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Decentralized wind power as part of the relief for an overstrained grid

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A case study on Northern Senja, Norway

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Abstract

The most significant factor in wind turbine siting is the wind conditions. Those often determine the economic and ecologic success of a project. Especially in topographically complex areas micro siting can be difficult and costly. Small and medium scale projects often lack the knowledge and resources for an extended in situ assessment. A combination of modelled wind data and the use of a geographic information system (GIS) could be an economical competitive approach to find and compare different wind power sites over a larger defined region.

This thesis looks at the small community of Northern Senja, a sparsely populated island in Northern Norway. It evaluates the possibility of community scale wind power (maximum 1MW nominal power) with the help of numerical weather prediction (NWP) wind data. The challenge therein lies in the incapability of mesoscale data to predict the influence of the island's highly complex topography on the wind flow. This mesoscale data is therefore interpolated to a finer grid and corrected for the effect of using a smoothed terrain model.

Production maps for a set of predetermined turbines are created with these corrected data and – together with non-wind related criteria – suitable wind power sites determined. One idea behind this approach is to use free accessible satellite data and to work economical on computational resources.

It is possible to correct the wind speed for height differences, but the method seems to underestimate the shear effects of the complex topography that leads to a probable overestimation of the expected production. Better tuning with the help of real life measurements, which currently are lacking, and an improved implementation of orographic roughness are proposed to resolve that challenge.

Acknowledgements

When starting studying Energy, Environment and Climate I told everybody that I want to dig deeper into the world of local, decentralized, renewable energy. Now, a couple of years later, this actually is one end of that story.
I want to thank my supervisor Yngve Birkelund for his guidance, the idea of this thesis and above all the patience and enthusiasm he showed during this project. Thanks goes also to Marit Hillestad, keeping always a door open when needed and to Thomas Bjørdal and Pål Preede Revheim from the NVES for their expertise in the field of medium scale wind power.

Also to my Norwegian friends, both in Tromsø and elsewhere in the country, which have shaped both my time here and me - and to my family back home, full of expectations: Takk and Danke.

A special thanks goes to my dear Eira, sailing by my side in good winds and helping me to stay on course also in stormy weather.

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1. Introduction:

Almost 100 percent of electricity produced in Norway is renewable, due to the country's mountainous topography, beneficial to hydropower production. The challenge in this region is to transport electricity from the producers to the consumers. Building new or upgrading already existing power infrastructure in Norway in general and in northern Norway in particular often is a challenge. A relatively small population distributed over long distances requires many and long power lines. In addition Norway's demanding topography can propel the cost for infrastructural upgrade. A way to avoid high upgrading costs is decentralized power production. Especially on Norway's many islands, this can be an alternative to highly expensive sea cables and power lines over steep mountain ridges.

Senja is Norway's second biggest island (1 590 km²) located at far above the polar circle at 69° North in the Midt-Troms region. Senja is with only about 7800 residents sparsely populated. Only 1900 of them live along the Northeastern outer coast, the so-called "yttersida" [SSB, 2019]. One main ambition of Norwegian politics is to stimulate its districts' development to avert rural depopulation. The main industries on Senja are fishing, fish farming and processing of seafood on the one and tourism on the other hand. In a region marked by high mountain ridges and deep fjords, where all infrastructure is mainly situated at the small stripes of flat land between the mountains and the sea, a fine balance between infrastructural development and keeping the natural surroundings as intact as possible has to be uphold. In recent years, this region has experienced a remarkable industrial development [Troms Kraft, 2019]. Regional companies process the seafood caught or farmed around the island and export the frozen products to the rest of the world. Though this is favourably, both in sense of minimizing the carbon foot print of those products (by minimizing the unnecessary transport) and for keeping the coastal community alive and generating jobs and economic growth, this development puts the grid owner into a difficult situation. Northern Senja is running out of power – the grid capacity becomes too small for the growing industry. Especially the deep freezing facilities with a high demand of electrical effect need a stable power grid to be able to operate properly and compete in an international market.

Building a costly cable from the mainland to the island (with a price tag of more than 250 MNOK) or local energy production with a Diesel generator (a solution used on a neighbouring island, but which will add 800t of CO_2 to the regions CO_2 balance by 2030 [Troms Kraft, 2019]) are seen as unfeasible. A third, more sustainable, solution is promoted in a collaborative project between the grid provider, the local industry and educational and research institutions where the interaction and synergy of local renewable energy production, energy storage and better energy efficiency is investigated. There is little energy production in that region: Three hydropower plants with a combined power of 15,7 MW exploit the possibilities of waterpower production, a bigger wind power plant with a nominal power production of 35 GW in Berg municipality failed with the municipality protesting devaluation of the landscape in a too high degree.

As wind power is a matured and economical feasible technology [Wagner, Mathur, 2018], it might find its place in the solution of Northern Senja's energy challenge. A decentralized approach could be the right balance between upgrading infrastructure in a smart and sustainable way and keeping the impact on Senja's nature as small as possible. In [Busby, 2012] community-scale wind power facilities define single turbines or small wind farms with just a few MW production. The legal framework in Norway permits the erecting of wind parks with up to five turbines and a rated maximum power of 1MW without requiring a bigger licensing process [Olje- og energidepartementet, 2015], only approval of municipalities has to be given within the legal framework. The amount of investment for those wind power facilities is manageable by industries, municipalities or collectives of private persons. Northern Senja as a coastal region provides strong winds, but a very complex topography disrupts the wind flow a lot. The right placement of future turbines is crucial, however too few local wind statistics over a long time period are available. Small (or medium) projects do not have the time or financial power for site assessments on various locations. A possible solution could be the combined use of modelled NWP (Numerical Weather Prediction) data and geospatial study to find a suitable site.

This thesis takes the situation of today's grid infrastructure deficits on Northern Senja as a starting point to examine the possibilities for small to medium scale wind energy production in complex terrain.

The usual approach for localizing a new site for a wind turbine is to fall back on local knowledge, simply finding a place that is known for being windy and then carrying out wind measurements on that spot to investigate if it is feasible. This project tries to cover bigger ground to begin with, to create a map of feasible areas at first. Although the local examinations will still be a viable part of the turbine site assessment - with the help of modelled wind data and geospatial analysis a preselection might be possible. This thesis aims to find out:

1. If and how it is possible to use WRF wind data in a geospatial approach to determine a well suited site for building a wind turbine in such complex terrain as can be found on Northern Senja
2. Where possible sites can be found on Northern Senja, according to the combined application of wind modelling and GIS (Geo information system) and if they can contribute to relieve the bottleneck situation there.

Chapter 2 of this thesis explains some basic theory about wind power calculation and multi criteria problem solving. In Chapter 3 a selection of different turbines is reasoned. Wind data from a numerical weather prediction model (NWP) is presented and schemes for correcting for the influences of Senja's complex orography explained. An overview of the non-wind related siting criteria is given and attribute values assigned to each criterion.
In Chapter 4 the wind data correction methods are compared and tuned. The non-wind related criteria are weighted and a wind power site assessing map generated. With that evaluation map three fitted areas for setting up wind turbines are established. On those sites production values are determined for each turbine type and their performance compared. In the end in Chapter 5 the reliability of this process is discussed and community scale wind power on Senja evaluated.

2. Theory:

2.1. Calculating the power output of a wind turbine:

The power output calculation for a wind turbine depends on two factors: The wind power density at a particular time and the specific power curve for a chosen wind turbine.
Power curves show the relationship between the produced power respectively to the wind speed and are dependent on the technical components of each turbine.
The power density (*WPD*) of the air flow through the swept area of the rotor blades (*A*) can be calculated by the equation

$$WPD = \frac{P}{A} = \frac{1}{2}\rho V^3$$

(2.1)

with ρ being the air density, and *V* the average wind speed within the time span over which the power density is calculated. That equation shows that wind with high speeds has a much higher energy content than low speed winds since the wind speed *V* is cubed. Averaging the wind speed over long time periods will consequently not show the correct power density.
The best result will be achieved for $\Delta t \rightarrow 0$. A time series of average wind speeds over time segments can be used to solve this problem numerically. The time interval Δt should be relatively small (in this case $\Delta t=10min$ seems sufficient for the whole period of one year).
Another widely used method of calculating the annual yield of a wind turbine is the statistical estimation by inserting a parameterized Weibull distribution of wind speeds into equation (*2.1*), but this analysis will make use of the time series over the wind speed from the WRF. The output power associated with the time series' wind speed is multiplied by the duration of the time interval Δt (10 min) over all time *t*:

$$Yield_{TS} = \sum P_{TS}\Delta t$$

(2.2)

This calculated yield can then be used to calculate the turbines' capacity factors (*CF*) which describe the theoretically produced yield divided by the maximum yield ($Yield_{Nom}$), achieved by continuous operation at full capacity, over the same time period, here one year.

$$CF = \frac{Yield_{TS}}{Yield_{Nom}} \tag{2.3}$$

A high capacity factor shows that the turbine is placed in an area with right conditions, or vice versa that the right turbine is chosen for an area. A good capacity factor today lies between 30% and 40%, but values up to 50% can be achieved [Miller, Keith, 2018].

2.2. Sub grid interpolation of the wind:

Using wind models for turbine site assessments is a cheap way of gaining a large amount of data. Wind flows over a large area with a high temporal resolution (and for a relatively long time period) can be simulated both cheaply and relatively fast. The downside of this approach is that the spatial expand of mesoscale weather simulation grows at the expense of either orographic accuracy or time resolution. The limiting factor is computational power. Nevertheless, mesoscale data has been shown to be a good initial point for further microscale examination. Methods of downscaling and corrections with regards to the influence of the surface on the boundary layer winds have to be applied. Taking into account the conservation of momentum of wind flows and the fact that the general flow above a smooth surface - as proposed in the simplified terrain used in the WRF - is not exposed to sudden horizontal shear, a smooth interpolation can be seen as an adequate approximation of sub grid wind speed. Other interpolation models like i.e. geo-statistical methods, which are based on spatial correlations between sample points, are more robust. They do not only produce value predictions between those points, but also a measure of the accuracy of them. Nonetheless those techniques are highly data consuming; additionally the determination of model coefficients requires experience and knowledge about the region, and are therefore omitted.

2.3. Geospatial analysis of the wind data applying an AHP process:

With a projected map of a turbine's annual yield a spatial analysis of possible wind turbine siting can be done. Geo information systems (GIS) provide the tools to develop and deploy a multi-criteria approach [Miller, Li, 2014]. Finding a site suitable for setting up a wind power facility is constrained by many more factors than the possible energy yield due to wind resources. Those can be grouped into two categories: exclusive factors and evaluation criteria – which after reaching a threshold value might become exclusive as well. Exclusive factors are used to mask the map of possible sites while evaluation criteria rate eligible areas after their suitability. The number of categories and rating of suitable areas can vary to a high degree according to the amount of different fields which are involved in the assessment and due to the qualitative description of suitability factors which often are subjective rankings. GIS have therefore shown a great potential in combining all those contributions to combine them into one map. [Bili, Vagiona, 2018].
A common used multi-criteria decision making tool in sustainable energy studies is the AHP (Analytical hierarchy process) method developed by Thomas Saaty [Saaty, 1980; Bili, Vagiona, 2018]. Every evaluation category is related pairwise with each other and given a value between 1 (equal importance) to 9 (extreme importance over the other category) or the reciprocal value if the second category seems more important. Those values are put into a comparison matrix and normalized over each column. The average over those pairwise weights describes the overall weight of each (sub) category.

Those weights can be implemented into the sum aggregation function of the (sub) categories and an overall evaluation value is contrived. In the process of wind power site assessment the distinction between non-wind related and wind related factors can be a useful approach.
Then on the next level of the evaluation process (hence "hierarchy process") the non-wind related criterion can be compared to wind related evaluations. That could be i.e. the average annual wind or the calculated annual yield for a specific wind turbine. Both criteria can again be weighted according to their importance. In the last step given alternatives are judged by those (weighted) criteria. In the case of geospatial analysis a map is created showing the rating for each alternative at each point of the map. This evaluation map is then clipped by

the exclusion areas which results in one single map over all possible wind turbine sites ranked after the weighted criteria.

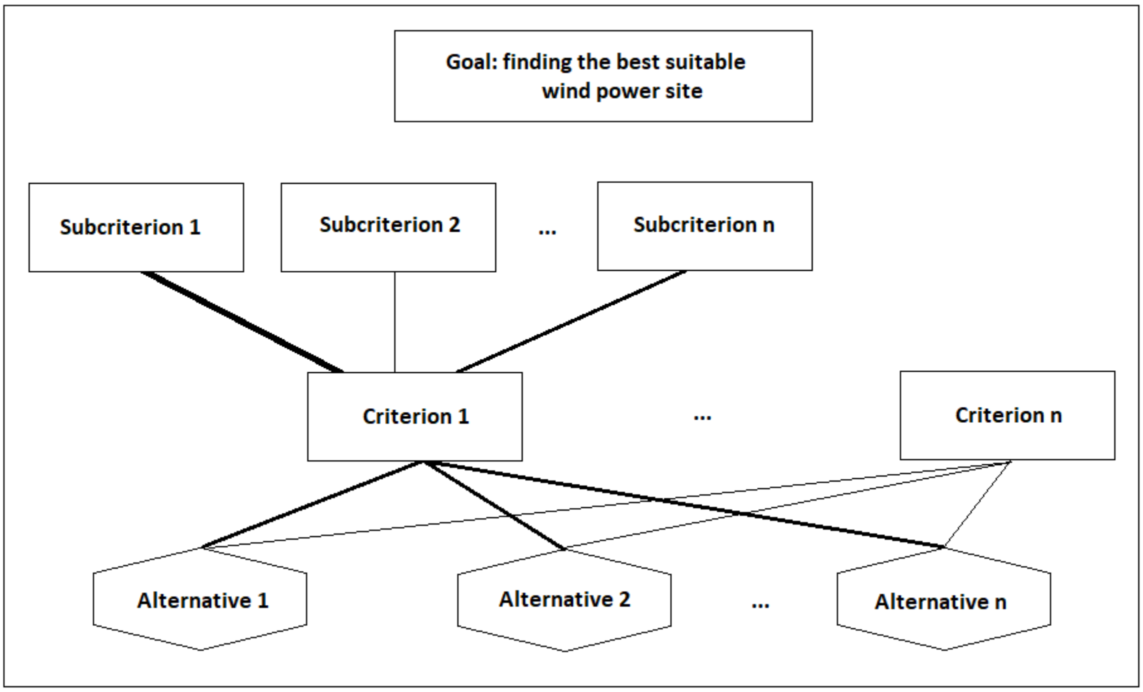


Figure 1: Schematic model of an analytical hierarchy process (AHP): Different alternatives are evaluated by a number of (weighted) criteria and ranged thereafter. The criteria might or might not have a couple of sub criteria or attributes; this way a complex hierarchy can be built.

3. Methods:

3.1. Preselection of wind turbines:

As mentioned afore the approach of first creating a yield map for different wind turbines before finding a suitable location for erecting a wind power facility allows for choosing the turbine type after own criteria, might it be economical, logistical or visual factors.
The criteria for the preselection of wind turbines in this study are:

1. A tower height of around 40m
2. Existing maintenance infrastructure
3. Rated power under 1 MW

The low tower height has two main advantages: Smaller towers are less disruptive during construction, transport and due to their lower size easier to place in complex terrain. Especially in the small community of Senja with narrow and curvaceous roads, the transport costs can be lowered – or the transport can even be made possible - with smaller turbine parts being transported. The other advantage is that lower wind turbine towers are also less disturbing visually. Relatively small wind turbines have higher chances to be accepted in near vicinity to populated areas, especially if those communities own them directly. Also the complex terrain shields wind turbines from being seen from afar. Smaller turbines blend into the surrounding topography more easily then bigger ones.
The existence of maintenance infrastructure is an important economic factor: The goal of the assessment is to place one ore a couple of turbines into this area. Each technical problem or even the regular upkeep has to be done by external maintenance companies. Thus having a wind turbine of a well-established trademark reduces costs or even, in a rural area with long proximity to the main cities, allows for a proper turbine operation. The maximum rated power criterion complies with the Norwegian regulations and is a size-limiting factor. The choice of the turbines could only be a qualified guess, but with the qualified help of the National wind energy centre Smøla (NVES), the choice went to five different turbine types, in three different production categories: Low (275kW rated power), medium (4-500) and high (up to 1MW)

Turbine	Rated power	Tower height
Vergnet GevMPR	275	32
Vestas V34	400	30
EWT DW52-500	500	35/40
EWT DW52-900	915	35/40
Enercon E-44	910	45/55

Table 1: Technical data over selected wind turbines

Those different turbine types are an example of a selection for different needs in the area of northern Senja. Bigger turbines produce more electricity, and since operating costs are small compared to the one time construction investment also normally economic feasible. Then again, the (wind) conditions in some areas might be better suited for one the smaller options.

3.2. Wind data from the WRF model and area of interest

This thesis reuses a sample of modelled wind data obtained by using a Weather Research and Forecasting (WRF) model in the regions of Troms and Nordland, Norway [Solbakken, Birkelund, 2018]. Wind speeds are modelled with a temporal resolution of ten minutes from the 1.1.2017 at 00:00 o'clock to the 31.12.2017 at the same time on a grid with roughly 1km distance between grid points.

That study uses a advanced Advanced Research WRF model (ARW) version 3.9.1. The elevation data (GMTED2010), obtained from the National Centre for Atmospheric Research (NCAR) have a resolution of 30 arc-seconds, roughly 1km. It also accounts for surface roughness by applying 20-category Moderate Resolution Imaging Spectroradiometer (MODIS) land use data (same source and resolution). The wind simulation is based on ERA-Interim reanalysis data obtained from the European Centre for Medium-Range Weather Forecast (ECMWF). By a one-way nesting strategy (information flow from higher domain to lower, but no feedback) over three domains this data is simulated and downscaled, with d3 being the innermost domain, having Northern Senja as centre point.

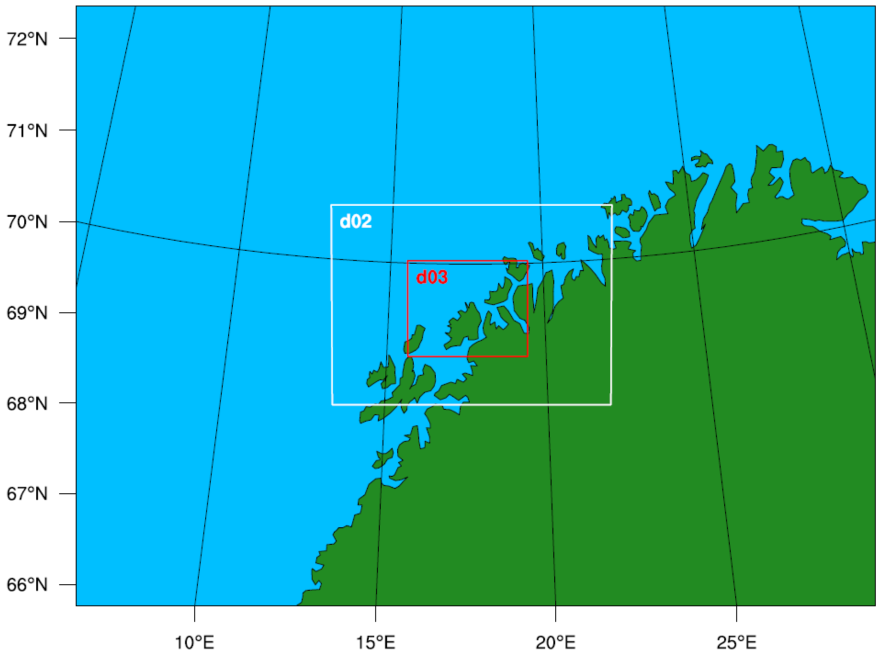


Figure 2: Nested domains (d1 being the whole map shown) for the WRF model, from [Solbakken, Birkelund, 2018]

The grid size is reduced from 25km in d1 to 5km and 1km in d2 and d3 respectively. The temporal resolution in d3 is 5 seconds, for numerical stability, while the output data is the 10 minutes average at each grid point. The simulation has been run for each week in 2017 with the initial data, with an extra 24 hours as spin up time for the simulations. To cover for all seasonal and diurnal variations the time span of one year was chosen. The simulated wind data, both the resulting speed and direction) was then evaluated statistically compared to measurements of three weather stations in that range (Hekkingen near Senja, Andøya and Tromsø).

A conclusion of this study shows that the WRF model is able to predict the main wind direction quite well, which is a good starting point for a further downscaling by taking in account the local orographic conditions. With respect to the winds speed the RMSE (Root mean square error), which describes the momentaneous errors of the evaluated data, indicates that this approach shows weaknesses; the models capability of reproducing rapid changes in wind speed are limited (figure 3).

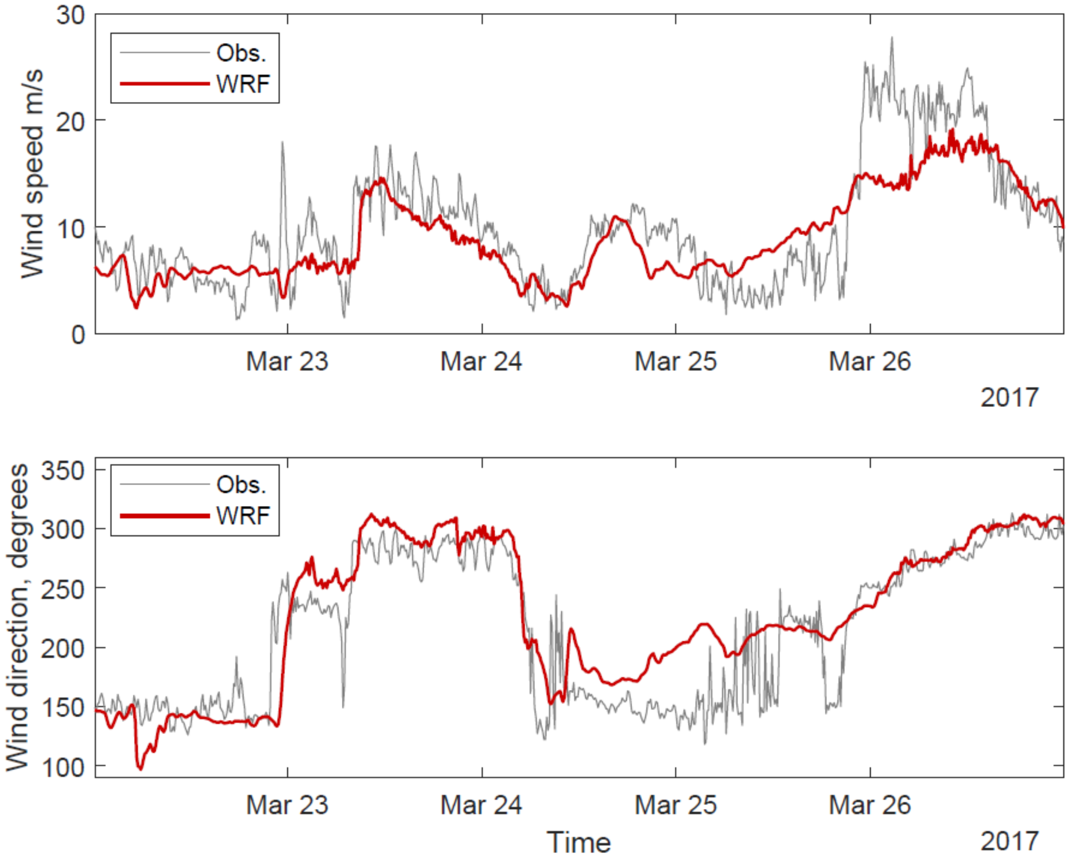


Figure 3: Deficiencies of the WRF model to catch instant changes in wind speed or direction, from [Solbakken,Birkelund, 2018]

Overall the study suggests a slightly overestimation of wind speeds due to the smoothening of complex topography in a coarser terrain model as used in the study. This overestimation occurs especially in regions with complex terrain; though with higher altitude the differences to measured values become smaller, as the influence of surrounding obstacles decreases.

This thesis uses wind data from an area which extends from 69,3 to 69,6 degrees North and from 16,8 to 18,2 degrees East. That area includes The Northern part of the Island Senja, the region of interest, but also the Kvitfjell mountain wind park as a reference on the Island of Kvaløya. The wind speed data is downscaled further by a factor of 3 from a 1 km to a 333 m grid size. A higher resolution would have been preferable, but were discarded due to considerations of computational power resources. In further corrections the data has to be evaluated for every ten minutes over the span of a whole year (52417 times) at each grid point. That resolution is suitable compared with the extent of base structures for wind turbine towers. A simple interpolation method based on the Akima spline [Akima, 1970] is used, a build in cubic interpolation method in MatLab. It is robust to outliers and deals well with fast changes in slopes (i.e. boundaries between mountain slopes and the sea level).

3.3. Orographic correction:

The course gridded elevation model from given data is not able to show the spatial variation of Senja's complex topography with the rugged mountain ridges cut through by rugged fjords. Therefore an orographic correction is applied to the interpolated data. A digital terrain model (DTM) with a horizontal resolution of 10m from the Norwegian mapping authority [Kartverket] provides the measured heights at the interpolated grid points (resolution: 333m). A finer and more detailed terrain model is so obtained and can be further exploited for orographic speed corrections.

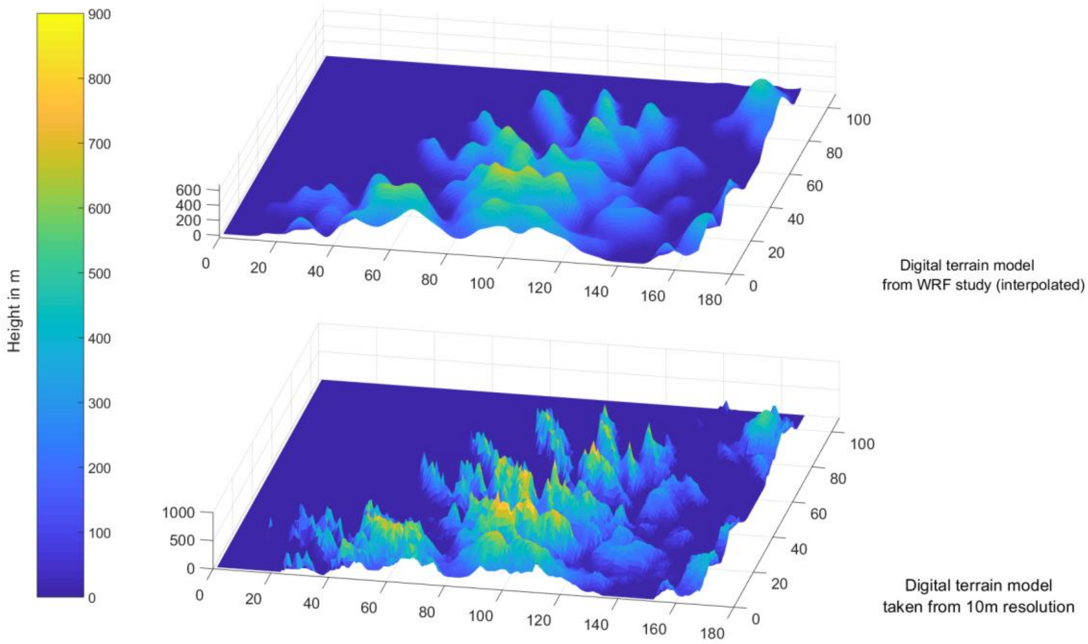


Figure 4: Differences between the smooth digital terrain models (DTM) used in the WRF model and DTM with higher resolution, Senja's orography and thereby its effect on wind data is better represented, created in MatLab

3.3.1. Central differences scheme:

[González-Longatt et al, 2015] proposes a combination of a spatial interpolation of the wind speed between certain grid points in combination with an orographic correction. The wind flow over crests and hills has been thoroughly examined [e.g. Wegley et al., 1980]. The conservation of mass and momentum principles inflict that the flow over an obstacle, over the increase of the terrain's slope *Δh/Δx*, needs to accelerate. An increase in height forces the flow line to bend and the wind speed to increase to comply with those principles. A simplification made is that pressure changes are linearly related to the change in height *Δh*. The one-dimensional orographic correction Cor_v is given by the equation:

$$Cor_v = f(\Delta h \frac{\Delta v}{\Delta x}) \tag{3.1}$$

A central difference calculation over the finer gridded terrain model combined with the earlier interpolated wind speeds, both in lateral *(v(x))* and longitudinal direction *(v(y))*, is executed. The final corrected wind speed at each grid point *(i,j)* is given by the equation

$$v_{cor}(x) = v(x)_{i,j} + \frac{1}{2}\left(\frac{(h_{i,j} - h_{i-1,j})(v_{i-1,j} - v_{i,j})}{\Delta x} + \dots \frac{(h_{i+1,j} - h_{i,j})(v_{i,j} - v_{i+1,j})}{\Delta x}\right) \tag{3.2}$$

along the line of i and by

$$v_{cor}(y) = v(y)_{i,j} + \frac{1}{2}\left(\frac{(h_{i,j} - h_{i,j-1})(v_{i,j-1} - v_{i,j})}{\Delta x} + \dots \frac{(h_{i,j+1} - h_{i,j})(v_{i,j} - v_{i,j+1})}{\Delta x}\right) \tag{3.3}$$

along j.

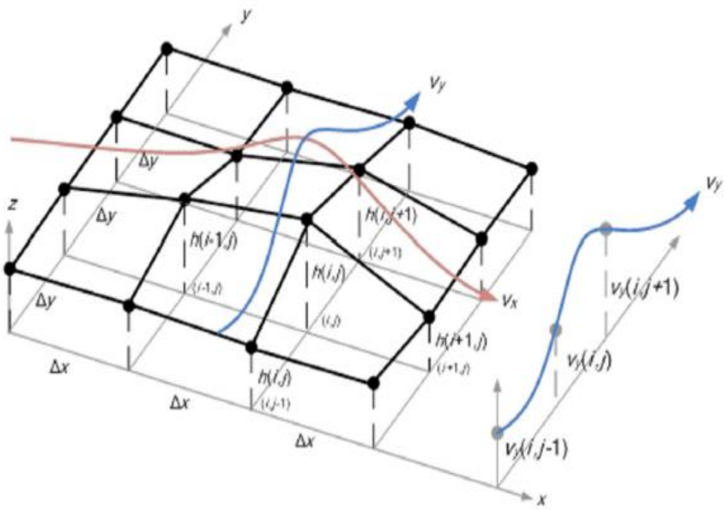


Figure 5: The forced change of flow over a hill on a grid (i,j), from [Gonzales-Longatt et al. 2015]

The advantage of this interpolation-correction scheme lies in its simplicity. Although, because of a high level of simplification, the data might be under-corrected. The aim is to see the underlying local orography in the corrected wind map. The calculations are performed with the help of MatLab.

3.3.2. Orographic roughness correction:

A second orographic correction method tried, is described in a study of [Howard, Clark, 2007]. A parametrization, which takes into account both the surface's roughness and residual - or detrended – orography, is applied to the interpolated WRF wind speed data. For this occasion the detrended orography is the difference between the underlying terrain model in the WRF simulation and the elevations obtained from the DTM10 (figure 6).
One way to consider those height differences is to understand them as an "orographic roughness", similar to the roughness length over moderate terrain [Grant, Mason, 1990]. To calculate this roughness only little additional data is needed which can be estimated from the finer gridded terrain model. One weakness of this process lies in neglecting the flow separation; the wind is corrected for surface and gravitational drag effects only. With narrow

valleys across the wind flow this problem can be neglected, but longitudinal winds divided by steep mountain ridges in north-south direction will not be caught.

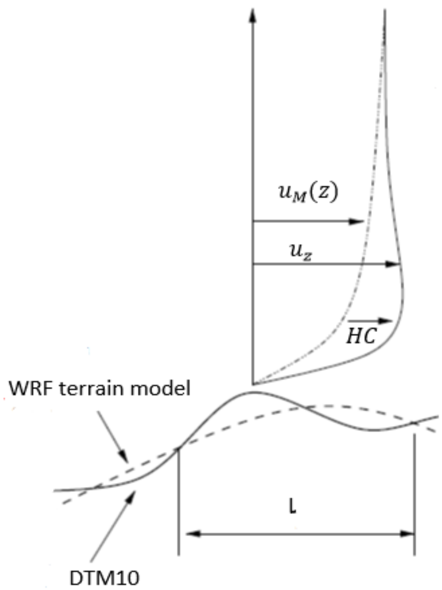


Figure 6: The initial wind speed $u_M(z)$ is corrected for roughness (omitted in this paper), a height correction HC is added to incorporate the sub grid orography (the difference between the WRF terrain model and a model with finer resolution, from [Howard, Clark, 2007] abridged

Additional to the WRF wind speed two parameters have to be calculated to describe the orographic roughness (OR). An assumed wind flow over a simplified area is altered by both friction and local displacement to the air masses by obstacles of the detrended orography (simply mountains "being in the way"). Two parameters for this roughness calculation have to be estimated: The mean obstacle height and density of obstacles along the wind flow.
The density of the obstacles is defined as the quotient of the transversal Area *A* of the obstacles and the horizontal span *S*.
For simplicity this problem is reduced to two two-dimensional cases, one in the longitudinal and one in the lateral direction. Wind diversion around obstacles will not be taken into account, but the influence of the obstacles on the wind speed along the flow lines.
In two dimensions the density *A/S* can be calculated by *h/l* (*l* is the mean distance between obstacles and h the average height). An estimate for *h* is determined by multiplying the standard deviation of the detrended elevation by two [Han C et al. 2015].

$$\frac{A}{S} \approx \frac{h}{l} = \frac{2\sigma_{elev}}{l}$$

(3.4)

In the Appendix the Matlab code for determining *h* and *A/S* is presented. To account for the rapid change between high mountain ridges and water surface, which also manifests itself in the unsolved orography, the length over which those parameters are determined has to be small enough. This minimizes the averaging of elevations with high standard deviations. The length segment must also be long enough to minimize the breaking up of obstacles. The chosen span is 12 grid points (4 km).

A typical profile of a slice and the modelled average surface can be seen in (figure 7):

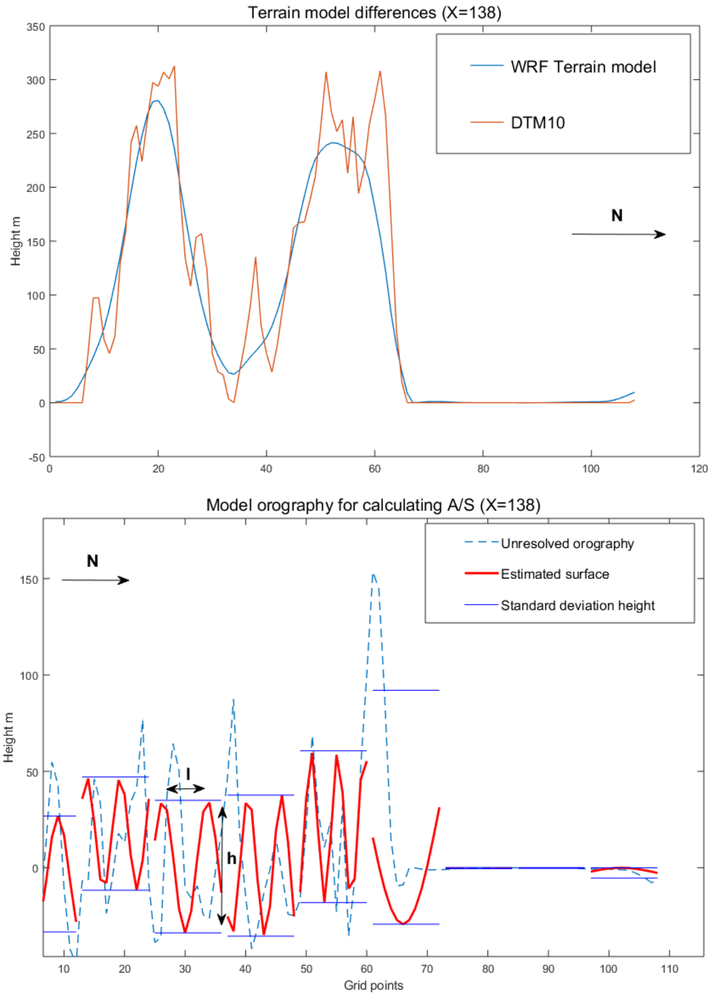


Figure 7: The terrain differences between the smoother and the finer model (above) are simulated as a sinusoidal over each length segment, created in MatLab

Above a reference height h_{ref} the WRF wind flow is undisturbed by the model height differences (similar to flow disturbances by surface roughness). This reference height differs with different terrain and can be estimated by the equation:

$$h_{ref} = \frac{h/2}{\pi \cdot A/S} = \frac{h/2}{\pi \cdot h/l} = \frac{l}{2\pi}$$

(3.5)

The outer wind layer with the same wind speeds as the WRF model provides the main flow, while the inner layer below h_{ref} is disturbed by orographic differences. The input wind speed into the inner layer will be the WRF wind speed at the reference height $u_M(h_{ref})$.

A roughness correction is suggested by the authors. The wind speed at the reference height as well as the roughness correction can be determined under the assumption of a neutral wind log profile below this height

$$u_M(h_{ref}) = u_M(z)\frac{ln(h_{ref}/z_0)}{ln(z/z_0)}$$

(3.6)

$$\bar{u}(z) = u_M(h_{ref})\frac{ln(z/z_0)}{ln(h_{ref}/z_0)}$$

(3.7)

with a roughness length z_0. The height above the surface *(z)* is assumed to be 40m for all further purposes, this analysis is only interested in the height correction, the altitude over the terrain stays the same.

The WRF model includes surface land use data and incorporates a surface roughness, thus a correction appears to be redundant. Combining equations *(eqn. 3.6)* and *(eqn. 3.7)* leads so to the result

$$\bar{u}(z) = u_M(z)$$

(3.8)

In further calculations the value z_0 is set to 0.0002 over water surfaces and to 0.055 over land. The main interesting land areas are either in mountainous areas with sparsely distributed objects or grasslands, so this simplification can be justified.

The sub grid orography can be represented by a sinusoidal system of hills and valleys. The height correction according to [Howard, Clark, 2007] considers the shear and surface stress in a log-law approach both for the outer and inner layer the bottom boundary condition $U_{HC}(z = z_0) = 0$. It can be written as

$$u_z = \bar{u}(1 + HC)$$

(3.9)

$$HC = \beta e^{\left(-z/h_{ref}\right)} \frac{u_M\left(h_{ref}\right)}{\bar{u}} \frac{1}{h_{ref}} (h_{Diff})$$

(3.10)

The inner layer wind profile (β) decays rapidly and the outer layer solution slowly compared to the height of the inner layer (h_{ref}). The total impact of the inner layer profile has hence little significance to the total result of the height correction and can be replaced by a factor of one (neglected) for computational simplicity.

The wind speed cancels out in the term $\frac{u_M(h_{ref})}{\bar{u}}$ so that

$$HC = F\left(z, href, z0, h_{Diff}\right)$$

(3.11)

is dependent only on variables given by the location. Therefor a transformation factor at each grid point can be pre-calculated. This transformation map can then simply be applied to the wind speed time series. From a computational point of view this is highly advantageous and work saving.

That scheme shows significant adjustment to the initial interpolated wind data. The wind speeds obtained follow the underlying topography much more closely than before correction (figure 8) where higher wind speeds are expected in higher altitudes.

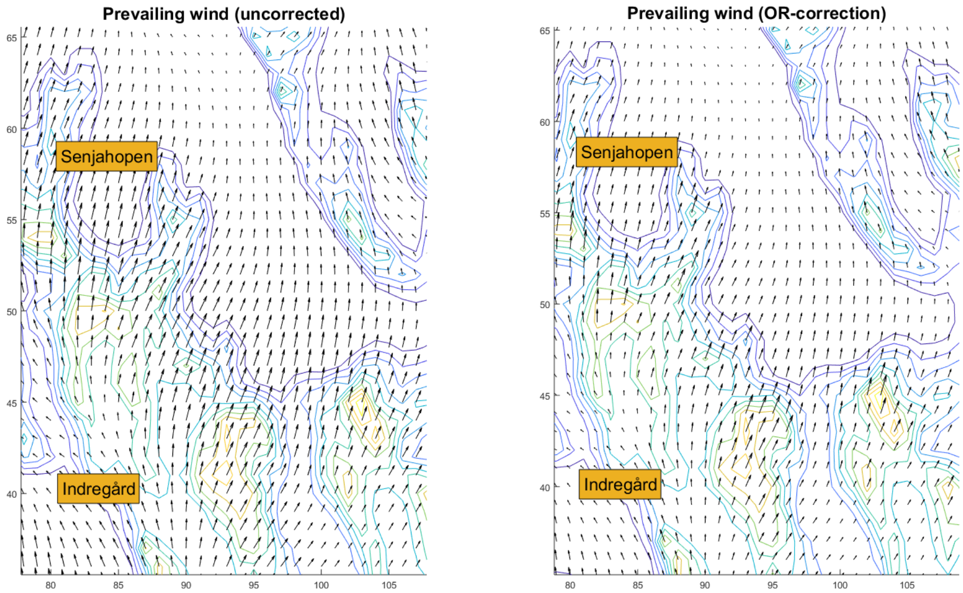


Figure 8: Clearly visible is the dependence of the wind speed (here represented by vectors) of the underlying orography in the corrected data (right). Winds of relatively higher magnitude are found above higher altitudes. In the uncorrected data (left) the prevailing wind seems to be undisturbed by the topography.

As described in [Howard Clark, 2007] and [Solbakken, Birkelund, 2018] there are different possibilities for a bias in the modelled speed to begin with and "some dependence of the error on actual to model height difference". Especially in places with a big difference between the smoothed and the improved terrain model this may lead to unlikely high wind speeds. Therefore a correction factor k1 is introduced to cope with the initial bias and a factor k2 to improve this method according to overestimation in speed adjusted for heights.

$$u_z = k_1 \bar{u}(1 + k_2 \beta e^{\left(-z/h_{ref}\right)} * \frac{u_M(h_{ref})}{\bar{u}} \frac{1}{h_{ref}}(h_{Diff}) \tag{3.12}$$

The resulting time series' are used to create maps of the corrected average wind speed over northern Senja together with the annual yield and the capacity factor of each wind turbine. This is done in a geospatial information system (GIS) program, namely QGis.

3.4. Non wind related criteria used in this thesis

In addition to the wind power potential other factors are evaluated in this study:

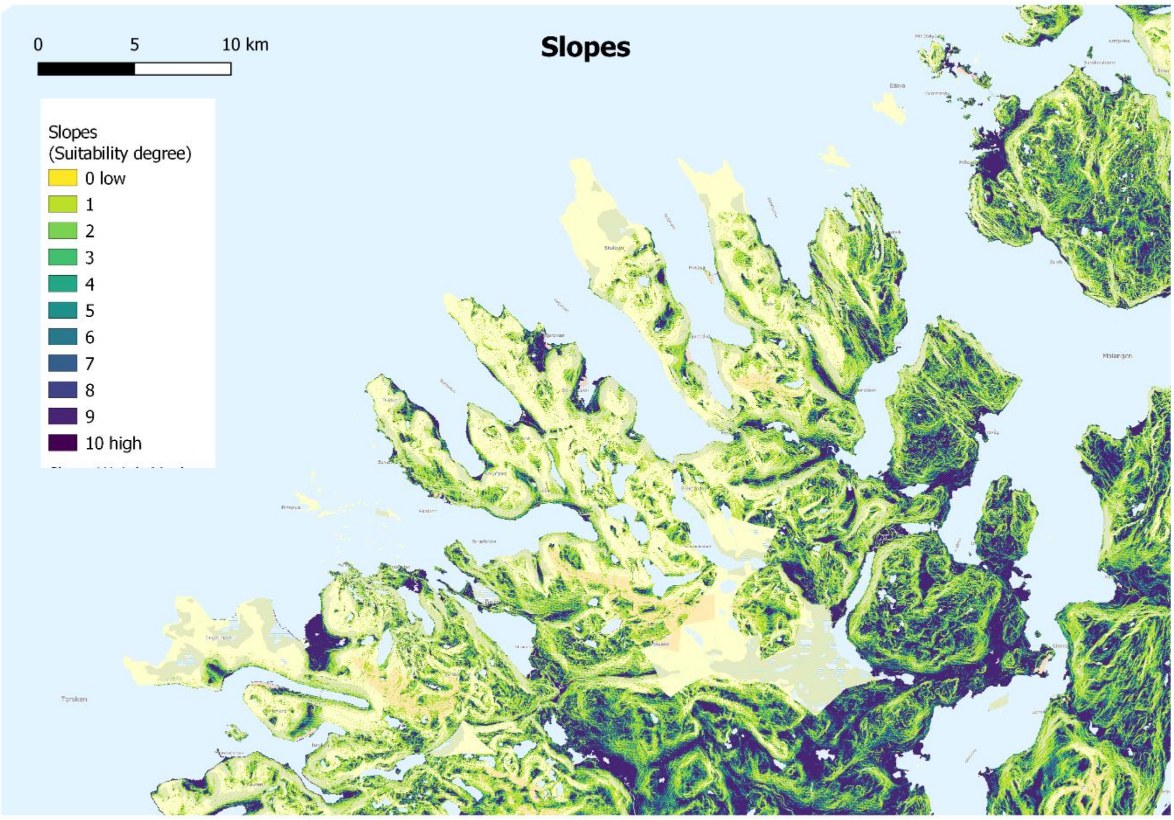
1. Slope
2. Surface (type, vegetation, land use)
3. Proximity to existing road network
4. Proximity to existing power lines
5. Recreational outdoor life areas
6. Nature conservation zones

Each aspect is valued and given a suitability grading from one to ten, which then is converted into a suitability map in QGis. Areas with the suitability value of 0 according to at least one category are not suitable for wind power production and will therefore be excluded from the further evaluation. All evaluation variables (but outdoor area) have threshold values. The natural conservation zones are seen as a solely exclusive criterion and will only add to the masking of the area. An overall mask layer is created in QGis and applied on all maps. All areas not of interest, which means not suitable for wind power production after given consideration, will so be taken out of further calculations. This thesis relies on data free available. Fortunately, Kartverket, the Norwegian mapping authority, aims to collocate and publicize geo data. They have developed tools to access public data both in web portals and directly in GIS-software [Kommunal- og moderniseringsdepartementet, 2018].

The slope accounts both as a technical and economical factor: Steep slopes increase the construction costs of the turbine because of the cost for levelling the ground or make it even impossible. The threshold value varies in the literature from 20% to 45%. Taking into account a complex topography and Norwegian expertise and infrastructure for building in difficult terrain the higher value might be appropriate, though steep slopes over 25% will get a low rank. The slope value only represents the local slope at a given point; accessibility by roads i.e. is not evaluated. The slopes are calculated in Qgis from the same digital terrain model which is used in the correction of the wind speed time series (DTM with 10m spatial resolution, [Kartverket]).

Slope (%)	Suitability
0	10
0-10	9
10-15	7
15-20	4
20-25	2
25-45	1
>45	0

Table 2: Suitability values applied to the steepness of the surrounding terrain

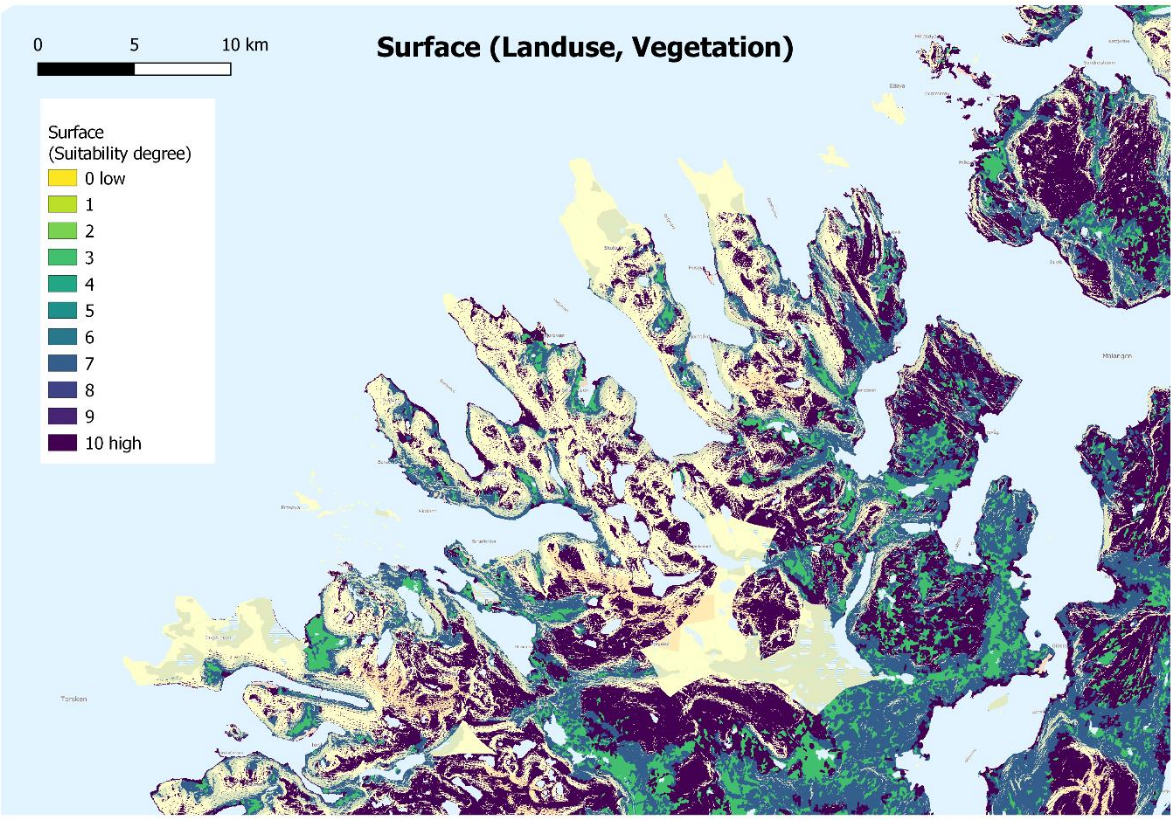


Figur 9: Slope suitability map over Northern Senja, created in Qgis

The surface type is both exclusive and evaluative: Areas as water bodies, infrastructure as roads and buildings, or glaciers are excluded from the possible sites. Farm and grassland are best suited – the sealed area of a wind turbine is relatively small, even together with the needed access roads; farming or grazing can continue even in buffer zones put up because of noise, shadowing or wind issues. Constructing on swamp areas is difficult, but might be possible, depending on the spatial extension of those areas, therefor areas marked as wetlands are not excluded. Wind turbines in forest areas have a much higher wind flow disruption due to vegetation. Thus the lower suitability value. Additionally constructional work in forests carries with it an extra deforesting around the transportation paths. Landuse data is obtained from the Norwegian Forest and Landscape Institute [Norsk institutt for skog og landskap, 2014].

Surface	Suitability
Farmland	10
Grassland	10
Forest	7
Swamp	3
Waterbodies, Ocean	0
Buildings, Infrastructure	0
Glaciers	0

Table 3: Different surface properties ranked after their impact on wind turbines above



Figur 10: Surface suitability map over Northern Senja, created in Qgis

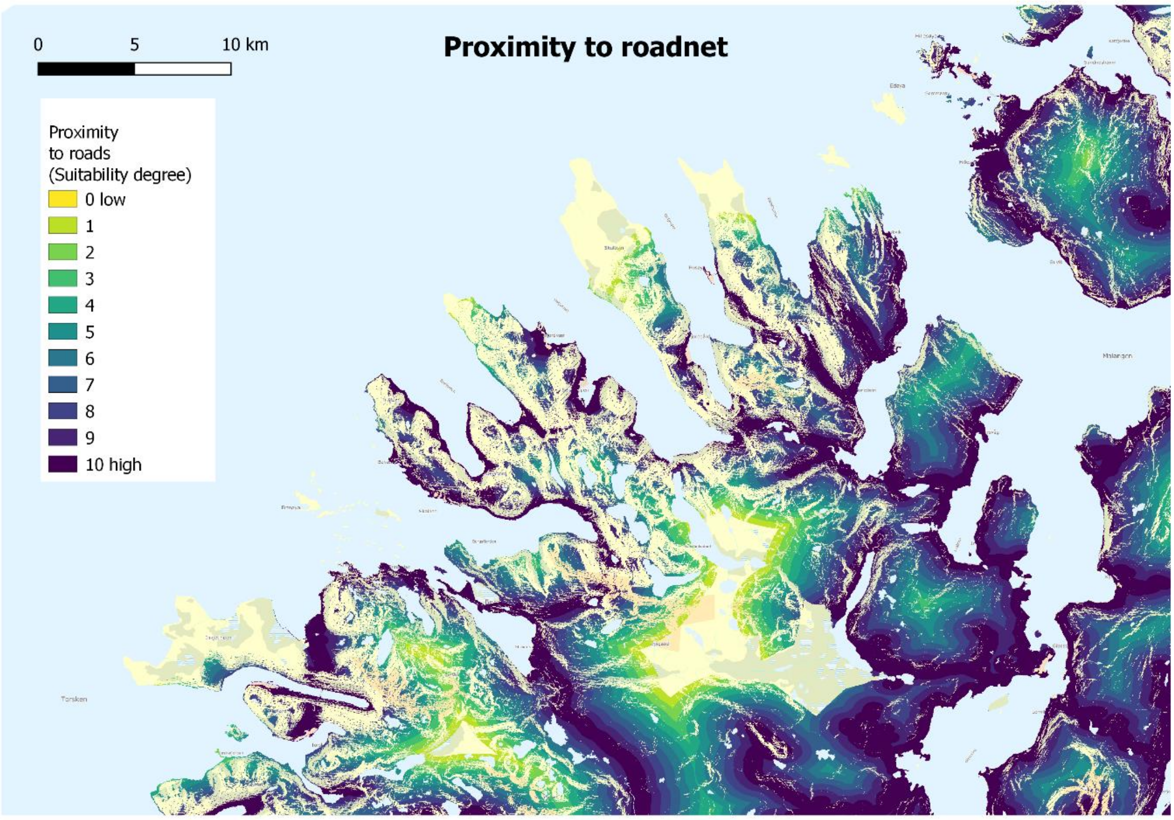
The further away from existing infrastructure the future wind power plant is situated, the higher are the investment costs. Road construction and grid connection stands for 10-14% of the levelled cost of energy (LCOE) in general; but, since each site has its specific properties

with its own challenges, investment costs can fast become 15% higher or lower than the average [NVE, 2015]. The fragmentation and destruction of natural habitats or migration routes is also more affected the longer away from already existing infrastructure a turbine will be placed.
Every distance from roads (power lines) above 5km (10km) and above has the suitability value of zero. Normalized to the amount of ten points the suitability can be calculated by

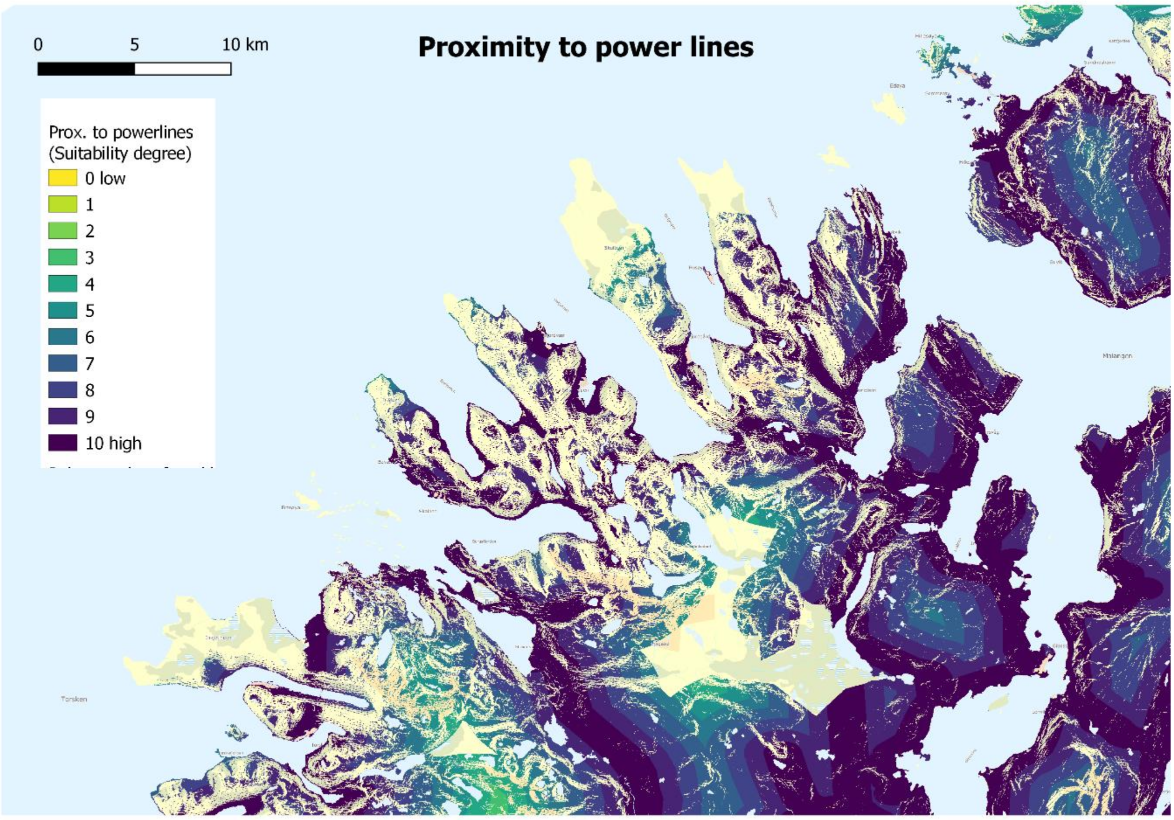
$$suitability = 10 - proxRoad/500 \tag{3.13}$$

$$suitability = 10 - proxPL/1000 \tag{3.14}$$

for roads and power lines. The negative effects (and costs) for roads are evaluated higher than for power lines. Road net data is taken from the Norwegian Mapping Authorities (Kartverket) and information about the grid from the Norwegian Water Resources and Energy Directorate [NVE, 2019].



Figur 11: Road net proximity suitability map over Northern Senja, created in Qgis

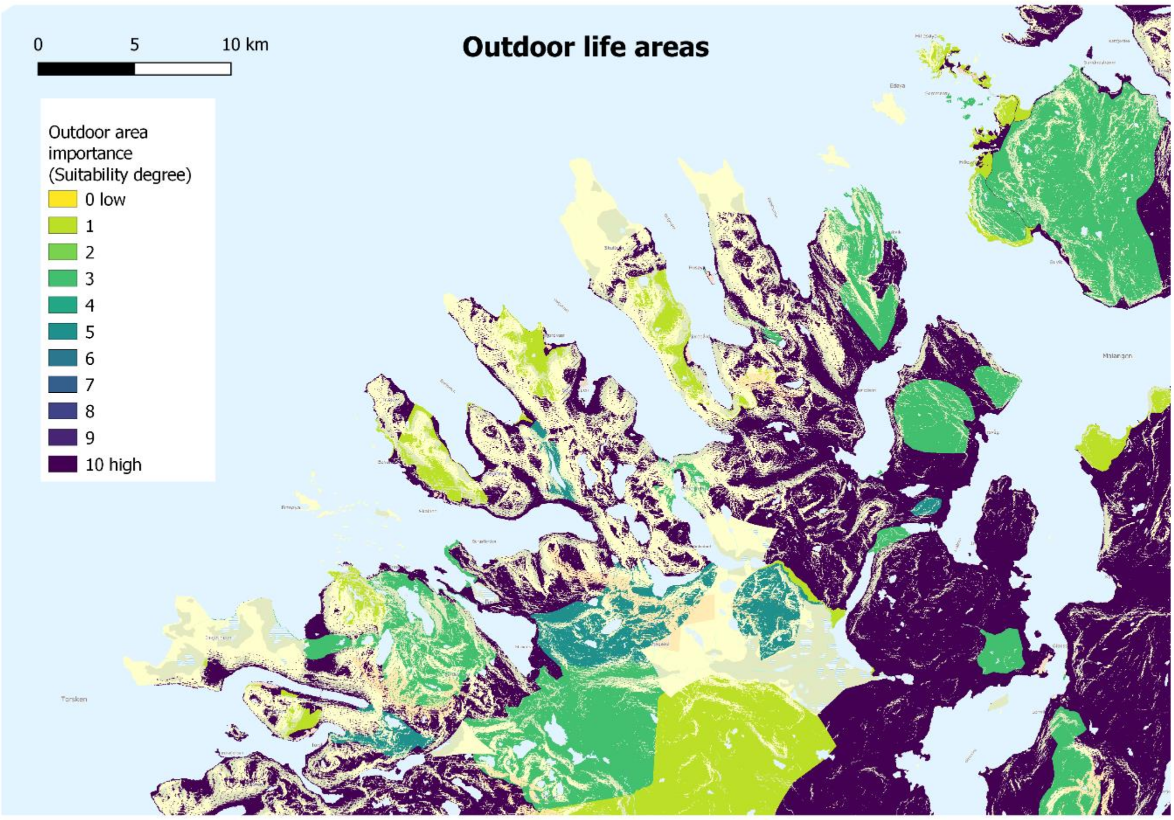


Figur 12: Road net proximity suitability map over Northern Senja, created in Qgis

In Norwegian culture the outdoor life plays a big role in the everyday life and is highly valuated not only for recreational purposes, but also in the means of public health. The approving municipal authorities on Senja (as a tourist destination both for Norwegians, but also on an international scale) have always to consider particularly the impact of new infrastructure to the landscape around. Even if the acceptance of small "self-owned" wind turbines is much higher than for wind parks, the destruction of local recreational areas plays a big role in the permitting process. The Norwegian Enveironment Agency, Miljødirectoratet, has commissioned a dataset which shows and rates the country's outdoor life areas and rates them due to frequency of use, local and national importance, quality of experiences (special landscape) future potential and accessibility, amongst other factors [Miljødirektoratet, 2014]. A total evaluation based on those specifics is then calculated. Translated to this suitability ranking this yields:

Outdoor area importance	Suitability
No Importance	10
Registered Outdoor area	5
Important	3
Very important	1

Table 4: Suitability values for the evaluation of the importance of outdoor life areas



Figur 13: Outdoor areas suitability map over Northern Senja, created in Qgis

Those maps are combined as a weighted and normalized sum of all five criteria as an overall evaluation map for the non-wind related factors. From there on different approaches are possible: A weighted product of that evaluation map and a map of the average corrected wind speed can be calculated to generate a suitability map over the whole area. This has the advantage that this map is independent of the technical data of a specific turbine. The average wind speed is an indicator for good wind conditions, but the distribution of low and high winds determines the outcome of the annual yield. So general suitability maps generated from different turbines' annual yield (to compare the gross production) or capacity factors (to compare the efficiencies) might be a better approach. The downside

here is that this is computational costly; maps over the whole area for each suggested turbine have to be generated, stored and compared with each other.
This study combines both approaches by:

1. Creating a (global) suitability map using the average wind speed
2. Using that map to define sub regions
3. Using the different turbines' capacity factors to find and compare different turbine placements

The weighting between non-wind related factors and the wind speed is set to 1:4 – both concerns about initial costs and social acceptability are overshadowed by the fact that a wind turbine has to produce power to fulfil its purpose. This is consistent especially since a good placement according to the wind conditions are crucial in the overall life time economy of a turbine [NVE, 2015]. The global suitability map is calculated by:

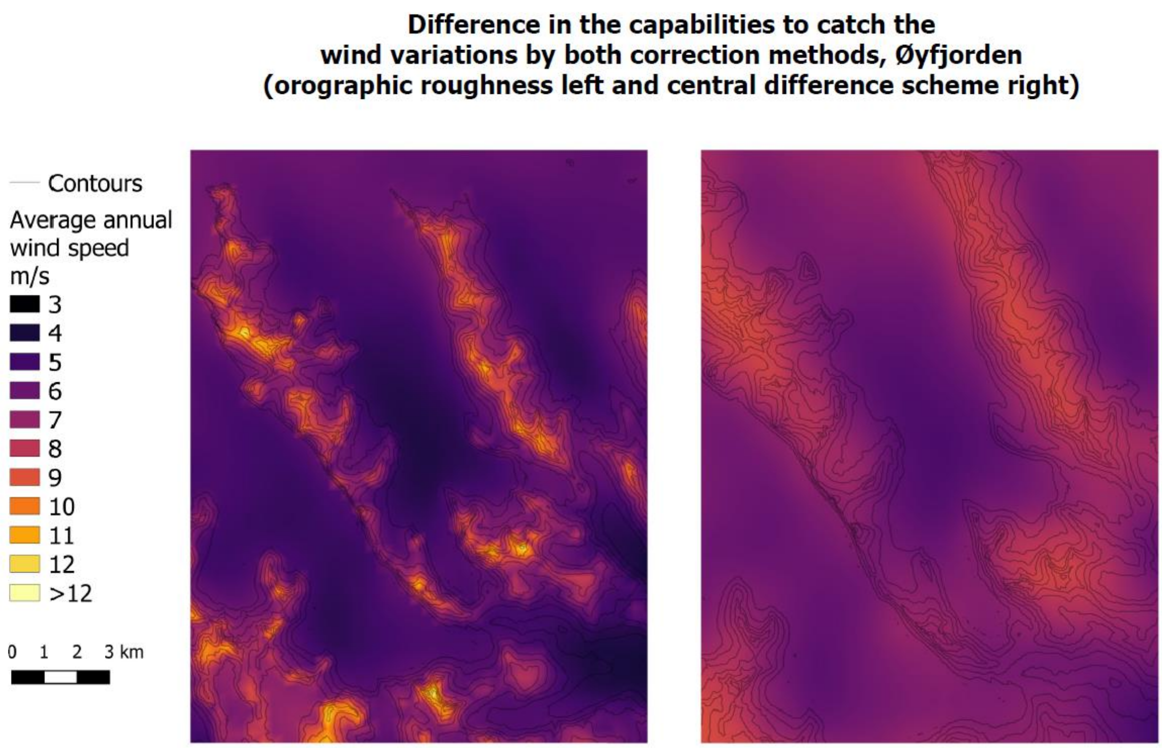
$$map_{global} = {map_{windspeed}}^4 * map_{non-wind\ related} \tag{3.15}$$

From there suitable areas are chosen to create a sub region in which the best fitted wind turbine placement is chosen.

4. Results:

4.1. Comparison of the correction methods

Both wind speed corrections neglect diurnal thermal winds up- or downslope which are caused by heating of night cold air masses in valleys over day time and a temperature gradient between those valleys and the surroundings at night. The diurnal temperature differences are not too high in Northern Norway, the sun does not go down in summer (or up midwinters) and temperatures do not rise that high at all normally, so the effect of diurnal thermal winds is expected to be minimal.



Figur 14: The orographic correction models show different abilities to adjust for underlying topoography. The Orographic roughness scheme (left) surpasses the central difference scheme by far. Clearly visible is the coincidence between topography and wind speed (left), created in Qgis

As can be seen on (figure 14) the orographic correction method proposed by Howard and Clark (the correction of orographic roughness method, OR) follows sharply the topography of the DTM model. The method utilizing a central difference scheme (CD) does not work satisfactually in that point, since the whole correcting effort is done to account for the influence of the unresolved orography. Data corrected with the OR method are therefore used in further analysis.

4.2. Tuning the orographic roughness correction (OR) model:

Real life data from weather stations or ongoing and realised wind power projects can help to tune the model due

Unfortunately not much real life data is available on such a local level. One of the three weather stations (Hekkingen fyr) mentioned in the study from which the WRF model data is taken from lies within the boundaries of this thesis' area. There are though some qualitative aspects which help to adjust this method. First a threshold value of annual average wind speed of 12m/s is applied. The maximum wind speed averages in the uncorrected data lie around 9m/s, a correction to a value one third higher should be the exception. On the Kvitfjell mountain on the adjacent island of Kvaløya in the North East of island a wind farm is being built and finished in autumn 2019. On the project description of that wind farm it is mentioned that the area has wind speeds of 7.4 to 9.0m/s. A realistic correction of the initial corrected wind data should correspond to that. In (table 5) the outcome for some different combinations of parameters can be seen.

		Hekkingen Fyr		Kvitfjell	Northern Senja	
k1	k2	Mean bias	RMSE	wind speeds	# speed >12 m/s	max speed
1,00	1,00	-0,2	4,0	10,5-11,5	414	21,2
1,00	0,60	-0,2	4,0	8,8-9,3	115	16,0
0,85	0,60	-1,2	3,9	7,3-8,8	20	13,6
0,80	0,70	-1,5	4,0	7,8-8,8	20	13,8
0,90	0,50	-0,8	3,9	around 8,8	16	13,3
0,80	0,6/0	-1,4	4,0	6,8-9,0	7	12,8

Table 5: Different combination of tuning parameters k1 and k2 show different effects on the mean wind speed bias and the root mean square error (RMSE) at Hekkingen Fyr weather station, average wind speeds in the area of Kvitfjell wind park an general number and magnitude of unlikely high wind speeds over Northern Senja

The values of 0,8 for k_1 and 0,6 or 0 for k_2 (according if the real orography lies above or below the elevation of the terrain model used in the WRF simulation) show an acceptable improvement in most of the given given control criteria: the overall average wind speed on Northern Senja and the wind speeds around Kvitfjell wind park. The change to a higher overestimation of the frequency of lower wind speeds at Hekkingen fyr weather station (figure) can be seen in the light of the fact that this weather station – on an island in the open sea - was the one of the three weather stations which were the least representable for

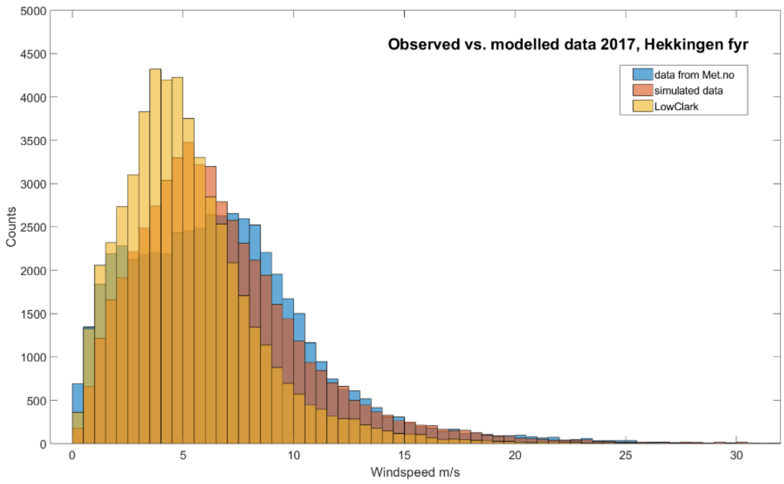


Figure 25: Histogram of observed [MET, 2019], modelled and tuned wind data at 10m above ground, Hekkingen Fyr, created in MatLab

the conditions of complex terrain. The original modelled data overestimates the mean annual wind speed at both other stations (with more similar terrain complexity) which leads to the conclusion that a general decrease of the modelled wind speed counterweights that effect. In practical terms a underestimation of the modelled wind speed allows for a more conservative examination of wind power production possibilities. The corrected wind speed will be calculated by:

$$u_z = 0{,}8 * \bar{u}(1 + 0{,}6 * \beta e^{\left(-z/h_{ref}\right)} * \frac{u_M\left(h_{ref}\right)}{\bar{u}} \frac{1}{h_{ref}} (h_{Diff}) \tag{4.1}$$

for locations where the real altitude lies above the smooth model's and

$$u_z = 0{,}8 * \bar{u}$$

(4.2)

for locations which in real life are below the model's altitude.

4.3. AHP analysis of the non-wind related criteria:

The five different evaluation features – slope, surface structure, proximity to roads and power lines and the value of outdoor (nature) areas – are set up against each other in the following way:

Slope	→	Surface	1/5
Slope	→	Prox. to roads	1/2
Slope	→	Prox. to power lines	2
Slope	→	Recreational areas	1/8
Surface	→	Prox. to roads	4
Surface	→	Prox. to power lines	9
Surface	→	Recreational areas	1
Prox. to roads	→	Prox. to power lines	3
Prox. to roads	→	Recreational areas	1/5
Prox. to power lines	→	Recreational areas	1/9

The Surface type attributes (including vegetation) is given a high grade of importance – especially the growth of trees impairs the expected yield of wind turbines in general, but relatively low structures in particular. Since combining outdoor recreational areas and wind turbine siting is a combination full of conflicts of interests and highly influential in the process of municipal approval, it has been given high importance over other factors. Both slopes, the proximity to the road net and to electrical infrastructure are economical parameters. In addition to that the construction of transportation paths through natural landscape (and to a certain, but smaller extent also the construction of power lines, at least in areas with little tree growth) contribute more expenses to that calculation. Altogether, the comparison matrix is shown in (table 6).

Category	Slope	Surface	Prox. to roads	Prox. to power lines	Outdoor areas	**Weight**
Slope	0,06	0,07	0,05	0,08	0,05	**6 %**
Surface	0,34	0,40	0,37	0,38	0,41	**38 %**
Proximity roads	0,11	0,10	0,09	0,13	0,08	**10 %**
Prox. to power lines	0,03	0,04	0,03	0,04	0,05	**4 %**
Outdoor areas	0,46	0,40	0,46	0,38	0,41	**42 %**

Table 6: The consistency rate (CR) of this normalized comparison matrix is 0.01, which is below the threshold of 0.1 and indicates a logical consistency in abovementioned pairwise comparisons

An overall non-wind related suitability map is created in Qgis by adding the weighted 5 sub criteria for each point on the map and normalizing it to the range from zero to ten.

$$Suitability = \frac{1}{5}\sum_{n=1}^{5} Weight_n * Criterion_n \tag{4.3}$$

Two characteristics mark the global suitability map: Firstly, the maximum value of suitability is 1.99, which is very low, considering a range from zero to ten. This is caused mainly by the combination of a high weight and generally low suitability values in the category of outdoor area importance. Both the weighting and the evaluating of the respective suitability values are in this case a subjective evaluation, even if a transparent process with clearly defined categories can secure credibility. An important point is that those areas not areas of a homogeneous composition. A general border was defined around those locations, but they

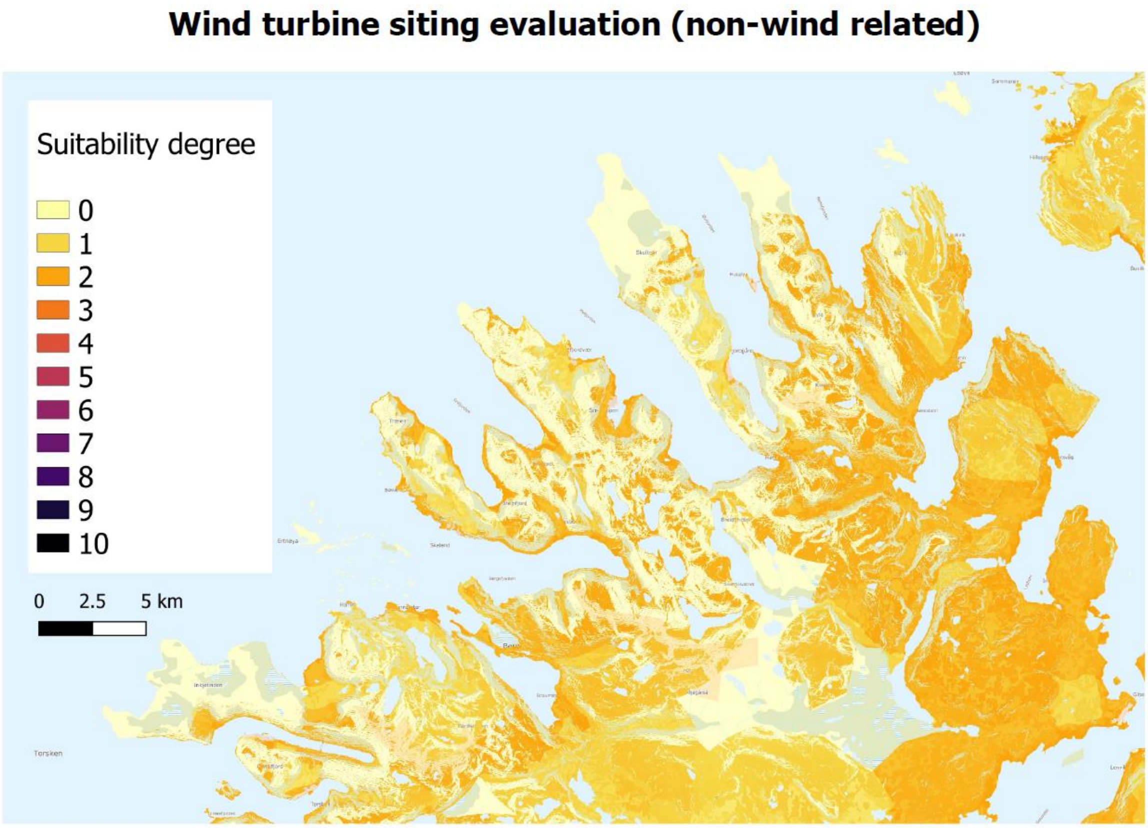


Figure 16: Evaluation map (non-wind related) over Northern Senja, created in Qgis

still can contain enclaves of infrastructure. Areas that i.e. are described "of high importance" can be cut by the road net and contain islets of buildings. A reconsideration of weighting criteria could be undertaken; the acceptance of wind power infrastructure is a highly subjective value and might change over time or along a decision process.
The second point is that an area of 913 km^2 (calculated in Qgis) in total is seemly for wind power siting, even though this total area is highly dispersed over the total area of Northern Senja and the suitability values vary from 0.44 to 1.99.

This suitability map is nonetheless a good indicator of the relative fittingness for wind turbine siting for possible locations on Northern Senja compared to each other.

4.4. Second level geospatial analysis: Finding fitted areas for wind power production

According to given modelled and corrected wind data Northern Senja provides high annual average winds, feasible for wind power production. Most of those high average winds are though found on steep mountain crests which are not suitable for assessing a production site. Masking the wind map cuts out those inaccessible areas. On the masked wind map in (Figure 17) a few areas with higher winds are shown, but the extent of those areas is limited and spread to a few regions.

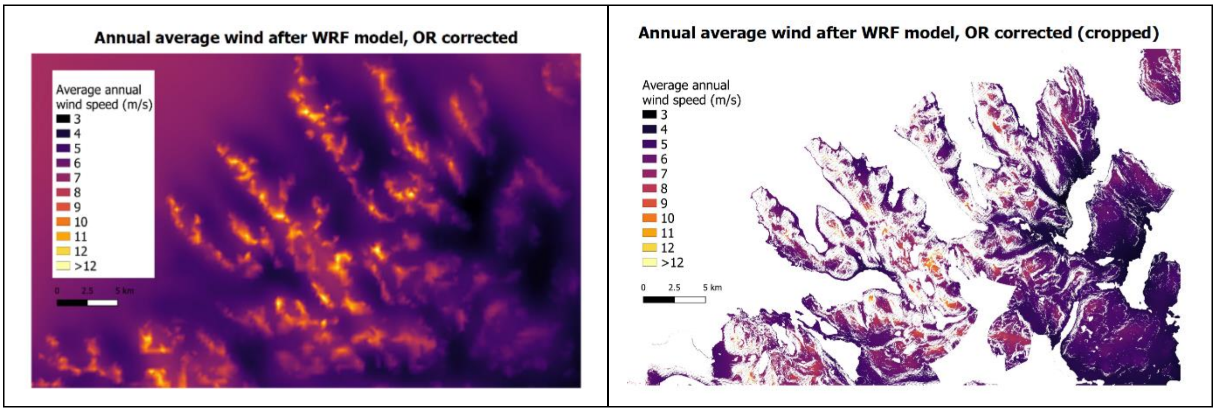
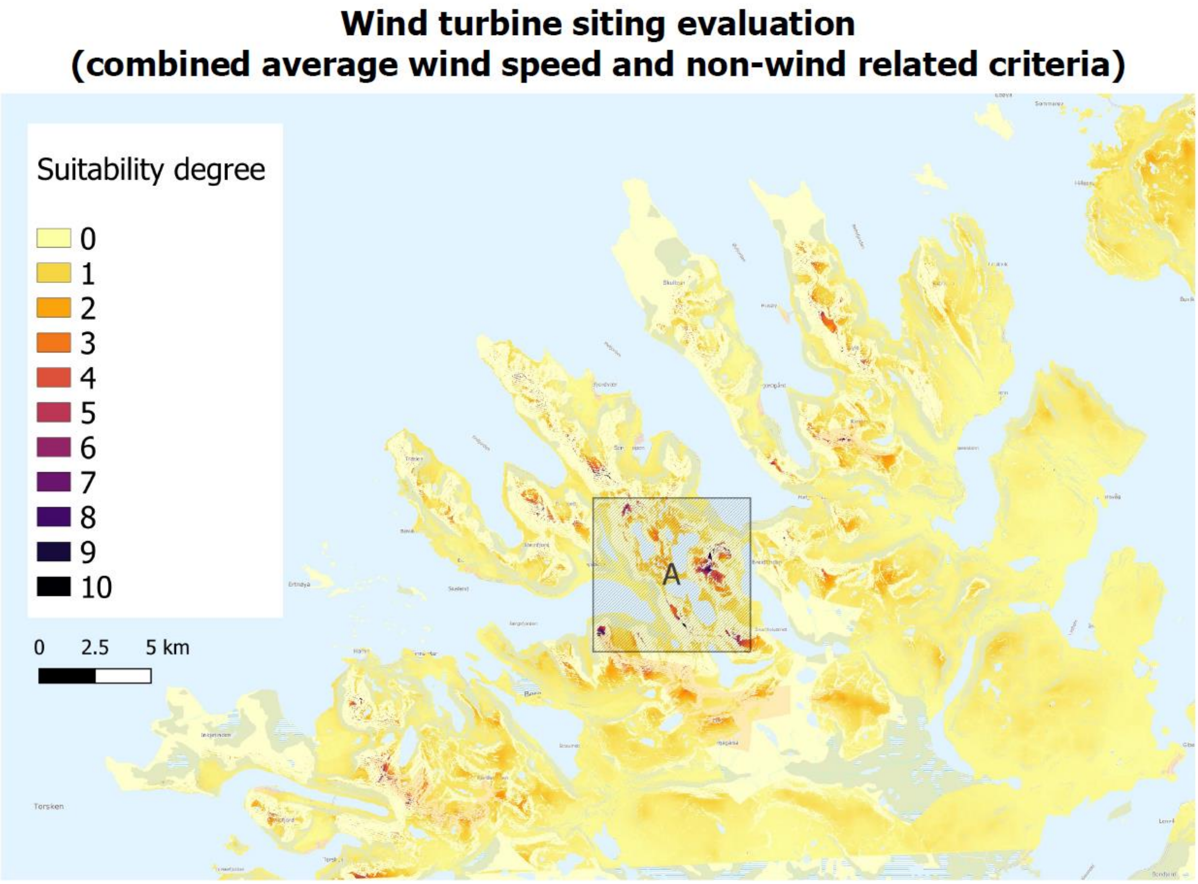


Figure 17: Average wind speed map over Northern Senja after the OR correction both unmasked (left) and masked for exclusive areas, created in Qgis



Figur 18: Overall wind power assessment evaluation map over Northern Senja, created in Qgis

When multiplying both maps weighted 4:1 those same regions appear as islets of high suitability on a map with else low values. The weighting of the wind speed by a power of 4 in (eqn. 3.15) amplifies the favourable high values on that map and the differences become more visible. On relatively flat mountaintops (in a else harsh and steep environment) near Bergsbotn (sub region A in figure 18) possible sites are conceivably found. Maps over that region showing the capacity factor can now be calculated easily (computational cheaply).

The capacity factor calculated for each turbine over that sub region leads to the conclusion that the best fitted turbine size is the medium size types, both the Vestas V34 (400kW) and the DW52 (500kW nominated power) show the highest capacity factors over given area around Bergsbotn – naturally highest at the higher altitudes. But also the other three turbines show acceptable values there. Comparing those maps with the evaluation map,

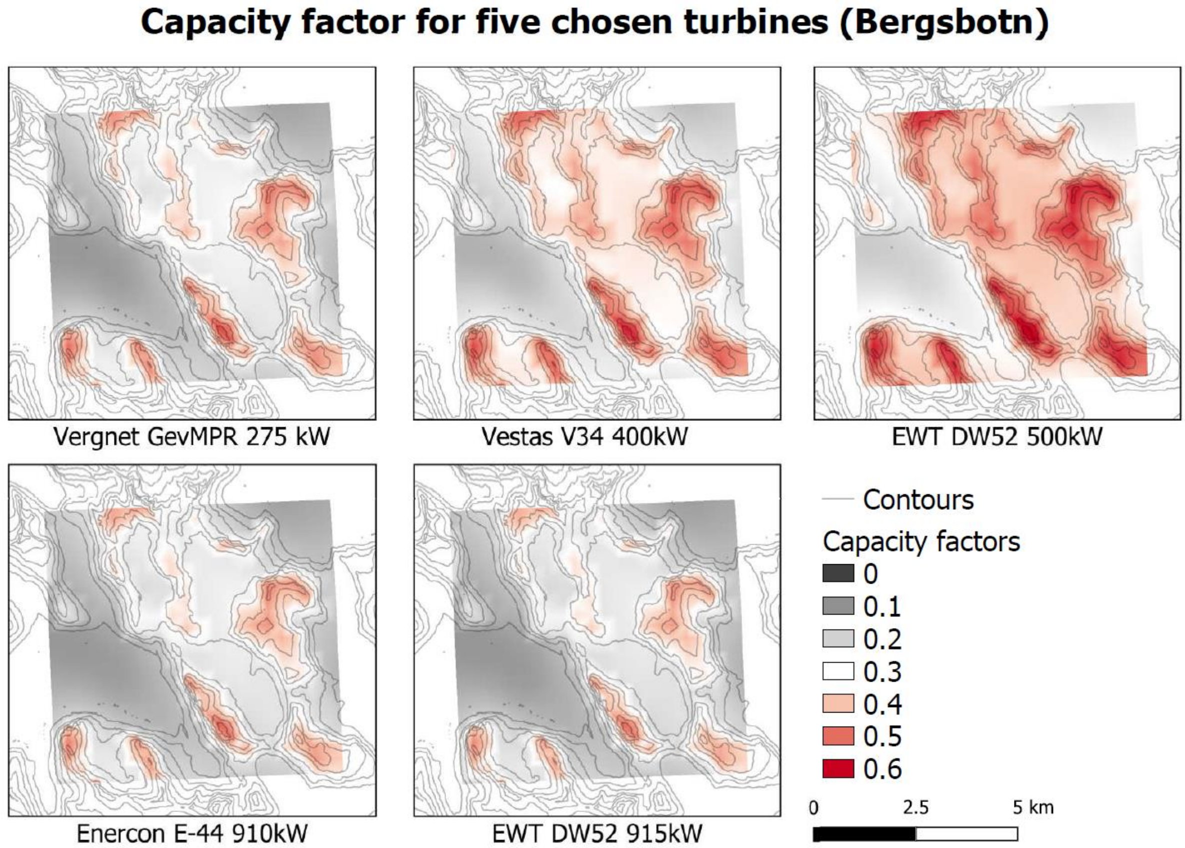
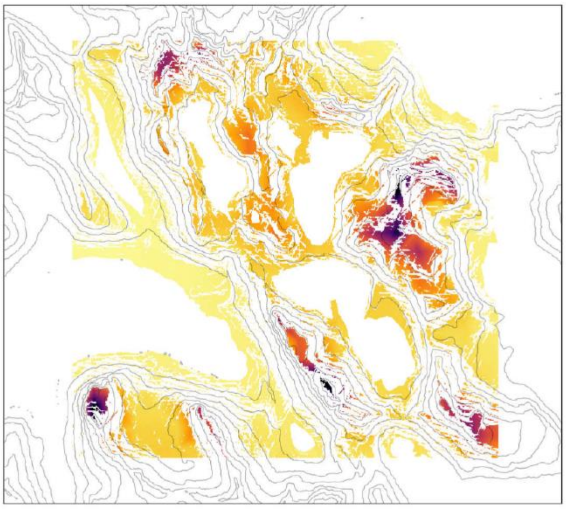


Figure 19: Capacity factors for five different turbine types around Bergsbotn, Senja, created in Qgis



Figur 20: Wind power evaluation map in sub region A, created in Qgis

Figur 21: Map over sub region A, from [Kartverket]

three regions stand out in suitability: The mountains Store Hesten, Storfjellet and Finnkona (Figure 20). Other areas with favourable capacity factor either are masked out by other factors or seem to be too difficult to reach when investigating the surrounding topography. Here a simple study of maps in and local knowledge of that area replaces the purely calculative method of the spatial analysis, due to shortcomings of that approach. The simplifying of evaluation criteria does not opt out areas that i.e. are on suitable terrain, if only the on-side slopes are considered, but unreachable because of the surrounding geography.

The estimated yield and capacity factors, for each turbine is shown in the (Tables 7-9) below.
In wind power site assessing processes usually a percentile of 15 to 25% is subtracted from the estimated production value to balance effects which were note taken into account like i.e. production loss due to icing, down time for maintenance or repairing the turbines.
In this thesis a percentile of 20% is subtracted from the calculated values for the yield and the capacity factor.

Finnkona, Bergsbotn (598m) - 17,4340; 69,4230

Wind turbine	NP in kW	Yield in MWh	CF
Vergnet GevMPR	275	927,7	39 %
Vestas V34	400	1483,0	42 %
EWT DW52-500	500	2024,6	46 %
EWT DW52-900	915	2945,9	37 %
Enercon E-44	910	2876,0	36 %

Store hesten (805 m), Mefjordbotn - 17,5620; 69,4500			
Wind turbine	NP in kW	Yield in MWh	CF
Vergnet GevMPR	275	1049,8	44 %
Vestas V34	400	1664,8	48 %
EWT DW52-500	500	2259,2	52 %
EWT DW52-900	915	3337,6	42 %
Enercon E-44	910	3262,0	41 %

Storfjellet (774m) 17,5620; 69,4440			
Wind turbine	NP in kW	Yield in MWh	CF
Vergnet GevMPR	275	1019,9	42 %
Vestas V34	400	1631,8	47 %
EWT DW52-500	500	2226,3	51 %
EWT DW52-900	915	3241,0	40 %
Enercon E-44	910	3164,9	40 %

Table 7-9: Calculated production values at the three best-suited places (Nominal power, annual yield and capacity factor)

5. Discussion and conclusion

5.1. Reliability of the modelled data

The calculated production values for the three given examples seem to be unrealistically high – especially taken into account that 20 percent are already subtracted from the estimated yield considering effects which were not taken care of by the model (unforeseen down time, icing, etc.). Capacity factors of wind power installations have a normal value between 20 and 40% [Miller, 2018]. The three examples show values of over 40% for almost all turbines in all cases, which might occur but probably not in that high amount.
The cases shown are of course best case scenarios for a perfect placement – turbines in real life have to be placed in some place in the near vicinity of those spots in a place which is suited for such constructions, but with somewhat less favourable wind conditions.

Still another cause seems to be an overestimation of the frequency of higher wind speeds which is not adjusted correctly by the orographic roughness scheme. Due to the power of three when calculating the energy content of a wind flow this overestimation leads to a noticeably high overestimation of the yield of a wind turbine. The modelled WRF data was shown to underestimate the effects of roughness and the resulting shear stress to the air flow over complex terrain [Solbakken, Birkelund, 2018]. Although the correction scheme efficiently adjusts the wind speed according to the altitude differences between the underlying terrain model and the real topography (Figure 14), this shear, slowing down the wind speed in near layers above, seems not to be adjusted for in its full extent.

A possible reason for this might be weakness in the estimation of the modelled sinusoidal hidden orography. In this thesis a simple projection approach was done in MatLab. Further investigation could lead to better estimation of the residual orography's roughness.
Another weakness might lay in the simplification of the elevation differences between model and real orography. The silhouette of the residual orography is different if applied to a flat zero plane than if it is added to the WRF model elevation. The airflow over two neighbouring residual peaks is not only affected by the residual height difference but by the orientation of

those peaks towards each other (their real altitude) as well. The angle of those peaks and troughs relative to the wind can be changed drastically when an irregular zero plane is presumed to be flat. Though this method makes a simplified calculation possible, it might work better in flatter terrain.

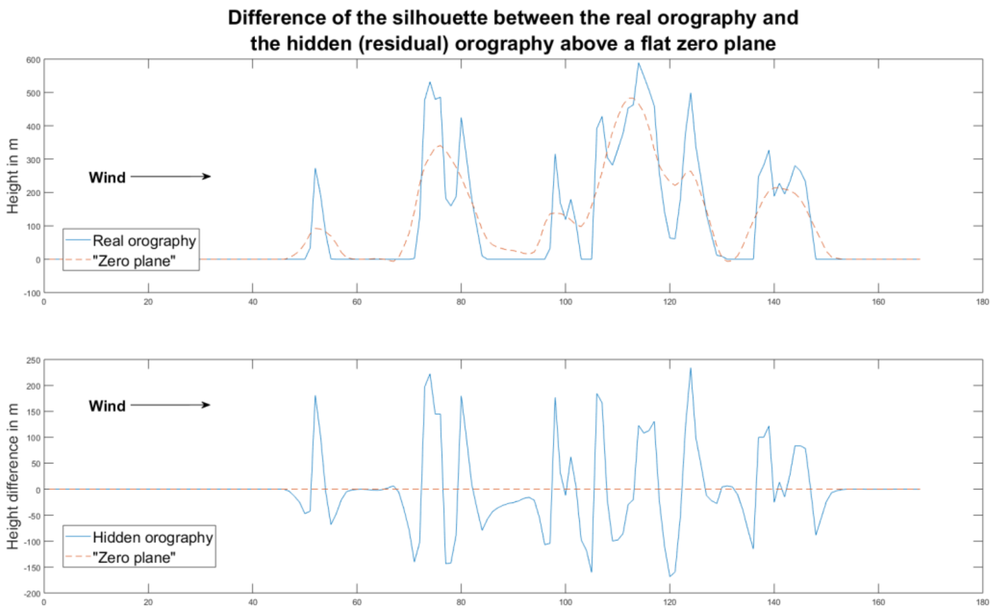


Figure 22: The angle of attack of the wind changes if the height of the residual orography is assumed to be on a flat zero plane instead on top of the underlying model's orography. This changes the silhouette and misrepresents the influence of that orography on crossing winds, created in MatLab

Another obvious weakness is the lack of reference measurements to tune the model correctly. One weather station an some reasoning using values which seem to be likely can't be enough, but give an idea about how to tune the model. With more in situ wind data this weakness easily can be eliminated.

In the current form the tuned WRF model data seem to be too unreliable, though - if this tuning process and the orographic roughness estimation are improved as described above – it might be successfully used for local wind power site assessment.

Using GIS software to find optimal wind power sites is a fruitful approach; the examples shown in this thesis can easily be adjusted by adding new or changing existing criteria and weights. Also the purely informatics process can be interrupted at any point and the results achieved along the way can be used as pre assessing tools. Onsite evaluation can not be circumvented, but GIS allows to compare a lot of data over a greater region within an affordable framework of time, money and resources.

5.2. Community scale wind power - a solution for Senja?

Can community scale wind power be a substantial help in improving the power supply of the Northern Senja community? Covering their own consumption, at least partially, should be a good incentive for the municipalities to opt for medium scale wind power assessment. A rise in the annual electrical consumption of Husøy and Senjahopen, two urban areas with highly energy consumptive industries, of respectively 2,5 and 7,7 GWh is predicted for the next 10 years [Troms Kraft, 2019]. In the examples used in this thesis, which are in near vicinity of exactly Senjahopen, annual productions up to 3,3 GWh are predicted. Taking into account the pre-set limitation of maximum installed power of 1MW without having to apply for a complicate authorisation process with the Norwegian Water Resources and Energy Directorate (NVE), a wind park of two turbines with 500 kW nominated power around the adjacent tops of Storfjellet and Store Hesten an annual yield of 4,4 GWh is theoretically possible. That could counterweight for 57 percent of the predicted growth in consumption. Though the unreliability of wind power in terms of producing electricity when needed – especially with industries like fish processing (freezing) with heavy electric loads in over shorter periods. An additional infrastructure containing battery storage facilities to store energy during peak production and other means of energy production are needed to cushion those effects. As part of a catalogue of different measures community scale wind power could contribute without having too much unwanted effect to the surrounding environment. The examined sub region only covered only one area near Senjahopen. Other projects in other communities, like mentioned Husøy, could further contribute here.

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Appendix: MatLab codes

Code for the central difference correction scheme:
Input: U40_stretch, V40_stretch (interpolated wind speeds), HGT_DTM10 (orographic model of the correction)

Orographic correction (Longatt,Medina,González)

```
U40_LMG = single(zeros(168,108,52417));
h = diff(HGT_DTM10);
for m=1:52417
  v = diff(U40_stretch(:,:,m));
  for i=2:167
    U40_LMG(i,:,m) = U40_stretch(i,:,m) + (-h(i-1,:).*v(i-1,:)-h(i,:).*v(i,:))./(2000/3);
  end
end
V40_LMG = single(zeros(168,108,52417));
h = diff(HGT_DTM10,1,2);
for m=1:52417
  v = diff(V40_stretch(:,:,m),1,2);
  for j=2:107
    V40_LMG(:,j,m) = V40_stretch(:,j,m) + (-h(:,j-1).*v(:,j-1)-h(:,j).*v(:,j))./(2000/3);
  end
end
```

Code for the orographic roughness correction scheme:
First average height and wavenumber have to be calculated to create a sinusoidal model of the residual orography. Then the transformation matrices (U- and V-direction) can be calculated.
Input: HGT_diff (residual orography), HGT_DTM10 (orographic model of the correction)

Finding average height and wavenumber:

```
for n=1:168

  for i=1:9
    xc = (i*12-11):(i*12);

    H_V(n,xc) = 2*std(HGT_diff(n,xc));
    [~, locsmax] = findpeaks(HGT_diff(n,xc),'MinPeakProminence',H_V(n,i*12)/5);
    [~, locsmin] = findpeaks(-HGT_diff(n,xc),'MinPeakProminence',H_V(n,i*12)/5);
    locs = sort([1 12 locsmax locsmin]);

  if  isempty(locsmin)==1
      if isempty(locsmax)==1
        L_V(n,xc) = 24;
        locsmax = 6;
      else
        L_V(n,xc) = 24;
      end
```

```
        elseif isempty(locsmax)==1
            L_V(n,xc) = 24;
            locsmax = locsmin+12;
        else
           L_V(n,xc) = single(2*mean(diff(locs)));
        end

        L_V(n,xc) = 333*L_V(n,xc);
    end

for n=1:108

    for i=1:14
        xc = (i*12-11):(i*12);

        H_U(xc,n) = 2*std(HGT_diff(xc,n));
        [~, locsmax] = findpeaks(HGT_diff(xc,n),'MinPeakProminence',H_U(i*12,n)/5);
        [~, locsmin] = findpeaks(-HGT_diff(xc,n),'MinPeakProminence',H_U(i*12,n)/5);
        locs = sort([1 12 locsmax' locsmin'])';

        if  isempty(locsmin)==1
            if isempty(locsmax)==1
                L_U(xc,n) = 24;
                locsmax = 6;
            else
                L_U(xc,n) = 24;
            end
        elseif isempty(locsmax)==1
            L_U(xc,n) = 24;
            locsmax = locsmin+12;
        else
           L_U(xc,n) = single(2*mean(diff(locs)));
        end


        L_U(xc,n) = 333*L_U(xc,n);
    end
end
```

Calculating Transformation matrices:

```
k1=0.8; % tuning parameters
k2hi=0.6;
k2lo=0;
z0=0.055;
Href_U = L_U./(2*pi);
Href_V = L_V./(2*pi);
Rough_U = log(Href_U/0.055)./log(40/0.055).*log(40/0.055)./log(Href_U/z0); %roughness factor
correction
Rough_V = log(Href_V/0.055)./log(40/0.055).*log(40/0.055)./log(Href_V/z0); %roughness factor
correction
```

```
for i=1:168
   for j=1:108
      if HGT_diff(i,j)<=0
         if HGT_DTM10<1
            z0=0.0002
         else
            z0=0.055;
         end
         Transform_U(i,j) =
k1*Rough_U(i,j).*(1+k2lo.*exp(-
40./Href_U(i,j)).*log(Href_U(i,j)./z0)/log(40/z0)./Href_U(i,j).*HGT_diff(i,j));
         Transform_V(i,j) =
k1*Rough_V(i,j).*(1+k2lo.*exp(-40./Href_V(i,j)).*log(Href_V(i,j)./z0)/log(40/z0)./Href_V(i,j).*HGT_diff(i,j));
      else
         if HGT_DTM10<01
            z0=0.0002
         else
            z0=0.055;
         end
         Transform_U(i,j) =
k1*Rough_U(i,j).*(1+k2hi.*exp(-
40./Href_U(i,j)).*log(Href_U(i,j)./z0)/log(40/z0)./Href_U(i,j).*HGT_diff(i,j));
         Transform_V(i,j) =
k1*Rough_V(i,j).*(1+k2hi.*exp(-40./Href_V(i,j)).*log(Href_V(i,j)./z0)/log(40/z0)./Href_V(i,j).*HGT_diff(i,j));
      end
   end
end
```

Then the time series' have to be multiplied by the transformation factors.
Input: U40_stretch, V40_stretch (interpolated wind speeds)

Orographic correction (Howard, Clark)

```
for n=1:52417
   U40_HowClark(:,:,n) = U40_stretch(:,:,n).*Transform_U;
end
for n=1:52417
   V40_HowClark(:,:,n) = V40_stretch(:,:,n).*Transform_V;
end
```