which work best with appropriate statistical values. However, since the goal is to obtain technologically possible values rather than the best forecast, data transformations and tests are not performed. The obtained forecasts align well with historic data for nuclear, solar, and wind power, but are slightly off for hydro and thermal power. The seasonality of these sources matches historic data, but the variation in peaks is not predicted. Improving the forecast for thermal power would require accounting for weather changes as a result of increasing global temperatures, which have uncertainties for the medium to long term. The presented results are within the bounds of current production and technically feasible to continue in the future.

3.2 *Electricity price*

To use a realistic price when determining the payback time of the turbines, the historic day-ahead electricity prices are shown in Fig. 4. The figures shows a decomposition of the price from 2017 to mid-April 2023. The data is extended to show the recent changes in data. The top line in the plot represents the monthly mean day-ahead price. The second line represents the trend, which is the motion of the production over time. If the power source follows a seasonal pattern, this pattern can be observed in the third plot. The scatter plot represents the residual, which is the data that is left after subtracting the trend and the seasonality from the observed data. The residual can be considered noise, the lower the residual, the more stable a source is.

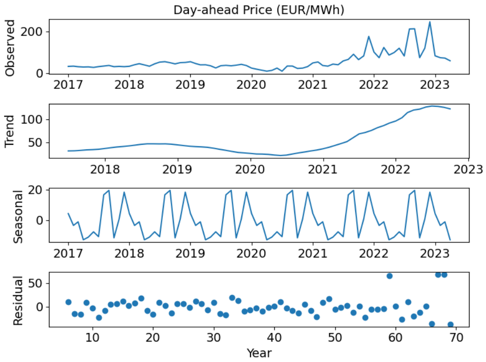

Figure 4. Decomposition of the monthly average electricity price in SE3.

The figure shows a large increase setting in from mid 2020. This rise started at the end of the COVID-19 pandemic and growing international demand (European Council, 2023). The war between Ukraine and Russia, but also heatwaves in the summer of 2022 resulted in a further increase in electricity price (European Council, 2023). The price is also seen to decrease rapidly from 2023. As can be seen from the residual plot, the stability increased from 2022. To neglect the instability and large increased prices, only the months in 2023 are used to determine an average price used later-on in determining the payback time. The seasonality observed in the figure is also neglected and only one value is used. The average price observed in 2023 is 73.81 EUR/MWh and is used for calculating payback times.

3.3 *Wind Analysis*

The weather greatly affects energy consumption, but with the introduction of renewables, production is increasingly influenced by it. To observe the behaviour of the wind around SE3, the data from the stations is analyzed to observe the seasonal differences. The monthly average wind speeds throughout SE3 have been visualized with the help of a Gaussian process regression model. To obtain an understanding of the average monthly wind speeds, the speeds over the region is shown for three separate months in Fig. 5. The wind speeds are gathered from stations with an elevation of 10m above sea level and are transformed to 200m above sea level to improve the clarity of difference in wind speed over land and over sea. With blue representing the lower wind speeds, and red higher wind speeds.

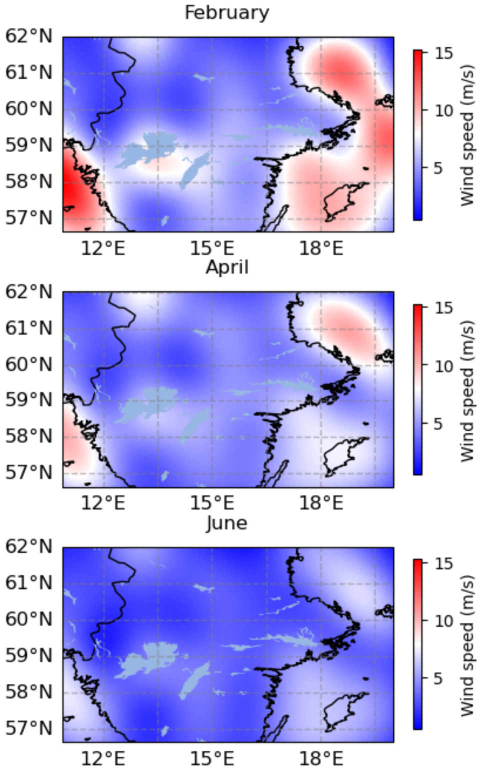

Figure 5. Average monthly wind speeds at 200m above ground level for February, April and June around the SE3 area in 2020.

It is found that the all months have higher wind speeds at offshore areas. The outer northeast and southeast show low wind speeds off the shore. This is due to a lack of stations in that area. Nevertheless, both areas are outside the exclusive economic zone, thus is does not influence the outcome of potential for wind power in SE3. Important to note is the change in scale of the wind speeds for the different months. The average monthly speeds can go up to 15 m/s in February, but also only reach half of that at about 7 m/s in June. The area between the greater lakes in western Sweden also show larger wind speeds. The higher wind speeds are recorded in the months October to March.

3.4 *Wind power distribution*

From the wind speed distribution, the shape and scale parameters can be determined. From this (3) and (4) can be used to calculate one turbine can generate in a grid cell, after which its capacity factor can be determined. Before the power can be calculated, the wind speeds are transformed to the speed at hub height of the turbine using the surface roughness length of the grid cell.

3.4.1 *Current power capacities*

The power that can be generated annually throughout SE3 with an onshore turbine having a power capacity of 3.5 MW and a hub height of 100 m and an offshore power capacity of 12.5 MW at 200m and its capacity factor is visualized in Fig. 6.

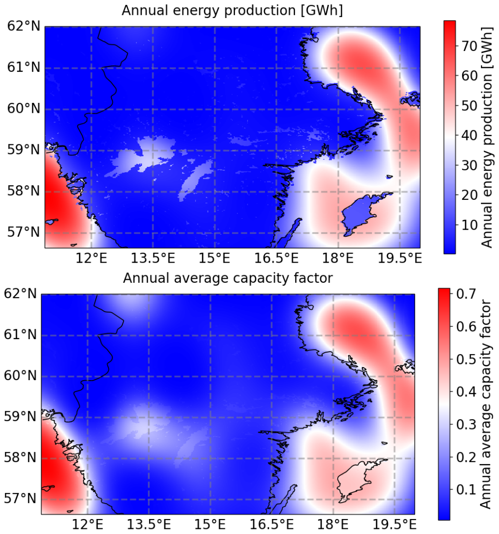

Figure 6. Visualization of the annual energy that can be produced around SE3 with a 3.5 MW onshore and a 12.5 MW offshore turbine and its respective capacity factor at the different sites.

The areas with higher capacity factors correspond to the areas where higher wind speeds are observed in Fig. 5. These areas in turn generate more power.

3.4.2 *Future power capacities*

How turbine capacities impact the potential is studied by increasing the turbine size to future potential turbine sizes considering technological advancements. With an onshore capacity of 15 MW at 190m and an offshore capacity of 25MW at 200m, the power that can be generated annually around SE3 and the respective capacity factor is visualized in Fig. 7.

The doubling in offshore production is explained by the doubling in capacity factor. The amount of energy that is produced onshore increases more than the increase in capacity factor due to the higher hub heights and thus the availability of higher wind speeds.

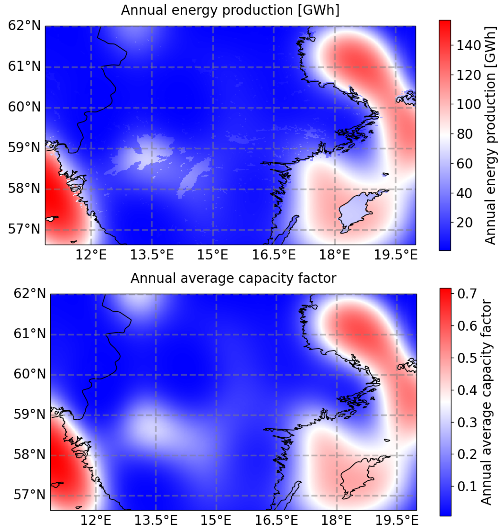

Figure 7. Visualization of the annual energy that can be produced around SE3 with a 15 MW onshore and a 25 MW offshore turbine and its respective capacity factor at the different sites.

3.5 *Payback time*

Combining the result of the electricity price and the annual power production, a payback time can be calculated. Payback time is defined as the ratio between annual cashflow and total investment cost which is determined as an average of 2021 European costs. The weighted average total installed costs for onshore in Europe is 1623 USD/kW, whereas for offshore it is 2775 USD/kW (IRENA, 2022). Which are assumed to stay the same. Annual operating costs are approximated based on public information from the Swedish Energy Agency. Payback times for all individual cells along the examined design space are calculated.

3.6 *Current power capacities*

Doing the calculations based on the results from Section 3.4.1, payback times are found to be generally below 10 years for offshore regions, which is visualized in green. Onshore however, a major part has high payback times of more than 20 years, visualized in red in Fig. 8.

Where the pattern observed shows high similarities with the pattern of the capacity factor distribution in Fig. 6. Looking into how much power can be generated in a year, the capacity can be calculated. Doing this for the regions with a payback time below 10 years, a total technical and economical capacity is determined for onshore and offshore turbines. Onshore a capacity of 14GW is found, while for offshore a capacity of 304GW is found.

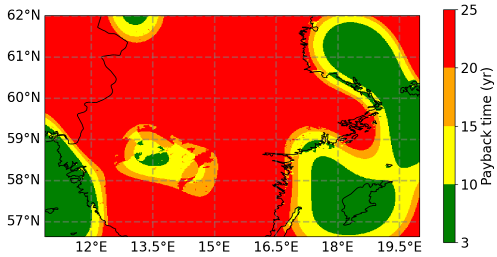

Figure 8. Distribution of payback times around SE3 for onshore and offshore turbines with current turbine capacities.

3.7 *Future power capacities*

Doing the same based on the results in Section 3.4.2 for the future capacities, a payback time distribution of a single turbine is visualized in Fig. 9.

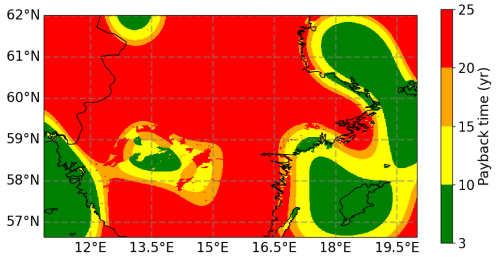

Figure 9. Distribution of payback times around SE3 for onshore and offshore turbines with turbine capacities possible in 2035.

The study identifies improved onshore and offshore capacities of 83 GW and 608 GW, respectively, with a payback time below 10 years. Local prices and changes in 2035 need to be considered for better accuracy. Power production and capacity factors show linear trends with higher capacity factors resulting in lower payback times. However, the calculations focus on individual turbines and do not account for the efficiency decrease in wind farms.

3.8 *2035 power production*

To put the results from Section 3.7 into perspective, the capacity is compared with the forecasted demand and supply in 2035. The maximum gap in demand and supply is found to be 33.7 TWh. Additional 3.85 GW wind power capacity would be needed to meet the annual demand. In a wind farm configuration, the turbines are assumed to lose 20% of their capacity in the south of Sweden (Holttinen, 2005). Assuming an offshore wind farm of 75 turbines in locations with a payback time below 10 years, where the capacity factor is averaged to 0.55, a farm can produce 7.5 TWh per year. Which means 4.5 of such farms can add to the total annual energy demand in 2035. Hence, the technically potential energy generated is sufficient to meet the annual energy demand in 2035 when considering payback times. However, the area studied is not fully within the exclusive economic zone and does exclude governmental restricted areas for wind farm sites. Next to this, the seasonality of energy production and the impact on the grid need further study. Factors such as load factor and grid losses should be considered to evaluate the effect of additional turbines on the grid. The calculated amount of farms is based on balancing annual consumption. As can be observed in Figs. 2 & 5, there is a seasonal dependency in available wind power. Renewable energy actually has hourly deviations which are difficult to predict, especially for long-term ahead. The hourly balancing between demand and supply is crucial to operate a stable grid. For proper balancing, the surpluses need to be well managed. Storing the surpluses is a crucial part to be able to supplement the shortages in production at other times.

4 Conclusion

The goal of this research was to study the technical potential capacity for wind turbines in the SE3 area. Based on the analysis performed here, it is found that the potential for supplementary wind power in the area is large. With the sustainability goal of reaching 100% in 2040, the role of wind power is important to be studied. This paper contributes to the knowledge of wind power in the area by comparing the current trends in individual power supply sources with literature values for future demand and observing that if the current trend is continued, the supply in 2035 can barely meet the demand. This means that a growth in supply is likely necessary in order to reduce the costs of electricity in SE3, as has been the goal of the introduction of different bidding in Sweden. Having observed the need for additional power in 2035, the role wind power can play has been studied. Both current turbine capacities and expected future turbine capacities can be used to locally produce additional renewable power considering initial economical factors and reach the sustainability goal. The tool made in this research allows for focusing on a specific area and performing basic economical calculations, which can be expanded beyond the payback time by adding additional parameters.

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