Wind power potential in Ollesbacken-Sikåskälen

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1. Introduction

1.1 Background

Wind energy is a growing industry and accounts for a larger share of the total produced electricity mix in Europe for each year. Onshore wind conditions are less consistent than offshore, with lower mean wind speeds and higher turbulence (Jenkins, Ekanayake, 2017). Much simplified it can be explained by greater variations in terrain and atmospheric conditions. Onshore sites therefore have more variability in the wind conditions. Before any wind farm development begins, a proper wind mapping analysis must be done to evaluate the site for wind power potential.

1.2 Objective and aim

A potential area for wind power development is Ollesbacken-Sikåskälen in Jämtland, Sweden. The aim of this report is to describe the parts that creates a development plan for wind farm site. The objective is to analyse the collected data and describe the wind conditions, make a profitability prognosis based on estimated production values of 10 ENERCON E-82 2MW turbines, show the suitability of the selected turbines and create a potential development plan that accounts for possible environmental impacts. The area is already a developed wind farm so initially it can be assumed that it's a suitable location.

2. Method

2.1 Data collection

The provided data for analysis is 10-min intervals of wind speeds (minimum, mean and maximum) and wind direction, measured over a period of 2 years (2012-2013) at 80m above ground. All turbine data was taken from the report by Ohlsen, von Eitzen, Sommer (2017), such as power and thrust coefficients, geometric data and decibel levels of the turbines. Hourly temperature and pressure data was downloaded from the closest active SMHI weather station in Hallaxåsen (SMHI, no date).

General spatial data was provided and specific data was collected from Artportalen for red-listed species, (Artportalen, no date) Skogsstyrelsen for biotopes and areas with natural values (Skogsstyrelsen, no date) and Riksantikvarieämbetet for ancient remains (Riksantikvarieämbetet, no date) and maps were created with QGIS. A regularly updated topographical webmap was used as background (Lantmäteriet, no date).

2.2 Data analysis

The main computations were done as vectorised operations with Python and the data analysis libraries, Pandas, NumPy, Matplotlib and windrose. The objective being to preserve the 10-min interval wind speeds to get as exact production estimates as possible. The calculations are based on mean wind speeds, and differences between min,mean and max winds speeds are only visualised. A higher resolution on the frequency is needed to include turbulent elements in the calculations.

2.2.1 Production estimation

Height correction to 100m hub height was done with the wind power law.

(1) $$u = u_r \left(\frac{z}{z_r}\right)^{\alpha}$$

Where,
u = Wind speed at corrected height.
u_r = Wind speed at reference height
z_r = Reference height
z = Corrected height
α = 1/7, neutral atmospheric stability constant

Air temperature and pressure data was interpolated to 10-min intervals. The air pressure was corrected to 600 m.a.s.l by a factor of 0.94, as from Andersson (2024). The air density was calculated from the ideal gas law, and then merged with the wind data.

(2) $$\rho = \frac{PM}{RT}$$

Where,
ρ = Air density (kg/m^3)
P = Air pressure (Pa)
M = Molar mass of air
R = Universal gas constant
T = Temperature

Potential wind energy was calculated as:

(3) $$P_w = \frac{1}{2}\rho A v^3$$

Where,
P_w = Power in wind
A = Swept area
v = Wind speed
R = Universal gas constant

Produced power was calculated as

(4) $$P_t = C_p P_w$$

Where,
P_t = Produced power from turbine
C_p = Power coefficient for the specific turbine

The C_p value varies with wind speed (Ohlsen, von Eitzen, Sommer, 2017).

Power (kW) was converted to energy (kWh) by:

(5) $$E_{total} = \sum_{i=1}^{t}(\frac{1}{6} * P_{i,10\text{min}})$$

2.2.2 Wind conditions

The ENERCON E-82 wind turbine has a cut-in speed of 2 m/s and cut-out speed beginning at 28 m/s (Ohlsen, von Eitzen, Sommer, 2017). Boolean indexing was used to remove all data points not within that interval.

The wind speed frequency was measured by classifying each recorded wind speed to it's closest integer and then calculating the probability for each integer between 2-28 was calculated. The wind speed frequency was then plotted against the Cp curve.

The wind conditions was visualised as a windrose. The frequency of the wind directions and corresponding strengths are used to optimise the placement of the turbines in the terrain and for computing wind wake losses.

2.2.3 Spatial analysis

Buffer zones was applied around environmental concerns such as, housing areas, red-listed species observations, protection of biotopes and other areas with high natural values. The lowest possible ground level for the project area was set at 480 m.a.s.l, with the highest hill in the area being at 540 m.a.s.l. How the terrain in the selected project area affects the wind is not examined further, but care was taken to not place many turbines behind the highest hill with regards to the most common wind directions. Additionally, construction was restricted on wetlands and farmlands, and the distances between turbines and roads were minimised by using established road layers. Buffers to roads was set to 200m.

2.2.4 Noise estimations

The mean noise level was set to 100 dB(A), after examining the available sound data (Ohlsen, von Eitzen, Sommer, 2017). The formula and constants for calculating the dB level at a distance was collected from Jenkins, Ekanayake (2017).

$$L_p = L_w - 10log_{10}(2\pi r^2) - ar \quad (6)$$

Where,
L_p = Sound level at selected distance r from point source
L_w = Sound level at point source
r = Distance from point source to selected position
a = 0.005 dB/m, atmospheric absorption constant

The possible noise polluted areas were manually measured and selected from the produced maps. Any increases due to interactions between multiple turbines or atmospheric conditions, such as inversion, were not considered. The level for acceptable noise pollution is set at 40 dB[A] in Sweden (Naturvårdsverket, 2020).

2.2.5 Wake losses

Losses from wind wakes exhibit some variance due to the wake distribution changing with wind speeds and interactions with other nearby turbines. Due to this, a gross estimation was calculated with the aim of producing a yearly worst-possible outcome along a few wind directions. The amount of turbines being affected by wakes in the chosen directions was manually measured in QGIS, so the precision regarding the amounts of affected turbines with respect to the wake's physical changes is not exact The wind speeds in the selected wind directions was extracted by a boolean index on all data points, after observing the wind speeds from the wind rose in the chosen directions. Possible increases in wind from channelised flow between wakes have not been taken into consideration.

Radius of the wind wake:

$$R_x = R_o + \alpha X \quad (7)$$

Where,
R_x = Wake radius at a distance X from turbine
R_o = Radius of the swept area of turbine
α = 0.08, atmospheric constant dependent on flow conditions
X = Distance from turbine

Wind speed loss in the wake:

(8) $$u_1 = u_0 + u_0\left(\sqrt{1 - C_t} - 1\right)\left(\frac{r_0}{r}\right)^2$$

Where,
u_1= Reduced wind speed at a selected distance from turbine
u_0 = Wind speed at turbine
C_t= Thrust coefficient of turbine

Thrust coefficient (C_t) varies with wind speeds, specified as a curve in Ohlsen, von Eitzen, Sommer (2017). The C_t was set to 0.8 up to 11m/s then a linear decrease by 0.05 for every increase in wind speed. This is not a realistic scenario, but was done for simplicity and not having access to true values.

From the resulting wind speed losses, a matrix was constructed with the shortest and longest distance between affected turbines along the columns and wind speeds along the rows. The matrix mean and standard deviation was calculated, and the resulting wind speeds losses were subtracted from all turbines situated within wakes. The wake wind power was calculated, and a power loss was calculated as the wake P subtracted from the free wind P. The total energy loss was summed and reduced by the frequency of the chosen wind directions. This adds another degree of uncertainty since the frequency calculation is not done as a vectorised operation.

(9) $$[U_{wake\ loss}] = [U_{free\ wind}] - [U_{wake}]$$

(10) $$U_{wake,mean\ loss} = \sum_{\substack{0 \leq i \leq m \\ 0 < j < n}} [U_{wake\ loss}]_{(i,j)}$$

(11) $$U_{wake} = U_{free\ wind} - U_{wake,mean\ loss}$$

(12) $$P_{loss} = \frac{1}{6} * (P_{free\ wind} - P_{wake})$$

(13) $$E_{total\ loss} = Freq_{wind\ direction} * \left(\sum_{i=1}^{t} \left(\frac{1}{6} * P_{i,loss}\right)\right)$$

2.2.6 Profitability estimation

The financial parameters unless otherwise stated was taken from Energiforsk (2021).

Lifetime: 30 years, (comparison done with 25 years)
Investment cost: 12 mil SEK/MWp
Mean price of electricity in SE2: 0.46 SEK/kWh (Elbruk, no date)
Operating costs: 0.08 SEK/kWh
Profit/kWh: 0.38 SEK/kWh

Annual produced energy: 53.87 GWh
LCOE: 0,24 SEK/kWh

The estimation is based on a bulk investment method and a LCOE (Levelised cost of electricity) method. Bulk investment is to calculate total investment costs,annual profits and payback period. LCOE (Levelised cost of electricity) method includes all the investment costs and operating costs in a value per produced kWh. The difference between the income and LCOE is the profits. Since all costs are included into a single value, a payback period can't be calculated as simply, but the method provides a different way of calculating costs and profit which might reflect the annual financial situation more correctly.

Bulk investment method:

(14) $$Total\ investment = Cost_{turbine} * amount\ of\ turbines$$

(15) $$Profits_{annual} = (Electricity_{mean} - operating\ costs) * Farm\ production_{annual}$$

(16) $$Payback\ period = \frac{Total\ investment}{Profits_{annual}}$$

(17) $$Lifetime\ profits = Profits_{annual} * (lifetime - payback\ period)$$

LCOE Method:

(18) $$Lifetime\ production = Farm\ production_{annual} * lifetime$$

(19) $$Lifetime\ costs = LCOE * Lifetime\ production$$

(20) $$Lifetime\ income = Electricity_{mean} * Lifetime\ production$$

(21) $$Lifetime\ profits = Lifetime\ income - Lifetime\ costs$$

(22) $$Costs_{annual} = \frac{Lifetime\ costs}{lifetime}$$

(23) $$Income_{annual} = \frac{Lifetime\ income}{lifetime}$$

(24) $$Profits_{annual} = \frac{Lifetime\ profits}{lifetime}$$

3. Results

3.1 Production estimates

There is significant more total available energy in the wind than what can be extracted as power, which is to be expected due to limitations such as the Betz limit and restrictions on the dimensioning of turbines. November-March can clearly be seen as the most productive time of the year, with a production peak happening in December/March at 750 MWh per turbine.

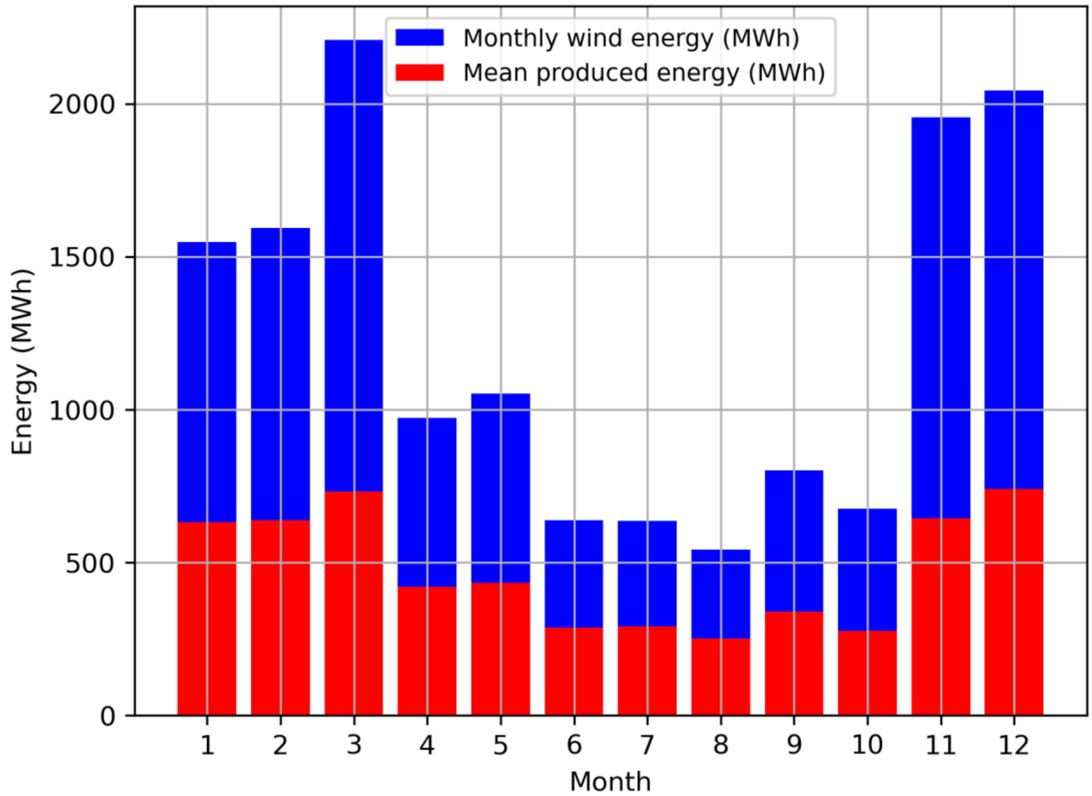

Fig 1. Differences between monthly produced energy per turbine and the available wind energy over the whole time period.

There is some year-to-year differences in monthly production values, while the mean yearly value only showed a 2% difference, 5,62 GWh in 2012 and 5,73 GWh in 2013. This would suggest that it's justified to measure over a time period of 2 years since margins are important in profitability estimations, but any longer would likely not change the production estimates much. It can also be seen that there are quite big differences monthly differences over the 2 years (up to ~30%,) yet the annual production value averages out to be within 2% of each other. This would suggest that it's highly credible that measurement periods shorter than a year is not preferable.

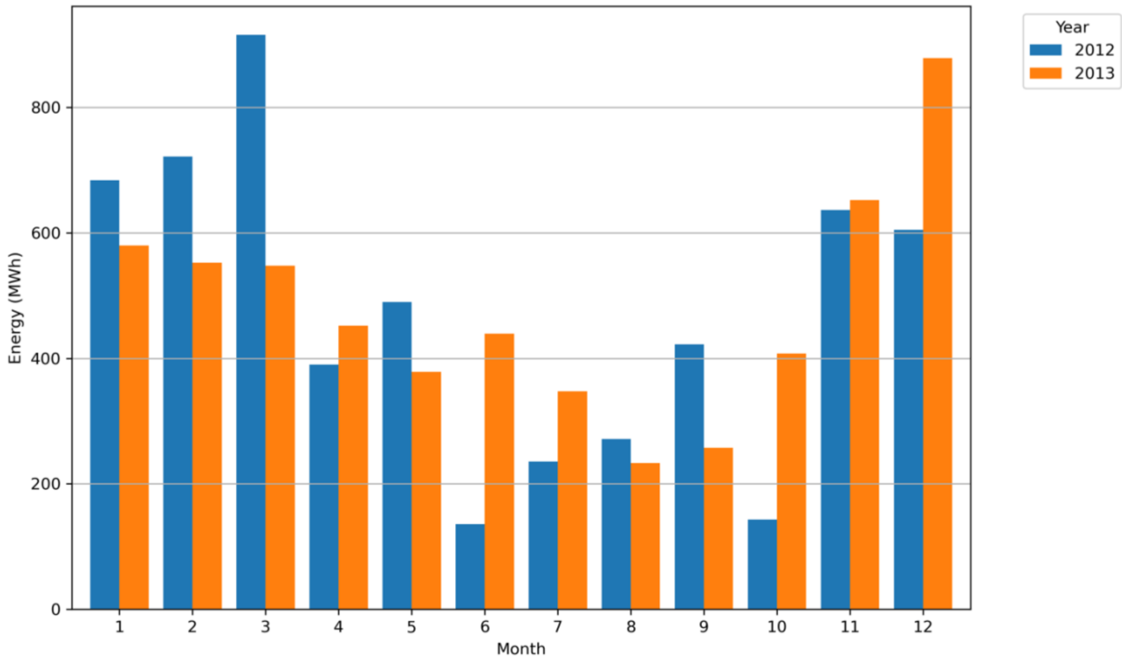

Fig 2. Differences between monthly production per turbine between the years 2012-2013.

A park with 10 turbines at 2 MW each, accounting for conversion losses of 3% and 2% maintenance time would produce 54,0 GWh/year in undisturbed winds with a capacity factor of 30.8, which is a normal value for on-shore wind (Statista, no date). Full load hour/specific yield is 2845 MWh/MWp.

3.2 Wind Conditions

The peak of the power coefficient matches the peak of the wind speed frequency fairly well. As can be seen in the wind power formula, increases in wind speeds significantly affects produced power, so the power coefficient should be larger than the frequency in the higher wind speeds. A scenario where the plotted curves changes place, would indicate that the turbine is not suitable for the location, but that is not the case here.

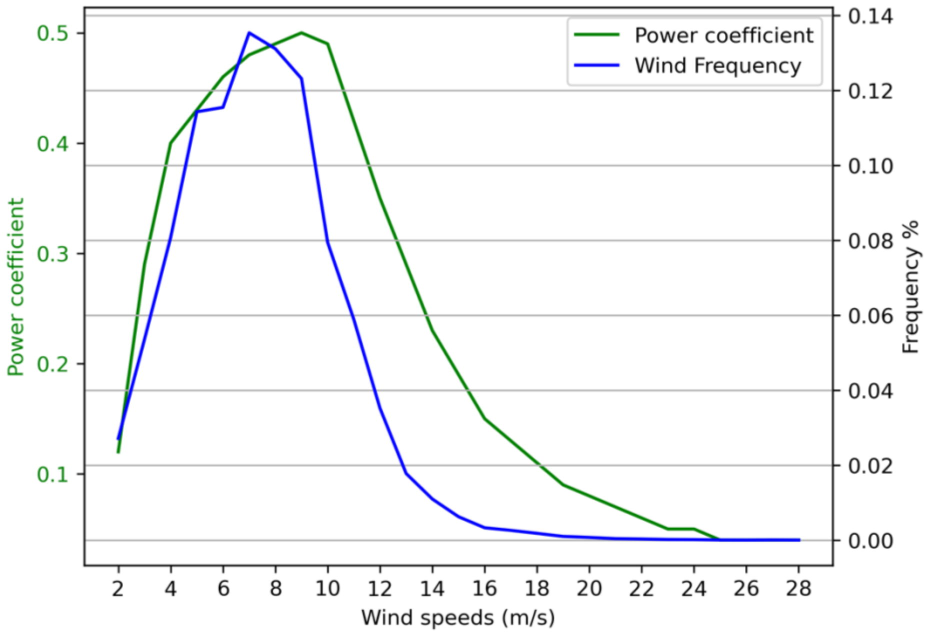

Fig 3. The differences between recorded wind speed frequency at the site and the Enercon E-82 turbine.

The variations in mean recorded wind speeds are quite large, roughly 3 m/s over the year. Since the calculations are based on the mean wind speeds, there would likely be a fairly significant difference in the total production estimates if the turbulent elements would be accounted for. Not accounting for turbulent elements introduces uncertainty in the estimations.

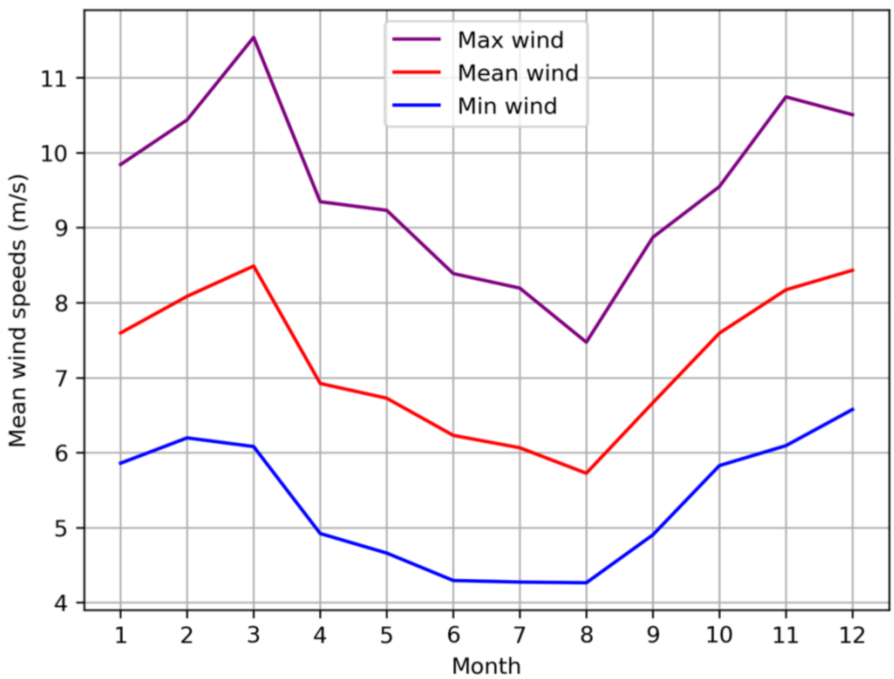

Fig 4. Differences between monthly mean winds between recorded min, mean and max winds

The wind blows most commonly from WSW-NW directions, ~40% of the time, where the strongest wind speeds are also recorded. S and SSE are also common wind directions. The placement of the turbines is therefore optimised in the WSW-NW direction, and the wind wake calculations are performed over the SW-SSE and the opposite NE-NNW directions (~41% of the time).

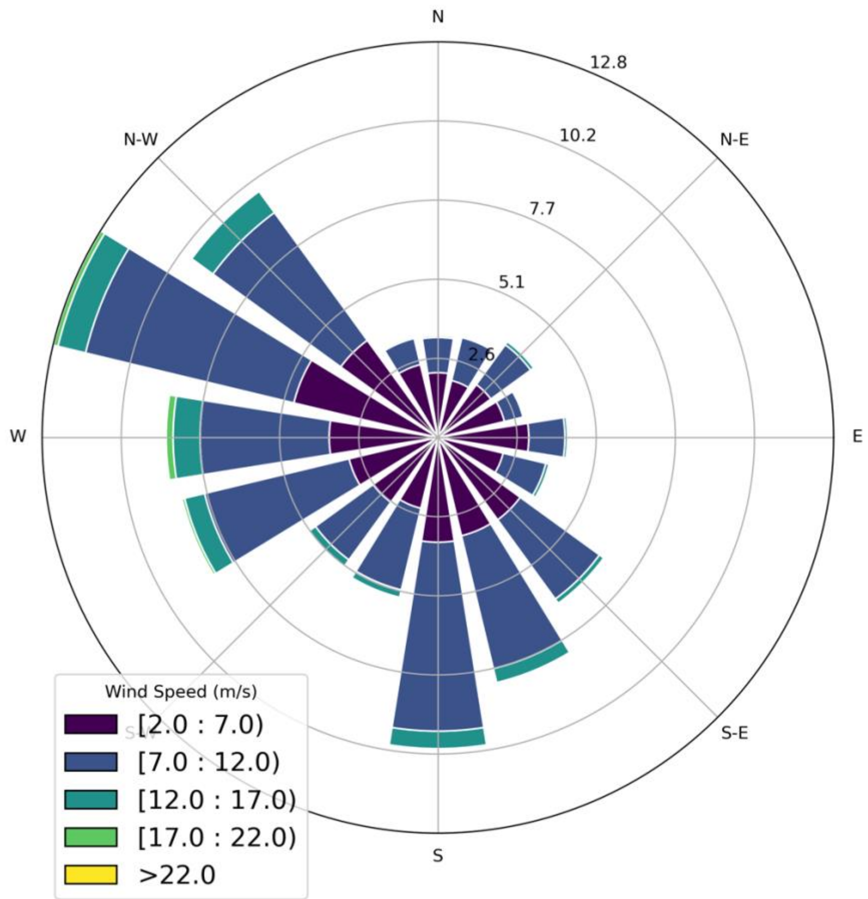

Fig 5. Windrose showing frequency of wind direction and speed.

3.3 Environmental concerns and optimised placement of turbines

The project area was picked because of few occurrences regarding environmental concerns, and a suitable elevation. Considering the most common wind directions, the turbines should preferably being placed to the left or the middle of the hill. The noise buffer was set to 600m as a working distance, but the final minimum distance to the closest turbine was greater than that.

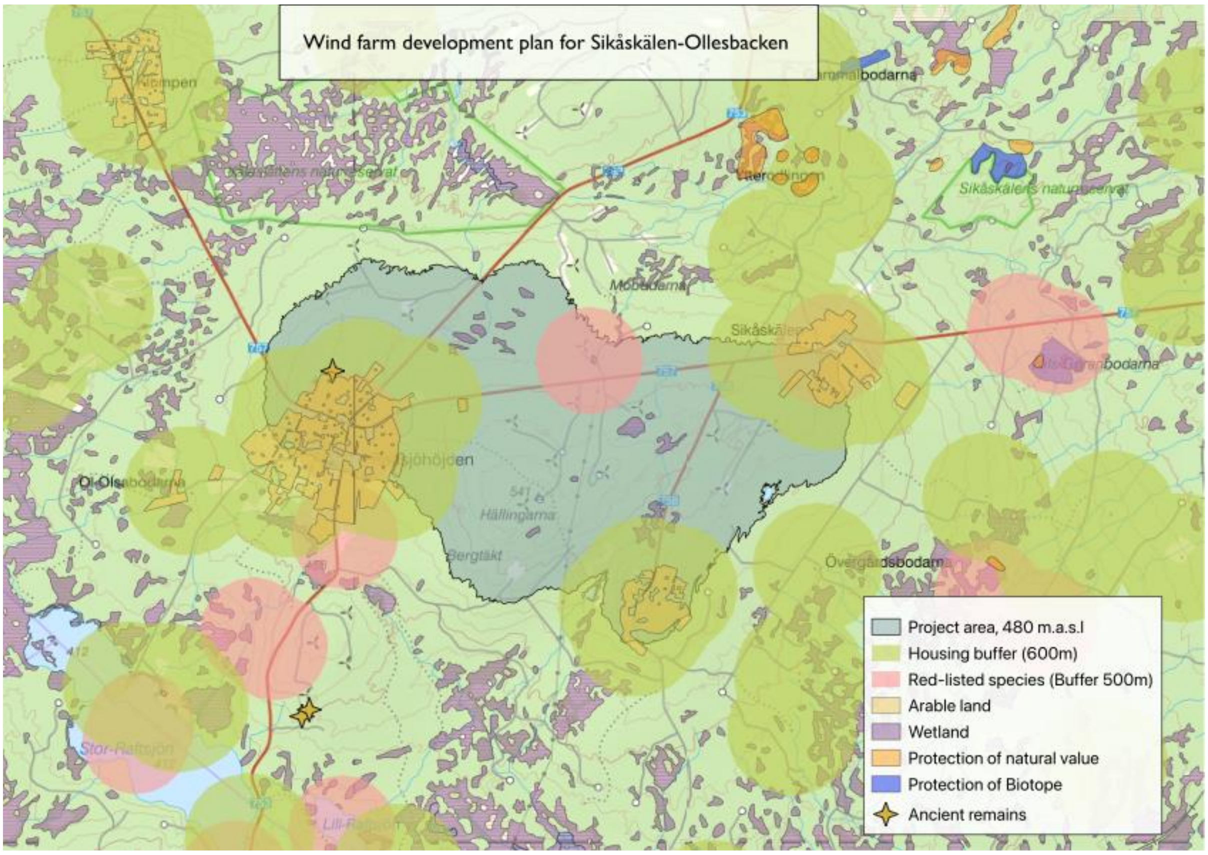

Fig. 6 Assessment of environmental concerns in area of Sikåskälen-Ollesbacken

Table 1. Levels of noise pollution (dB) depending on point source sound level.

	80 dB	85 dB	90 dB	95 dB	100 dB	105 dB	110 dB	115 dB	120 dB
750 m	10.8	15.8	20.8	25.8	30.8	35.8	40.8	45.8	50.8

The closest turbines affecting housing areas with noise pollution is 750m away from Raftsjöhöjden. Considering the turbine produces noise around 100 dB level, without any amplifications due to atmospheric conditions, the housing areas should be protected from prolonged noise pollution. The map of optimised placement shows the potentially affected areas.

Furthermore all turbines are placed so that any possible noise pollution will occur in wind directions that have low frequency, to additionally lower the risk of consistent noise pollution. One potential area of concern could be the nature reserve north of Raftsjöhöjden which will receive some levels of consistent noise pollution during southernly winds. Only 2 turbines are placed further than 200m from established roads.

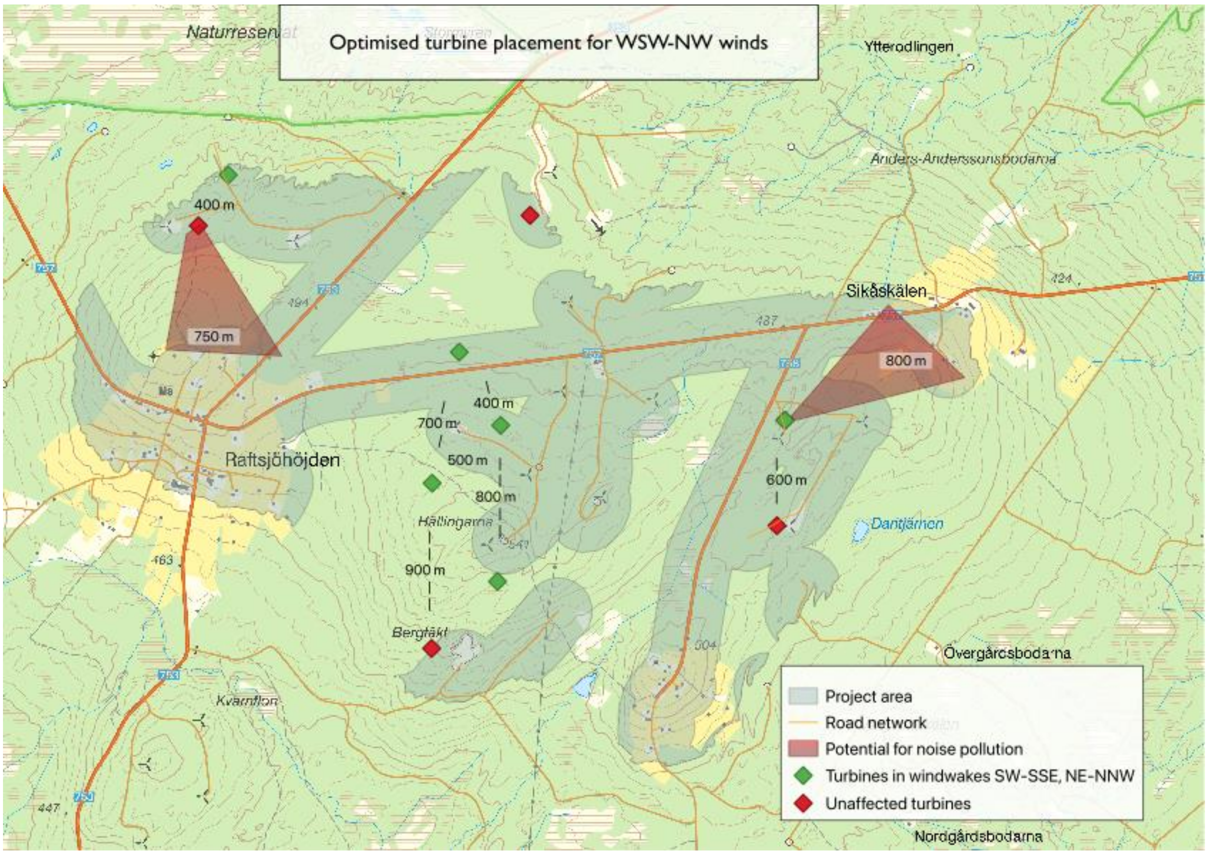

Fig. 7. Optimised placement of turbines for WSW-NW directions. Possible noise pollution zones are highlighted in red.

3.4 Noise pollution

As can be seen in Fig. 7, there are 2 potential areas for noise pollution. The calculations were performed over the shortest distance, which is 750 m. The mean sound level is 100 dB, and the sound level would have to go above 110 dB for the noise pollution to rise above 40 dB. How the wind turbine noise adds to the sound landscape at the housing areas is not examined further.

Table 4. Decibel levels at a distance of 750m from the point source with varying point source sound levels.

	80 dB	85 dB	90 dB	95 dB	100 dB	105 dB	110 dB	115 dB	120 dB
750 m	10.8	15.8	20.8	25.8	30.8	35.8	40.8	45.8	50.8

3.5 Wind wakes and production losses

The wind wake is transferred over a distance. How the terrain might affect the wakes are not looked into further, rather this shows an idealised case of the distribution of wakes behind turbines.

Table 2. Wake radius and the distance from the hub.

	100m	200m	300m	400m	500m	600m	700m	800m	900m	1000m
Wake radius (m)	49.0	57.0	65.0	73.0	81.0	89.0	97.0	105.0	113.0	121.0

The mean wind speed loss was calculated from the wind speed loss matrix as 0.803 m/s and a standard deviation of 0.306 m/s.

Table 3. Wind speed losses in wake for specific combinations of distances and wind speeds.

	400m	500m	600m	700m	800m	900m	1000m
2 m/s	0.349	0.283	0.235	0.198	0.169	0.146	0.127
4 m/s	0.697	0.567	0.469	0.395	0.337	0.291	0.254
6 m/s	1.046	0.85	0.704	0.593	0.506	0.437	0.381
8 m/s	1.395	1.133	0.939	0.79	0.674	0.582	0.508
10 m/s	1.744	1.416	1.173	0.988	0.843	0.728	0.635
12 m/s	1.546	1.256	1.04	0.876	0.747	0.645	0.563
14 m/s	1.623	1.318	1.092	0.919	0.785	0.677	0.591
16 m/s	1.661	1.349	1.118	0.941	0.803	0.693	0.605
18 m/s	1.663	1.351	1.119	0.942	0.804	0.694	0.605

SW-SSE winds which occur for 27% of the year gives a reduction in produced energy of 367 MWh/year ± 148 MWh/year. 6 affected turbines equal a total estimated loss of 2202 MWh/year ± 890 MWh/year.

NE-NNW winds occur for ~14% of the year with equaling a total reduction from 6 turbines by 1142 MWh/year ± 462 MWh/year.

Total wind wake losses are 3.34 GWh/year ± 1.35 GWh/yeara. These are fairly significant yearly losses (3.7-8.7%) considering the yearly production from 10 turbines is 54 GWh. Although the method is blunt and many factors haven't been accounted for, the spectrum between mean and standard deviations is a realistic outcome of production loss, and it does show the importance of optimised placement of turbines. However, potential increases in wind speeds between wind wakes in the most common directions WSW-NW could make up for some these losses, but that's not delved into further. Mean total energy production for 10 turbines including mean wake losses is 50.7 GWh/year, which lowers the total capacity factor to 28.9. A realistic yearly outcome in production is within 49 GWh/year – 52 GWh/year.

3.6 Profitability estimation

The total investment cost includes all stages of the development. Modeling of the economical parameters such as financing, loans and interest rates are not taken into account. How the price of electricity may vary in the future, and whether the wind farm functions on a PPA or on the variable spot-price is also not taken into account.
The possible variations in profitability for a project like this is therefore much greater than what this simple estimation shows.

Total projected investment costs: 240 mil SEK

Bulk investment method:

Total lifetime operational costs: 121 mil SEK
Total lifetime costs = 361 mil SEK
Annual profits: 19.2 mil SEK
Payback time: 12,5 years, ~ 40% of expected lifetime
Total lifetime profits: 338 mil SEK

If the lifetime is cut to 25 years, the total profits is 241 mil SEK, 29% profit loss from a 5 year shorter lifetime. Considering the initial period might be burdened by potential factors such as interest payments, extending the lifetime of the turbines is important for maximising profits.

LCOE method:

Total energy production over the park's expected lifetime (30 years): 1,616 TWh
Total lifetime costs: 365.5 mil SEK
Total lifetime income: 700 mil SEK
Total lifetime profits: 335.5 mil SEK
Annual income = 23 mil SEK
Annual costs = 12 mil SEK
Annual profits = 11 mil SEK

Mean lifetime income, profits, and costs:

Total lifetime income: 700 mil SEK
Total lifetime costs: 363 mil SEK
Estimated lifetime profits: 336 mil SEK

The lifetime profits will greatly depend on how much the lifetime can safely be extended. At 30 years expected lifetime, the expected profits is ~ 48% of investment and operational costs for both methods.

4. Discussion

Although the project is in many ways a great simplification, 2 years of available data enables some certainty in the production output. A calculated capacity factor of 28.9 is very close to the Swedish average capacity factor of 28.6 for onshore wind power (Statista, no.date), which means that the site is a suitable location for wind farm development. The elements of uncertainty stems from the wind being represented as 10-min intervals, when a large amount of the wind energy comes from the turbulent elements on a timescale of 10s to 10min (Jenkins, Ekanayake, 2017), this is confirmed by the amount of variation between minimum, mean and maximum winds in figure 4. A timeseries with a higher resolution would enable more exact production estimates.

The projected turbine was suitable for the site conditions. The wind speed frequency distribution matches the power coefficient, which means that on most occasions the available wind energy is being converted to electricity as efficiently as possible by the specific turbine. Nevertheless, it can't be stated that this turbine is more effective for the site than other turbines on the market. Also, raising the hub height to 140m would probably be a realistic scenario if the wind farm was developed today, which would further increase production output.

The amount of environmental concerns inside the project area was fairly limited, which made the impact assessments easier to do. There's certainly much more available spatial data that could be analysed, which would further limit the exact turbine locations. Even if the noise pollution is not modeled in detail, preventative measures of placing the turbines carefully makes sure that the noise rarely goes towards housing areas during edge cases with suitable atmospheric conditions such as inversions, when the noise travels further. Areas of concern regarding the noise pollution are, overall changes to the sound landscapes by the housing areas, and how the nature reserve and it's animals will be affected by the low level of constant noise from southernly winds. These concerns could certainly be modeled further and examined on-site to gain a better understanding of the potential effects.

The wind wake losses are a fairly significant loss to the overall production, and they show the importance of optimising the final placement of the turbines. There is of course some uncertainty in the estimations since the method is not very specific, and this uncertainty is perhaps the largest out of all the possible factors regarding the production of the wind farm. Although in this case only losses was considered, and considering the wind farm is optimised for the most common wind directions, further work could examine any potential increases in production due to channelised flow.

The profitability calculations are basic but it does show that it could be profitable to develop a wind farm in this location. Estimating with 2 different methods shows the intuitive understanding that there's many possible differences in finanical management, but that a productive site will always be attractive in terms of profit. As the numbers would suggest, the site is already a developed wind farm.

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