Remote wind speed sensing for site assessment and normal year correction

The use of sodar technology, with special focus on forest conditions

Daniel Gustafsson

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KTH School of Industrial Engineering and Management
Department of Energy Technology
STOCKHOLM, SWEDEN
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Abstract

This thesis aims to give the wind power industry better tools to approach the uncertainties of the wind climate, by describing the wind characteristics in forests, remote wind speed sensing technologies, and normal year correction methods.

This thesis includes a wind analysis of a forest site in the southern part of Sweden, which indicates significantly lower wind speed than the MIUU model, high turbulence and pronounced wind shear. It also contain a comparison of the measurements from 4 December 2007 until 29 June 2008 by an AQ500 sodar from AQ System and a 97 m met mast instrumented with cup anemometers and wind vanes. Finally, the thesis includes an assessment of different methods and sources of data for normal year correction based on the wind index approach.

The sodar and mast analysis concludes that the measurements of the AQ500 are trustworthy. The difference in mean wind speed compared to cup anemometer is in the magnitude of 0.1 m/s and the turbulence readings show good conformity for wind speeds up to 12 m/s.

The normal year correction analysis concludes that depending on the lengths of the period of the measurements, different sources are best used. The Danish production index is best used for the eleven month of available data for this thesis, but for longer measurement campaigns NCAR data could successfully reduce the uncertainties.

Due to confidentiality reasons some of the content of the internal report for Vattenfall has been left out of the public report. This is primarily information about the site of the measurements (referred to as Site A), but also some of the conclusions and a proposed measurement strategy.
Executive Summary

This paper is the result of a Master’s thesis of 30 credits performed at Vattenfall Vindkraft AB in Räcksta, Stockholm. The report consists of three major issues. Firstly, different remote wind speed sensing technologies are reviewed leading to a sodar-mast measurement comparison. Secondly, different wind parameters are described with special focus on the conditions in forests, followed by an assessment of wind potential and wind characteristics for the forest site referred to as Site A. Thirdly, different ways to normal year correct wind data are evaluated and compared, applicable for the wind measurements from Site A. The report also consists of a number of minor parts, such as descriptions of power supply and theft protection alternatives for remote sensing equipment, methods for wind potential mapping, wind data uncertainties and a comparison of the energy yield by different suppliers and models of wind turbines.

Sodar performance evaluation

Wind characteristics at a site can be explained by a number of parameters. The mean wind speed together with the wind distribution determines the wind potential at the site, which is the most important factor. The prevailing wind direction is also important, especially when considering wake effects. For sites in forests the turbulence and wind shear are also very important.

From December 2007 to June 2008 simultaneous measurements by sodar and met mast, at 150 m distance, were performed. The sodar from AQ System, the AQ500, measures all of these parameters with precision in the same magnitude as for cup anemometers. For unfiltered data the difference in measured mean wind speed by the sodar and the cup anemometers, is about 0.1 m/s at met mast levels 40-97 m, and for the top level at 97 m it is 0.12 m/s. For the filtered data, consideration was taken for inadequate sodar positioning (two weeks), wake effect of met mast (on both sodar measurements and cup anemometers), cup anemometer under-speeding due to freezing and over-speeding due to high turbulence. Filtering out all of these sources of errors gave a wind speed difference of no more than 0.02 m/s and a coefficient of correlation of 0.90.

The difference in mean turbulence intensity was also studied, and the deviation between the different technologies was less than 1% for wind speeds of 5-12 m/s at the 97 m. For higher wind speeds the deviation became larger, but the number of data was also reduced significantly.

Compared to a regular met mast a sodar unit does not disturb the airflow, is not at risk of freezing or over-speeding like cup anemometers and measures at higher heights. It is quickly deployed at a site, needing only the permission of the landowner. Using sodar technology is also economically favourable, especially for short-term measurement campaigns. Compared to lidar systems, the AQ500 has better vertical resolution, needs less maintenance and costs less than a quarter in investment. The problem with remote sensing technology is primarily an uncertainty in the quality of the measurements, and as a consequence, wind turbine suppliers do not fully accept these data yet. This study and others might be a step towards increased acceptance. Other disadvantages are increased measurement uncertainty for sites
with extreme small-scale topography and the need of positioning the sodar unit at a certain distance from the forest edges.

Overall, the use of the sodar from AQ System, especially for initial site measurements, seems most promising.

**Wind assessment: conditions in forests**

The evaluation of Site A produced a number of results that may, with some reservation, be considered general for sites in forests, especially in the south of Sweden and for plain topography. The MIUU-model highly overestimated the wind potential at the site with about 1.4 m/s for the standard 1x1 km² resolution and about 1.1 m/s for the 500x500 m² resolution. Together with the extreme Weibull distribution of the wind speed, this corresponds to an overestimation of the production at the site by almost a factor of two.

The mean wind speed measured at the site from October 2007 to August 2008 was 5.8 m/s at 100 m, which corresponds to an annual production of about 4000 MWh for a wind turbine with 90 m rotor diameter and 100 m hub height. Increasing the rotor diameter to 100 m would increase the production by more than 20% since the turbine rarely operates at its rated power. Increasing the height of the tower would give an increased production of roughly 1.2% per meter, corresponding to 50% increased production at 140 m.

At 100 m the turbulence is quite high, particularly at wind speeds above 12 m/s, but it is uncertain due to the small amount of data whether or not the IEC turbulence limits are exceeded at these wind speeds. Though, if the hub height is increased, the measured turbulence are well below the limits, according to the sodar data.

**Normal year correction**

To adjust the measured data at the site to better represent the long-term conditions, a number of methods for normal year correction are applied and evaluated. Since long-term wind measurements at the site are not available, the results from different indices are instead evaluated based on statistically estimated parameters. First, the standard deviation of the monthly corrected production is calculated, which quantifies how representative the index is for the specific site. This typically gives an uncertainty of between 4% and 6% in standard deviation. Then the uncertainty of the mean value for the index is estimated, for which the number of months included in the index is the most important parameter. The typical standard deviation for the long-term mean is 2-5%.

The indices that are evaluated are the Swedish official index, the personally-devised Swedish, Kalmar and Målajord indices, the Danish index, the Danish regional index of Jutland, as well as four types of NCAR indices. NCAR indices are based on a global meteorological model generating wind speed values on a 2.5° latitude x 2.5° longitude grid. While the other indices are based on production, NCAR data are based on wind speed and are thus applied differently. Production indices based on the NCAR data are, however, also constructed.

To increase the accuracy the indices are generally applied on a monthly basis instead of applying the index value for the complete measurement period. Furthermore, in addition to evaluating the standard index method, where the production (or wind speed) based on
measurements is simply divided by the index method for each month, a regression method is also used. This is based on the hypothesis that the indices and the actual wind conditions at the site do not vary to the same extent.

The result from the regular correction method indicated that the use of the Danish index gave the least amount of uncertainty at about 5.6% in standard deviation for the annual production estimate of 4130 MWh. The two next best methods were one of the NCAR production indices estimating annual production to 3660 MWh at 6.2% in standard deviation, followed by the index from the turbine in Målajord estimating 3850 MWh at 6.3% in standard deviation.

The regression correction method reduced the uncertainty for all indices by about 1%, except for the NCAR wind indices that were improved from about 13% to about 5%. This is due to the fact that the variation of the measured wind at the site was much lower than the variation for the NCAR data. The Danish index still produced the least uncertain results of 3980 MWh at 4.9% in standard deviation. This was followed by NCAR wind data at 3520 MWh and 3790 MWh at 4.9% and 5.2%, respectively.

Which index that is best to use does, however, depend on how long the available measurement period is. For measurements under six months for this particular site the, Målajord index would give the least uncertainty since it best represents the conditions at the site. For measurements between six and twelve months, the Danish index is best applied. Longer measurement periods might best be corrected with an appropriate NCAR regression wind index, since the certainty in long-term data becomes the most important parameter.
Acknowledgements

I wish to thank Vattenfall for the opportunity to perform this thesis in their organisation, providing me with experience and knowledge as well as personal growth. I appreciated the openness and helpfulness from everyone within Vattenfall, as well as from several people outside the organisation of Vattenfall.

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1 Introduction

Citizens, governments and companies are gradually increasing the priority of renewable energy. Climate change and resource depletion are urgent issues that need to be addressed with force. Among the different available sources of renewable energy, wind power is one of the most commercial and likely that will grow most substantially in the near future.

Sweden is currently far behind its neighbouring countries Denmark and Germany in installed capacity, but ambitions are high. Today, 1.4 TWh of electricity is produced by wind energy, which is 1% of the total electricity demand in Sweden. The current national target for 2015 is to produce 10 TWh from wind energy, but recently the Swedish Energy Agency proposed that the Swedish government should increase this target to 30 TWh by 2020, equivalent to about 20% of the electricity consumption in the country.¹

Vattenfall AB, a major power production company, has extensive plans for expanding its wind power production. The goal is to produce 8 TWh electricity from wind power by 2016. This means that a large number of wind power plants needs to be constructed in different types of terrain, both on land and offshore. The need can be estimated to be 3000 MW installed capacity to be able to produce this amount of electricity. Vattenfall recently constructed the largest wind power farm in Sweden at Lillgrund, and its 48 turbines will produce approximately 0.33 TWh electricity per year. All together the company owns more than 500 turbines of which 100 are located in Sweden. New projects are planned offshore as well as onshore, for instance, a 20 billion SEK investment prospect for 4 TWh of wind turbines in Swedish forests.²

On land, the meteorological conditions are far more complex than at sea. Hilly terrain and forests cause the wind conditions to vary significantly. This requires great knowledge of wind speeds and distribution at the sites that are to be used for wind power. Since the power in the wind is proportional to the cube of the wind speed, even small differences could have a significant effect on the energy yield.

Uncertainties in wind speed, for prediction of annual yield or dimensioning of turbines, add both technical and financial risks that result in a higher price of energy. Accurately predicting future wind conditions minimises these risks, and that is the focus of this thesis.

1.1 Scope

The scope of this Master’s thesis is to study the measure-correlate-predict chain for wind potential assessment, as well as to expand the knowledge of micrositing at land-based sites. This includes studying the accuracy of wind measurements by the AQ500 sodar compared to a cup anemometer fitted mast, the local meteorological climate at Site A, and evaluating production predictions by different normal year correction methods. The main focal point is wind speed, but turbulence and wind shear are also taken into consideration and also used for power curve correction.
1.2 Target readers

This report is mainly directed to people with experience in wind power and wind measurements, but the first chapter of the report contains basic information about wind characteristics and wind power. Thus an interest in the topic should be sufficient to comprehend and appreciate the contents of the report.

1.3 Methodology

This thesis has been conducted through literature reviews of scientific papers, websites of relevant companies and institutions, and internal Vattenfall documents, as well as interviews and discussions with some of the Swedish experts in wind power related issues. Some of the information might not have been available to a regular student, while some information might not have been easily accessible to a Vattenfall employee.

The data analysis has mainly been conducted with Microsoft Excel. This has overall been sufficient, though it also has had some drawbacks. The Master’s thesis has included travelling to gain general knowledge and particularly to learn how to handle the AQ500 sodar.

1.4 Outline

This chapter one includes general introduction and information about the paper.

Chapter two of the report provides background to the analysis in section three, but it also includes general topics in wind power and some independent work. The background section consists of a literature study, with general information about the relevant sites and wind measurement basics, including a comparison among the different available technologies but with special focus on the sodar equipment. This is followed by a brief description of different methods of wind potential mapping and a study of different methods of normal year correction of wind data. The end of chapter two is dedicated to measurement uncertainties.

Chapter three consists of an extensive data analysis. Measurement data are compared from sodar and mast at Site A from 4 December 2007 to 26 June 2008 and sodar data from two separate positions at the site are also studied. The wind climate at Site A is then analysed based on eleven months of mast data, and the results are used in a normal year correction study. Here different methods for normal year correction are tested and compared.

Chapter four contains the discussion and conclusions, followed by recommendations for further work. Due to confidential reasons some information is only included in the Vattenfall internal report, presented in the appendix. Last, the extensive list of references is presented.

The ambition for the report and especially the analysis has been to be as comprehensive as possible, and thus there is not the traditional structure of methodology, results and discussion, but more an integrated presentation.
2 Background

2.1 General Site and project information

This part presents some general information concerning the site specific to this thesis. It also describes the present status of Vattenfall’s remote sensing project.

2.1.1 Site A

In the province of Småland in the south of Sweden Vattenfall is investigating the possibility of erecting up to 30 wind turbines in the forest holding of Site A. Pre-studies have shown good wind and ground conditions at the site, and since 8 October 2007 a 97 m high mast fitted with anemometers has been measuring the wind. Between 4 December 2007 and 26 June 2008, a sodar unit was also located at the site.

This thesis contains a comparison of data from the anemometer equipped mast and the sodar unit, an evaluation of the wind characteristics, as well as the normal year correction of the measurements for the site.

The MIUU mean wind, based on the 1x1 km² resolution, at the site is about 6.7 m/s at 72 m above the zero-shift plane and 7.6 m/s at 103 m above the zero-shift plane.

For confidentiality reasons a more precise description and location of the site can only be included in the Vattenfall internal report. The internal report contains this information in the appendix.

2.1.2 Vattenfall remote sensing project

Vattenfall has extensive plans to test and use different remote sensing technologies. As of July 2008 Vattenfall has possession of one sodar AQ500 from AQ System and an additional five AQ500s will be delivered during the fall. These will be placed at various sites where they will accumulate data for a period of at least three to six months. The last three sodars have been requested to have an increased measurement height of 200 m, compared to the first and the second unit that were limited to 150 m.

Vattenfall has also ordered one sodar system, the Windcube from Leosphere. This will first be stationed together with both the measuring mast and a sodar unit to compare all three measurement methods. To test the Windcube’s response to cold climate, it will be moved to Gjörvik, in northern Sweden, sometime during the autumn 2008.
2.2 Wind characteristics

There are several wind parameters that need to be measured and taken into consideration when looking for sites for wind turbines. Wind speed and direction are the most obvious parameters, but turbulence, wind shear and maximum wind gusts are also important.

Wind is generated by pressure differences, which are generated by temperature differences. The temperature differences are in turn caused by the sun’s uneven heating of the atmosphere and the surface of the planet. The Coriolis effect due to the rotation of the planet also affects the wind patterns. Near the surface the wind is to a high degree influenced by the topography, obstacles, the surface roughness and the stability of the atmosphere, but at a certain height (about 1000 m above ground) the wind is undisturbed by the surface and is called the geostrophic wind. Meteorology can be divided into three main classes; micro, meso and macro meteorology, which correspond to local, regional and global scales.

An ordinary wind turbine can, at best, extract slightly over 50\% (compared to the theoretical Betz’s limit of 59\%) of the energy in the wind to produce electricity. This is called the coefficient of performance ($c_p$) and together with the power in the wind, it governs the produced power of a wind turbine, which are shown in Formula 1.

\[
P_{\text{wind}} = c_p \frac{\rho A v^3}{2}
\]

where $P_{\text{wind}}$ is the power in the wind, $\rho$ is the density of the air, $A$ is the rotor area and $v$ is the speed of the wind. Thus, even small differences in wind speed affect the yield significantly, with some exceptions. The cut-in wind speed for an ordinary wind turbine is approximately 4 m/s, and only when the wind exceeds this speed do the turbines generate electricity. The rated wind speed is about 12 m/s, and at this speed the generator is running at its maximum. For higher wind speeds the power production is constant at this rated power, until the wind speed reaches the cut-out speed, at about 25 m/s. It is not economical to design the wind turbine for higher wind speeds, since they are quite rare and the turbines are then turned out of the wind to prevent damage. The rated power is typically 2 MW for standard on-shore turbines, but commercial turbines of well above 3 MW also exist.

It is not enough to focus only on the mean wind speed at a particular site, but consideration must also be taken to the wind distribution, e.g. how often the wind speed is equal to each specific value. The Weibull distribution generally describes the wind variations quite well. The shape is governed by the shape parameter, which is usually between 1.7 and 2.3 and where 2.0 corresponds to the Rayleigh distribution. The scale parameter closely corresponds to the mean wind speed. The effects of varying these parameters are shown in Figure 1.
The wind energy resource is intermittent, i.e. not always available. This is indicated by the capacity factor, which equals the actual power production divided by the power that would be produced if it had been running at rated power for the whole time. Depending on the characteristics of the site and the wind turbine, the capacity factor varies significantly, but could generally be approximated as 0.25 for land sites and 0.30-0.35 for offshore locations. However, this does not mean that the wind turbines are only in operation for 25-30% of the time. In reality they operate 65-90% of the time, but mostly below the rated power. The temporal distribution of the wind energy is somewhat matched to the electricity demand with the least wind during nights and the summer. 

The wind does not only vary during a year, but also from year to year. Between one year and another the mean wind speed can vary 20%, which according to Formula 1 gives differences in wind energy as high as 70%. For this reason it is not enough to measure the wind for only one year, if the data are not adjusted to correspond to a normal year. This is called normal year correction.

### 2.2.1 Wind shear

The wind speed also varies with height as implied earlier, and this is called wind shear. The higher the roughness of the earth’s surface the more the wind speed is reduced, in relation to the geostrophic wind. A forest slows down the wind considerably, while a water surface affects the wind far less. The wind shear profile is also dependent on the atmospheric stability, which can be neutral, unstable or stable. The power curve of a turbine is only valid below a specified low shear, thus an unusually large difference demands some adjustment of the power curve. There are some different methods to calculate the wind speed \(v\) at a specific height \(z\), based on a reference speed \(v_r\) at a reference height \(H_r\). When the roughness length \(z_0\) of the surrounding surface, Formula 2 can be applied.
The roughness length can be found in Table 1. It is also possible and often preferable to calculate the surface roughness with measurement data from two or several different heights at a specific site.

<table>
<thead>
<tr>
<th>Roughness class</th>
<th>Roughness length [m]</th>
<th>Landscape type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0002</td>
<td>Water surface (no waves).</td>
</tr>
<tr>
<td>1</td>
<td>0.03</td>
<td>Open agricultural area. Only softly rounded hills.</td>
</tr>
<tr>
<td>2</td>
<td>0.055</td>
<td>Agricultural land with some houses and sheltering hedgerows.</td>
</tr>
<tr>
<td>3</td>
<td>0.4</td>
<td>Small towns, agricultural land with many sheltering obstacles. Low forest.</td>
</tr>
<tr>
<td>4</td>
<td>1.6</td>
<td>Large cities with tall buildings. Tall, thick forest.</td>
</tr>
</tbody>
</table>

Table 1 - Roughness classes and lengths

To improve the accuracy and extend the range of Formula 2 from about 100 m to 300 m, the modified log law can be applied, as presented in Formula 3. This takes the atmospheric stability into consideration by including the gradient height (h). The gradient height corresponds to the altitude when the shear stress is zero and it is approximately 2000-2500 m, depending on the atmospheric stability. It can be calculated by dividing the friction velocity by six times the Coriolis parameter. The Coriolis parameter in turn is twice the Earth’s angular velocity \(7.29 \cdot 10^{-5} \text{ rad/s}\) multiplied by sine of the latitude at the location. When using Formula 3 the gradient height generally needs to be empirically determined.  

\[
v = v_r \cdot \frac{\ln(z / z_0) + 5.75 \cdot z / h}{\ln(H_r / z_0) + 5.75 \cdot H_r / h}
\]  

(3)

An alternative relationship to calculate the wind profile is presented in Formula 4, where \(\alpha\) is the wind shear coefficient. This is also called the 1/7th wind power law, since \(\alpha\) often can be approximated as 1/7, though this is not the case for forest regions, with higher wind shear.  

\[
v = v_r \cdot \left( \frac{z}{H_r} \right)^\alpha
\]  

(4)

If one knows or estimates \(\alpha\) or \(z_0\) but still wants to use the other relationship, Formula 5 can be used, giving deviations of only a few percentage for standard conditions.
\[ z_0 = 15.25 \cdot e^{-1/\alpha} \] (5)

Starting from Formula 2 or 4 there are at least three different methods to calculate the wind profile for a site. The most common is the overall mean method, where the mean wind speed at each level is used to calculate the overall wind shear parameter. This could either be done for all data or limited to the data exceeding the general cut-in speed of about 4 m/s. The second method is the parameter average where the wind shear parameter is calculated for each ten-minute average based on two levels, preferably the two highest levels for a met mast. This wind shear parameter is then averaged for all ten-minute-data that are available. The third method is the extrapolated time series and is similar to the second method. However, instead the wind speed at the hub height is calculated for each ten-minute-data and averaged for the complete period. Generally, the power law is best used with the overall mean method, whereas the accuracy of the methods applied for the logarithmic law differs for different terrains. Neither of the different wind shear relationships can be said to produce consistently better results.\(^{12}\)

It can generally be said that the most accurate wind shear profile is produced when the calculation is based on wind speed data above 4 m/s. The variations in wind shear from one year to another could differ as much as 7% for complex terrain, but the accuracy is often ±1% after just seven months of measurements. The predictions are least accurate in hilly terrain, followed by forested terrain, whereas the best results are produced for flat terrain.\(^{12}\)

An important consideration when using the surface roughness in calculations is that it can be changed instantly when crops are harvested, trees are felled or snow covers the ground. Special consideration must be taken to where the wind is blowing from, since the surroundings are rarely uniform.\(^{16}\) The prevailing wind direction (i.e. where the wind is most often blowing from) in Sweden is west or southwest.\(^ {13}\) The wind direction can be described with the azimuth angle, where 0° corresponds to wind direction north and 90° corresponds to wind direction east.\(^ {16}\)

Formulas 2 through 4 are not always valid though. For some meteorological conditions, for instance because of a large temperature difference between land and sea in the spring and summer or by the temperature equalisation in the atmosphere at night, stable stratification is formed. This produces low-level jets that give a wind speed maxima at somewhere between 100 m and 400 m. These low-level jets can also be produced locally by the topography. If the wind profile is measured with a lower mast than the hub height of the proposed wind turbine at a specific site, the wind data must then be extrapolated for the higher heights. If low-level jets are prevailing, the energy in the wind will be severely overestimated, which stresses the fact that sufficient measurements are needed to support calculations.\(^ {14}\) Remote sensing technologies generally measure above the height of the wind turbine, thus eliminating the problem.

### 2.2.2 Turbulence

Parameters that highly affect the lifetime of a wind turbine are maximum gust speed, turbulence and inclined/vertical wind. Turbulent flow, in contrast to laminar flow, is much more irregular with whirls and vortices, and it is created by surfaces or obstacles (trees or
other wind turbines). This causes increased mechanical loads and fatigue, but higher turbulence can also reduce the wakes behind obstacles and other wind turbines. When analysing a sample of wind data, this can be seen as short-term fluctuation (in the magnitude of seconds) and it can be expressed as turbulence intensity (TI). The turbulence intensity is a function of the standard deviation of the measured wind speed \( \sigma_u \) and mean wind speed \( U \) as presented in Formula 6.\(^{15} \)

\[
TI = \frac{\sigma_u}{U}
\]  

(6)

The standard deviation is calculated with Formula 7.

\[
\sigma_u = \sqrt{\frac{1}{N_s - 1} \sum_{i=1}^{N_s} (u_i - U)^2}
\]  

(7)

\( N_s \) is the amount of samples during, for instance, a ten-minute interval and \( u_i \) is each sample data.\(^{15} \) Turbulence is normally averaged over ten-minute periods, since the frequency variations of kinetic energy at the micro-meteorological range are best captured within this period without adding the variations of longer term fluctuations.\(^{10} \) For neutral conditions where the wind profile corresponds to Formula 2, the turbulence intensity for a smooth terrain can be estimated with Formula 8.\(^{16} \)

\[
TI \approx \frac{1}{\ln \left( \frac{z}{z_0} \right)}
\]  

(8)

The turbulence intensity at 50 m and at 15 m/s is about 8% offshore, 13% over plains and even above 20% for forests. Different wind turbines are designed for different maximum values of turbulence intensity.\(^{16} \) The turbulence is usually calculated in 10-minute intervals, because this corresponds to a minimum in the wind frequency spectra. Increasing the time would pronounce long-term variations in the wind, while reducing the time would overestimate the effect of gust winds and reduce the statistical quality.\(^{17} \)

Wind turbine manufacturers produce machines to sustain different wind conditions, in accordance with the IEC 61400 standard. These standards relate to mean wind speed and maximum gust speeds (I, II, III, IV) as well as the amount of turbulence tolerated (A, B) as seen in Table 2, where the wind speed is measured at hub height, the average is for 10 minutes and for the density of the air of 1.225 kg/m\(^3 \).\(^{18} \)
### Table 2 - Turbine classification according to IEC 61400

<table>
<thead>
<tr>
<th>Turbulence intensity class</th>
<th>A</th>
<th>B</th>
<th>-</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulence intensity at 15 m/s (TI15)</td>
<td>18%</td>
<td>16%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Value of parameter “a”</td>
<td>2</td>
<td>3</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The parameter “a” determines the slope of the accepted turbulence intensity, TI(U), as a function of wind speed (U) at hub height according to Formula 9.

\[
TI(U) = TI_{15} \frac{15/\sqrt{U} + a}{(a + 1)}
\]  

<table>
<thead>
<tr>
<th>Average wind speed class</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual average wind speed (m/s)</td>
<td>10</td>
<td>8.5</td>
<td>7.5</td>
<td>6</td>
</tr>
<tr>
<td>50-year return gust speed (m/s)</td>
<td>70</td>
<td>59.5</td>
<td>52.5</td>
<td>42</td>
</tr>
<tr>
<td>1-year return gust speed (m/s)</td>
<td>52.5</td>
<td>44.6</td>
<td>39.4</td>
<td>31.5</td>
</tr>
</tbody>
</table>

This is illustrated in Figure 2, which shows that high turbulence at high wind speed is most severe with respect to turbine wear and fatigue.

**2.2.3 Special considerations for wind in forests**

The majority of the wind turbines today are situated in coastal areas, on plains or off-shore, and this is due to a number of reasons. The mean wind speed is generally lower in forests because of the more severe boundary layer created by the trees, resulting in decreased energy yield. Both the turbulence intensity and the wind shear are higher, causing higher fatigue and mechanical load that lead to less availability and more maintenance.
On the other hand, two-thirds of Sweden is covered by forests\textsuperscript{21}, and the advantages with forest sites include lower land price, efficient natural resource management through dual land use, less visual impact and often reduced conflicting interests.\textsuperscript{22} The increased turbulence in forests can also help reduce the wake effect and hence improve the overall efficiency of wind farms. This also enables the turbines to be spaced closer together.\textsuperscript{17}

When making calculations to adjust for the height of the wind measurements (for instance, with WAsP) three special considerations need to be made for forest sites. When using Formula 2, 3 or 4, a displacement height of approximately $\frac{3}{4}$ of the tree height must be deducted from both the specific and the reference height according to Bergström\textsuperscript{105}, while other literature suggests 0.8 of the tree height. This is called a zero-plane displacement\textsuperscript{23} and is illustrated in Figure 3, where $h$ is the tree height and $d$ is the corresponding displacement height.

![Figure 3 - Zero-plane (d) in forests\textsuperscript{24}](image)

The surface roughness can be estimated with 7.5-10\% of the tree height\textsuperscript{25}, but in reality both the surface roughness and the displacement height are dependent on the type and the density of the forest. Different kinds and different shapes of treetops also affect the turbulence and the wind shear in different ways.\textsuperscript{16} For non-forest locations the turbulence intensity decreases with wind speed in conjunction with the IEC demands shown in Figure 2, but for forest locations the turbulence has a consistently high value for up to five times the height of the treetops. This can cause problems when trying to fulfil the turbulence demands of the turbine manufacturers.\textsuperscript{26}

The effects of changing surface conditions do not affect the wind conditions at the wind turbine hub heights instantly, since it needs some distance to come into effect. According to Bergström\textsuperscript{105} the wind conditions at 100 m are mostly affected by the surface conditions at a distance of between one and five kilometres. Lars Landberg, on the other hand, separates the effective surface roughness and the effective displacement height at the standard hub heights of modern wind turbines. He states that a change in surface roughness at a forest edge is taken into full effect at a downwind distance of between 10 and 100 times the tree height, while the change of effective tree height is taken into full effect at a downwind distance of between 5 and 50 times the tree height.\textsuperscript{106}
Swedish cultivation of the forest has led to more than 80% of the trees in the forest being conifers (spruce and pine), whereas the rest are deciduous trees (birch and asp). In southern Sweden the height of the trees can reach as high as 30 m before they are felled every 55-75 years. In northern Sweden they are felled every 120-140 years when they reach 15-17 m. The felling and growth of trees must thus be considered when estimating the energy production at a specific site for several years in advance. The cultivation of the forest can cause other problems. For instance, when only part of the forest is felled, which is the usual procedure, the clear-cuts generate increased turbulence compared to a uniform forest.

Despite the precautions with wind power in forests there are a number of wind farms and turbines already situated in forests. Most of them are located in the USA, Canada, Germany, Great Britain and France, but several projects are under development in Sweden as well. In the forest of Sveskog more than 500 turbines are planned and 15 turbines were already constructed up to the fall of 2007.

2.2.4 Wind turbine design for forest sites

The choice of wind turbine and its features is essentially an optimization problem where technology and economy need to work together in order to find the best solution. Depending on the point of view, the best solution could be either the most profitable per MWh, the highest energy production or, most likely, a combination of high profit and high energy yield. Besides general good practice and efficient equipment there are at least two design issues where optimization is needed. However the choices for an energy company, such as Vattenfall, are limited to what the wind turbine manufacturers offer.

One (or two) parameter(s) to design is the relative size of the rotor compared to the generator. A smaller generator would be more effective in producing electricity in low wind conditions, but it would not be able to capture all the energy in the wind for stronger wind conditions. It is possible to use both a small and a large generator to be able to get both the advantages, but obviously this would come to greater cost. A large rotor diameter would be able to capture more of the energy from wind speeds below the rated wind, but on the other hand, it would be more expensive, generate higher mechanical loads and produce a larger wake behind the turbine. The standard rotor diameter is about 90 m, but there are also 100 m rotors available and under development.

The other solution for sites with low wind conditions, especially for sites with severe wind shear, is to increase the tower height. The most common tower is a steel tubular tower, which are manufactured in 20-30 m sections and bolted together at the site. These towers are conical to optimise strength and material use. There are also concrete towers and lattice towers. Lattice towers require less material, but while material costs are reduced manufacturing and maintenance costs are increased. Lattice towers also give less wind shade than tubular towers and due to their visual appearance they are very rare for large, new wind turbines. Guy wired towers are another possibility, but they have the disadvantages of increased land use and risk of sabotage.

Two obvious problems with increased hub height are the increased cost and visual intrusion, but the latter problem is somewhat reduced by the forest. Less obvious problems with tower
heights of above 100 m are the resonance frequencies caused by the rotation of the blades and the increased size of the lower part of the turbine tower. With a diameter of above 4 m for a steel tubular tower road transportation is even more complicated. To solve this problem for a project in Germany, Nordex has used a hybrid tower consisting of a concrete base of 60 m and a steel tubular tower of 60 m on top.\textsuperscript{32} Another supplier of high towers is Fuhrländer who offers a 2.5 MW machine with rotor diameters of 80, 90 and 100 m and a lattice tower with heights of 100, 117, 141 and 160 m.\textsuperscript{33}

Under normal circumstances approximately 20\% of the price of a wind turbine is for the tower.\textsuperscript{30} The cost of increasing the hub height varies for different heights, suppliers and solutions, but there are some sources for estimating the additional cost. NREL has released a technical report presenting cost-scaling models, which indicate an additional cost compared to a 100 m tower of about one million SEK for 120 m and 2.6 million SEK for a 150 m tower.\textsuperscript{34} This model is however mainly aimed at tower heights below 100 m, introducing an underestimation. A more reasonable figure, which is mentioned in the literature, is about three million in additional cost for a 120 m concrete hybrid tower compared to a 100 m steel tubular tower.\textsuperscript{35}

2.2.5 Wake effect

Since the wind turbine extracts energy from the wind, the wind leaving the turbine has a lower wind speed and also increased turbulence. This is called the wake effect and can reduce the production of wind farms substantially. For Lillgrund wind farm with 48 turbines positioned 3.3-4.3 rotor diameters apart, the total wake effect corresponds to about 20\% of the production or in other words it has a park effect of 80\%.\textsuperscript{36} This is however quite extreme, and ordinarily the distance between wind turbines is five to nine rotor diameters apart in the prevailing wind direction and three to five diameters in the direction perpendicular to the prevailing wind direction.\textsuperscript{36} Depending on the size of the park the energy loss due to the wake effect varies.\textsuperscript{37}

For sites in forests the turbulence is generally quite high, but this can have both advantages and disadvantages. Since the ambient turbulence is higher the wake effect is decreased to a certain degree, enabling a closer spacing of the turbines with regard to wind speed. However, since the turbulence is already quite high, a greater distance might be needed for the wind conditions with respect to turbulence to drop below the accepted limit for the turbine in the wake.\textsuperscript{38}

2.3 Wind Measurements

The process of constructing a wind turbine or a wind farm consists of many different steps, ranging from technical, economical and legal issues. Determining the specific wind conditions for sites is necessary both for choosing the construction site as well as for designing certain characteristics of the wind turbine. The energy content in the wind determines the amount of power that can be produced, which decides the economic
feasibility. A high degree of accuracy in predicting the production and wind characteristics minimises the economical and technical risks, making the project more favourable.39

A first step after receiving the task to construct one or several wind turbines is to get an idea where the wind is strong enough. This is generally done with the help of a wind atlas, which for Sweden means the wind energy maps by MIUU or SMHI. These data are based on data collected for many years and at many different stations. Wind data for sites between measurement points has been calculated with the help of data from nearby stations and knowledge of the prevailing terrain in each area. This can be done with the software WAsP and is called the wind atlas method.40

If the pre-study indicates that the construction of a wind turbine (or a wind farm) could be economically feasible, at the same time as other important considerations such as environmental impacts, local acceptance, permits, land and electric grid issues are not insurmountable, the company can take the next step. Now the energy production needs to be calculated more precisely, with regards to the turbine’s power curve and the wind frequency distribution. The wind turbine supplier delivers the power curve, leaving the wind frequency distribution to be determined. 40

This can be done in two ways. In favourable conditions, this can be calculated from one or several reference wind turbines or measurement station(s) nearby. This is generally cheap, but does not provide as accurate data as the alternative. The alternative is to install measurement equipment at the investigated site, which records the wind speed and direction for a longer period of time. This also provides information about wind shear, and turbulence intensity. This is commonly done with the use of cup anemometers placed at different heights on a mast, which preferably should be at the same height as the intended wind turbines in order to minimise uncertainties. Wind vanes measure the direction of the wind and thermometers and barometers are used to supply the temperature and the pressure.41 This equipment could also be placed on existing masts for telecommunications. 42

As the size of the turbine has grown, erection and maintenance have become expensive and permits time-consuming. With larger rotor areas the importance of knowing the wind speed over the whole area and not just for the height of the nacelle has increased. For these and other reasons remote sensing techniques, such as sodar, lidar and satellite are of great interest and under strong development. 43

2.3.1 Characteristics of wind measurement equipment

The alternative wind measurement methods of anemometer, sodar, lidar and satellite all have their strengths, weaknesses, useful applications and development potential. In order to properly assess these, the important characteristics of wind measurement equipment must first be addressed.

When examining the measurement data there are some key characteristics that should be considered. The accuracy refers to the mean difference between the recorded value and the actual value, while the precision refers to the dispersion of single measurements. Other important performance parameters are the reliability and the availability of the instrument. 44
For the instrument itself the time constant is defined as the time it requires to respond to 63.2% of a stepwise change in the input signal. This can also be expressed as a distance constant, where the time constant is multiplied by the average wind speed. Finally, the sampling rate of the instrument is simply the frequency of which the signal is sampled. 44

There are also less technical parameters of importance, such as cost and legal framework, like building permits. The amount and type of maintenance and the lifetime of the equipment may also be significant.

The different wind measurement techniques compared in this report are two types of sodars, cup, propeller and sonic anemometers, as well as lidar and satellite technologies.

2.3.2 General information about sodar technology

Sodar is an abbreviation for sound detection and ranging and is a ground-based remote sensing instrument. The instrument emits short pulses of sound upwards and measures the sound that is reflected back. The reflected sound changes its frequency proportional to the wind speed along the sound propagation path, according to the Doppler effect. 45 The sound is scattered back because of small-scale fluctuations in the acoustic refractive index. This is caused by inhomogeneities in the temperature field that are moving with the wind or for a bistatic sodar, which is explained further down, mostly by velocity fluctuations. 46 The relationship between the change of frequency (Δf), the transmitted frequency (f), the speed of sound (c) and the air speed relative the transmitter (v) is described by Formula 10. 47

\[ Δf = f \frac{v}{c} \]  

(10)

The current temperature is needed to calculate the correct speed of sound, and this can be done either with an integrated temperature sensor or by manual input. It can be calculated with Formula 11, where T is the temperature in Kelvin. 48

\[ c = \sqrt{401.88 \cdot T} \]  

(11)

A source of error for a sodar system is the temperature measurement. Since the speed of sound is a function of temperature, it affects both the calculations of the measurement height and the Doppler shift. If the assumed or measured temperature is higher than the actual temperature, the recorded wind speed is reduced and vice versa. For example a temperature difference of about 10°C produces an error of about 4%. 49

A sodar emits either one or multiple frequencies. The frequencies are between 2 kHz and 6 kHz, which are in the audible range and might thus cause some nuisance. The altitude of measurements is calculated through the propagation time between the transmission and the reception of the sound pulse and it is thus possible to measure the wind speed at different heights simultaneously with a single sound pulse. 49

There are several advantages to sodar (and lidar) systems compared to the regular anemometer measurement procedure. A sodar unit is quickly deployed due to its portable feature and since no building permits are needed. This does however create a vulnerability
to theft and sabotage, and there is still a need for a stable platform and a power supply. Remote sensing equipment also measures the complete wind shear profile of interest for wind power, compared to mast measurements that due to the increased cost with increased height at best measure to the hub height. This is particularly a problem if low-level jets are formed at the site, which the mast will be unable to detect, and the subsequent extrapolation of the wind profile then highly overestimates the wind potential at the site. A further advantage with remote sensing technology is that the measurement equipment does not disturb the flow like the supporting structure of a mast does. Finally, there are economic incentives for choosing sodar technology for both short- and long-term wind measurements, due to the lower installation cost, but the technology can demand more surveillance and maintenance. 49

There are several different types of sodar configuration. These can be sorted according to their transmitter/receiver arrangement in either monostatic, where the signal is transmitted and received with the same instrument or bistatic, where the signal is transmitted by one transducer and received by another transducer. Alternatively, sodar units can be divided in phased array sodars and multiple-antenna sodars (also called parabolic dish sodars). 78

The majority of the sodars in use are monostatic due to their more compact antenna size, easier operation and generally greater altitude coverage, but a bistatic sodar has better signal-to-noise ratio for high wind speeds, can be operated in continuous mode and the scale of the measurement can be reduced. Reducing the scale of the measurements means that the volume of air from which the backscattered signal is received is limited to a couple of meters, instead of the magnitude of one hundred meters for monostatic sodars. This can produce better turbulence readings50 and improve the resolution problem caused by small-scale topography, such as lesser hills. A possible setup for a bistatic sodar is a central transmitter working with three surrounding receivers, whereas the monostatic solution only has one central combined unit. Figure 4 illustrates the configuration difference between the two. 50

![Diagram of monostatic and bistatic configurations](image)

**Figure 4 – An illustration of the different setups for mono- and bistatic sodars**

There are a number of companies in the sodar business, with the largest being Remtech, Atmospheric Systems Corporation (formerly Aerovironment), Metek, Scintec and AQ System. The first four use the phased array configuration, while AQ System applies the multiple-antenna configuration. 51 The phased array systems are to some extent more widespread, at least until recently, but the WISE project (wind energy sodar evaluation) funded by the European Union has concluded that neither of these are particularly close to
substituting standard measuring masts. The report states that they are unreliable, especially in the case of bad weather or high background noise. 52

This conclusion does not directly apply to the AQ500 from AQ System53, since they use a different configuration, and it is this product that Vattenfall has invested in. Presently Vattenfall owns one AQ500 and has contracts for five additional units to be delivered in the autumn 2008.52 The AQ500 is also the unit this Master’s thesis is focused on.

2.3.3 Multiple-antenna configuration, the AQ500

AQ System has developed the AQ500 over a number of years, and their business is currently very successful with delivery contracts for the rest of the year. They have recently doubled their production capacity and will double it once more 1 October 2008 to be able to produce two systems per week. They have delivered sodars to many of the big wind energy prospectors in Sweden, including Vattenfall, Vindkompaniet, and Arise Windpower. 115

The AQ500 is a monostatic three-antenna configuration with the parabolic transducers horizontally offset by 120°. The beam angle from each horn is inclined 15° from the vertical axis, with the beam angle of 12°.55 Since the vertical resolution is ±6 m the measured data are for a volume rather than a scalar point, which essentially is the case for cup anemometer data. Especially in the case of a high wind shear this resolution can cause an underestimation of the wind speed, but to correct for this a filter is used particularly at lower heights where the profile is most pronounced.54 Figure 5 presents the measurement volume graphically. By not taking the beam angle into consideration, the volume at 50 m consists of a circle with a diameter of 26 m as base, and at 150 m the circle has a diameter of 78 m. Taking the beam angle into consideration, which adds another 6° offset from the vertical axis, the circles have the diameters of 36 m at an altitude of 50 m and 108 m at an altitude of 150 m. This corresponds to a time constant at an average wind speed of 6-7 m/s for the highest altitude at about 10 s. This must be kept in mind when using the sodar for turbulence measurements and where there are small-scale changes in topography and surrounding surface. 115, 53

![Diagram of AQ500](image)

Figure 5 – The measuring volume of the AQ500 based on inclination, beam angle and vertical resolution
The antenna unit only weighs 38 kg, has a diameter of 1 m and a height of 1.4 m. But to support the unit with regards to power, where no grid connection is economically feasible, and to hold the equipment for data recording and sending, AQ System supplies a trailer solution. Figure 6 shows the antenna and the trailer, though the picture of the trailer is downscaled by 50% compared to the antenna pictures. The trailer is roughly 3.5 m long, 1.6 m wide and 2 m height and weighs about 1000 kg. The power demand of the sodar varies according to the background noise, which might require increased signal strength, and the weather conditions, which might require heating in the case of snow. The pulse power can be 300 W, but is ordinarily lower and not continuous, which means that the power needed is 30-50 W, supplied at either 12 V DC or 220 V AC. If not grid connected, this is supplied by a diesel engine running some hours every day to charge the 12V battery pack. An attempt with a renewable energy supply through photovoltaic cells has been made, but further investigation is required before replacing diesel completely in a reliable way. The possible mode of operation is also highly dependent on at which part of Sweden the unit is deployed, due to varying amount of solar irradiation, with the winter months as the critical design issue.

![Figure 6](image1.jpg)

Figure 6 – The full view of the AQ500 unit to the left, the antenna unit in the middle and the trailer for the sodar to the right. (The scale of the trailer should be doubled)

The AQ500 can operate in a wide range of weather conditions, from −40°C to +60°C, from 10% to 100% relative humidity and in both snow and rain.

The data output from the unit is based on the standard ten-minute average and is supplied for every five meters from 20 m to 150 m, which optionally could be extended to 500 m. It supplies the wind direction, horizontal and vertical wind speed, the standard deviation of the horizontal wind and a signal-to-noise ratio (quality index) for each height and ten-minute-average. Optionally it can also produce the standard deviation of the vertical wind speed and the wind direction. It applies an advanced signal processing based on a fourth-order Chebyshev filter (Fast Fourier Transform, FFT), and the receiver gain is 110 dB. It transmits the frequency of 3144 Hz, but it is possible to use multiple frequencies. The pulse rate can be varied, which affects the power consumption. The maximum rate is limited by the reduction of the echo and the desired height of the measurements. Since the three transducers transmit one at a time, it takes three seconds for each cycle. However, to be able to measure at lower heights, a cycle with transmission time of 75 ms is first used to measure the wind profile up to 45 m, followed by a cycle with transmission time of 150 ms to measure...
the wind profile from 50 m and upwards. For a sodar calibration of 150 m measurement height, the complete cycle is completed in approximately 4-5 s, thus a ten-minute average are a result from 100-15000 measurements from each antenna. If the sodar is calibrated to measure higher altitudes, the pulse power is increased and the pulse frequency reduced, giving fewer measurements per ten-minute average. 54

According to the AQ500 manual the range of the horizontal speed-readings are 0-50 m/s and its accuracy is better than ±0.1 m/s. For the vertical wind speed the range is ±10 m/s and the accuracy is 0.05 m/s. For the wind direction the accuracy is 2-3 degrees. 55

<table>
<thead>
<tr>
<th>System specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height: 120 cm</td>
</tr>
<tr>
<td>Width: 100 cm</td>
</tr>
<tr>
<td>Weight: 38 kg</td>
</tr>
<tr>
<td>Temperature range: - 40 to + 60 degrees C</td>
</tr>
<tr>
<td>Humidity range: 10 to 100% RH</td>
</tr>
<tr>
<td>Altitude range: 15 - 150 (500) m</td>
</tr>
<tr>
<td>Height interval: 5 (-25) m</td>
</tr>
<tr>
<td>Wind speed range: 0 - 50 m/s horizontally ± 10 m/s vertically</td>
</tr>
<tr>
<td>Accuracy: 0.1 m/s horizontally 0.05 m/s vertically</td>
</tr>
<tr>
<td>Transmitting frequency: 3144 (2850 – 3550) Hz</td>
</tr>
<tr>
<td>Acoustic power (max): 4 W</td>
</tr>
<tr>
<td>Pulse power (max): 300 W</td>
</tr>
<tr>
<td>Power requirement: 12DC or 220 VAC</td>
</tr>
<tr>
<td>Power consumption: 30 - 50W</td>
</tr>
</tbody>
</table>

Table 3 – AQ500 specifications 55

A disadvantage with the AQ500 is that remote sensing technology is not yet fully accepted by wind turbine manufacturers, if not supported by mast measurements.

2.3.3.1 Positioning the unit

The quality of the data obtained with the sodar is dependent on the surrounding area. When placing the unit on open fields or off-shore, the only consideration that needs to be made is that of any nearby wind turbine or measurement mast. Positioning on forest sites is not as easy where ideal locations are not available or that obvious. According to the AQ500 manual there are three criteria that can be used to select a good position: 55

- Open space of at least 100 m in every direction or less than 10 m to one obstacle and more than 100 m to any other obstacle. (Less than 10 m means that the
propagation path for the sound is less than the lowest measurable altitude of 20 m.)

- If unable to find such a position, orient the sodar in order to minimise the reflected area of the obstacle.
- Turn the sodar unit with the obstacle at an angle between two antenna directions; preferably 60° offset from any of the antenna directions.

In spite of the guidelines of 100 m of open space, AQ System advises that 30-40 m of free space is often satisfactory. Since a clear-cut of 100 m in every direction might not always be possible or desirable at the point where the measurements are to be performed, the alternative recommendation is then considered. After installing the sodar at a site it is possible to study the fixed echo in the frequency spectrum for the backscattered sound, in order to evaluate the location. If there is a fixed echo it will give an indication with a high magnitude of the frequency of the transmission, i.e. without any Doppler shift. The echo is most likely to interfere at measurement heights equal to twice the distance to the obstacle, but can also interfere at higher heights in the case of dense forest where the sound can delay, echoing between the trees.\(^5^6\) The fixed echo will also be possible to detect in the produced wind shear profile that would show lower mean wind speeds at the altitude of the fixed echo.

2.3.3.2 Installation and relocation

The sodar unit is easily movable, and as a part of this Master's thesis, the unit was moved from Site A to another site. The procedure is simple, but is described step by step below for complete comprehensiveness: \(^5^6\)

Uninstallation:  
1) Switch the sodar off (main switch).
2) Put the control unit for the diesel generator in stop mode.
3) Flip up the support legs (collect the stone plates under them).
4) Secure loose objects and lock the trailer up.

The AQ500 is then moved to the new location. A regular car with at towing hitch can usually do this, but for some locations special solutions need to be made. If the terrain is only somewhat uneven the use of a tractor could solve this, but the trailer is not constructed for off-road driving. For even more inaccessible sites, such as offshore or mountainous regions, the use of a helicopter could solve the problem.

Installation:  
1) First and foremost the trailer should be positioned according to the guidelines described in section 2.3.3.1. Then it should be fairly balanced both widthways and lengthwise.
2) Then the supporting legs are used for coarse adjustment, followed by the fine-tuning with the legs of the antenna unit. There is a spirit level within the sodar.
3) Make sure the air intake and exhaust pipe for the diesel engine is reasonably cleared from flammable sources, such as long grass.
4) Turn the main switch on.
5) Put the diesel engine in manual. It then starts and begins to charge the batteries after one minute. Make sure everything works well. Then turn it to auto mode.

6) Check the direction of the trailer with the compass. This is input to the software.

7) If there is potential for problems, such as proximity of forest, check the signal spectrum to detect any echo problems.

2.3.3.3 Previous tests and comparisons with traditional measurements

Several scientific studies ensuring the reliability of the AQ500 have been conducted. Some of these are presented here. Some are very recent, while others are a few years old, for which the quick development of the AQ500 needs to be kept in mind.

From 1 to 27 October 2004, AQ System performed a verification test at Näsudden, Gotland. The wind data from the sodar unit was compared with the 120 m high meteorological mast located 210 m from its position. There are many wind turbines at Näsudden, the closest not further than 240 m from the mast, that affect the local wind characteristics, but the unique height of the meteorological mast makes the comparison important nevertheless. The test results conclude a total availability of 96%. In comparison with anemometer wind speed, the coefficients of determination were 0.96 at 60 m and 0.98 at 120 m. The wind profile generated by the sodar corresponded very well with the profile from the mast. 57

From June to September 2005 Risø National Laboratory conducted a study of two sodar units (the AQ500 and the AV4000 from AeroVironment) and one lidar (Zephir from QinetiQ Ltd) in offshore conditions. The comparison between the sodar measurements and the lidar measurements shows a good conformity with a correlation of about 0.99. The AQ500 has slightly higher spreading of wind speed compared to the AV4000, but on the other hand the AV4000 produces more values that deviate significantly from the sodar data. The wind profiles between the Zephir and the AQ500 are very similar, while the wind profile from AeroVironment’s sodar has a different slope and might be affected by fixed echoes from a nearby radio antenna. No problems with background sound or the low turbulence were detected, which would have lowered the data quality. No calibration of the remote sensing equipment was performed, and the results compared with the mast were still good, indicating errors no larger than 4-5% for any of the equipment. Of the sodar units the AQ500 had the smallest error. 58

From 1 to 29 April 2008, AQ System performed a test together with Arise wind power and Hans Bergström at Uppsala University. It was conducted in Markaryd in southwest Sweden. The site is forested and the meteorological conditions during the period were typical of spring with large variations. The data was compared to a 100 m high mast located at a distance from the sodar of 327 m. The wind speed readings from the mast at 40 m, 60 m, 80 m and 100 m had correlation coefficients with the sodar of 0.94, 0.95, 0.96 and 0.97, respectively, and the wind speed indicated by the sodar was generally a little lower. Possible explanations to this, which are not mentioned in the report, apart from individual measurement uncertainties, are the distance between the two measurement positions and over-speeding by the anemometers. For the turbulence data the AQ500 indicated a higher
mean wind speed standard deviation of approximately 6% and coefficients of determination between the two data sets of between 0.8 and 0.9. 59

Finally, for the first months of sodar data from Site A, Lasse Johansson at Vattenfall Power Consultancy has performed an initial evaluation. The evaluation covers the first 64 days of measurements between the beginning of December and the beginning of February. The data availability for the sodar is 98% for wind speed and 93% for turbulence. With respect to all data the average wind speed of the sodar was 1.5% higher than that of the anemometer. However, due to low temperatures affecting the anemometers to standstill or slow down, the result when eliminating the low temperature data was a 1.9% lower average wind speed for the sodar measurements. For this reason the analysis has generally been conducted on the data for which the temperature is above 0°C, and this is limited to 70% of the total data.4

Compared to the study at Näsudden, the mean error and the standard deviation for the anemometer and sodar comparison are both much larger, corresponding to 5-10 cm/s for the mean error and about 65 cm/s for the standard deviation. It is suggested that this is connected to the increased turbulence that affects one or both of the measurement technologies.

The study found that the sodar wind speed tends to overestimate the wind speed when measuring wind below 3 m/s, but since the cut-in speed is higher than this, it is not that important.

The measured wind profiles for the anemometers and the AQ500 correspond well, but extrapolating the anemometer data to heights above the mast height would overestimate the wind potential. A wind direction comparison could not be performed completely due to poor alignment of the wind vanes on the mast.

The study of the turbulence data from the two sources showed significant differences. Below 50 m the turbulence intensity from the sodar data was about 3% less, and above 50 m it was as much as 6% less. The mean turbulence intensity at 100 m was about 15%.4

2.3.4 Phased Array configuration

Like the multiple-antenna configuration, phased array sodars emit sound pulses and then measure the Doppler shift of the backscattered signal. The phased array configuration also needs a certain beam inclination, but this is achieved by controlling the relative phases of the signals from different antennas, thus amplifying the radiation pattern in some direction and suppressing it in other directions. 60

The array can consist of as few as 16 or over 100 elements.61 The ratio of the received and transmitted signal at 100 m is typically 1014, thus the sodar technology can potentially be quite sensitive to background noise. The choice of frequency is an optimisation problem. The background noise decreases and the resolution increases with higher frequency, but the atmospheric absorption and thus the maximum measurement height decreases simultaneously. 60
Compared to the AQ500 the phased array products available have similar performance specifications, but with a somewhat lower wind speed accuracy of 0.1-0.5 m/s.60 The wind speed readings are underestimated, and comparison with anemometer data shows a regression line with a slope of 0.97 to 0.995.60 Furthermore phased array sodars have problems with precipitation and wind speed above 15 m/s, and due to filtering this leads to low availability. Testing has revealed wind speed underestimation as high as 10% and overestimation as high as 6% for different tests. The WISE project concludes that the phased array sodars should be used together with a met mast of at least 40 m for continuous calibration. 52

Based on the information available for the sodar of the AQ System and other sodar systems on the market, it seems clear that the general features of AQ500 are superior, and it will be the focus of the rest of the report.

2.3.5 Cup and propeller anemometers and wind vanes

Cup anemometers are by far the most common type of wind measurement technology. This is because the cup anemometers give accurate and precise wind measurements, there is substantial experience with them, and they are robust and relatively inexpensive. Still, they are not perfect and there are some problems, especially with dynamic response calibration and when the wind has an angle of attack relative to the horizontal plane. 63

The cup anemometer consists of a body, with fastening, cable entries, possibly heaters and a signal generation device, a shaft, a rotor and usually three cups. The standard cup anemometer is primarily designed to measure wind speed in the horizontal plane, which is also the component of the wind that normal wind turbines are able to extract. There are also cup anemometers designed to measure the total wind speed, including the vertical component. However, no cup anemometer behaves perfectly in either of these desired ways.63

![Figure 7 – Some different kinds of cup anemometers](image)

There are a number of different designs available on the market, as seen in Figure 7, with different features. Different parameters influence the measurement in a number of different ways. If the shaft is long, the body affects the flow less, and if the body and fastening are not uniform, it will affect flows differently depending on the direction. A bigger rotor diameter will give better linearity, but also decrease the dynamic responsiveness. The type of bearings and signal generation device influence linearity and dynamic response, particularly with
varying temperatures. The shape of the cup affects both the sensitivity to the vertical wind component and the dynamic response to a high degree, but also the linearity due to edge effects.\textsuperscript{63} Taking all this into consideration, one easily understands that the anemometer furthest to the left in Figure 7 is most likely the one with the highest precision.

As discussed earlier, an instrument’s dynamic response is often measured as a time constant, but for anemometers it is more adequate to describe their ability to respond to change in wind speed with a distance constant (a given wind-run). Due to this, the cup anemometer responds more quickly to increasing wind speeds and responds faster at higher wind speeds. As a result of this, a cup anemometer will indicate a higher mean wind speed in fluctuating wind compared to the actual value – a phenomenon that is called over-speeding. This error is however quite low at ordinary conditions, typically below 0.3%. Formula 12 is an approximation of the over-speeding error (E), as a function of the turbulence intensity (TI) and the distance constant (d):

\[
E = TI^2 \cdot (1.8d - 1.4)
\]  

Because of their inability to respond instantaneously to wind speed changes, a cup anemometer is not able to measure the true turbulence intensity. This highly depends on the distance constant, and an anemometer with a distance constant of 3.5 m will report 5% less turbulence intensity than the true value. Instead of 20% it will report 19%. This is called dynamic filtering.\textsuperscript{63}

Anemometers need to be calibrated in a wind tunnel, and re-calibration should be performed at least every six months.\textsuperscript{63}

The placement of the anemometers on the mast also affects the accuracy of the wind measurements. To avoid, or at least minimise, disturbance, the anemometer should be placed on the top of the mast, but wind measurements are needed at different heights. For this purpose the measurement devices are placed on booms no less than seven mast diameters away from the mast, with the vertical distance between the anemometer rotor and boom of at least 12-15 boom widths. It is an advantage to use a double set of sensors at each level, placed on two booms in opposite directions, and when the wind conditions are analysed, data from an undisturbed anemometer could always be used. Since most measurement masts are supported with tower guys, to be able to reduce the dimension of the mast, it is important that these do not distort the measurements before the anemometer. The flow distortion is dependent on the relationship among the anemometer, the mast and the direction of the flow, but adopting these principles will keep the disturbances below 0.5%.\textsuperscript{63}

Climate conditions can cause some problems for a measuring mast, such as the risk of lighting and effects of rain, which both need to be considered during the design. For cold climates, such as Sweden, the worst troubles are connected to low temperatures, ice and snow. Accumulation of ice and snow on the cups changes the aerodynamics, and low temperatures increase the friction in the bearings. Applying heating can solve these problems\textsuperscript{63}, but when grid connection is not available, it is seldom used because of the increased cost of stand-alone electricity generation.\textsuperscript{17}
When best practice and equipment are used, the standard uncertainty for ten-minute averages with cup anemometer are in the range of 0.5-1.5%. 63

Cup anemometers need to be complemented with wind vanes in order to measure the direction of the wind. Knowledge of the wind direction is important when planning wind farms, in order to properly assess the wake effects. Vanes are designed to rotate into the wind by having a shape that causes unequal momentum about the axis for the area exposed to the wind. Phrased differently, the wind vane positions itself to minimise air resistance.63

The wind vane works together with a potentiometer that produces a varying electrical signal, depending on the azimuth angle. Previously all potentiometers were of the 360° format, but due to their construction they have a “dead area” or “slot” of approximately 2° for which the potentiometer instead indicates one of the directly surrounding values. To solve this problem the 540° format is available, which combines two potentiometers and does not have any “dead area”.64 The accuracy of wind vanes is typically ±2° and the threshold, i.e. minimum working wind speed, is less than 0.5 m/s. 65

A similar wind measurement equipment is the propeller anemometer, and some fundamental issues with the cup anemometer can be applied to this type as well. The propeller type anemometer is basically a propeller that faces the wind with the aid of wind vanes. The propeller responds primarily to the wind in its actual direction, thus needing a wind vane. By applying a second degree of freedom (pitching), it can also measure the wind in the vertical component, which gives the total wind vector (speed and direction). This can also be accomplished by using one stationary propeller anemometer for each axis, followed by some calculation software.69 This type is suitable for measuring turbulence due to its low distance constant64, but the propeller-bivane version can be unstable in highly turbulent conditions, whereas the three-axis version produces uncertainties because of structural wind shading and irregular wind angles. 49

The cost of a standard equipped measuring mast is about 1 MSEK, and the cost of equipping an existent telecommunication mast is about 0.2 MSEK. To be allowed to construct a mast in Sweden and other countries, one needs a building permit from the municipality. 70

Instrumenting an existing telecommunication mast is done quickly, but it has a little less accuracy than a normal measuring mast because of the difference in mast design. Permission is needed from the owner of the mast and the owner of the land, but not from authorities. 66

2.3.5.1 Equipment used in the measurement mast at Site A

The cup anemometer installed at Site A is at the 25 m level produced by Vaisala Oyj and of the type WAA151. It has an accuracy of ±0.17 m/s, a threshold of <0.5 m/s and a distance constant of 2.0 m. It has been properly calibrated.67 For the other levels (40, 60, 80, 97 m) Thies First Class anemometers were installed. Its accuracy is better than 0.3 m/s, with a threshold of less than 0.3 m/s and a distance constant of less than 3 m.68

The wind vanes are produced by Vector Instruments and of the type W200P. The prescribed performance is ±0.5° in precision and ±3° accuracy in steady winds above 5 m/s. The threshold of the wind vane is about 0.6 m/s. 69 The wind vanes are placed at 40, 60 and 97 m.4
2.3.6 Sonic anemometer

A sonic (also called ultrasonic) anemometer works on an entirely different scale and principle than the sodar, but it still uses sound pulses to measure the wind speed. It sends out a high frequency (about 100 kHz) acoustic pulse in each axis, which can be understood from Figure 8. It then measures the difference between the transit time and the time it would take if the wind speed were zero. This time difference ($\Delta t$) can be expressed as in Formula 13.\(^49\)

$$\Delta t = \frac{2d}{a^2} V_d$$  \hspace{1cm} (13)

where $a$ is the speed of sound, calculated from the air temperature, $d$ is the path length and $V_d$ is the wind speed. From these calculations the wind speed vector can easily be calculated.\(^49\)

![Figure 8 – Two different sonic anemometers 70, 71](image)

The sonic anemometer has a very high resolution, as low as 0.5 cm/s, and a very high precision. The sample rate can be very high, for instance 20 Hz. However, the supporting structure and sensing heads distort the wind and thus produce measurement errors. Some sources, like the IEA wind measurement recommendations,\(^49\) suggest low and unimpressive accuracy, while a number of suppliers of sonic anemometers claim accuracies as good as ±0.03 m/s or ±1%.\(^72, 73\)

Sonic anemometers functions poorly in precipitation, but can function well down to −30º. If the equipment starts to ice up, the data quality deteriorates, but using heating can help this.\(^74\) The cost is much higher than for a regular cup anemometer.\(^49\)

Due to its properties it is suitable to measure turbulence, but not to measure mean wind speed for wind turbine site assessment.\(^49\)
2.3.7 Lidar

Lidar is an abbreviation for light detection and ranging and works according to the same principle as sodar, but by using light instead of sound. It measures the Doppler shift of radiation scattered by aerosols in the air by sending light in the IR spectra. This is emitted upwards in normally a 30º (but possibly 15º) cone in order to measure wind speed in all three spatial dimensions. This causes some problems for larger measurement heights where the wind speed is slightly underestimated due to a larger probe area inside the cone, but applying correction filters could solve this. There are two types of sodar: pulsed or continuous wave. Pulsed systems use signal timing to obtain vertical distance resolution, whereas continuous wave systems rely on detector focusing. 78

There are two leading products on the market, Zephir by QinetiQ (Natural Power) and Windcube by Leosphere, which are shown in Figure 9.

![Figure 9 - Leading sodar products: Zephir to the left 75, Windcube to the right 76](image)

The two products operate according to slightly different principles, where Zephir uses continuous wave emission while Windcube uses pulsed-wave emission. 77,78

Zephir produces three-second averages for up to five different measurement heights, with a prescribed maximum height of 150 m. 78 Windcube produces one-second averages for up to ten heights and has a maximum range of 200 m. The maximum range does, however, depend on the weather and visibility; for very clear days (visibility over 10 km) or very foggy days (visibility about 100 m), the range is reduced. 77 Near the coast the aerosol density in the air is quite high, which improves the data availability. 81 The Leosphere sodar has a spatial
resolution (vertical) of 26 m, but this can be improved to 13 m through correlation with other measurements. The Windcube has a spatial resolution of 20 m. 77

Both systems have a very good availability of above 95% and compared to measurements with cup anemometers, they both have good conformity, with deviations of less than 3% for Zephir77 and ±0.2 m/s for Windcube (at 30°, ±0.3 m/s at 15°).78

The horizontal components are minimally affected by weather conditions, such as cold, rain or snow, but the vertical component is invalid in case of downpour. At least for Zephir, the vertical component does not give satisfactory results, and there is also some underestimation of the turbulence intensity and extreme wind values (gusts). 78 When the sodar is measuring at 150 m, the measuring diameter at 30° is 173 m, which correlates to the instrument’s distance constant. This makes the measurement of turbulence and gust winds inadequate for high heights. Windcube has a partial solution to this problem where the angle is reduced to 15° for turbulent areas, and this reduces the measuring diameter to about 80 m. 77

Zephir has a total weight of 134 kg, which makes it easy to move and mount at sites83 and the price of the product is approximately 1.3 MSEK.79 Windcube is even easier to handle with a weight of only 45 kg77, and its price is between 1.4 and 2 MSEK. The price information includes everything except a transportation solution (e.g., trailer) and a power supply (e.g., diesel engine) for about 100 W. The cost of these is about 65 kSEK for the transportation and 16 kSEK for the power supply. 79 A lidar system needs regular maintenance about once or twice a month.80

There is no need to apply for any permits, except from the owner of the land.77

Lidar is, similar to sodar, a quite new technology that still needs to be tested and evaluated further in order to obtain certain knowledge of its different properties.78 For temperatures below -10°, lidar systems generally function poorly, because of component malfunction, and the data produced are thus unreliable. 81

It is possible to use sodar from satellites and airplanes or mounted on wind turbines for power performance measurements.83

Vattenfall has purchased a Windcube sodar, delivered in September 2008, and it will be initially tested at Site A.82

2.3.8 Satellite

A further possibility for measuring wind data is by satellite, which can be done by several techniques. Generally, the use of satellite is only applicable for measurements in the open sea, and it is conducted by observing the structure of the surface. This data then needs to be transferred to hub height, through models and calculations.83

From a scatterometer data are recorded twice a day with a resolution of 25 km. These kinds of wind maps have been recorded for most places of the globe since 1999, but because of the low resolution, observations closer than about 40 km offshore are not available. Regretfully
this is where the biggest potential for offshore wind farms is. These measurements are labelled QuikScat.83

Another technique that can be used is SAR (Synthetic Aperture Radar), which can cover the sea closer to the coast. However, less SAR data are available, which limits the accuracy. 83

The accuracy for satellite wind measurement is usually limited to a standard deviation of 1.1 m/s, but when very good data are available it could be as low as 0.6 m/s. Taking this into consideration and the fact that offshore wind establishments are rather large-scale, the use of satellite measurements are limited to pre-feasibility studies. 83

2.3.9 Summary

The different technologies have different strengths and weaknesses, and also different applications. For instance, is it not possible to exchange in situ measurements with satellite in terms of reliable data, but for pre-studies, satellites have time and cost as advantages. Propeller anemometers will be used for special studies of turbulence, but have been available long enough to show they will not substitute cup anemometers. Sonic anemometers might develop past anemometers, but for now they are a bit too unreliable due to the flow impact from the supporting structure. Cup anemometers with wind vanes on met masts will probably be the most common method in the near future, but sodar and lidar systems are getting a larger and larger share of the market. According to some testing the lidar can show a slightly higher accuracy than its competitive remote-sensing technique, but it also has a price nearly three times as high.

Both sodar and lidar systems have the same increasing measurement volume with increasing altitude compared to the met mast, but on the other hand, they have a vertical range far surpassing a regular met mast. A possible considerable source of error is both systems’ vertical resolution of more than 12 m, which could be significant if the wind shear profile is very pronounced. Table 4 summarises the applications, strengths, weaknesses and costs for the different solutions.
<table>
<thead>
<tr>
<th>Application</th>
<th>Strengths</th>
<th>Weaknesses</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cup anemometer (on mast)</td>
<td>Wind speed</td>
<td>Reliable</td>
<td>Vertical wind, over-speeding, cold climate</td>
</tr>
<tr>
<td>Propeller anemometer (on mast)</td>
<td>Turbulence</td>
<td>Responsive</td>
<td>Functionality in extreme turbulence</td>
</tr>
<tr>
<td>Sonic anemometer (on mast)</td>
<td>Primarily turbulence</td>
<td>Extremely responsive</td>
<td>Expensive, structural impact on wind</td>
</tr>
<tr>
<td>Sodar (AQ500)</td>
<td>Wind profiling for site assessment</td>
<td>Portable, does not disturb the wind</td>
<td>New technology, turbulence and gust winds</td>
</tr>
<tr>
<td>Lidar</td>
<td>Wind profiling for site assessment</td>
<td>Highly portable, does not disturb the wind</td>
<td>New technology, turbulence and gust winds, expensive</td>
</tr>
<tr>
<td>Satellite</td>
<td>Offshore, pre-study</td>
<td>Inexpensive and quick</td>
<td>Lack of data, accuracy</td>
</tr>
</tbody>
</table>

Table 4 – Application, strengths, weaknesses and approximate cost of different measurement technologies

### 2.4 Supplementary equipment for remote sensing technology

For sodar and lidar units some supporting equipment is needed, for which special consideration needs to be addressed. This is for instance protecting against theft and supplying the units with the needed power. These aspects are addressed in this section.

#### 2.4.1 Theft protection

One of the disadvantages with easily-movable equipment like sodar and lidar, is that it is just as easy to move it for thieves. To protect the equipment from this, there are some alternative solutions. Camera surveillance is one option, but that would be expensive because of the need for someone monitoring the different sites. Another option would be to secure the equipment to the ground or build a fence, but that, if done properly, would be costly and time-consuming and also reduce the equipment’s advantage of being portable. It could be hard to secure it enough with these measures.
Nevertheless, Nicolas Deve at Leosphere, supplier of Windcube, indicates that clients use anchoring and fences. Hiding it well through digging a hole in the ground or building some sort of shelter could also protect the equipment.81

A more plausible solution could instead be a tracking system, which would send an alarm if the equipment is moved. There are several products for this purpose developed for cars and boats that could be used for the remote sensing equipment as well. Some work with GPS technology, while others work with GSM and VHF tracking systems. The GPS system instantly gives you the position of the object within a distance of a few metres, while the GSM only produces the nearest mast and the search then needs to be continued with a VHF tracker from the mast area. GSM-systems have the downside that they generally do not work outside Swedish borders.

A study of different alternatives on the market is presented in Table 5.
Contacts with retailers also revealed that there is a need to use specially-licensed installation companies for most of the products in Table 5, which would add some more costs and demands. However Guard Systems does not require special installation, and AQ System have already equipped the remote sensing units of EON with both FleetGuard and TrackGuard. Given this useful information as well as its reasonable price and an apparent user-friendliness, the investigation concluded that FleetGuard was a good solution.

Table 5 – Summary of alternative theft protection, including features and costs

<table>
<thead>
<tr>
<th>Product</th>
<th>Source</th>
<th>Features</th>
<th>Initial cost</th>
<th>Annual cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRACKme</td>
<td><a href="http://www.trackme.se/">www.trackme.se/</a></td>
<td>- GSM/VHF&lt;br&gt;- SMS if removal from defined masts or if power cut or manipulated&lt;br&gt;- Very small&lt;br&gt;- Battery for 6 months&lt;br&gt;- GPS for TrackMe Duo&lt;br&gt;- Internet service&lt;br&gt;- GSM and VHF&lt;br&gt;- Tracing included in all of Scandinavia</td>
<td>About 4000 SEK (possibly +828 SEK)</td>
<td></td>
</tr>
<tr>
<td>Track-Guard</td>
<td><a href="http://www.guardsystems.se">www.guardsystems.se</a></td>
<td>- GPS&lt;br&gt;- Online map feature&lt;br&gt;- SMS for removal from defined zone or if unplugged&lt;br&gt;- Runs on 9-34 voltage (power needed)&lt;br&gt;- Service 24 / 7</td>
<td>1920 SEK</td>
<td>2396 SEK</td>
</tr>
<tr>
<td>FleetGuard</td>
<td><a href="http://www.guardsystems.se">www.guardsystems.se</a></td>
<td>- GPS and GSM&lt;br&gt;- Motion detector&lt;br&gt;- Battery up to 3 years&lt;br&gt;- Small</td>
<td>3944 SEK</td>
<td>1880 SEK (1750 after negotiation)</td>
</tr>
<tr>
<td>TrimTrac</td>
<td><a href="http://www.navkin.com/TrimTrac.htm">www.navkin.com/TrimTrac.htm</a></td>
<td>- GPS with GSM&lt;br&gt;- Motion sensor&lt;br&gt;- Battery (up to 6 months)&lt;br&gt;- Adapter for OM3e&lt;br&gt;- SMS for removal from defined zone and for low voltage</td>
<td>3995 SEK</td>
<td>1188 SEK</td>
</tr>
<tr>
<td>FlexView SRT299</td>
<td><a href="http://www.flexview.com/">www.flexview.com/</a></td>
<td>- GPS&lt;br&gt;- Battery (up to 6 months)&lt;br&gt;- Adapter for OM3e&lt;br&gt;- GPS&lt;br&gt;- Alarm for removal from defined zone and for low voltage&lt;br&gt;- No subscription cost&lt;br&gt;- No GSM card or internet overview&lt;br&gt;- Water proof</td>
<td>3100 SEK (3600 SEK)</td>
<td>2000 SEK</td>
</tr>
<tr>
<td>InCase OM3(e)</td>
<td><a href="http://tracking.televilt.s">http://tracking.televilt.s</a> e/produkt.e.php</td>
<td>- GPS</td>
<td>3100 SEK</td>
<td>2000 SEK</td>
</tr>
<tr>
<td>Red Knows minitracker</td>
<td><a href="http://www.redknows.com/index.cfm?ID=64&amp;vs=49&amp;vss=64">www.redknows.com/index.cfm?ID=64&amp;vs=49&amp;vss=64</a></td>
<td>- Alarm for removal from defined zone and for low voltage&lt;br&gt;- No subscription cost&lt;br&gt;- No GSM card or internet overview&lt;br&gt;- Water proof</td>
<td>5395 SEK</td>
<td>-</td>
</tr>
</tbody>
</table>
Contact with Magnus Nilsson at Guard Systems, confirmed this possibility and an initial deal for one FleetGuard unit was sealed. The price was negotiated to 3550 for the initial investment and 1800 for the annual cost. Nilsson also recommended that Vattenfall consider investing in the TrackGuard unit further on, as EON has, but the doubling of the cost with little added security speaks against it. Another option would be to hide the FleetGuard well in the remote sensing unit and/or wait for a new version of FleetGuard that is battery-powered, and thus could more easily be well hidden.

Red Knows minitracker could also be a good solution, especially because of its annual cost. However, the unit has some disadvantages compared to the Fleetguard. It is controlled by SMS and has no Internet portal where one can see the different units and easily make the desired adjustments. One would lack a good overview if one had several units and it is also only possible to send SMS to three numbers. 84

Contacting the company behind Red Knows revealed that there is no actual cost associated with the GPS communication, which can be useful information to consider before signing any additional agreement with Fleetguard. 84

In connection with the relocation of the sodar from Site A, a FleetGuard was installed in the trailer. This was connected to the batteries and initial operation has shown no problems.

2.4.2 Power supply

The current power supply of the AQ500 is a diesel generator combined with a battery pack. To be able to reduce the amount of maintenance, especially for refilling the diesel tank, use a more environmentally-friendly power supply and possibly reduce costs, an alternative energy solution could be used. There are essentially two renewable energy providers that could be interesting to study: photovoltaic cells and micro wind turbines. Since Vattenfall is conducting much of their prospecting in forests and since a micro wind turbine would then need a relatively high mast, this option is excluded.

The remaining alternative is PV cells that could be attached to the side of the sodar trailer. Discussing the possibilities with AQ System with regards to size and available PV cells on the market, the largest area that could be used was 1.4 x 3 m². The PV cells with the largest yield for this limited area were three 160 W cells. The cost of these together with a power regulator was about 22000 SEK. Calculations show that this would cover the power demand from at least the beginning of March to the middle of October, when using standard inclination.

The recommended (standard) inclination of the PV cells to maximise the power for the whole year should be equal to the latitude. However, since there is a big surplus in the summer, then the inclination should be set to maximise the production during the period from March to October. For average latitudes of 55-60° the best inclination would then be about 70°.

Without PV cells the trailer consumes about two litres of diesel per day and the standard tank needs to be refilled once a month. With the PV cells about 80% of the annual diesel consumption could be saved, and this corresponds to about 8000 SEK based on the present
price of diesel. The payback time, based only on the diesel savings is thus less than three years.

2.5 Methods for wind potential mapping

The first action a company interested in constructing wind turbines needs to take is to limit their scope to one or a few certain geographical areas. This pre-study is performed with a method with low resolution, which provides estimates of the wind resources at different sites. This section presents the most common methods.

2.5.1 MIUU model

The MIUU (Meteorological Institute of Uppsala University) model, developed by Hans Bergström, has been used to calculate the wind potential down to a 1 km horizontal resolution (2007 version). This meso-scale model uses the data of the geostrophic wind (strength and direction), sea and land temperatures, topography, roughness and land use to produce the annual average wind at 49, 72 and 103 m above the zero-plane displacement for all of Sweden. A comparison between the results of the model and actual measurements shows good agreement in general, but where there are severe small-scale topography variations that the resolution does not satisfactorily cover, the wind speed tends to be overestimated by the model. Comparing the annual mean wind speed at different sites shows that 46% of the model data are within ± 3%, 77% is within ± 6% and 94% is within ± 9% of the measured data. However, the verifications have mostly been performed in coastal and mountainous areas, not in forest land.

Figure 10 shows the results for 103 m above the zero-plane displacement. Besides offshore locations the wind is generally better in southern Sweden, with the exception of some places in the mountains in the north.
The MIUU model has been verified with measurement data for one forest location, Emmaboda in Småland, which indicated that the model is valid for forest sites and that the wind potential in forests is higher than previously expected. There are, however, also concerns that it overestimates the wind potential in forests. Furthermore, since the model produces the wind potential x meters above the zero-plane, which for some forests is more than 20 m above the ground level, there is a hidden “cost” of extending the hub height to achieve the stated potential.

MIUU models with higher resolution, i.e. 500 m, 250 m or 100 m, could also be supplied.

### 2.5.2 NCAR/NCEP reanalysis project

The two American institutes, the National Center for Environmental Prediction and the National Center for Atmospheric Research, jointly conduct the NCEP/NCAR reanalysis project. It is essentially a macro-scale, global model that uses historical data, hence reanalysis, to produce atmospheric data. The model uses data from weather balloons (rawinsondes and pibals), land surface, ships, aircrafts, satellites, etc. from 1948 until today. The model includes all major physical processes relevant for climate studies. The model adapts a Gaussian grid of 194x94 nodes, which it transforms into a regular 2.5° longitude x 2.5° latitude grid that corresponds to a distance between nodes of about 210 km. The vertical resolution is defined
by 17 pressure levels (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10 mbar), but some variables are calculated for fewer levels. Pressure levels are used instead of levels defined by altitude, since this gives a better representation of the low-level wind affected by the topography and the levels are closest spaced near the surface. The temporal resolution is four times per day (00:00, 06:00, 12:00, 18:00) and the produced values are instantaneous, not averages.87

NCAR/NCEP supplies the geostrophic wind, which is shown in Figure 11, as well as wind speed and direction at lower altitudes. Three alternative near-surface wind fields are available: the 1000 mbar wind field, the lowest sigma level (0.995) and the 10-meter data.88 The data are publicly available at www.cdc.noaa.gov in a number of different types of output archives to satisfy different needs.87

![Figure 11 – Geostrophic wind (m/s) through NCAR/NCEP](image)

2.5.3 Wind potential through energy production

An additional source for wind potential assessment is based on the statistics for energy production by wind turbines presently and previously in operation. This information is publicly available in Sweden as well as in Denmark, at www.vindenergi.org/driftuppfolj.htm and www.vindstat.dk, and since it contains actual production data it can be a useful source for mapping areas with good wind potential. However, for Sweden the number of turbines is still quite few and not well-distributed spatially across the country. There are also some problems with the reporting of downtime, due to mechanical problems or maintenance, and for extreme winds, when the turbines are shut down. Different power curves and site-specific information are not addressed by this methodology either.95

Until now, this statistic has chiefly been used for normal year correction, but at Vattenfall Jan-Åke Dahlberg is leading a project to develop the wind potential through this data source.17
2.5.4 Other wind potential assessment models

There is also a number of other software that could be used to assess wind potential. To complement the MIUU-model Hans Bergström has, together with Stefan Söderberg, developed the COAMPS model to operate in similar fashion as the MIUU model, but by not simplifying the conditions to assume hydrostatic air masses.\textsuperscript{105}

Another possibility for wind assessment on a larger scale is the software from Storm weather centre, which is based on a forecasting model, but could be used to produce the wind conditions for a large geographical area based on present and past data as well.\textsuperscript{89}

For small-scale assessment, micrositing, the previously mentioned WAsP included in WindPRO, is being used by a large part of the industry. However, the use of computational fluid dynamics is also being developed, where Windsim is one of several examples.

2.5.5 SMHI and other mast measurements

SMHI has a number of meteorological stations all over Sweden from which data can be bought. There are about 145 active stations and another 23 series of data from stations no longer in operation. Most of these are only 10 m and thus provide far from the reliable wind data at hub heights, which are desired to minimise uncertainties.\textsuperscript{90} There are however a few exceptions with anemometers on top of lighthouses on the Swedish east coast (Svenska Högarna 24 m, Söderarm 18 m, Örskär 39 m, Brämön 16 m, Lungö 16 m and Järnäsklubb 16 m).\textsuperscript{91}

There are also higher mast measurements within the Swedish research program Vindforsk V-120, consisting of the 30 m high mast on Östergarnsholmen measuring offshore conditions, the 36 m mast in Suorva measuring wind conditions in the mountains, and foremost the 120 m high (previously 145 m) met mast on Näsudden, Gotland.\textsuperscript{92}

SMHI-data are not publicly available, but can be purchased at a reasonable price. The current pricing is 9700 SEK (+sales tax) for eight wind speed and direction values per day (three-hourly data) per ten years of data and station. These data can then be used together with data from other sources in WAsP software, to evaluate local wind potential.\textsuperscript{93} However, studies by Krieg (1999) concluded that for this to be valid, the two positions must either be very close, or if both the site in mind and the met mast are either close to the shore or far from the shore and inland. Under these conditions a comparison has shown that the difference between standing turbines and calculated production was between −5\% and +6\%.\textsuperscript{93}

SMHI also conducted an early wind atlas of Sweden in 1992 where the country’s area was divided in A, B, C or D class according to the wind potential.\textsuperscript{94}
2.6 Normal year correction

As mentioned in section 2.2 the wind varies significantly from year to year. The wind measurements conducted one year do not directly produce the wind potential prognosis for the coming 20-25 years, which is the lifetime of a turbine. For this reason the data obtained must be normal year corrected, which can be done with wind indices. The available indices (related to Swedish conditions) are Swedish production indices, Danish production indices and the geostrophic wind indices. The longer the data for a specific site has been collected, the less uncertain the prognosis becomes, but it is also possible to normal year correct shorter measurement series of a couple of months.  

The general procedure when using indices is first to decide about which statistical data will be used for generating the index, either turbine production data or meteorological data. Then the length of the period generating the mean value should be decided, where as long a period as possible is usually desired, but limited by the availability and quality of the data. Then the index (I) can be calculated according to Formula 14:

\[ I = \frac{U_{\text{per}}}{U_{\text{ref}}} \]

(14)

where \( U_{\text{per}} \) is the statistical data for the period of the wind index (e.g. a month or a year) and \( U_{\text{ref}} \) is the mean value for the reference period for the same data source (e.g. 5, 12 or 20 years). The frequency of publication by production statistics is on a monthly basis and for comparison this is used for the other indices as well. The data source could, for instance, be the energy production of all Swedish wind turbines or a physical parameter, such as mean wind speed. These different bases for the index need different considerations when applied. For instance, if the fundamental parameter is wind speed, as in the NCAR/NCEP geostrophic wind index, the average wind speed needs to be adapted to wind energy production, possibly by using the square or the cube of the wind speed when calculating the index. The index is then used with the specific site data that has been measured (\( U_{\text{m}} \)) to get the normal year corrected value (\( U_{\text{ncy}} \), as shown in Formula 15.

\[ U_{\text{ncy}} = \frac{U_{\text{m}}}{I} \]

(15)

2.6.1 Official Swedish production index

The Swedish Wind Index can be collected from www.vindenergi.org/driftuppfolj.htm and it is presently based on more than 770 of the over 850 Swedish wind turbines. The wind turbines included in the index are shown in Figure 12. The system has been running since 1988, but from 2002 the more reliable automatic system started. Vattenfall Power Consultancy is responsible for the system, but the data are publicly available. Both monthly and yearly indices are presented.

In contrast to the desired form of wind index, the Swedish publicly available index is not available for each month compared to all the previous months. Instead the current month is compared to the average of the same months of earlier years (e.g. January 2008 is compared
to all previous January months). It is also available for the year so far compared the same period earlier years, and the latest 12 months compared to the same period for previous years. To use this index correctly the results would also have to be corrected for the average seasonal variations of the year.99

The index is normalised with regards to the installed capacity, and the downtime for the turbines is also filtered from the results.98 However, due to the fact that the wind turbine owners report downtime manually, the documented downtime is significantly less than the actual downtime. This means that the normal year correction based on the Swedish production index underestimates the available wind resource when not taking the total downtime into consideration.95 The reported wind turbines have an availability of 98.7%, but when downtime is reported automatically the availability only reached 94.7%.98

The basic methodology does not make any distinction among wind turbines at different sites, sizes, heights or power curves.98 Although power curves are to some extent standardised, there are differences among different sizes and turbine producers. The index also does not consider the reduction due to the wake effect for wind turbines in wind farms.95

The Swedish production index cannot provide a good statistical coverage for the last twenty years, which would be desirable when estimating future wind potential.17 For instance, there were only 14 small wind turbines when the project started in 1989. In 1996 there were 90 turbines, in 1998 almost 200, and since 2000 there have been more than 300 turbines.

Figure 12 – Location of the turbines included in the Swedish production index statistics
connected to the project, providing a better statistical dataset. The index presented by Vindforsk is, for the latest years, based on the mean production for the last twelve years. This is shown together with the Danish index in Figure 13.\textsuperscript{98}

![Figure 13 – Danish and Swedish official production indices for the last 10 years](image)

For the counties with a fairly high number of turbines, annual regional wind indices are also calculated. These regional indices are available for Gotland, Halland, Skåne and Västra Götaland, all having more than 100 wind turbines and also Kalmar, having slightly more than 50 wind turbines. For this report the index of Kalmar could be interesting to look at, since Site A is located within Kalmar County. For the period from 2005 to 2007 the Kalmar index was 94\%, 88\%, and 110\%, indicating a very high conformity with the Swedish index. Considering the fact that a strong majority of the wind turbines in the statistics are located in the southern parts of Sweden this is quite reasonable.\textsuperscript{98} Since all production data from 2002 and onwards are publicly available, it is also possible to create individual regional wind indices, delimited to fit the user’s need in each situation.

Statistics are also published on a monthly basis, but only as a single index for the whole of Sweden. The reference period is based on the production for the same month for the previous twelve years, and it is thus inappropriate to use for normal year correction. Still, this is very likely performed sometimes, and it is for reasons included in the analysis section. The index is presented in Figure 14.\textsuperscript{98}

Research to improve the Swedish Wind Index is being conducted within the Vindforsk program V-114 Vindindex with Hans Bergström as coordinator, and the goal is to regionalise the index and base it on physical parameters, such as wind speed measurements, instead of operation statistics.\textsuperscript{100}

### 2.6.2 Personally-devised Swedish index

To be able to use the Swedish wind statistics to produce a more useful wind index, a personal wind index was devised, based on the unprocessed production statistics\textsuperscript{101}. Due to lack of time this is based on simple principles. First, for each month the total production by Swedish wind turbines are summarised. This is then divided by the maximum theoretical production by all turbines, which have been producing any amount of power for the specific month (thus sorting out turbines that have been out of operation for the entire month). This
is equivalent to an overall capacity factor for all the Swedish turbines. This monthly capacity factor is subsequently divided by the average capacity factor (23%) for the complete data coverage to produce the monthly index. The index is based on data from February 2002 to August 2008, i.e. 78 months. At the beginning of the period, there were 114 wind turbines in the statistics and at the end 731.

It is assumed that the biased introduced by downtime, etc., will even out due to the fairly high number of turbines. The results differ significantly from the official Swedish index, which can be seen on a monthly basis in Figure 14.

![Figure 14](image)

**Figure 14 – Swedish official and personally-devised production indices on monthly basis**

A regional index is also calculated according to the same principles. This index includes Kalmar county and a turbine in Mälajord somewhat inland from Kalmar. The included turbines are presented in Figure 15. For the first year about 15 turbines were included, for the second, about 30 turbines and for the last year, about 60 turbines.

It could also be interesting to use the single wind turbine in Mälajord as a source for a wind index, since it is located in the middle of the forest. Though, it has only been in operation since July 2004 and thus only offers a short-term reference period. Comparison with the Danish index does, however, show that the wind index for the period is fairly close to “normal”, with an average value of just below 100%. The results are presented in Figure 16.
Since these personally-devised wind indices are based on quite short-term data to be used for long-term correction, it would be wise to compare the period with the average wind index for a reference wind index. Best suited for this purpose is the Danish wind index. For the Swedish national and the regional Kalmar wind indices, the average Danish wind index for the same period was 94.6%, while for the Målajord index the average Danish wind index was 95.6%. Because of this normal year correction, any of these indices are likely to underestimate the wind potential at a site. This is also reflected in the mean value for each index for the measurement period, where the Swedish index is 113% while the Danish index is 100%. Based on this, using the Swedish index would give an underestimated normal year corrected result. A mean to correct for this problem could be to adjust the Swedish index value for each month by the Danish average and thus get slightly lower index values each month.
This is reasonable only under the assumption that the Danish index is representative for the other indices. The correlation with the Swedish index is 0.95, with the Kalmar index 0.90 and with the Målajord index 0.83, thus to some extent verifying this. In the analysis section of this report only the Swedish index is tested with this kind of adjustment, since the bias introduced is difficult to estimate.

2.6.3 Danish Wind Index

The principle of the Danish Wind Index is the same as for the Swedish index, based on the production of the present wind turbines. However, Denmark has a stronger tradition of wind energy, which presents reliable statistics from 1979. With about 2600 turbines in operation during several years, it provides better data and the opportunity for the eight regional indices.\textsuperscript{95} Still, before 2003 only a few hundred machines were included in the statistics, which lowers the overall reliability of long-term comparisons. The data are publicly available at www.vindstat.dk, and the years from 1979 is used as reference. Together with the wind speed the prevailing wind direction is also available. Despite its advantages over the Swedish index, the Danish index is further geographically offset for sites in Sweden, reducing its precision and applicability for Sweden slightly. The Danish annual index is presented in Figure 13. On a monthly variation the deviation to the Swedish index is larger, but both indices follow the same general trend.\textsuperscript{102}

Since Denmark has several regional wind indices easily available, it is possible to use one of these to normal year correct a series of measurement. The choice of which index that should be used could be decided by geographical proximity, terrain similarities or through statistical comparison. Checking the correlation coefficient between the measured data and the wind index can aid in this choice. Figure 17 presents the different regions. One must take into consideration that Bornholm is actually situated quite some distance to the east of Zeeland.\textsuperscript{102}

![Figure 17 – The different regions for regional wind indices in Denmark\textsuperscript{102}](image-url)
2.6.4 Geostrophic/NCAR Wind Index

Since the driving force for near-surface wind utilised by wind turbines is the geostrophic wind, it could be used to study the variability of the wind and to normal year correct wind energy production. NCAR/NCEP geostrophic wind data are available since 1948, although limiting the reference period to 30 years renders similar mean wind. Depending on how the wind index is going to be applied, it should be calculated in different ways. If the goal is to normal year correct the mean wind speed, which then could be applied for different power curves, Formulas 14 and 15 with U-values corresponding to the different mean wind speeds are used. Though, if the values for the energy production at a site for a specific turbine have already been produced and the goal is instead to normal year correct the energy production, a slightly different approach is needed. The power in the wind is proportional to the cube of the wind speed, but the energy production of a turbine is determined by its power curve and thus does not extract an equal percentage of the energy at all wind speeds. Using the square of the wind speed has shown much better results and is therefore recommended when an index directly related to the energy production is needed. However, the most accurate method is to use the normal year corrected wind speed data with the specific power curve for the turbine that is being considered for the site. 105

Instead of using the data for the geostrophic wind at high altitude directly, it is possible to use the data as input to a meso-scale model. Filtered through a meso-scale model the wind index produced can be more accurate. 103 The data used for creating the NCAR index used in this thesis are therefore filtered through a model that calculates the wind speed data at heights of 2 m and 10 m. The data are retrieved through WindPRO, which downloads the data from http://www.cdc.noaa.gov. However, the resolution is low, and the effect of the surface is simplified, and surface roughness is only roughly estimated in the nodes. 105 The wind speed at the lower level is calculated from the NCAR model levels of 850 hPa (corresponding to roughly 1 km) and upward. 108

Since the NCAR data are produced in a 2.5º x 2.5º longitudinal and latitudinal grid and through WindPRO produced for two different altitudes, the choice of data series used as a reference is not self-evident. Using the closest node to the location of interest is a good start; however, due to the roughness of the model this node does not necessarily represent the local wind conditions at the site. Instead it is wise to check the correlation between the measured data and the NCAR data for a number of nearby nodes. 104

Due to the nature of the index, each node produces its own local index, but nearby nodes will generally produce quite similar wind indices.

Using the location of Site A, which is situated at 57.3ºN 16.0ºE, the node at 57.5ºN 15.0ºE is closest. However, it is also interesting to check the correlation between the measured data and the three other nearby nodes (55.0ºN 15.0ºE, 55.0ºN 17.5ºE, 57.5ºN 17.5ºE). To better represent the geostrophic wind conditions, the average of four adjacent nodes could also be used. 105 The coefficient of correlation is generally the same, indifferent of the height of the measurement, but varies significantly for different nodes.

Evaluating each node against the measured data could be performed either by using the ten-minute average corresponding to the NCAR data (since the NCAR data are momentaneous)
or by averaging the measured data for 0-6 h or ±3 h for each NCAR data. The use of the different approach did, however, have little effect on the actual results. Similarly, the use of the shorter sodar data for higher measurement heights or the use of the eleven-month mast data did not affect the results significantly.

The closest node does show the highest degree of conformity with the measured data, surpassing the correlation with the four-node average only slightly. The surface data have consistently higher coefficients of correlation. Table 6 presents the coefficient of performance with the date at 57.5ºN 15.0ºE, based on the ±3 h average approach and 97 m measurements.

<table>
<thead>
<tr>
<th></th>
<th>6 - hour data</th>
<th>Daily averages</th>
<th>Monthly averages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement vs. surface data</td>
<td>0.76</td>
<td>0.87</td>
<td>0.94</td>
</tr>
<tr>
<td>Measurement vs. u10 data</td>
<td>0.64</td>
<td>0.82</td>
<td>0.93</td>
</tr>
</tbody>
</table>

**Table 6 – Coefficient of correlation between NCAR data and measurements**

Based on this acceptable correlation the monthly wind index for the NCAR data are calculated. This is calculated with the last 30 years as the reference period. Based on the whole eleven-month measurement period, the wind speed indices are 106.4% for surface and 101.9% for u10 data. The month-by-month index is available in Appendix 1, while a comparative presentation is presented in Figure 18.

From the NCAR data it is also possible to calculate an equivalent production index based on the wind speed to the power of two as mentioned earlier. This is presented in Appendix 1 and Figure 18.

![Figure 18 – NCAR production index on monthly basis for the last year](image)

### 2.6.5 SMHI data indices

Yet another source for index calculation is data acquired from one of the number of SMHI met stations. The advantage is that these data are actual wind conditions, but there are a
number of disadvantages associated with this data. The masts are generally only 10 m high, which especially for forest regions may not be representative of the wind conditions at 100 m and above. As an example, the correlation between the wind measurements at Site A by the sodar between 20 m and 150 m is only 0.67. There might also be a problem with the standard of the instruments equipped to the masts that leads to an unfavourable choice between either greater measurement uncertainties or greater distances between the station and the site. The price for the data from one station is about 10 000 SEK for each year.\(^{106}\)

Particularly for the latter reason, no index based on SMHI data was part of the analysis.

### 2.6.6 Comparison of the different indices

Studies conclude that the Danish wind index correlates well with the geostrophic wind index, and both correlate quite well with a wind index based on measurements at the high mast at Näsudden on Gotland. The Swedish official wind index on the other hand does not show the same conformity. However, both the wind on Näsudden and in Denmark are far less affected by the surroundings, such as forests and topography, than what is the case for the wind index based on the Swedish turbines.\(^{95}\) According to Bergström the Danish wind index is best in the southern parts of Sweden, and the geostrophic wind index tends to overestimate periods of large deviations of wind speed.\(^{107}\)

A general improvement of each index is to calculate each index on a monthly basis, which especially improves the normal year correction of measurement periods shorter than one year. The Danish and Swedish indices can be regionalised to the desired extent and possibly also be limited to wind turbines at similar size and hub height, i.e. for forest locations where the wind shear is significant. The risk with a high degree of classification is that the amount of data in each class becomes so low that the index is no longer statistically representative. Suggestions have also been proposed to adapt the wind indices with regards to the wind direction, but with no breakthrough yet.\(^{108}\)

To compare all the different indices from October 2007 to August 2008, the coefficients of correlation between the indices are calculated. The correlation is generally very high at 0.97 and above, with the Swedish official index as the only exception, having a coefficient of correlation of about 0.85 with all other indices.

Furthermore it would be interesting to study the average index value and the standard deviation based on a monthly basis for the different indices during the period. This, together with the deviation of the production based on the actual measurements, is presented in Table 7. All monthly index values are presented in Appendix 1.
## Average Index value and Standard deviation

<table>
<thead>
<tr>
<th>Location</th>
<th>Average Index value</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jutland</td>
<td>98%</td>
<td>52%</td>
</tr>
<tr>
<td>Danish index</td>
<td>100%</td>
<td>49%</td>
</tr>
<tr>
<td>NCAR u10 (wind)</td>
<td>101%</td>
<td>28%</td>
</tr>
<tr>
<td>NCAR u10 (production)</td>
<td>105%</td>
<td>54%</td>
</tr>
<tr>
<td>NCAR surf (wind)</td>
<td>106%</td>
<td>28%</td>
</tr>
<tr>
<td>Målajord</td>
<td>108%</td>
<td>48%</td>
</tr>
<tr>
<td>NCAR surface (production)</td>
<td>112%</td>
<td>53%</td>
</tr>
<tr>
<td>Swedish personal (unadjusted)</td>
<td>113%</td>
<td>51%</td>
</tr>
<tr>
<td>Swedish personal</td>
<td>119%</td>
<td>54%</td>
</tr>
<tr>
<td>Swedish official</td>
<td>120%</td>
<td>34%</td>
</tr>
<tr>
<td>Kalmar</td>
<td>124%</td>
<td>50%</td>
</tr>
</tbody>
</table>

Table 7 – Average index value and standard deviations for different indices, based on the period from October 2007 to August 2008

Studying these results one can easily see the pattern that the Danish indices are indicating an average wind climate period, followed by the NCAR indices indicating a period with moderately higher wind speed, while the Swedish indices suggest a period of significantly higher wind speeds. The standard deviations of the indices are about 50% for all production indices, except the Swedish official index due to already explained reasons. The NCAR wind indices both have an understandably lower standard deviation of 28%.

Even if the correlation between two indices is very strong, the average index values differ significantly, which means that the results of normal year correction are highly dependent on the choice of index.

### 2.6.7 Use of a regression model to normal year correct

Another method that could be used for normal year correction is based on regression. It is based on the hypothesis that the wind at a site does not necessarily vary to the same extent as the wind included in an index. This could, for instance, be reflected in the shape factor for the Weibull distribution, which for Site A was extremely high (about 3, instead of the normally assumed 2).

It is possible to adapt the index to fit the measured data better by for example two approaches presented here. The simplest index \( I_a \) is constructed by multiplying the index deviation from 100% for each month \( I \) by a factor \( a \) as shown in Formula 16.
\[ I_a = (I - 100\%) \cdot a + 100\% \] (16)

By this method a value of \( a \) of above 1 would adapt the index for a site with higher variation than the index and a value below 1 would adapt it for sites with less variation. An extended version of Formula 16 would be to include a super positional adjustment by adding an extra term \( b \) in the expression. It could also be possible to use a formula with the square of the index deviation.

### 2.7 Wind data uncertainties and convergence

To be able to analyse and establish a reasonable strategy, it is essential to be aware of the uncertainties in the measurements and in the production predictions. This is presented in this section.

A crucial question for wind power projects and site assessment is how long the measurement series should be and what uncertainties the data have. Högström\(^95\) has conducted a study of the statistical dispersion of historical data for Näsudden, by comparing both uncorrected and normal year corrected measurements with the geostrophic wind speed index. The long-term average (at 54 m) was 7.08 m/s, and in Figure 19 the standard deviations of the wind speed in absolute and relative numbers are shown for the two data series.\(^95\) In Figure 20 the statistical dispersion for the wind energy is derived through the cube of wind speed dispersion. Figure 21 shows the statistical dispersion for the power production based on the square of the wind speed as mentioned in section 2.6.4. Figure 21 also includes worst-case data from an EMD study as a reference.\(^109\) One must keep in mind that the standard deviation and the worst case of twenty samples are not equivalent, but both indicate the uncertainty of the measurement.

![Figure 19](image-url)  
*Figure 19 – Statistical dispersion of the wind speed vs. duration of the measurements*
Figure 20 – Statistical dispersion of the wind energy vs. duration of the measurements

Figure 21 – Statistical dispersion of estimated production vs. duration of measurements

Studying Figure 21 is most interesting, since it shows the uncertainty in power production, which of course is the whole purpose of wind turbines. First of all it is clear that performing the normal year correction on any set of data reduces the uncertainty by roughly 50%, which is a very good start. Furthermore, the uncertainty decreases strongly from about 30% after one month to about 13% after six months. An additional six months will only decrease the uncertainties to 9.5% and after a total of six years the uncertainties will be just 3%. For the EMD numbers the uncertainties after one year of measurement are clearly higher, at about 15% for the normal year corrected value, but then drop more quickly with additional years of measurements and reach 5% uncertainty after three years.

This is all based on best practice, with regard to the selection of the wind measurement equipment, its calibration, mounting and position on the site. The final production uncertainty is also dependent on the micrositing – the siting of the turbine in relation to the wind measurement position and to the wake effect of multiple turbines. Other significant uncertainties are the power curve and turbine availability. The total uncertainty for a
project could generally not reach below 5% (in terms of standard deviation of the production), not even when best practice is applied. 111

Noteworthy is that uncertainties in wind shear and turbulence are very low after less than one year of measurements. 111 Assessing these parameters on much shorter data demands greater knowledge and experience and a more thorough analysis. To make a proper analysis it is important that the wind is both from the prevailing wind direction(s) and at the appropriate wind speed. 112
3 Analysis

The analysis covers the sodar performance evaluation, including sodar-mast and sodar-sodar comparisons, and the wind assessment for Site A, including an analysis of different wind indices and wind turbines. The intent is to make a comprehensive, easy-to-follow presentation, including both reasoning and discussion.

3.1 Comparison of sodar and cup anemometer measurements

This comparison of sodar and cup anemometer measurements is aimed at following up Lasse Johansson’s initial report, but through a different approach and methodology. The parameters being studied are wind speed, wind direction and turbulence, and the data coverage is the simultaneous measurement by sodar and by mast from 4 December 2007 to 29 June 2008.

Before the two series of data could be properly compared some data conditioning needed to be applied. When comparing the recorded time series for the anemometer and the sodar data, it was found that on 1 February 2008 one hour of sodar data was copied from the previous value for the time to concur with coordinated universal time (UTC). Assuming the anemometer data are recorded according to this, these values are deleted from the comparison and the data prior to this point in time relabelled with the universal time.

Furthermore, the sodar clock automatically changed to daylight saving time on 30 March 2008 at 2:00. Once again this is corrected to universal time, which does not take daylight saving time into consideration. A double set of data for 4 April 2008 is removed as well.

For the met mast data the only inconsistency found was a lack of data between 14:20 and 15:50 on 26 March 2008. This could be solved through setting these values as the mean values of the immediate prior and subsequent data or simply removing this period from the comparison analysis. The latter method is applied since it introduces less bias. To ensure that the two time series are in sync, the beginning and the end of the time series are checked, confirming the consistency.

Apart from these above-stated problems with the two sets of data, there are some other considerations to keep in mind. One is the under-speeding by the anemometer because of freezing due to inadequate heating of the anemometers, which can cause both frozen bearings and icing of the cups. Another problem is the over-speeding by the anemometer due to high turbulence. There are also the two different sodar positions at the site and unavailable sodar data to be taken into consideration, as well as directional dependence.

3.1.1 Mean wind speed and time series for conditioned data

The mean wind speeds at the site calculated for the hub heights of the two test turbines at 80 m and 100 m (extrapolated for mast data), as well as at the 97 m level are presented in Table 8.
### Table 8 – Mean wind speed for sodar and cup anemometer at 80 m, 97 m and 100 m

<table>
<thead>
<tr>
<th></th>
<th>At 80 m</th>
<th>At 97 m</th>
<th>At 100 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodar mean value (m/s)</td>
<td>5.30</td>
<td>5.79</td>
<td>5.87</td>
</tr>
<tr>
<td>Cup anemometer mean value (m/s)</td>
<td>5.39</td>
<td>5.90</td>
<td>5.98</td>
</tr>
</tbody>
</table>

Presented in relative figures these correspond to 1.64% at 80 m, 1.99% at 97 m and 1.95% at 100 m. Figure 22 and Figure 23 present the time series for wind speed and turbulence at 97 m.

**Figure 22** – Wind speed as a function of time for sodar and cup anemometer at 97 m

**Figure 23** – Turbulence as a function of time for sodar and cup anemometer at 97 m
The figures also include a sliding mean for the two time series, which is based on the last 24 h. While the scattering of sodar and cup anemometer for ten-minute-averages is significant, the differences based on daily mean values are quite low. To be able to perform a more detailed study of the relationship between sodar and mast data, another approach is taken and presented in section 3.1.2 and onwards.

### 3.1.2 Scatter plots with regression and correlation for conditioned data

Based on the conditioned data, scatter plots for wind speed, turbulence intensity and wind direction deviations are presented in Figure 24, Figure 25 and Figure 26, respectively. For the scatter plots the coefficient of correlations ($R^2$) and linear relationships based on the least square method is also included. The linear relationships are tested on both “$y=ax+b$” form and “$y=ax$” form, where $y$ corresponds to sodar data and $x$ to anemometer data. No filtering for under or over-speeding, the sodar position or high/low values of turbulence or wind speed have been done.

The measurements are evaluated at the same height when this is available. For the highest wind speed readings of the mast the measurements are however at different heights. For turbulence and wind speed, this is solved by interpolation of the sodar data from 95 m and 100 m, while the wind direction is compared directly to the 95 m sodar measurement. The introduced error due to this approach is assumed insignificant.

The amount of data compared in the figures below is 29931 ten-minute averages, corresponding to 208 days.
Figure 24 – Wind speed comparison between sodar and cup anemometer at 25-97 m
Figure 25 – Turbulence comparison between sodar and cup anemometer at 25-97 m
Studying Figure 24 and the results from the regression analysis, one sees the general trend shows good conformity between the two measurement methods. The coefficient of correlation is increasing with altitude and reaches 0.81 for 97 m. The linear regression only shows a slightly better correlation than the proportional regression, and thus only the simpler proportional relation is discussed further. The results indicate that the sodar measurements give wind measurements of 3.2% lower at 97 m and 3.6% lower at 80 m compared to the cup anemometer. This can be compared to the values presented in Table 9. The mean deviation, when sodar data are subtracted from anemometer data, is 0.12 m/s at 97 m and 0.088 m/s at 80 m. The standard deviation is, however, a lot higher and is close to 0.80 m/s. This can be compared with the specified sodar accuracy of ±0.1 m/s and the anemometer specification of ±3% (above 5 m/s).
For the turbulence data it is clear that the correlation is not that strong and that the sodar generates a significantly higher number of extreme turbulence data. The regression analysis also implies that the mean turbulence intensity generated by the sodar is higher than that of the cup anemometer. The turbulence intensity value is particularly high for the sodar data at low wind speeds and since Figure 25 is based on all wind speeds, this is contributing quite significantly. For further analysis, see sections 3.1.4 and 3.1.8.

Finally, the wind directions show a moderate correlation. The mean difference and the standard deviation of the difference are presented in Table 10. The sodar indicates, on average, a direction of 10⁰, -0.3⁰ and 5.8⁰ higher than those of the wind vanes. This problem with precision might be due to incorrect installation and configuration of the wind vanes, as implied by Lasse Johansson in his initial report. Even if the precision is quite good, the interrelated accuracy here measured by the standard deviation is still quite high, as presented in Table 10.

The following sections investigate the effect of different filtering. Generally the cause and effect of different filters are applied without any combination of filters, but this issue is addressed in section 3.1.11. Often only the 97 m data are presented to shorten the presentation, and these is also the most important data for wind potential assessment.

### 3.1.3 Effect of sodar positioning and fixed echoes

To test possible bias introduced by the measured data from the first sodar position closer to the forest, the analysis was performed without this data. The results showed essentially an unchanged outcome of the regression results and the coefficients of correlation for both the wind speed and the turbulence intensity at all measurement heights, though a slight deviation did occur for the wind speed regression results at 97 m from $y = 0.97x$ to $y = 0.96x$. The other statistical properties presented in Table 9 and Table 10 remained almost the same.

If instead the measurement data from just the first position are analysed, the results change more distinctly. For the first position the average wind speed measured by the sodar compared to the cup anemometer is about 0.20 m/s lower for 60 m, 80 m and 97 m, and the
regression analysis indicates that the sodar measures 6-7% lower wind speed. The relationships for the turbulence intensity have also changed, indicating that the sodar underestimates the turbulence with about 6% independent of height.

Since the first position only covers two weeks of measurement, and including the data does not alter the results significantly, these measurements are included in the following analysis. For each case, however, the effect of removing these data is checked, but not included in the results or discussion.

3.1.4 Effect above cut-in and below rated wind speed

The comparison in section 3.1.2 includes all parameters, but when performing a wind assessment the relevant information is first and foremost for wind speeds above the cut-in speed. Since this is between 3 m/s and 5 m/s, 4 m/s was set as the limit. Ten-minute averages when both the sodar and the cup anemometer data were below 4 m/s, were thus filtered out, leaving 27526 ten-minute averages.

This filtering had little effect on the regression results for the wind speed and only improved the mean wind speed deviation slightly, i.e. to 0.11 m/s at 97 m. The wind direction analysis remained the same with regards to the difference in wind direction, but lowered the mean standard deviation to about 13°. This is related to the instruments’ inherent properties, for instance, the threshold wind speed for the wind vane. For the turbulence measurements the results were further improved, which are presented in Figure 27. The regression relationship is closer to strict proportionality, and the coefficient of correlation is twice as good. Though, the coefficient is still only 0.31 and the spread is still large.

![Regression relationship for wind speed and turbulence intensity](image)

**Figure 27 – Turbulence comparison with data from below 3 m/s filtered out (at 97 m)**

The same approach can be applied to the wind speed measurement above the rated speed, which is usually about 12 m/s, since differences in this range do not affect the wind potential.
assessment either. Adding this filter leaves 24287 ten-minute averages. Once again the results from the wind speed regression analysis is not affected to any significant degree, but the mean wind speed deviation improved slightly down to 0.10 m/s.

For the wind direction and turbulence measurement this filter is not equally valid, since the variation in both turbulence and wind direction above the rated wind speed are still important.

### 3.1.5 Effect of wind direction dependence

When studying the effect of wind speed in different wind directions, the most interesting direction to study is N/NW, since the sodar measurements in this direction are in the wake of the mast. The lattice mast, with its equipment and supporting wires, might affect the leeward wind with increased turbulence and decreased wind speed. The other wind direction that might be suspected of producing biased values is when the cup anemometers are in the wake of the mast and the wind vanes located on the same level.

To investigate this, a study of the wind speed ratio between the sodar and the cup anemometer (at 97 m) covering each 10º interval is presented in Figure 28. The data collection is based on the wind vane at 97 m, but corrected for the 6º offset indicated by the sodar. On average each sector consists of 830 ten-minute averages, and the minimum number of averages is 337. The figure indicates a reasonable overall conformity, with a few exceptions. From 330º to 360º the wake effect of the mast is quite clear, but the sodar indicated wind speed is also reduced from 0º to 70º, although not equally much. This could be due to the surroundings where the mast is situated directly on the edge of the forest to the north, while the sodar are distanced about 150 m from the same forest edge. The mast booms are mounted in the alignment that the cup anemometers are in the wake of the wind vane and mast for wind direction of approximately 290-320º, and this might explain the increased speed in this range.

![Figure 28 – Mean wind speed ratio between the sodar and the cup anemometer at 97 m](image)
Based on this information, the data for the wind direction at 290° to 10° (284° to 6° indicated by the wind vane) are thus filtered out to remove the bias from the wake effect on each instrument. This filters out about 24% of the total data. The results for the mean wind speed deviation and the regression results remain the same – the two errors even out. However, the wind speed correlation is improved to 0.87. Two other effects that could be noticed in the figure are the apparent speedup by the cup anemometers for directions just outside the mast wake (260°-280° and 340°-360°) and the effect on the wind speed readings when the mast is directly downwind of the cup (120°), where a small wind speed decrease could be detected. Removing these sections from the analysis as well, however, removes too much data to be an option.

**3.1.6 Effect of under-speeding by anemometers**

Due to inadequate heating of the anemometers (except at 40 m), freezing caused severe under-speeding by the anemometer. This can be observed in Figure 24 as the scatter points close to the y-axis (sodar wind speed), for which the anemometer indicates almost 0 m/s. This can also be observed in Figure 22 and the more detailed Figure 29 that focuses on the period between 21 December and 28 December.

![Figure 29 – Wind speed for sodar and cup anemometer at 97 m from 21/12 to 28/12 - 07](image)

Figure 29 indicates that freezing not only causes total standstill, but also slow-down. This makes the analysis more difficult, since not only the wind speed readings of 0.24 m/s (corresponding to standstill due to anemometer calibration) should be disregarded. The number of wind speed readings of 0.24 m/s for the whole period is 259, which is almost 1% of the data. Removing the under-speed data can be done by a few different approaches. In Lasse Johansson’s initial report for Site A, all measurements at below 0°C discarded. While this removes all freeze data, it also removes many other data points as well. Based on the temperature at 97 m it removes 16% of all the data, and since wind speed and temperature correlates to a certain degree this would introduce a new bias instead. A more refined method is to use both the temperature data and a measure of deviation between the cup
anemometer data and a reference measurement. This reference could, for instance, be the sodar data or the anemometer at 40 m, for which no freezing seems to occur. Using the sodar data also introduces a bias since data that deviates significantly would be discarded and hence possibly produce a higher degree of correlation than what is actually the case, while the comparison with the 40 m measurement has a high degree of uncertainty due to the obvious difference in measurement height.

Based on the standard deviation between the sodar and the cup anemometer data, at about 0.8 m/s, and the assumption that the deviation is normally distributed, one can choose a filter that does not exclude too much valid data. Setting the limit to twice the standard deviation would statistically exclude 2.4% of the “no-freeze” data, while using three times the standard deviation would statistically only exclude 0.1% of the valid data. Together with the condition that only temperatures below 0°C are at risk, about 2% of the “no-freeze” data would be excluded for twice the standard deviation and 0.09% when using three times. Applied to the actual data 794 data points (2.6% of total data) are filtered out for twice the standard deviation and 422 data points (1.4% of total data) for three times the standard deviation. Both produce similar results and both leave a few cup anemometer data points at standstill, thus the more strict filter based on three times the standard deviation is presented in Figure 30 (to the left). Evaluated at 97 m the results are a better correlation of 0.87, but an increasing mean wind speed deviation to 0.17 m/s.

The alternative filter method was to use the cup anemometer at 40 m, which did not seem to experience slow-down due to freezing. First, the wind speed data from 40 m are extrapolated to 97 m using the mean wind shear profile. Then the data points for which the extrapolated value is more than 2 m/s higher than the 97 m measurement are filtered out. This corresponds to 256 ten-minute averages (0.9% of total data) and the resulting graph is presented in Figure 30 (to the right). Using a smaller deviation filter of, for instance, 1.5 m/s produces the same results, but filters out about 700 ten-minute averages (2.3% of total data). For some reason the mean deviation between the sodar and the anemometer is decreased to 0.11 m/s for the 2 m/s filter, while the 1.5 m/s filter increases the mean wind speed difference to 0.16 m/s, which is the more reasonable effect of the filter. Due to this and the lower correlation between the sodar and the 97 m cup anemometer for this method, it is thus deemed less reliable than the sodar-based filter.
Figure 30 – Filtering for cup anemometer under-speeding due to freezing, at 97 m. To the left the sodar data are used and to the right the cup anemometer at 40 m is used.

3.1.7 Effect of over-speeding by anemometers

In contrast to the under-speeding as discussed above there might also be an over-speeding error (see section 2.3.5) due to the increased turbulence in forests. Therefore the effect of this is reduced from the actual cup anemometer data and the comparison at 97 m. The mean value for the wind speed is reduced by 0.06 m/s, which effectively reduces the mean difference between the sodar and the cup anemometer to 0.05 m/s. The correlation remains the same, while regression results change to $y = 0.955x$.

3.1.8 Turbulence study

The comparison of sodar and cup anemometer performance in measuring turbulence was in previous sections only compared on sodar turbulence intensity versus mast turbulence intensity. A more relevant investigation takes the wind speed at the measurement into consideration, corresponding to the IEC turbine classification that allows higher turbulence intensity at lower wind speeds than at higher wind speeds.

Figure 31 presents scatter plots for the unfiltered turbulence data as a function of the wind speed for both the sodar and the cup anemometer. Since the turbulence intensity was not affected to any significant extent by the different filters used, the unfiltered data should be fairly reliable. The two graphs are similar, but the sodar data are slightly more spread and higher, especially at lower wind speed.
Figure 31 – Scatter plots for sodar and cup anemometer turbulence. To the left the sodar data at 100 m are presented and to the right the cup anemometer data at 97 m are presented.

What is often requested and for which the IEC standard is classified, is the mean value for the turbulence as a function of the wind speed. This is presented in Figure 32 for an 80 m tower, a 97 m and a 100 m tower. Once again both measurement technologies follow the same pattern. Based on especially the cup anemometer data it seems that at 97 (100) m an A-class turbine is the only viable option. When studying the figure one must take into consideration that the data for higher wind speeds are scarce. Above 15 m/s neither measured more than 20 ten-minute averages for any 0.5 m/s interval and an interval with more than 100 averages does not appear until wind speeds of 12 m/s and lower. Based on the observed higher scattering of the sodar data, the data produced by the cup anemometer could therefore be considered most reliable for higher wind speeds. Based on this the site might not measure up even to the highest turbulence classification.

Figure 32 – Turbulence as a function of wind speed for cup anemometer (left) and sodar (right)
To better be able to compare the readings from the two sources, Figure 33 presents the difference at each wind speed. The figure only includes wind speeds for which there were at least 50 measurements from both technologies. This excludes measurements above 12 m/s at 80 m and measurements above 13 m/s at 97 m. If the limit instead would be set to 150 measurements the 12, 12.5 and 13 m/s wind speed data for 100/97 m would not be included either, and in that case the sodar data mean deviation compared to the cup anemometer would only be 0.35% for wind speeds above 5 m/s. At 80 m the difference is generally greater, which most likely is related to the higher overall turbulence at this lower level.

The great deviation at lower wind speeds, where the sodar measurements indicate a far greater value, could be due to the increased effect of friction for the cup anemometers at lower wind speed. The indicated higher deviation at wind speeds above 11-12 m/s has not been seen in other studies.\textsuperscript{113}

![Figure 33 – Turbulence intensity difference between sodar and cup anemometer as a function of wind speed, for 80 m and 100/97 m (sodar – cup anemometer)](image)

**3.1.9 Comparison of calculated production**

Despite the different methods presented and performed above, the purpose of collecting wind speed data is to calculate the production at the site. This production is calculated with the power curve for the two machines erected at the site, Nordex N90, and for their two hub heights of 80 m and 100 m. This then gives a more useful measure of the differences between the cup anemometer and sodar measurements. The mast data are here extrapolated the additional 3 m according to the mean wind shear profile, but this has little effect on the accuracy of the comparison. The unfiltered data are used for both sodar and cup anemometer.
The calculations based on the sodar data indicate a production of 5.7% lower at 80 m and 4.8% lower at 100 m. If these values would be corrected to normal year production, the difference would remain fairly constant.

### 3.1.10 Wind shear comparison and production for increased hub heights

For the comparison of the wind shear profile, the first step was to check if the mast data from the full period (October to August) gave similar results as the mast data when the sodar was simultaneously measuring (December to June). At all five anemometer levels the wind speed for the sodar period was 0.16-0.18 m/s higher for the simultaneous measurement period, thus verifying the conformity. For the remaining comparison the measurements from the sodar period are used.

The cup anemometer data are processed with a least square method based on all three relationships mentioned in section 2.2.1. The power law corresponds very well, with a wind shear coefficient of 0.40 and a displacement height of 10.0 m. The simple logarithmic law does not produce a good fit and suggests no displacement height and a surface roughness of 7.1 m. The modified logarithmic law corresponds equally well as the power law mathematically, but the suggested parameters are unrealistic. The surface roughness is 4.18 m, the gradient height is 767 m and the effective zero-plane displacement is 5.8 m.

To compare the curve fitting, the same least square method is applied on the sodar data only for the heights corresponding to the mast levels. However, none of the relations produce a realistic result with this approach. Using the logarithmic law it suggests no displacement height and a surface roughness of 6.5 m and using the modified logarithmic law results in a gradient height of 376 m. For the power law the least square solution is a displacement height of 1.3 m and an exponent of 0.47. Discussing the problem with Mats Hurtig at AQ System concludes that there might be a problem with the filtering of low-level data to correct for the effect of pronounced wind shear in combination with the 12 m height resolution. Hurtig refers to the fact that they have had little field-testing for this filter and that he would try to improve the filter accordingly. He would also recalculate the data recorded at Site A according to the modified filter, but due to time shortage the outcome of this is left outside this report. If all the sodar data, from 20 m to 150 m, are used for the least square method analysis, conditions are slightly different and the results for especially the power law are improved. The suggested zero-shift displacement is 6.3 m, and the shear coefficient is 0.42. Although it does not fully correspond to the theory and the observed tree height, the
displacement height is in the right magnitude, and the different displacement height might be related to the position of the sodar some distance away from the forest edge.

Figure 34 presents the wind shear profiles together with the power law fitted to the mast data (based on all wind speed data). The wind speed indicated by the sodar is consistently 0.08-0.12 m/s lower than the mast data, apart from the 25 m level where the mast data are 0.12 m/s lower. The extrapolation of the wind data for heights above the mast height seems to overestimate the wind speed, i.e. by 0.22 m/s at 150 m.

![Figure 34 - Wind shear profile by sodar, mast data and power law fitted to the mast data](image)

If the same analysis is limited to wind speeds above 4 m/s, similar results are obtained. The parameters for the power law fit for the cup anemometers are 0.45 for the wind shear coefficient and 7.8 for the displacement height. The difference at the mast levels of 40 m to 97 m is reduced slightly to 0.02-0.06 m/s lower wind speed for the sodar, while the sodar data for the 25 m level are 0.20 m higher. The overestimation of the extrapolated mast data at 150 m with this method is even greater at 0.29 m/s. However, a more comprehensive and interesting measure is the impact the extrapolation of mast data has on the production. This is presented for the Nordex N90 turbine in Table 12 below. Depending on which profile parameters that are used, the relative mast deviation at 150 m is either +2.4% for the recommended profile estimation or −1.7% for the parameters based on data for all wind speeds.
### Profile parameters

<table>
<thead>
<tr>
<th>Based on data above 4 m/s</th>
<th>Ratio</th>
<th>100 m</th>
<th>125 m</th>
<th>150 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mast/sodar relation</td>
<td>105.4%</td>
<td>106.3%</td>
<td>107.9%</td>
<td></td>
</tr>
<tr>
<td>Mast/sodar relation</td>
<td>100.0%</td>
<td>100.9%</td>
<td>102.4%</td>
<td></td>
</tr>
<tr>
<td>normalised to 100 m ratio</td>
<td>105.4%</td>
<td>106.3%</td>
<td>107.9%</td>
<td></td>
</tr>
<tr>
<td>Based on all data</td>
<td>Mast/sodar relation normalised to 100 m ratio</td>
<td>100.0%</td>
<td>98.6%</td>
<td>98.3%</td>
</tr>
</tbody>
</table>

**Table 12 – Production comparison for sodar and extrapolated mast data**

#### 3.1.11 Multi-filtering comparison

A number of different varieties of filters were used to find, assess and possibly reduce some of the sources for error. The wind direction dependence on the mean wind speed was quite high, but mast shading of the cup anemometers and sodar measurement volume seem to even out each other’s effect on for example the mean wind. However, removing the possibly shaded wind direction data improved the correlation to 0.87. The same effect of essentially even each other out could be observed by the under speeding due to freezing and over speeding due to high turbulence and similarly the correlation was improved to 0.87. The error introduced by the different sodar positions was fairly low.

Since many of the filters exclude a significant amount of data applying all filters exclude almost half of the data, leaving 16242 ten-minute averages. The results for 97 m is a 0.02 m/s higher mean wind speed indication by the cup anemometer, a correlation of 0.904 and a regression result of $y=0.99x$. However, the validity of these results is not perfect.

For further discussion see section 4.
3.2 Sodar positioning and fixed echoes

The sodar unit at Site A was first positioned closer to the forest, from 4 December to 18 December, but this position was, by AQ System, considered too close to the forest to produce the desired high quality data. At this first location some of the sound reflected on the nearby trees, disturbing the measurement’s signal-to-noise ratio, hence decreasing data quality and availability.\textsuperscript{114,115} Consequently it was moved to a new location, where fixed echoes were no longer a problem. The initial location was approximately 10-15 m from the edge of the forest, at a height of about 15 m. The unit was then moved another 30 m from the edge of the forest. The installation was also improved slightly with sound dampening above the opening of the trailer.\textsuperscript{4}

To be able to use the sodar in forest areas, it is crucial that reliable information about the positioning of the sodar is acquired. For this reason the measurements of the first and second locations at Site A are compared and analysed. The data availability and the data quality for the different positions are therefore compared. The first measurement was between 4 December 2007 00:00 and 18 December 2007 23:50 and consisted of 2160 ten-minute averages, while the second measurement was between 19 December 2007 00:00 and 29 June 2008 00:00 and consists of 27932 ten-minute averages.

The impact of different wind conditions is assumed relatively small in this comparison.

3.2.1 Data quality and availability

The overall availability for the first position was 97.9\%, and for the second position it, was 98.7\%. Expressed as the total unavailability this corresponds to 2.05\% and 1.31\%. A study of the availability as a function of the altitude of the measurement is presented in Figure 35. The largest relative difference is between 85 and 130 m. This indicates that the distance to the forest has a distinct impact on the data availability. The availability corresponding to the forest edge, i.e. less than 60 m (double the distance to the trees) is only affected to a slight degree. Instead the impact can be seen at double the distance to the trees, 50-60 m. This could be related to the fairly dense forest that could delay echo between the trees, according to Mats Hurtig at AQ System.

![Figure 35 – Data availability at the two positions at Site A, for different heights](image-url)
The data quality index is related to the signal-to-noise ratio and is calculated by the sodar software. For the first position the average data quality was 112.7, and for the second position it was 100.3. Figure 36 shows the data quality as a function of measurement height. It does not correspond well to the availability analysis or the hypothesis that the position nearest to the forest would reduce the accuracy of the measurement data. This could depend on, for instance, reduced turbulence closer to the edge of the forest, since eddies need some distance to grow\textsuperscript{20} or possibly the software’s calculation of the index. Discussing the phenomena with AQ System concludes that the power of the sound pulses was reduced to conserve energy for the new position, where no fixed echo was present and that is most likely the reason for the increased quality index.

![Figure 36 – Data quality index at the two positions at Site A, at different heights](image)

### 3.2.2 Biased values, un-filtered errors and availability

When the data quality of measurement is too low, AQ System’s software filters out these measurements. The database that Vattenfall uses solves the problem with gaps in the data file by replacing the filtered data with the closest previously available ten-minute average. This can cause some problems for extreme conditions when the data quality is considered too low for an extended period of time. It has been shown that the overall data availability is very high, but, for instance, when the wind speed is very high (closer to 30 m/s) the data availability might drop and cause problems, with severe inconsistency of wind speed indications at different heights. This has, however, only happened for five ten-minute averages during the full measurement period (7 December 2007 10:50, 11:00, 13:30 & 13:40, and 1 May 2008 03:40) and might thus not be considered a huge problem.

For this reason it is important to know in which conditions the data quality and availability drops. This is also important in order for the user of the sodar to know the limitations of the product. If it, for instance, would consistently fail to operate in extreme winds or extreme turbulence, this would reduce the features of the technology and demand more complementary measurements. Due to the changed pulse power and thus new conditions for especially the quality index (see section 3.2) for the new position at Site A, a comparison of the index would be most uncertain. What could produce somewhat better results would be
to simply compare the wind conditions when the sodar data are available compared to when they are unavailable.

Interesting parameters to study would be the indicated sodar wind speed, anemometer wind speed and turbulence given by both the sodar and the cup anemometers. The wind data related to the average conditions are compared in Table 13. Measurements are taken at 100 m and 150 m for the sodar, and for the anemometer the wind speed is extrapolated from the 97 m measurement, based on the average \( \alpha \)-value (power law fit) for the mast data. Anemometer turbulence data are only directly taken from the 97 m measurements. At 100 m 223 ten-minute averages were unavailable, corresponding to 0.75\%, while at 150 m 1729 10-minute averages were unavailable, corresponding to 5.8\%.

<table>
<thead>
<tr>
<th>Wind speed</th>
<th>Turbulence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Anemometer</td>
</tr>
<tr>
<td>Unavailable period / full period (100 m)</td>
<td>98.9%</td>
</tr>
<tr>
<td>Unavailable period / full period (150 m)</td>
<td>103.5%</td>
</tr>
</tbody>
</table>

Table 13 – General characteristics of the wind for unavailable sodar data

Based on the comparison for 100 m, the wind speed conditions during sodar unavailability do not differ significantly from the available reference, for neither sodar nor anemometer readings. The turbulence readings seem slightly increased based on the anemometer data, and the sodar readings could therefore be underestimating the turbulence to some degree.

For the 150 m comparison, the analysis has less accuracy due to the extrapolated anemometer data, but it still does not show any significant deviation from the reference period. The sodar wind speed data are lower, but not enough to call for any conclusions. For the turbulence data recorded by the anemometer, however, one decisive deviation can be observed, even though the sodar unit does not indicate the same value. This indicates that the sodar could have trouble measuring the wind during periods of very low turbulence. That the cup anemometer turbulence is measured at 97 m is not that crucial since it is a relative measure.

Based on these findings it can be said that the wind conditions during the unavailable sodar measurements are not, on average, extreme in nature, and thus the results produced by the sodar are not significantly altered due to the unavailable measurements.

There was also a temperature difference of about 1\(^\circ\)C lower on average for the unavailable data as well as a reduction of the difference in temperature among the three levels with thermometers (40 m, 60 m, 97 m) of about 30\%.

Considering the AQ500’s means of measurement based on small-scale temperature fluctuations, the results are understandable. With smaller temperature differences and less fluctuation/turbulence in the atmosphere, the amount of unavailable data is likely to
increase. This could also be seen in Figure 37 where the unavailable data at 150 m are presented as a function of the time of the day they occur. During nighttime, when the sun is not heating the surface and thus causing uneven temperatures and fluctuations, most of the unavailable data occur. This is connected to stable atmospheric conditions, which the sound is unable to break through sufficiently. Other sources of decreased data availability, such as high ground level wind speed or high background noise, are not issues at the site.

![Figure 37 - Unavailable data as a function of the hour of the day](image-url)
3.3 Wind potential and characteristics at Site A

The wind conditions at the site are assessed with regard to horizontal and vertical wind speed, turbulence, wind direction and wind shear profile. The mean wind speed and production are also compared to MIUU data and Rayleigh distributed wind. Generally eleven months of mast data are used (October 2007 to August 2008), but this is also complemented by sodar data for some studies.

3.3.1 Horizontal wind speed

The wind speed distribution for the mast data from October to August at 80 m and 97 m are presented in Figure 38. Least square fitted Weibull distribution curves are also included. At 80 m the shape parameter is 3.04 and the scale parameter 5.82, and at 97 m the shape parameter is 3.00 and the scale parameter 6.48. The coefficients of correlation between the Weibull fit and the measured data are 0.995 at 80 m and 0.993 at 97 m, thus the wind distribution correlates well with the Weibull distribution. On the other hand, assuming a Rayleigh distribution, where the shape parameter is 2.0 would not properly describe the wind climate at the site.

![Wind speed distribution at 80 m and 100 m at Site A](image)

To describe the wind climate at the site, the mean wind speed at three different heights based on mast measurements from October 2007 to August 2008 are presented in Table 14. As a reference and indication of the conditions at higher hub heights, the sodar measurements from December 2007 to June 2008 are also included. The mean difference between the shorter sodar data period and longer mast data period is about 0.07 m/s and thus the extrapolated mast wind speed at 125 m and 150 m can be approximated to 6.40 m/s respectively 6.86 m/s.
### Table 14 – Mean wind speed at different heights for Site A (sodar and mast data for seven respectively eleven months of measurements)

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>Mast measurements (m/s)</th>
<th>Sodar measurements (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 m</td>
<td>3.66</td>
<td>3.76</td>
</tr>
<tr>
<td>80 m</td>
<td>5.23</td>
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<tr>
<td>100/97 m</td>
<td>5.82</td>
<td>5.87</td>
</tr>
<tr>
<td>125 m</td>
<td>-</td>
<td>6.47</td>
</tr>
<tr>
<td>150 m</td>
<td>-</td>
<td>6.93</td>
</tr>
</tbody>
</table>

3.3.2 Normal year corrected wind speed

The mean wind speed can be normal year corrected in order to more accurately describe the climatological wind characteristics at the site. This can be conducted in several ways. A simple and straightforward approach is to use the NCAR wind speed index, either for the entire period or to apply the index for each month and then average the results. This is performed on both surface and u10 data, but since the correlation with the u10 data was lower and the standard deviation of monthly mean wind speed is increased when applying the u10 data, the use of surface data are considered better. Based on discussions with Erik Nilsson at Uppsala University (graduate researcher of studying normal year correction), the more refined method of month-by-month correction is used instead of correcting the wind based on the entire period. The results are presented in Table 15.

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>NCAR corrected mean wind speed (m/s)</th>
<th>80 m</th>
<th>100 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month by month</td>
<td>5.10</td>
<td>5.65</td>
<td></td>
</tr>
<tr>
<td>Entire period</td>
<td>4.94</td>
<td>5.50</td>
<td></td>
</tr>
</tbody>
</table>

Table 15 – Normal year corrected wind speed at Site A, based on NCAR surface data

Another option is to use one of the available production indices to correct the wind speed, but then the uncertainty is increased. Based on the Danish production index and the personally-devised Swedish production index (based on production data from 2002), using the month-by-month approach, the results in Table 16 are obtained. These are based on the assumption that the production is proportional to the square of the mean wind speed. Once again, the method of using the production index to correct wind speed is quite uncertain.

<table>
<thead>
<tr>
<th>Production index corrected mean wind speed (m/s)</th>
<th>80 m</th>
<th>100 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Danish index</td>
<td>5.53</td>
<td>6.13</td>
</tr>
<tr>
<td>Personally-devised Swedish index</td>
<td>5.15</td>
<td>5.72</td>
</tr>
</tbody>
</table>

Table 16 – Normal year corrected wind speed at Site A, based on Danish wind index and personally-devised Swedish wind index
While the Swedish index shows a result similar to the NCAR index, the Danish index shows a significantly higher wind speed. While the correction with the Danish index reduces the standard deviation of the mean wind speed and thus seemingly gives a less uncertain mean wind speed indication, the reduced spread is quite limited. The Swedish index gives a much higher degree of reduction in monthly mean wind speed spread, indicating a better correction method.

### 3.3.3 Measurements compared to MIUU data

The MIUU data (1x1 km² resolution) for the area was about 7.6 m/s at 103 m above the zero-shift plane and about 6.7 m/s at 72 m above the zero-shift plane. With the help of the software Snurran-II, developed by Jan-Åke Dahlberg for Vattenfall Vindkraft AB, the MIUU data corresponding to the mast location are interpolated to the correct coordinate by nearby grid points and to the appropriate height by a power law fit to the three levels of MIUU data available. Table 17 presents the MIUU data for the three standard MIUU levels, as well as for the two hub heights, compensated for a 10 m displacement height according to section 3.3.6.

<table>
<thead>
<tr>
<th>49 m</th>
<th>70 (80) m</th>
<th>72 m</th>
<th>90 (100) m</th>
<th>103 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean MIUU wind speed (m/s)</td>
<td>5.92</td>
<td>6.67</td>
<td>6.73</td>
<td>7.25</td>
</tr>
</tbody>
</table>

**Table 17 – MIUU mean wind speed at Site A**

Based on the equivalent MIUU wind at 80 m and 100 m above ground level, the deviation compared to the measured and the normal year corrected (month-by-month approach) mean wind speed is presented in Table 18.

<table>
<thead>
<tr>
<th>80 m</th>
<th>100 (97) m</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIUU – measured wind (m/s)</td>
<td>1.44</td>
</tr>
<tr>
<td>MIUU – NCAR index corrected wind (m/s)</td>
<td>1.57</td>
</tr>
<tr>
<td>MIUU – Swedish index corrected wind (m/s)</td>
<td>1.52</td>
</tr>
<tr>
<td>MIUU – Danish index corrected wind (m/s)</td>
<td>1.14</td>
</tr>
</tbody>
</table>

**Table 18 – Comparison of MIUU wind speed with measured and corrected wind at Site A**

It is clear that regardless of which set of data the wind speed is compared with, the MIUU model severely overestimates the mean wind speed at the site. On average the MIUU data indicate a wind speed of more than 1.4 m/s higher than that of the normal year corrected wind speed. This difference is far from the standard deviation of the MIUU model or one year of measurements of about 0.3 m/s.

Snurran-II also calculates the mean wind shear for the site, based on the three available levels. The wind shear coefficient was 0.334, which is significantly below the measured wind
shear. The underestimation of the surface roughness could be a major reason for the difference.

Vattenfall has also requested a higher resolution (500 m x 500 m) MIUU simulation for the area. The result from this is about 0.3 m/s lower than the original MIUU result, but it still differs significantly from the measured data. Bergström’s explanation is that the mast is situated in the lee of a ridge at about 55–60 m higher ground than the mast position and that the model is not of a sufficiently high resolution to include this.\textsuperscript{116}

Furthermore these results can be used to calculate the potential production at the site. {	extit{Snurran-II}} uses the wind distribution based on NCAR data and provides the production potential at 80 m hub height of 6270 MWh and at 100 m hub height of 7340 MWh.

### 3.3.4 Potential power production (not normal year corrected)

Based on the power curve for the Nordex N90 turbine (Figure 46) being installed at Site A, the corresponding power production to the wind distribution is calculated.

The subsequent power production and capacity factor for each month for the two hub heights are presented in Figure 39. One initial remark is that the energy yield for a 100 m tower is as much as 39\% higher compared to an 80 m tower. The annual production is 2870 MWh at 80 m and 3980 MWh at 100 m.

![Figure 39 – The potential power production and capacity factor for each month during the measurement period (not normal year corrected) at 80 m and 100 m](image)

To investigate the effect of higher hub heights the production and the relative increase compared to 100 m are presented in Table 19, based on the eleven months of extrapolated mast data and the seven months of sodar data. Both sources of information give similar results and results, are also the same when different normal year correction methods are applied. The production increases significantly with higher hub heights.
To improve the quality of the production prediction the data should be normal year corrected, which is done in section 3.5.

### 3.3.5 Potential power production (based on Rayleigh distribution)

It is not an uncommon practice in wind energy calculations to assume a Rayleigh distributed wind. However, using this method can introduce a bias, especially if the actual wind distribution differs significantly from the actual conditions, as in Site A. If the same mean wind speed as measured by the mast would be prevailing, but instead distributed according to a Rayleigh curve, the production would be as presented in Table 20.

<table>
<thead>
<tr>
<th></th>
<th>80 m</th>
<th>97 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power production (MWh)</td>
<td>3 499</td>
<td>4 509</td>
</tr>
<tr>
<td>Capacity factor (%)</td>
<td>20.0%</td>
<td>25.7%</td>
</tr>
</tbody>
</table>

**Table 20 – Production and capacity factor for Rayleigh distributed wind**

Compared to the results from the actual wind distribution, this method overestimates the yield by 15% at 80 m and by 10% at 97 m.

For further discussion see section 4.

### 3.3.6 Wind shear profile

The wind profile is different for different wind directions and for different times of the day, but to limit the extent of this analysis only the overall wind shear profile is presented. This wind shear profile at the site is presented in Figure 40 with both mast and sodar data. According to the mast data the least square fitted displacement height is 10.1 m and the wind shear coefficient is 0.42, while the sodar data are best fitted to the same shear coefficient but 6.3 m displacement height. This might be related to both the limitations of the sodar measurements and the fact that it was positioned further away from the forest edge.
3.3.7 Wind direction

The wind direction at a particular site is important to take into consideration, especially when several turbines are to be built. The wind direction can then be used to assess the wake effect and support micrositing decisions, for example, at which optimal distance the turbines should be placed in different directions.\cite{117}

This is often illustrated with a wind rose, presenting the wind, the wind energy or the production distribution from each sector. The standard number of sectors, used in the European wind atlas, is 12 sectors\cite{117}, and this has also been used for this analysis presented in Figure 41. The vast majority of the energy is produced from winds originating from the west. The figure is based on the mast data at 100 m, but sodar data for the much shorter period produced the same result.
3.3.8 Turbulence

The turbulence is, as mentioned earlier, crucial for wind turbines situated in forests. Based on the findings in section 3.1.8 the turbulence is too high at the 80 m level, even for the highest turbine turbulence class, thus it is more important to study the characteristics above this height. Figure 42 presents the turbulence intensity as a function of wind speed at three sodar heights (100 m, 125 m and 150 m) and the turbulence measured by the cup anemometer at 97 m. Data at wind speed where less than twenty ten-minute averages are available are excluded. The IEC standard prescribing the maximum allowable turbulence intensity is also included. Some data for very high and very low wind speeds are not included in the figure, but these are within the IEC limits.
The limits are not exceeded for wind speed below 8-9 m/s, rather the problems occur above 10 m/s. Figure 43 focuses on the more critical area in this range. It shows that the difference between mast and sodar measurements, particularly at the highest wind speed where the data coverage is low, puts the mean turbulence on different sides of the IEC limit. With increased hub height, this is no longer a problem and it could even potentially be possible to use a turbine class B.

3.3.9 Vertical wind component

The sodar does not only provide the horizontal wind speed, but also the vertical component. Knowledge of the vertical wind speed could for instance, be used to assess the anemometer
data that are for the horizontal component, but are also influenced by the vertical wind. The following analysis is done with the complete data set from both positions 1 and 2.

A strong majority (99%) of the vertical wind speed data are within ±1 m/s for all heights, but there are some exceptions. The maximum positive (upwards) speed is about 5 m/s, while the maximum negative (downwards) speed is 6.9 m/s. The extreme values for the downward winds can be found, seemingly randomly, at all altitudes, whereas the extreme values for the upward wind are found between 90 m and 110 m. Figure 44 shows the mean value for the vertical wind component for the entire set of data. The shape of the curve is likely due to the local topography and surface conditions, including the forest edges, but could also be related to the sodar measurement principles. Especially the unconformity between 45 m and 50 m is likely to be caused by signal processing.

![Figure 44 – Mean value of vertical wind component as a function of height](image)

Figure 45 presents the sorted data for four levels, and it illustrates that the vertical wind is close to zero most of the time. The few data outside the ±2 m/s interval have been left out, since these were acquired during periods with exceptionally low data quality index.
Based on this it can be concluded that the cup anemometers and their sensitivity to inclined flow should not be a major problem for measuring the correct horizontal wind component. Also, the vertical winds at the site should not cause much added wear on the turbines.

3.4 Comparison of different turbines

One possibility for improving the power production and/or capacity factor is to make an appropriate choice of turbine.

The two turbines already erected at the site are Nordex N90 at 80 m and 100 m. However, due to the recognised low wind conditions, it would also be interesting to evaluate the performance of a number of low-yield wind turbines with rotor diameter of 100 m. Several of these are not yet in production though.

The results presented in Table 21 are based on the mast data from November 2007 to June 2008. The data are for a hub height of 100 m, and they are not normal year corrected, since this does not significantly change the ratio between the different wind turbines. Applying normal year correction on the production would on average reduce the production by about 8% for all wind turbines. Similarly, evaluating the increased production with increased hub height is essentially equal for all turbines. To compare for increased heights, an approximation of 1.2% increased production per meter increased hub height can be applied.
The turbine with a 100 m rotor produces far more than the other turbines, and the Kenersys machine has the highest production of them all. The best capacity factor was the Siemens 100 m rotor machine, since it has a smaller generator, though neither of the power curves for Siemens and Kenersys 100 m rotor diameters has been verified. Based on the production per rotor area, the evaluated turbines all produce 646–690 kWh per year and square meter.

The results are due to different power curves for each of the machines, which are thus presented in Figure 46. Since above 90% of the energy is produced at wind speeds between 5 m/s and 10 m/s (and about 80% between 6.5 m/s and 9.5 m/s), this part of the power curve is particularly important and relative power production in this range is specially studied in Figure 47.

Figure 46 – Power curves for the turbines compared

Table 21 – Production comparison among eight turbines (not normal year corrected)
Figure 47 – Power curves for the turbines compared

For further discussion see section 4.
3.5 Comparison of methods for normal year correction

As mentioned in section 2.6, there are several different wind indices that can be used, and there are different ways of how to apply them. This section contains some different normal year corrections based on the mast data from October to August. For power production calculation, the power curve of the Nordex N90 is used. The different methods do not only represent the specific location of Site A, but also provides some general insights into the differences among the studied methods.

3.5.1 Choice of indices and method of evaluating the results

There are not only different sources of indices, but also different approach when using the index data. The simplest method is to only correct the production with the mean wind index for the entire period of the measurements. However, a slightly more refined method is to perform the normal year correction month by month, by using the specific wind index with the measured data for each month. This gives a better result and is thus used for all in the calculations below, except one evaluation with the Danish index to demonstrate the different results produced.

The indices evaluated are described in section 2.6, and they are the official Swedish index, a personally-devised Swedish index (both corrected and not corrected with the Danish long-term value), the Danish index, NCAR wind and production indices, as well as the regional and local indices of Kalmar, Jutland and Målajord. Jutland is used because the index correlated best with the calculated production, while the Kalmar index was a geographically rational data source, and Målajord, because it involved a wind turbine both in the forest and geographically close to Site A. All monthly index values are presented in Appendix 1.

3.5.2 Results by different indices

To summarise the results in a comprehensive way the results are presented for 100 m hub height only in Table 22. The normal year correction methods are sorted in descending order based on predicted production. The Swedish personally-devised index, labelled adjusted, presents the result when the Swedish production statistics have not been corrected with the Danish long-term data. NCAR data are, as previously discussed, presented both based on the method of correcting the wind speed and on the method of correcting the production.
Annual production (MWh):

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncorrected</td>
<td>3980</td>
</tr>
<tr>
<td>Swedish official</td>
<td>3210</td>
</tr>
<tr>
<td>Swedish personal</td>
<td>3620</td>
</tr>
<tr>
<td>Swedish personal (adjusted)</td>
<td>3820</td>
</tr>
<tr>
<td>Kalmar</td>
<td>3400</td>
</tr>
<tr>
<td>Målajord</td>
<td>3850</td>
</tr>
<tr>
<td>Danish</td>
<td>4130</td>
</tr>
<tr>
<td>Danish (full period)</td>
<td>3990</td>
</tr>
<tr>
<td>Jutland</td>
<td>4330</td>
</tr>
<tr>
<td>NCAR surface (wind)</td>
<td>3820</td>
</tr>
<tr>
<td>NCAR u10 (wind)</td>
<td>4380</td>
</tr>
<tr>
<td>NCAR surface (production)</td>
<td>3660</td>
</tr>
<tr>
<td>NCAR u10 (production)</td>
<td>4000</td>
</tr>
<tr>
<td>Average</td>
<td>3850</td>
</tr>
</tbody>
</table>

Table 22 – Summary of normal year correction results for 100 m hub height, Nordex 2.5 MW, N90

The results produced with the different methods differ quite significantly. It is not possible to know with certainty which of the methods that produces the best results, but some insight into this can be obtained. One observation that can be made is the difference between the Danish index based on a monthly basis and on the full period, indicating that there is an apparent difference in results.

3.5.3 Comparison of the results from normal year correction

The usefulness and uncertainty of the result by using different indices can be based on different criteria. One method is simply to study the basis for the index and the data source used to generate different production and wind indices in relation to the site data for which it is applied. For instance, the NCAR data are generated for single points relatively close to the site, but on the other hand, they are based on a low-resolution model. The Danish index is based on geographically offset production statistics, but has long-term statistics based on a large number of turbines. The Swedish personally-devised index is based on geographically closer turbines, but the turbines are still spread out over the whole of Sweden. The Kalmar
index is geographically very close to Site A, but the data coverage, especially for the first years is scarce, and the conditions a bit inland can differ significantly from those on the coast and offshore. The turbine in Målajord is located close to Site A and at fairly equal conditions, but using a single turbine is sensitive to local wind deviations and downtime of the machine.

A statistical approach to evaluate whether or not an index is appropriate to correct measured data are to look at the correlation between each index and the production calculated from the measured wind data. This is presented in Table 22. The highest correlated index is that of the single turbine in Målajord, followed by the Jutland index. The NCAR wind indices are also included in this analysis, but one must keep in mind that the wind indices in this comparison are compared with the production and not measured wind.

<table>
<thead>
<tr>
<th>Coefficient of correlation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Swedish official</td>
<td>0.92</td>
</tr>
<tr>
<td>Swedish personal</td>
<td>0.93</td>
</tr>
<tr>
<td>Swedish personal (adjusted)</td>
<td>0.93</td>
</tr>
<tr>
<td>Kalmar</td>
<td>0.93</td>
</tr>
<tr>
<td>Målajord</td>
<td>0.98</td>
</tr>
<tr>
<td>Danish</td>
<td>0.95</td>
</tr>
<tr>
<td>Jutland</td>
<td>0.96</td>
</tr>
<tr>
<td>NCAR surface (wind)</td>
<td>0.95</td>
</tr>
<tr>
<td>NCAR u10 (wind)</td>
<td>0.94</td>
</tr>
<tr>
<td>NCAR surface (production)</td>
<td>0.95</td>
</tr>
<tr>
<td>NCAR u10 (production)</td>
<td>0.93</td>
</tr>
<tr>
<td>Average</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Table 23 – Correlation between production based on measurements and different indices

Another approach to test the different indices is to look at the corrected results on a monthly basis for each of the indices. For an ideal correction method each month would be adjusted to the same meteorological value. Subsequently, the higher the spread of the monthly production based on each index, the less precise an index is. This method of comparison is however, not a direct measure of the accuracy of the indices. This is indicated in the results for the adjusted personal Swedish index compared to the unadjusted personal Swedish index (giving the same results), but also in the quite low deviations of the official Swedish index. The relative standard deviation for the corrected production for each index is presented in Table 24.
<table>
<thead>
<tr>
<th></th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swedish official</td>
<td>20%</td>
</tr>
<tr>
<td>Swedish personal</td>
<td>19%</td>
</tr>
<tr>
<td>Swedish personal (adjusted)</td>
<td>19%</td>
</tr>
<tr>
<td>Kalmar</td>
<td>19%</td>
</tr>
<tr>
<td>Målajord</td>
<td>13%</td>
</tr>
<tr>
<td>Danish</td>
<td>17%</td>
</tr>
<tr>
<td>Jutland</td>
<td>19%</td>
</tr>
<tr>
<td>NCAR surface (wind)</td>
<td>41%</td>
</tr>
<tr>
<td>NCAR u10 (wind)</td>
<td>43%</td>
</tr>
<tr>
<td>NCAR surface (production)</td>
<td>19%</td>
</tr>
<tr>
<td>NCAR u10 (production)</td>
<td>22%</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>23%</strong></td>
</tr>
</tbody>
</table>

Table 24 – Standard deviation of normal corrected production on a monthly basis

According to this study the Målajord index would be the least uncertain followed by the Danish index. Most of the indices give 17-20% in monthly standard deviation, corresponding to less than 6% in annual standard deviation based on the features of normal distributed functions. The Swedish official index also shows a decent standard deviation, but this might be due to its lower inherent standard deviation and the fact that the conditions at Site A seem to vary less than the average.

This can be compared to the monthly standard deviation of the uncorrected production, which is 45%, or the standard deviation of the monthly mean wind speed, which is 16%. Using the majority of these indices thus lowers the uncertainty by half. Using the NCAR wind indices does not seem to lower the uncertainties to any significant extent based on these results. The approach of applying the index values to each individual ten-minute average might introduce a bias, and different approaches could instead be tested.

### 3.5.4 Use of a regression model to normal year correct

As explained in section 2.6.7 a more advanced method of correction would be to use a regression model. The three methods proposed were proportional correction, linear correction adding a second term or using a version of second order with the square of the index deviation as one of the factors. To be able to determine the best values for the invariables, the values that minimise the monthly standard deviation are chosen.
The results from the method described in Formula 16 are presented in Table 25, with respect to monthly standard deviation and resulting normal year production.

<table>
<thead>
<tr>
<th></th>
<th>“a”</th>
<th>Monthly standard deviation</th>
<th>Normal year production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swedish official</td>
<td>1.46</td>
<td>16%</td>
<td>3080</td>
</tr>
<tr>
<td>Swedish personal</td>
<td>0.87</td>
<td>18%</td>
<td>3750</td>
</tr>
<tr>
<td>Swedish personal (adjusted)</td>
<td>0.88</td>
<td>18%</td>
<td>3580</td>
</tr>
<tr>
<td>Kalmar</td>
<td>0.91</td>
<td>18%</td>
<td>3400</td>
</tr>
<tr>
<td>Mälajord</td>
<td>0.91</td>
<td>11%</td>
<td>3790</td>
</tr>
<tr>
<td>Danish</td>
<td>0.85</td>
<td>15%</td>
<td>3980</td>
</tr>
<tr>
<td>Jutland</td>
<td>0.80</td>
<td>14%</td>
<td>4060</td>
</tr>
<tr>
<td>NCAR surface (wind)</td>
<td>0.51</td>
<td>16%</td>
<td>3520</td>
</tr>
<tr>
<td>NCAR u10 (wind)</td>
<td>0.48</td>
<td>17%</td>
<td>3790</td>
</tr>
<tr>
<td>NCAR surface (production)</td>
<td>0.84</td>
<td>16%</td>
<td>3590</td>
</tr>
<tr>
<td>NCAR u10 (production)</td>
<td>0.80</td>
<td>18%</td>
<td>3830</td>
</tr>
<tr>
<td>Average</td>
<td>0.85</td>
<td>16%</td>
<td>3670</td>
</tr>
</tbody>
</table>

Table 25 – Results from normal year correction by regression (single parameter)

The Swedish official index is the only index that needs to be adjusted for increased variation, and this is due to its inherent smoothing of variations for different seasons. For all the other production indices, the adjustment factor is between 0.80 and 0.91. If excluding the NCAR wind indices, the standard deviation is reduced by 3% and the predicted annual production is decreased by about 100 MWh. The “a” parameter for the NCAR indices is more extreme at about 0.5, indicating that the NCAR variation is approximately twice as high as the actual measurements. The monthly standard variations are decreased significantly from 41-43% to 16-17%, while the predicted annual production is reduced by 300 MWh for surface data and 590 MWh for u10 data.

Using the method of superposition, where a second term is added to the adjustment of the index, the standard deviation of the monthly production values is not decreased, while the decrease of using the second order adjustment is quite insignificant. The results of the normal year correction do, however, change to some extent, but since these method does not add any considerable improvement in precision they are rejected.
3.5.5 Estimated uncertainty for different methods

On the basis of the monthly standard deviation for different methods, the uncertainty for the different normal year corrections based on the full period can be calculated with Formula 17:

$$\sigma_{corr} = \sqrt{\frac{\sigma_{\text{monthly}}^2}{n_1}}$$  \hspace{1cm} (17)

$\sigma_{corr}$ is the standard deviation for the whole period, $\sigma_{\text{monthly}}$ is the monthly standard deviation and $n_1$ is the number of months in the period.\textsuperscript{122} The results from this calculation for both the regular method and the regression method are presented in Table 26. The Swedish official index is left out of the presentation, since it was deemed incorrect. The result for the adjusted Swedish personally-devised index with this evaluation is the same as for the unadjusted, though the total uncertainty for the adjusted index is more difficult to assess and thus not calculated.

<table>
<thead>
<tr>
<th>Resulting standard deviation</th>
<th>Regular correction</th>
<th>Regression correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swedish personal</td>
<td>5.7%</td>
<td>5.3%</td>
</tr>
<tr>
<td>Kalmar</td>
<td>5.7%</td>
<td>5.6%</td>
</tr>
<tr>
<td>Målajord</td>
<td>3.9%</td>
<td>3.4%</td>
</tr>
<tr>
<td>Danish</td>
<td>5.2%</td>
<td>4.4%</td>
</tr>
<tr>
<td>Jutland</td>
<td>5.8%</td>
<td>4.3%</td>
</tr>
<tr>
<td>NCAR surface (wind)</td>
<td>12.4%</td>
<td>4.9%</td>
</tr>
<tr>
<td>NCAR u10 (wind)</td>
<td>13.0%</td>
<td>5.2%</td>
</tr>
<tr>
<td>NCAR surface (production)</td>
<td>5.6%</td>
<td>5.4%</td>
</tr>
<tr>
<td>NCAR u10 (production)</td>
<td>6.6%</td>
<td>4.1%</td>
</tr>
</tbody>
</table>

Table 26 – Resulting standard deviation for the different normal year correction indices

However, there is also an uncertainty in the long-term data that is the base for each index. This is generally higher for the Swedish indices and particularly the Målajord index that is based on the shortest period of data. This uncertainty can be estimated by calculating the standard deviation of the monthly index values for each index and subsequently use Formula 18: \textsuperscript{122}
\[ \sigma_{\text{long}} = \sqrt{\frac{\sigma^2_{\text{index, monthly}}}{n_2}} \]  

(18)

where \( \sigma_{\text{nyc}} \) is the standard deviation for the long-term mean, \( \sigma_{\text{index, monthly}} \) is the monthly standard deviation of the index and \( n_2 \) is the number of months the index is based on. These results are presented in Table 27. The monthly standard deviation is based on all months, except for NCAR data where only 20 months are used for calculation reasons though the results should still be reasonably accurate. The table also includes the statistics for the NCAR wind series, but one should keep in mind that the variation in wind is naturally less than the variation in production.

<table>
<thead>
<tr>
<th></th>
<th>Monthly standard deviation</th>
<th>Number of months</th>
<th>Resulting standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swedish personal</td>
<td>36%</td>
<td>79</td>
<td>4.1%</td>
</tr>
<tr>
<td>Kalmar</td>
<td>38%</td>
<td>79</td>
<td>4.3%</td>
</tr>
<tr>
<td>Målajord</td>
<td>35%</td>
<td>50</td>
<td>5.0%</td>
</tr>
<tr>
<td>Danish</td>
<td>41%</td>
<td>356</td>
<td>2.2%</td>
</tr>
<tr>
<td>Jutland</td>
<td>36%</td>
<td>128</td>
<td>3.1%</td>
</tr>
<tr>
<td>NCAR surface (production)</td>
<td>48%</td>
<td>360</td>
<td>2.5%</td>
</tr>
<tr>
<td>NCAR u10 (production)</td>
<td>47%</td>
<td>360</td>
<td>2.5%</td>
</tr>
<tr>
<td>NCAR surface (wind)</td>
<td>24%</td>
<td>360</td>
<td>1.3%</td>
</tr>
<tr>
<td>NCAR u10 (wind)</td>
<td>24%</td>
<td>360</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

Table 27 – Statistical uncertainties of the long-term data

On production basis the Danish index is the most certain value, with NCAR data only slightly more uncertain. All Swedish indices have significantly higher inherent uncertainties.

3.5.6 Total uncertainty for normal year correction

To estimate the total uncertainty of different methods of normal year correction both the uncertainty in applying the correction and in the long-term average of the data source for each index must be considered. This can be calculated with Formula 19: 122

\[ \sigma_{\text{nyc}} = \sqrt{\sigma^2_{\text{corr}} + \sigma^2_{\text{long}}} \]  

(19)

To better understand the relationship between the uncertainties and the impact of the length of the data Formula 20 is presented: 122
This is applied for each method and index and presented in Table 28.

<table>
<thead>
<tr>
<th>Resulting standard deviation</th>
<th>Regular correction</th>
<th>Regression correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swedish personal</td>
<td>7.1%</td>
<td>6.7%</td>
</tr>
<tr>
<td>Kalmar</td>
<td>7.2%</td>
<td>7.0%</td>
</tr>
<tr>
<td>Målajord</td>
<td>6.3%</td>
<td>6.1%</td>
</tr>
<tr>
<td>Danish</td>
<td>5.6%</td>
<td>4.9%</td>
</tr>
<tr>
<td>Jutland</td>
<td>6.6%</td>
<td>5.3%</td>
</tr>
<tr>
<td>NCAR surface (wind)</td>
<td>12.5%</td>
<td>4.9%</td>
</tr>
<tr>
<td>NCAR u10 (wind)</td>
<td>13.1%</td>
<td>5.2%</td>
</tr>
<tr>
<td>NCAR surface (production)</td>
<td>6.2%</td>
<td>5.4%</td>
</tr>
<tr>
<td>NCAR u10 (production)</td>
<td>7.1%</td>
<td>5.9%</td>
</tr>
</tbody>
</table>

Table 28 – Total standard deviation for different methods of normal year correction

Based on these results the Danish index is the best production index for the site, both for regular and regression correction. The second best production index is the NCAR surface index, with the normal year correction based on the Målajord index not far behind. The NCAR wind indices give a very high uncertainty for the standard approach, but when the regression approach is used the uncertainties are greatly reduced. The NCAR surface wind index has only a slightly higher standard deviation (0.05%) than the Danish index.

The total uncertainty is based on the applied correction, the concurrent measurement period, the long-term average deviation and its long-term averaging period. Thus, using different sets of measurement data (sites, reference sources and periods) will generate different uncertainties. If a very short measurement period is available, the uncertainty in the long-term index average is less important and the applied correction (corresponding to the correlation) is of greater importance. As an example, if normal year correction would instead be based on only six months of site measurements, the best source for normal year correction would not be the Danish index, but the Målajord index. And the opposite, for a longer measurement campaign than twelve months, the NCAR surface wind index would produce the lowest uncertainties. Between six and twelve months the Danish index gives the best results.
3.5.7 Seasonal effects

It has been suggested that normal year corrected measurements based only on the less windy months of the summer will not give a satisfactory result. For this reason the monthly corrected result for the six best indices are presented in Figure 48. From this figure a small trend supports this claim. Comparing the mean for November to March with the mean for April to August indicates a difference of 57 MWh per month, corresponding to 16% or 680 MWh annually for the regular regression. The overcorrection is, however, not as strong for the regression method giving only a deviation of 30 MWh per month, corresponding to 9% or 360 MWh annually. This seasonal effect should thus be kept in mind.

![Figure 48 – Normal year corrected result on a monthly basis for six different methods](image-url)
3.5.8 Summary of normal year correction results

The best results and their corresponding uncertainty are presented in Table 29. For further discussion see section 4.

<table>
<thead>
<tr>
<th>Predicted result (MWh)</th>
<th>Estimated uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Regular correction</strong></td>
<td></td>
</tr>
<tr>
<td>Danish</td>
<td>4130</td>
</tr>
<tr>
<td>NCAR surface (production)</td>
<td>3660</td>
</tr>
<tr>
<td>Målajord</td>
<td>3850</td>
</tr>
<tr>
<td><strong>Regression correction</strong></td>
<td></td>
</tr>
<tr>
<td>Danish</td>
<td>3980</td>
</tr>
<tr>
<td>NCAR surface (wind)</td>
<td>3520</td>
</tr>
<tr>
<td>NCAR u10 (wind)</td>
<td>3790</td>
</tr>
</tbody>
</table>

Table 29 – Results from normal year correction methods with the least estimated uncertainty.
4 Discussion

According to the division of the thesis into several subtopics, this section is likewise separated into these different issues for discussion. First the sodar performance and its future use are discussed, followed by the site evaluation of the forest holding and the results from different methods of normal year correction. Finally a measurement strategy is proposed.

4.1 Sodar performance and its implication

The comparison of the sodar and the mast measurements at the site was initially intended as a strict sodar performance evaluation, though recognising the imperfection of the cup anemometers forced an extension of the analysis. Even though the errors of under-speeding due to freezing and over-speeding due to high turbulence essentially evened out each other’s impact on the mean wind speed, both errors were in the same magnitude as the indicated difference between the sodar and the cup anemometers. This indicates that the fundamental uncertainties in measurement data are not intrinsically below ±0.1 m/s (at least not to any significant degree). Thus, the small difference in indicated wind speed by the sodar and the cup anemometer can be regarded as a result of inherent uncertainties, and therefore the measurements by cup anemometer and by sodar can be considered equally valid. The comparison of the measurements of wind direction was not ideal, with unknown calibration errors, but the sodar measurements of wind direction could still be trusted, by studying the technique.

The results from the turbulence study also opened up for a new application for the sodar. Previously the larger averaging volume of a sodar unit was assumed to be unable to accurately measure the turbulence, but with a corresponding time constant of less than twenty seconds the bulk of the turbulence, which is at the scale between 20 seconds and 3 minutes, is covered adequately. The indication for turbulence intensity at wind speeds above 13 m/s lacked sufficient statistical data coverage, but the indication was that the sodar results would underestimate the turbulence. However, other studies conclude otherwise, and thus this would be interesting to verify with further tests.

The features of the AQ500, with its increased measurement height, mobile nature and the possibility for immediate deployment without the need of permits, present a number of advantages compared to the cup anemometer. It also eliminates the risk of freezing of bearings, icing of cups, over-speeding due to high turbulence and wake effect of the met mast. Even though applying best practice procedures can minimise all these, all sources of error cannot be eliminated. The disadvantages with the sodar are much related to positioning. In forests the sodar must be placed in a clearing with a minimum distance of about 30 m to trees of normal height; otherwise the effect of fixed echoes will compromise the measurements. The effect of severe small-scale topography, such as hills with steep slopes, must also be considered and could sometimes limit the use of the sodar. Another problem with the sodar technology is that is currently not completely accepted by the turbine suppliers, thus demanding complementary measurements by met mast. However,
considering the performance of the AQ500, it should only be a matter of time (and perhaps persuasion) before the technology is fully accepted.

### 4.2 Site evaluation and forest site characteristics

The evaluation of Site A produced a number of interesting results, which are not only valid for the specific site but also, to a certain degree, generally for sites in forests, particularly in the south of Sweden.

The mean wind speed at the standard hub height is about 5.8 m/s (or between 5.5 and 6.1 m/s after normal year correction), and this is too low for any size of wind farm to be profitable and thus feasible to construct. The differences compared to MIUU data, from both the regular 1x1 km² resolution and the 500x500 m² resolution, are far greater than the standard deviation from the measured verification of the MIUU results at 0.3 m/s. The difference in mean wind speed of more than 1 m/s is most likely a result from erroneous parameterisation of the forest by the model. Based on the three different heights of MIUU data, the corresponding shear coefficient is just 0.33 compared to the measured coefficient of about 0.42. This indicates that the model underestimates the surface roughness of the forest, and as a result the production predictions based on MIUU data are almost doubled compared to the actual measurements.

Based on these findings and the fact that Site A is a fairly non-complex site with regards to topography, it is probable that the validity of the MIUU model in forests is low. Thus the optimism for erecting a large number of wind turbines in forests is greatly diminished. Wind turbines in forests would then be limited to sites with particularly favourable conditions, such as sites on the west coast of Sweden and sites with hills to offer a natural extension of the towers of the wind turbines.

However, the analysis also showed that increasing the rotor diameter to 100 m would increase the production remarkably. Similarly, increasing the hub height offers a complementary solution to increase the energy yield. Though there is relatively little experience with these solutions today, the possibilities may be promising in just a couple of years.

Studying the results from the turbulence analysis, though the results are unclear for higher wind speed, may demand an increased hub height regardless of the wind speed. The IEC turbulence limits must be managed not only in order for the turbine suppliers to offer their warranty, but also to reduce the risk for increased wear. Increasing the hub heights significantly reduces the turbulence profile.

Another factor that reduces the production estimates for the site is the high value of the shape parameter for the Weibull distribution of the wind speeds. The reduction compared to nominal Weibull distribution for the same mean wind is as high as 10%, and this should be kept in mind if assuming the standard distribution.
Finally the wind rose for the site is dominated to a high degree by wind direction west. Depending on the wind farm size and layout, this could be more or less favourable with regards to wake effects.

4.3 Normal year correction

The discussion about normal year correction in this thesis is based on a study of a specific site and for eleven months of measurements. The analysis is aimed at generating general guidelines and conclusions, but the accuracy of some of the claims could use some further verification in order to be generally applicable. The estimated uncertainties could differ from the actual standard deviation since they are based on a sample, though the effect is probably quite low.

The total uncertainty for normal year correction is based on two main factors. The first is how representative the index data are for the specific site. This can be checked by the coefficient of correlation between the site measurements (or the production based on these measurements) and the index values for the concurrent period. However, to cover also the possibility of different degrees of variation of the wind, a better approach could be to check the standard deviation of the monthly normal year corrected results. The second uncertainty is related to the long-term average of the wind index. This is about 2% for thirty years of data, 3% for ten years of data and 5% for five years of data. The uncertainty introduced by changing the input to the production statistics (introduction of new turbines) is only indirectly included in these. This could potentially have a qualitative impact on, for instance, the Swedish index, since its data coverage has been growing rapidly the last five years.

The uncertainty in normal year correction is far from the only source of uncertainty when assessing a site. Apart from smaller uncertainties in measurement data, et cetera, a complex site in a forest has great uncertainties in power curve correction and especially in extrapolation of measured data to other locations within the site. Thus, the uncertainty in wind potential assessment will always be great, regardless of how well the normal year correction is performed. Still, there are several advantages in minimizing the uncertainties as much as possible.

Depending on how long the measurement period is, different indices could be appropriate. For short measurement periods the most important factor is the correlation with the index, while for longer measurement campaigns the impact of the long-term coverage of the index is more important. For this reason adjusting indices that are more representative for the measurement site with indices that have a better normal year correction could be a successful method; however, checking the effect on the total uncertainty has not been possible in this thesis.

Based on the analysis of the results from the different methods and sources of normal year correction, some of the indices are recommended not to be used (or at least used only with great caution). The Swedish official index is based on incorrect principles and should not be applied. The Swedish personally-devised indices lack long-term coverage to provide a sufficiently certain base for a wind index. However, the total uncertainties of normal year
correction are not exceptionally high, and for the Målajord index, just above 6%. The Danish index gives the best result overall at about 5% and should be preferred to the Danish regional index of Jutland (for instance), due to better statistical coverage. Though for the southwest part of Sweden, the assumed increase in correlation might justify the use of one of the regional indices.

For the NCAR indices the surface index always produces the best results for this specific site, consistent with its better correlation. The NCAR production indices produce fairly good and useful results, both for the regular method and for the regression method. The best NCAR correction is nevertheless the NCAR surface when adjusted with the regression method and estimated uncertainties are practically as low as for the Danish index. The value of the regression constant at about 0.5 is, however, very low, indicating that the NCAR wind varies roughly twice as much as the site measurements. This can be confirmed by looking at the standard deviation of the monthly mean wind speed, which is 28% for NCAR data and 16% for measured data. The Weibull distribution at the site is quite extreme with a shape factor of about three, and thus the regression results are reasonable. Based on the standard deviation of the production based on the measurement and the standard deviation of each index, the hypothesis that the wind variations at the site are significantly different from those of the indices are confirmed. This can also be seen in the regression factor for the production indices, which were all below one.

Using the full-period method for correction instead of the monthly method changes the results by, on average, slightly over 100 MWh annually. This corresponds to almost 5%; and for this specific period, and site the indicated production is consistently less with the full-period method. Equally important is that by using the full-period method, it is not possible to apply the regression correction technique.

The normal year corrected results for the site were just about 4000 MWh with an uncertainty of roughly 5%.
4.4 Conclusions

Several conclusions and recommendations can be made, based on the results from this Master’s thesis. The sodar unit, the AQ500 from AQ System, produces high-quality wind speed measurement results with equal or less uncertainty than a met mast instrumented with cup anemometers. The turbulence readings are also deviating little from the cup anemometers, for relevant wind speed and for a sufficient number of readings. For reasons of features, performance and cost, a sodar unit should be preferred to a met mast for most circumstances with modest topography and the existence of sufficiently large clearing for sites in forests. If long-term measurements are planned, a mast could be preferable due to less maintenance and operation cost. Presently measurements from met mast are also needed to satisfy the turbine suppliers, but this can hopefully change within a few years.

The conclusions from the assessment of the forest site are that the turbulence is very high and the wind potential is too low to erect the standard turbines, with rotor diameters of about 90 m and hub heights at about 100 m. Higher towers and bigger rotor areas could solve both the problem with turbulence and energy yield.

Furthermore, the MIUU-model is severely overestimating the wind potential for the forest site of this thesis, possibly because of a too low assumption of the surface roughness of the conifer forest.

The evaluation of different normal year correction methods showed that most methods had an uncertainty of 5-7%. The best index for this particular site and measurement period was the Danish index, but using the single turbine in Målajord or the NCAR production index also produced good results. Applying a regression method to modify the indices to adjust for the specific conditions at the site, reduced the uncertainty for all indices. Especially the NCAR wind indices improved significantly with this method, consequently making these equally useful as the Danish index.
4.5 Further work

Though the sodar evaluation performed in this report is extensive and based on a long period of measurements, there are some aspects that might need further verification. Though nothing indicates that the AQ500 would measure less accurately with increased height, for instance, due to increased measurement volume, it could be of interest to verify the measurements with a mast up to 150 m. Since the mast and the sodar wind profile are concurrent up to 100 m this is more of a formality though. A more interesting area to study further is the turbulence readings, mainly for higher wind speeds. The turbulence readings at higher wind speed could probably be quite accurate, but verification is needed to ensure this. Using a high quality instrument to measure turbulence, such as sonic anemometers, the uncertainties of the sodar readings could be measured with better precision.

It would also be highly interesting to compare the AQ500 to lidar systems, which is generally more accepted in the industry, but is both more expensive and more sensitive.

The uses of remote wind measurements also have the advantage of measuring the wind characteristics over the whole rotor area. This could effectively be used as input for power curve correction. The power curves specified by the suppliers are not valid for sites with extreme wind shear, which is likely to reduce the power production, or for very high turbulence, which will also affect the production. The effect of varying density due to changing ambient temperature should also be considered. This power curve correction could first be performed theoretically, and then be verified by actual production by turbines situated in the forest.

Another benchmarking that would be very useful, would be to compare the number of different models for wind potential mapping, both on the larger and smaller scales. On the larger scale this should be performed by comparing the results from the different methods to long-term measurements spread over large areas and for varying kinds of surroundings. On the smaller scale this would be particularly interesting for more complex sites; but if a moderately complex site would be chosen, the use of several sodar units could be used to study the performance of different models.

The study of normal year correction could be both extended and more in-depth. What is not included in the comparison of the normal year method in this thesis, is the effect of using reference wind measurements as the source for the index. Based on the correlation comparison for different heights, the 10 m SMHI masts could be inappropriate, but this needs further study. The method to use a long-term index, such as NCAR or Danish statistics, to adjust more representative index sources based on fewer years, such as a single turbine or a nearby measurement mast, should also be studied. Furthermore, the choice of averaging period is somewhat arbitrary as one month, since the production statistics are presented on this basis, but other averaging periods might produce better results. Less than one month could be difficult to generate with respect to the presented production statistics, but two, three or four months (perhaps corresponding to the seasons) would be of interest to study. Finally, the different methods should preferably be evaluated for a site with long-term data from heights in the magnitude of wind turbine hub heights, to give the most certain indications.
Appendixes

1 Normal year correction indices

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Swedish official</td>
<td>73%</td>
<td>118%</td>
<td>111%</td>
<td>172%</td>
<td>160%</td>
<td>140%</td>
<td>82%</td>
<td>77%</td>
<td>140%</td>
<td>99%</td>
<td>147%</td>
</tr>
<tr>
<td>Swedish personal (adjusted)</td>
<td>77%</td>
<td>118%</td>
<td>124%</td>
<td>195%</td>
<td>170%</td>
<td>138%</td>
<td>65%</td>
<td>42%</td>
<td>89%</td>
<td>56%</td>
<td>98%</td>
</tr>
<tr>
<td>Swedish personal</td>
<td>81%</td>
<td>125%</td>
<td>131%</td>
<td>206%</td>
<td>180%</td>
<td>146%</td>
<td>69%</td>
<td>44%</td>
<td>94%</td>
<td>59%</td>
<td>103%</td>
</tr>
<tr>
<td>Kalmar</td>
<td>85%</td>
<td>146%</td>
<td>135%</td>
<td>205%</td>
<td>171%</td>
<td>139%</td>
<td>87%</td>
<td>53%</td>
<td>102%</td>
<td>53%</td>
<td>118%</td>
</tr>
<tr>
<td>Målajord</td>
<td>64%</td>
<td>114%</td>
<td>100%</td>
<td>193%</td>
<td>162%</td>
<td>133%</td>
<td>76%</td>
<td>40%</td>
<td>115%</td>
<td>54%</td>
<td>100%</td>
</tr>
<tr>
<td>Danish</td>
<td>56%</td>
<td>122%</td>
<td>104%</td>
<td>192%</td>
<td>159%</td>
<td>140%</td>
<td>49%</td>
<td>40%</td>
<td>95%</td>
<td>60%</td>
<td>82%</td>
</tr>
<tr>
<td>Jutland</td>
<td>53%</td>
<td>118%</td>
<td>98%</td>
<td>196%</td>
<td>167%</td>
<td>135%</td>
<td>46%</td>
<td>37%</td>
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<td>54%</td>
<td>70%</td>
</tr>
<tr>
<td>NCAR surf (wind)</td>
<td>88%</td>
<td>120%</td>
<td>115%</td>
<td>153%</td>
<td>146%</td>
<td>117%</td>
<td>83%</td>
<td>65%</td>
<td>100%</td>
<td>76%</td>
<td>102%</td>
</tr>
<tr>
<td>NCAR u10 (wind)</td>
<td>85%</td>
<td>114%</td>
<td>109%</td>
<td>155%</td>
<td>140%</td>
<td>109%</td>
<td>80%</td>
<td>59%</td>
<td>94%</td>
<td>72%</td>
<td>96%</td>
</tr>
<tr>
<td>NCAR surface (prod.)</td>
<td>81%</td>
<td>132%</td>
<td>125%</td>
<td>206%</td>
<td>195%</td>
<td>128%</td>
<td>69%</td>
<td>40%</td>
<td>100%</td>
<td>58%</td>
<td>100%</td>
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<tr>
<td>NCAR u10 (prod.)</td>
<td>78%</td>
<td>123%</td>
<td>117%</td>
<td>214%</td>
<td>180%</td>
<td>115%</td>
<td>64%</td>
<td>36%</td>
<td>87%</td>
<td>51%</td>
<td>88%</td>
</tr>
<tr>
<td>Average</td>
<td>75%</td>
<td>123%</td>
<td>115%</td>
<td>190%</td>
<td>166%</td>
<td>131%</td>
<td>70%</td>
<td>48%</td>
<td>101%</td>
<td>63%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 30 – Monthly values for all normal year correction indices used, regular correction method
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
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</tr>
</thead>
<tbody>
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<td><strong>Swedish official</strong></td>
<td>61%</td>
<td>126%</td>
<td>116%</td>
<td>205%</td>
<td>187%</td>
<td>158%</td>
<td>74%</td>
<td>66%</td>
<td>158%</td>
<td>99%</td>
<td>169%</td>
</tr>
<tr>
<td><strong>Swedish personal (adjusted)</strong></td>
<td>80%</td>
<td>116%</td>
<td>121%</td>
<td>183%</td>
<td>162%</td>
<td>133%</td>
<td>70%</td>
<td>49%</td>
<td>91%</td>
<td>62%</td>
<td>98%</td>
</tr>
<tr>
<td><strong>Swedish personal</strong></td>
<td>84%</td>
<td>122%</td>
<td>127%</td>
<td>192%</td>
<td>170%</td>
<td>140%</td>
<td>73%</td>
<td>51%</td>
<td>95%</td>
<td>65%</td>
<td>103%</td>
</tr>
<tr>
<td><strong>Kalmar</strong></td>
<td>86%</td>
<td>142%</td>
<td>132%</td>
<td>196%</td>
<td>165%</td>
<td>136%</td>
<td>89%</td>
<td>57%</td>
<td>102%</td>
<td>57%</td>
<td>116%</td>
</tr>
<tr>
<td><strong>Målajord</strong></td>
<td>67%</td>
<td>113%</td>
<td>100%</td>
<td>185%</td>
<td>156%</td>
<td>130%</td>
<td>79%</td>
<td>45%</td>
<td>113%</td>
<td>58%</td>
<td>100%</td>
</tr>
<tr>
<td><strong>Danish</strong></td>
<td>62%</td>
<td>119%</td>
<td>104%</td>
<td>178%</td>
<td>150%</td>
<td>134%</td>
<td>57%</td>
<td>49%</td>
<td>96%</td>
<td>66%</td>
<td>85%</td>
</tr>
<tr>
<td><strong>Jutland</strong></td>
<td>62%</td>
<td>114%</td>
<td>98%</td>
<td>177%</td>
<td>154%</td>
<td>128%</td>
<td>57%</td>
<td>49%</td>
<td>99%</td>
<td>63%</td>
<td>76%</td>
</tr>
<tr>
<td><strong>NCAR surf (wind)</strong></td>
<td>94%</td>
<td>110%</td>
<td>107%</td>
<td>127%</td>
<td>123%</td>
<td>109%</td>
<td>91%</td>
<td>82%</td>
<td>100%</td>
<td>88%</td>
<td>101%</td>
</tr>
<tr>
<td><strong>NCAR u10 (wind)</strong></td>
<td>93%</td>
<td>107%</td>
<td>104%</td>
<td>126%</td>
<td>119%</td>
<td>105%</td>
<td>90%</td>
<td>80%</td>
<td>97%</td>
<td>87%</td>
<td>98%</td>
</tr>
<tr>
<td><strong>NCAR surface (prod.)</strong></td>
<td>84%</td>
<td>127%</td>
<td>121%</td>
<td>189%</td>
<td>180%</td>
<td>124%</td>
<td>74%</td>
<td>50%</td>
<td>100%</td>
<td>65%</td>
<td>100%</td>
</tr>
<tr>
<td><strong>NCAR u10 (prod.)</strong></td>
<td>83%</td>
<td>119%</td>
<td>114%</td>
<td>192%</td>
<td>164%</td>
<td>112%</td>
<td>71%</td>
<td>49%</td>
<td>89%</td>
<td>60%</td>
<td>91%</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>75%</td>
<td>123%</td>
<td>116%</td>
<td>190%</td>
<td>167%</td>
<td>131%</td>
<td>70%</td>
<td>48%</td>
<td>101%</td>
<td>63%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 31 – Monthly values for all normal year correction indices used, regression correction method
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