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# Modeling the Weibull shape parameter to improve estimates of the annual wind energy potential in Sweden

**Bastian Berlin**

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Disclaimer

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Master thesis, 30 credits, in *Physical Geography and Ecosystem Analysis*

Supervisor
Jonathan Seaquist
Lund University, Department of Physical Geography and Ecosystem Science

Exam committee:
Andreas Persson & Vaughan Phillips
Lund University, Department of Physical Geography and Ecosystem Science

## Abstract

Wind energy is one of the fastest growing renewable energies in Sweden. To support this growth, it is essential to give stakeholders, such as investors, municipalities and policy planers, access to high accuracy and high-resolution wind speed data. Essential components for an accurate wind energy potential prediction are the average long-term wind speed and the probability of occurrence of wind speeds. The probability is usually modeled either by the Weibull probability density function (PDF) or the Rayleigh PDF. For the case of Sweden, the average wind speed and Weibull shape parameters, as the main components of the Weibull PDF were available. However, the accuracy of the shape parameter was unknown. This study evaluates whether there is a considerable difference between using the Weibull PDF or the Rayleigh PDF for assessing the annual wind energy potential at sites in Sweden. Due to the unknown accuracy of the shape parameter, a new model approach to model the shape parameter was proposed. A generalized additive model (GAM) was built out of the tested relationship between shape values at known locations and other geographical variables. It was tested if the modeled shape values resulted in a considerably more accurate energy prediction than the Rayleigh PDF. The results showed that the accuracy of the Rayleigh PDF was considerable lower than the one from the Weibull PDF and the GAM model PDF. The study also showed that the Rayleigh PDF is probably only a good representation for the wind conditions in the southern third of Sweden and it underestimated the potentials in the northern parts considerably. The GAM model seemed to perform well, had a high accuracy and it’s predicted values were in line with literature. It proved to be a good alternative to model the Weibull shape parameter and use it for wind energy potential predictions.

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## List of abbreviations

PDF - Probability density distribution

k - Shape parameter

c – Scale parameter

GAM - Generalized additive model

MIUU-model - Meteorological Institute Uppsala University model

CLC - Corine land cover

AIC - Akaike information criterion

GCV - Generalized Cross Validation

K-S test - Kolmogorov-Smirnov test

MAE - Mean absolute error

RMSE - Root-mean-square error

# 1.0 Introduction

Renewable energies have seen a steady growth in many countries during the last years, and certain technologies have been deployed more than others in various countries. The share of Sweden's national energy production attributable to wind energy grew from 1% in 2006 to 9% in 2016. The number of installed wind turbines increased from 86 in 1992 to 3334 in 2016 with an increase in annual energy yield from 0.027 TWh to 15.5 TWh for the same years (SEA. Energimyndigheten 2016). One of the essential components of planning new wind power plants is detailed knowledge about the energy potential of different locations.

The wind-derived energy has a cubed relationship with wind speed, which makes it crucial to accurately predict the local long-term wind conditions (Burton et al. 2011). The Swedish Energy Agency has supported stakeholders, such as for example municipalities and investors, by giving detailed information about average wind speeds for different altitudes (SEA. Energimyndigheten 2011). The data is based on the MIUU-model, a three-dimensional meso-scale higher order numerical model, developed at the Meteorological Institute of Uppsala University (MIUU) in Sweden. The model did not require additional input data from meteorological stations and simulated 192 days of hourly data to model a highly accurate average wind speed (Bergström and Söderberg 2008). The prediction of the wind energy potential is in general not only based on an accurate average wind speed but also on estimates of the probability of occurrence of wind speeds at a location. This is usually described by a Probability Density Function (PDF). It is generally agreed that the Weibull PDF results in a good estimate of the wind speed probability density at a site (Figure 1). The Weibull PDF consists of a scale (c) and a shape parameter (k). The scale parameter is related to the annual average wind speed. The shape parameter can be estimated using a sufficiently long-time series of wind measurements and is used to define the curvature of the PDF (Hau 2006; Burton et al. 2011; Masters 2013).

## 1.1 Aims and Hypotheses

This study aimed to investigate the impact on the annual energy potential in Sweden by using the different PDFs. They will be evaluated and compared at the meteorological stations in Sweden and for the whole country. One PDF is based on the simulated data of the MIUU-model, which was used to model the Weibull shape parameter for Sweden. It is referred as the Bergström and Söderberg (2008) PDF. However, the authors pointed out that the uncertainty of the parameter was high since the modeled time series was rather short. An actual accuracy assessment was never performed (Bergström and Söderberg 2008). Another PDF used in this study was the Rayleigh PDF. The annual wind energy potential of Sweden has been modeled in another study using the Rayleigh PDF instead of the Weibull PDF (Siyal et al. 2015).The Rayleigh PDF uses a fixed shape parameter of $k = 2$ and is used when not enough wind speed data is available to model the Weibull PDF (Hau 2006; Burton et al. 2011; Masters 2013). The authors of the study of Sweden's wind energy potential suggested that high resolution average wind speed data together with high resolution shape parameter values might increase the accuracy of the wind energy potential predictions (Siyal et al. 2015). It was possible to model the Weibull PDF based on the wind speed measurements at the meteorological stations in Sweden. The following hypothesis was formulated to test if using the Weibull PDF would result in a more accurate energy potential prediction.

> **$H_1$:** There is a considerable difference between using the Weibull PDF or the Rayleigh PDF for assessing the annual wind energy potential at a site.

In countries with an evolving wind energy market, researchers have often focused on creating wind atlases. Based on complex meteorological models, high resolution data such as average wind speeds and Weibull shape parameters were created for different altitudes (Krenn et al. 2011; Truhetz et al. 2012; Niemela et al. 2013).

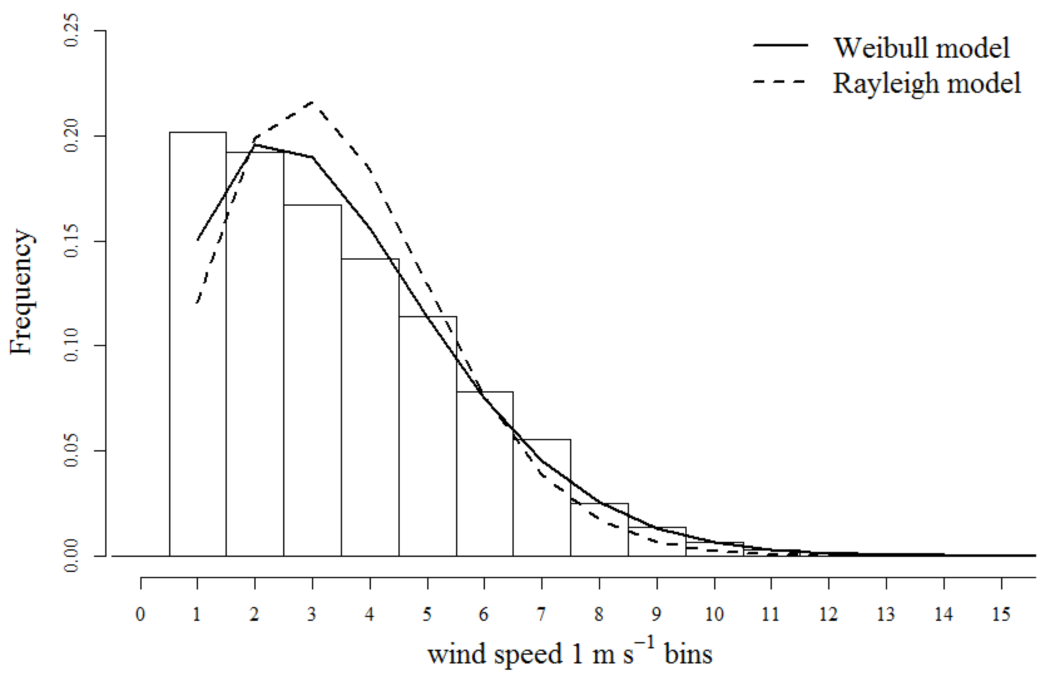


Figure 1: Wind speed histogram at Åmot station, Rayleigh PDF and Weibull PDF with a scale parameter of 5.4 and a shape parameter of 1.69. Wind data based on SMHI. Sveriges meteorologiska och hydrologiska institut (2017)

Since the MIUU-model might not have modeled the most accurate shape values, the aim of this study is to suggest a new and more accurate way of modeling the shape parameter. In contrast to the general approach, which used meteorological models, a generalized additive model (GAM) is proposed. Different geographic variables, such as latitude, elevation and surface roughness have an effect on the local wind conditions (Hau 2006; Burton et al. 2011). Therefore, the relationship between the shape parameter and these geographic variables, is tested. The shape values of the Weibull PDF based on data from the Swedish meteorological stations were used for this purpose. Based on the detected relationships, a GAM model was built to predict the shape parameter and then evaluated. The GAM model was referred to as the model PDF in this study. The following hypotheses were tested to support this approach.

> **$H_2$:** There is a correlation between geographical variables and the Weibull shape parameter.

> **$H_3$**: Modeled Weibull shape parameters based on geographical variables result in a considerably more accurate energy prediction than the Rayleigh PDF.

Based on previous research and the available data in Sweden, the following steps were undertaken to support ongoing research for wind energy. The last step was done to evaluate if a short, modeled time series was enough data to model the shape parameter successfully.

- It was tested if the annual wind energy potential in Sweden calculated using the Weibull PDF was more accurate than the annual wind energy potential calculated using the Rayleigh PDF.
- It was investigated if there was any relationship between the shape parameter and other explanatory variables.
- A GAM model to predict the shape parameter was built and its accuracy was evaluated and compared to the other PDFs.
- The Bergström and Söderberg (2008) PDF was evaluated and compared to the other PDFs.

## 2.0 Background

### 2.1 Wind energy potentials

Stakeholders, such as governments, municipalities and investors, have an interest in different forms of wind energy potentials or outputs for countries, regions or smaller areas. The wind energy potential can be categorized into five different formats (Table 1). A majority of these are some form of restriction or reduction scenario of the total energy content also called the theoretical potential. A potential analysis could be helpful in planning processes, policy frameworks and investment strategies.

Many factors might influence the installation and distribution of wind turbines in an area. Firstly, some areas might have more favorable wind conditions than others. Secondly, areas could be protected by law from the installation of wind turbines. Thirdly, the provision of a grid infrastructure might increase the building costs in certain regions or fourthly, there is a political support of other energy sources. The different potential analyses can help in investigating the effects of these and other factors and recommend still favorable areas for the installation of wind turbines. In this context this study analyzed if an improvement of the process of estimating the technical wind energy potential might affect the potential for wind turbines in certain areas. This study modeled the technical energy potential since it provided a more realistic estimate of a wind turbine's productivity at a location.

Table 1: Different wind energy potentials and their descriptions (Wijk et al. 1993; Mentis et al. 2015)

| Potential | Description |
|---|---|
| Theoretical potential | The total energy content of the wind (W $m^{-2}$ swept area). |
| Geographic potential | The area available for wind turbine installation based on geographical constraints e.g. urban areas, steep slopes etc. ($km^2$). |
| Technical potential | The annual energy generated by a wind turbine after including losses based on technical constraints and the power density of the wind turbine (kWh $year^{-1}$). |
| Economic potential | The technical potential that takes for example the cost of alternative energy sources into account (kWh $year^{-1}$). |
| Implementation potential | The amount of economic potential that can be implemented within certain time restrictions, institutional constraints, policy frameworks and supportive incentives (kWh $year^{-1}$). |

## 2.2 Implementation of the Weibull PDF

One of the most crucial pieces of information for all wind energy potential analyses is detailed and preferably high resolution data about the wind conditions of the study area (Burton et al. 2011). The optimal case is to have long-term wind measurements, which cover the whole area, to be able to estimate the wind characteristics and based on that, their potential. Usually a 30-year period is considered necessary to estimate long-term wind conditions at a site. However, at least 5 years of data, or in other cases 10 years, can be sufficient to get an acceptable estimate. (Manwell et al. 2009; Burton et al. 2011)

One way of estimating the probability of occurrence of wind speeds, is by using the Weibull PDF (Hau 2006; Burton et al. 2011; Masters 2013). Both, scale and shape parameter are used to model the Weibull PDF. The shape parameter decides on the curvature of the PDF (Figure 2). A change in the shape parameter might therefore have a substantial impact on the estimated potential. If only the average wind speed is available for a site, the Rayleigh PDF is used. It is a special case of the Weibull PDF with a scale parameter based on the average wind speed and a fixed shape parameter of k = 2, like it can be seen in Figure 2 (Hau 2006; Burton et al. 2011; Masters 2013). A lower shape value indicates a more even spread of the wind speed probabilities. A value around k = 2 if often found in areas, which have an occasional storm, which would be less frequent when the shape value further increases.

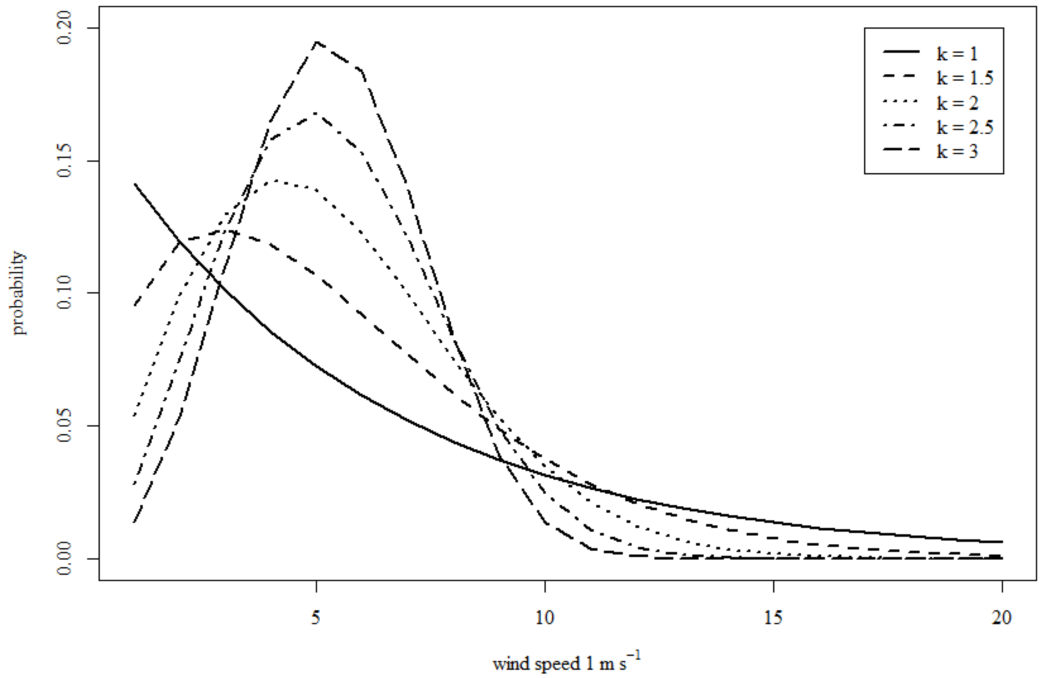


Figure 2: Weibull PDF with a scale factor of 6 and different shape parameters k = 1, 1.5, 2, 2.5, 3. The Rayleigh PDF is based on k = 2

In most studies where the wind energy potential for areas is modeled, the Rayleigh PDF is assumed instead of the Weibull PDF (EEA. European Environment Agency 2009; Sliz-Szkliniarz and Vogt 2011; McKenna et al. 2014; Siyal et al. 2015). This method is used due to the lack of time series of wind speed data for entire areas. The theoretical impact of using the Rayleigh PDF was tested by using different shape parameters (k = 1.75–2.4) within a sensitivity analysis (EEA. European Environment Agency 2009). It showed that for annual wind speeds between 5 m $s^{-1}$ and 11 m $s^{-1}$ the variance in full load hours was less than 10 %. Full load hours refer to the amount of hours a turbine is on full capacity in a year. Yet, studies demonstrated that complex meteorological models can be used to create wind speed time series for whole areas and the Weibull shape parameter was modeled based on these time series (Bergström and Söderberg 2008; Krenn et al. 2011; Niemela et al. 2013; Mentis et al. 2015). The goal of these models was usually to create a so-called wind atlas with a high spatial resolution. A wind atlas can give information about the average wind speed, major wind directions and shape parameters for different altitudes above ground. The meteorological models were usually a combination of a mesoscale model with a low resolution together with a downscaling method to account for the small-scale variations in wind conditions (Krenn et al. 2011; Niemela et al. 2013; Mentis et al. 2015). However, the problem with this approach was that the models did not always create long enough time series to model the true long-term variation of wind speeds (Bergström and Söderberg 2008; Mentis et al. 2015).

Table 2 gives an overview of different studies, which were mainly done to create a national wind atlas. The studies showed how Weibull shape parameters can be calculated based on modeled wind speed data and evaluated. All the mentioned studies had either no attempt to model the Weibull PDF or meteorological models were used to simulate wind speed data for the Weibull PDF and other wind characteristics. The models were able to simulate in some cases a large amount of data with a rather high resolution. However, most studies only evaluated the wind speed measurements and not the shape parameter, which might be problematic due to the cubed relationship between energy and wind. This might increase the uncertainty for stakeholders to use such data since the error in the energy potential might be higher.

Table 2: Summary of literature concerned with the modeling and implementation of the Weibull shape parameter and its evaluation

| Study area and resolution | Implementation of Weibull PDF | Error and evaluation |
|---|---|---|
| **Mentis et al. (2015)** | | |
| Africa, 6 km x 6 km | Daily wind speed data for one year (1° x 1° resolution) combined with average wind speed data (6 km x 6 km res.) and bilinear interpolation. | Comparison of the technical energy potential based on the Weibull PDF and Rayleigh PDF resulted in differences of 5% along the whole continent, but with maxima of more than 100% at certain locations. |
| **Niemela et al. (2013)** | | |
| Finland, 250 m x 250 m for various altitudes | 3-hour average wind speed data for 2 years based on a meso-scale model (2.5 km x 2.5 km res.) with a downscaling approach. | Evaluated for a few meteorological stations with an average error of ±0.3 m s-1 at coastal sides and only 1% inaccuracy at inland sites |
| **Krenn et al. (2011); Truhetz et al. (2012)** | | |
| Austria, 100 m x 100 m for various altitudes | Wind speed data modeled for 10 years based on a hybrid dynamical geo-statistical model (2 km x 2 km res.) combined with station data (254 stations), in combination with a downscaling approach and error corrections. | The goodness of fit of the Weibull PDF was evaluated by the Kolmogorov-Smirnov test (average D-value of 0.36). Cross-validation for the average wind speed as standard variation of 0.8 m s-1 |
| **Bergström and Söderberg (2008)** | | |
| Sweden, 1 km x 1 km for various altitudes | Hourly wind speed data modeled for 192 days based on a three-dimensional meso-scale numerical higher-order closure model. Did not use any station data as input. | Average difference between measurements from stations and the model. For 87 % of the comparisons the differences were within ±0.4 m s-1. |

## 2.3 Process and components of calculating wind energy potentials

The process of estimating the annual wind energy potential at a site included several steps and additional information about the local wind conditions and in most cases about a specific wind turbine. Wind speed is usually measured at 10 m station height every 10 minutes, from which hourly averages are calculated. Since most wind turbines have a hub height ranging from 60 m to 100 m, the wind speed is adjusted for the additional gain in altitude. This was done by implementing the roughness from the ground cover at the locations and either applying the logarithmic height formula (Hau 2006). The wind speed measurements are generally represented in histograms with 1 m $s^{-1}$ bins and their frequency of occurrence. The frequency was calculated for each of these bins, which included all the values ±0.5 m $s^{-1}$ around each bin value. As already mentioned, the probability of the occurrence of wind speeds is given by the Weibull PDF or the Rayleigh PDF. The Rayleigh PDF is assumed to be the most common PDF for wind conditions and is supposed to be a good fit for most wind sites (Chang 2011; Masters 2013; Bilir et al. 2015). However, Figure 1 shows one example of a site where the wind conditions did not follow the Rayleigh PDF but instead the Weibull PDF resulted in a better fit.

Information about the wind conditions is enough to calculate the theoretical wind energy potential but this information by itself is not very useful for any stakeholder. The technical potential is based on the theoretical potential but places it in relation to the energy a wind turbine can harvest. For that, an essential part of calculating the technical wind energy potential is information about a specific wind turbine type. Wind turbines are mostly built to fit specific wind conditions and so a wind energy potential scenario only covers the case of the chosen wind turbine model.

Each turbine model has a unique power curve describing how much energy is harvested for a range of wind speeds. The power curve incorporates the efficiency of the energy conversion, the optimized speed in comparison to a certain wind frequency and the power limits of the electrical generator. Additionally, the cut in wind speed and cut out wind speed are the thresholds of power production, insuring that strong winds are not damaging the turbine but also a certain minimum energy is produced (Hau 2006). The maximum efficiency of extracting power from the wind is 59.3% and called the Betz' law. The actual efficiency from a turbine is in general much lower and is usually given by the turbine manufacturer in form of a coefficient of power. The power coefficient is the ratio between the energy in the wind and the energy the wind turbine can extract (Masters 2013; Carrillo et al. 2014).The product of the Weibull or Rayleigh PDF and the power curve multiplied by the number of hours per year results in the technical annual energy potential at a location for a specific wind turbine. Additionally, maintenance times and other stand still times can be incorporated, but should not be higher than 5% of the full operating time (Hau 2006; Siyal et al. 2015). The result is an estimate of the technical wind energy potential.

# 3.0 Methods

## 3.1 Study area

Sweden is a northern European country with a small population in comparison to its area. Vast areas are covered by forests and lakes and the level of urbanization is rather low (Figure 3C). The country is divided into 21 counties and there appear some large regional differences considering the distribution of different land covers. Most arable areas are in the southern third of the country, mainly in the most southern county and around the largest two lakes “Vänern” and “Vättern” and on the largest island Gotland. The northern two-thirds are mostly covered by forest, lakes and wetlands. The highest elevations with around 2000 m to 2100 m can be found in the northwest and west (Figure 3B).

Sweden’s long coast line, the long mountain chain in the west and the areas around the large lakes might provide favorable conditions for wind turbines. However, the dense forest cover might have a negative effect on wind conditions, due to the higher surface roughness (Silva et al. 2007). Sweden showed a steady growth in wind energy with a share of 9% in 2016 of the national energy production. In the same year there were in total 3334 wind turbines installed, with an annual energy yield of 15.5 TWh (SEA. Energimyndigheten 2016). The distribution of the energy yield and the wind turbines per county is displayed in Figure 3A. There appears to be clear differences between the counties in how many wind turbines were installed and how much energy was produced. Mainly the counties on the west coast and the counties in the northern parts of Sweden had the largest share of turbines and energy yield. Counties with long coasts did not necessarily install more wind turbines than counties with less coastline, even though coastal conditions might be favorable for wind turbines. Counties with access to mountain areas also seem to have a larger number of wind turbines installed.

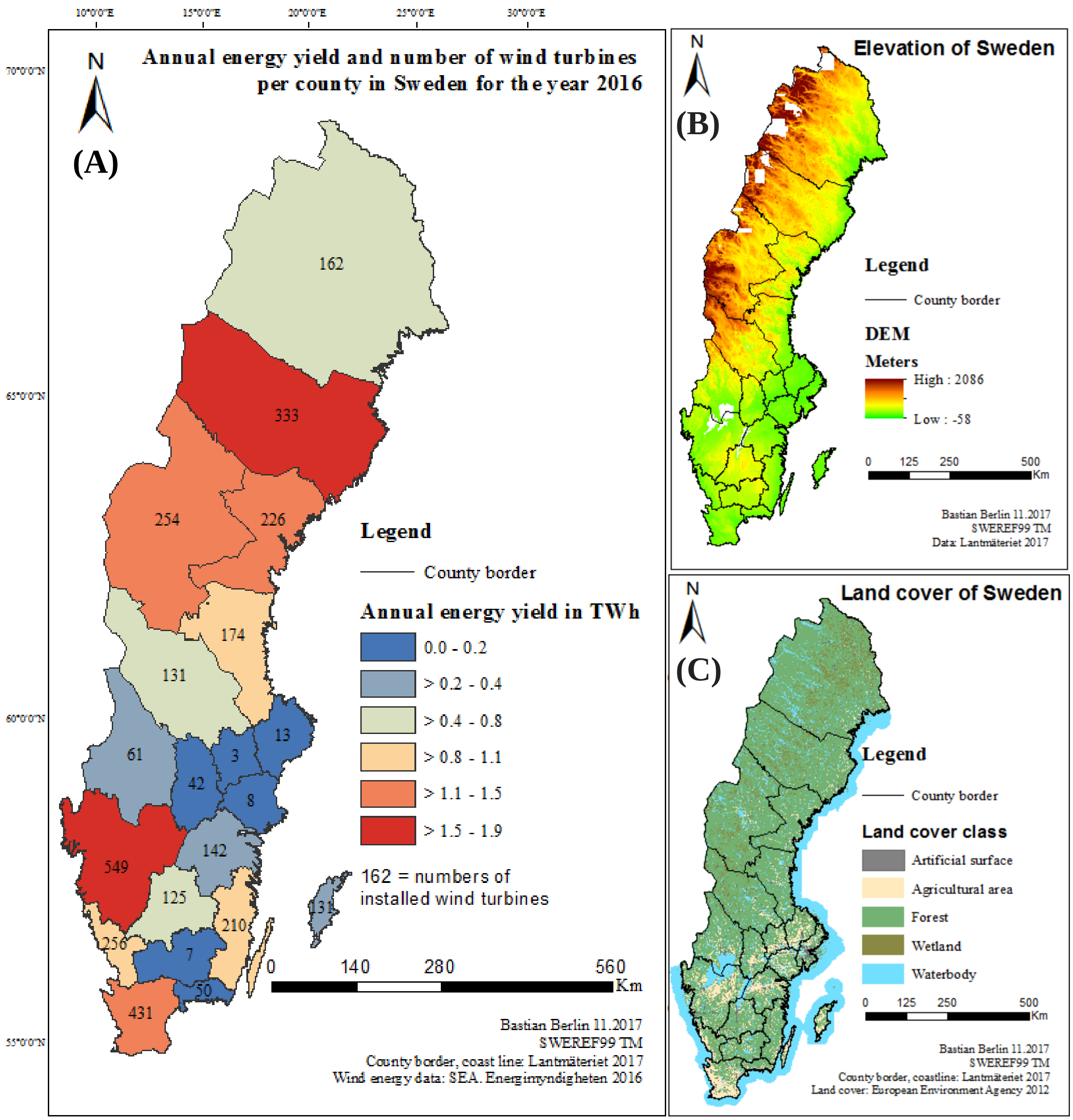


Figure 3: Annual energy yield and number of wind turbines per county in Sweden for the year 2016 (A). Elevation of Sweden (B) and Sweden's land cover (C)

### 3.2 Data and model variables

The simplest approach to describe wind is by looking at it as a result of pressure differences due to irregular surface heating by Sun energy and the influence of the Coriolis force as a result of the earth's rotation. The distribution of continents and oceans creates a global wind pattern, which is influenced by more regional and local geographic features such as mountains and plains, smaller water bodies and on an even more local scale, the effects of surface objects such as forests and urban constructs (Burton et al. 2011). This multitude of factors, their different scales, distributions and impacts makes it so hard to accurately predict and analyses the characteristics of wind. The following data and variables were considered to be of importance for the analysis and modeling of the Weibull shape parameter. Additional information about these variables is summarized and listed in Table 3.

**Wind speed data:** Wind speed data were obtained for 165 meteorological stations from the Swedish Meteorological and Hydrological Institute (SMHI. Sveriges meteorologiska och hydrologiska institut 2017). The stations were chosen based on data availability for a sufficiently long time period. The obtained wind speed data were in form of hourly averages for the period between 01.01.2011 – 31.12.2016, which was assumed to be a sufficient time sequence to obtain a representative state of the local wind conditions. The station data seemed to be of two different qualities. A median analysis of the hourly station data indicated that 51 stations measured wind speed in integers and the rest in decimals with one digit after the comma. In addition, the annual wind speed average at 90 m altitude for the whole of Sweden was obtained from SEA. Energimyndigheten (2011). The wind speed was calculated based on the modeled data of the MIUU-model (Bergström and Söderberg 2008).

**Latitude:** Latitude in a global context plays a major role for analyzing wind patterns since for example, wind fluctuations are higher in the medium continental latitude due to the impact of incoming low pressures. The spatial variability is mostly due to the different climatic regions in the world, which is best characterized by the latitude (Hau 2006; Burton et al. 2011). The latitude information was included for each meteorological station.

**Longitude:** Longitude was used as a variable for capturing the influence of the western mountain range bordering the neighbor country Norway. The mountains might have a large influence on the weather and climate conditions in Sweden since they are a climatic barrier between the Atlantic Ocean and Sweden. This might result in differences in wind speed distributions in the mountains, close to the mountains and far away from them. The longitude information was included for each meteorological station.

**Distance to sea/larger water bodies:** Coastal regions are usually windier than inland regions for the reason of differences in heating over water and land surfaces. Coastal regions receive cool sea air flowing inlands during the day and cold airflows from inlands to the sea during the night, due to air pressure differences based on thermal effects (Hau 2006; Burton et al. 2011). The distance to the sea or large water bodies was used as a variable to incorporate this impact on the variations in wind speeds. Sweden has large amounts of smaller and larger water bodies and a very long coastline. Even a small water body might have an effect on the local wind pattern but in this study only the effects of large water bodies were considered. To emphasize this, only the actual sea and the two largest lakes “Vänern” and “Vättern” were considered in this study. The Euclidean distance to the chosen water bodies was calculated in 50m steps to be coherent with the resolution of other datasets.

**Elevation:** Higher wind speeds are usually experienced on top of mountains or hills and lower wind speeds in valleys and on lee sides of higher elevations. The reason is a general increase of wind speeds with increasing altitudes and mountain tops reaching into these layers of higher wind speeds. In addition there is an acceleration effect of the wind flow on top and the surroundings of hills and mountains (Troen and Petersen 1989; Burton et al. 2011). The elevation information was included for each meteorological station. Elevation data for the rest of Sweden was obtained from Lantmäteriet (2004) but included some data gaps mostly in the northwestern mountains. The data were aggregated by the mean to fit the 500 m resolution of the wind speed data.

**Slope:** Steep slopes can increase wind speeds, especially in the range of slopes of 1:3 to 1:4 (Hau 2006; Manwell et al. 2009). Slope was calculated based on the elevation data from Lantmäteriet (2004). It was calculated with the help of ArcGIS, which calculated the slope for the center cell of a 3x3 matrix based on the change of the horizontal and vertical directions of the surface from the center cell (ESRI ArcGIS 2016). The basic formula for calculating the slope is:

$$slope = a\tan(\sqrt{([dz/dx]^2 + [dz/dy]^2)}) \cdot \frac{180}{\pi} \quad (1)$$

($dz/dx$) = horizontal surface

($dz/dy$) = vertical surface

**Surface roughness:** The surface roughness has an important impact on a very local scale since obstacles such as trees or buildings are reducing the wind speed significantly (Troen and Petersen 1989; Burton et al. 2011). The surface roughness was used in the form of the roughness length and the roughness length values were obtained based on the study of Silva et al. (2007)

(Table 4). The surface cover, corresponding to the roughness length is based on the Corine land cover (CLC) with a 20 m resolution (EEA. European Environment Agency 2012).

**Average wind speed / Scale parameter:** Since the Weibull PDF consists of the scale parameter, based on the average wind speed and the shape parameter, it might be beneficial for the model to analyze this relationship. Based on this, exploring the influence of the average wind speed in form of the scale parameter might yield additional information.

**Weibull shape parameter based on Bergström and Söderberg (2008):** The MIUU-model for average wind speed was also used to model the Weibull shape parameter. It models 4608 hourly wind speed values from which the Weibull values were estimated. The authors pointed out that the time series might not be sufficiently long to model the Weibull parameters and that some areas might be underestimated (Bergström and Söderberg 2008). The values were used as a comparison to the values modeled in this study and were referred as, the Bergström and Söderberg (2008) PDF.

**Table 3:** Data and Model variables, their unit, coverage, resolution, estimated error and source

| Variable | Unit | Coverage | Resolution | Error | Source |
|---|---|---|---|---|---|
| Wind speed | $m\ s^{-1}$ | Met. stations | - | ±2 % RMSE | SMHI (2017) |
| Ave. wind speed | $m\ s^{-1}$ | Sweden | 500 m | - 0.03 $m\ s^{-1}$ ave. diff. | SEA. Energimyndigheten (2011) |
| Latitude | dd | Met. stations | - | - | SMHI (2017) |
| Longitude | dd | Met. stations | - | - | SMHI (2017) |
| Elevation | m | Met. stations | - | - | SMHI (2017) |
| Elevation | m | Sweden | 50 m | 2.5 SE | Lantmäteriet (2004) |
| Distance to water | m | Sweden | 50 m | ≤ 25 m | Based on EEA. European Environment Agency (2012) |
| Slope | degrees | Sweden | 50 m | 1.57 SE | Based on Lantmäteriet (2004) |
| Surface roughness | roughness length m | Sweden | 10 m-25 m | 0.5 of resolution | (Silva et al. 2007; EEA. European Environment Agency 2012) |
| Weibull shape | unit less | Sweden | 1 km | - | Bergström and Söderberg (2008) |

**Table 4:** Corine Land Cover classes, their codes and roughness length (m). Based on Silva et al. (2007)

| **CLC Classes** | **CLC Codes** | **Roughness Length** $z_o$ **(m)** |
|---|---|---|
| Continuous urban fabric | 111 | 1.2 |
| Broad-leaved forest; Coniferous forest, Mixed forest | 311;312;113 | 0.75 |
| Green urban areas; Transitional woodland/shrub; Burnt areas | 141;324;334 | 0.6 |
| Discontinuous urban fabric; Construction sites; Industrial or commercial units; Sport and leisure facilities; Port areas | 112;133;121;142;123 | 0.5 |
| Agro-forestry areas; Complex cultivation patterns; Land principally occupied by agriculture, with significant areas of natural vegetation | 242;243;244 | 0.3 |
| Annual crops associated with permanent crops; Fruit trees and berry plantations; Vineyard; Olive groves | 241;221;222;223 | 0.1 |
| Road and rail networks and associated land | 122 | 0.075 |
| Non-irrigated arable land; Permanently irrigated land; Rice fields; Salt marshes | 211;212;213;411;421 | 0.05 |
| Sclerophylous vegetation; Moors and heathland; Natural grassland; Pastures | 321;322;323;231 | 0.03 |
| Dump sites; Mineral extraction sites; Airports; Bare rock; Sparsely vegetated areas | 131;132;124;332;333 | 0.005 |
| Glaciers and perpetual snow | 335 | 0.001 |
| Peat bogs; Salines; Intertidal flats | 422;412;423 | 0.0005 |
| Beaches, dunes, and sand plains | 331 | 0.0003 |
| Water courses; Water bodies; Coastal lagoons; Estuaries; Sea and ocean | 511;512;523;522;521 | 0 |

### 3.3 Wind turbine specifics

The technical wind energy potential is always based on a specific wind turbine since some of the turbine specifics are needed for the calculation process of the energy yield. Since the technical wind energy potential for Sweden was already calculated in the study from Siyal et al. (2015), a similar wind turbine model was used for the wind energy potential calculations. The Vestas V112 3075 onshore with a hub height of 94 m and a maximum power yield of 3075 kW is used in this study (Windenergie im Binneland 2017). Additional wind turbine specifics are listed in Table 5.

Table 5: Specifications of the Vestas V112 3075 onshore (Windenergie im Binneland 2017)

| **Specification type (unit)** | **Quantity** |
|---|---|
| Rated power yield (kW) | 3075 |
| Hub height (m) | 94 |
| Rotor diameter (m) | 112 |
| Swept area ($m^2$) | 9852 |
| Cut in wind speed ($m\ s^{-1}$) | 3 |
| Rated wind speed ($m\ s^{-1}$) | 12 |
| Cut out wind speed ($m\ s^{-1}$) | 25 |

The wind energy potential was calculated for a hub height of 90 m, since average wind speed coverage for Sweden is only available for 90 m heights and not for the 94 m hub height of the wind turbine. Additionally to the turbine specifics, one of the necessary information's to assess the wind energy at a site is the power curve of the chosen wind turbine (Figure 4). The figure shows how much energy there is in the wind and how much the turbine can harvest maximum. The plotted Rayleigh PDF puts that in relation to the probability density of the wind speeds.

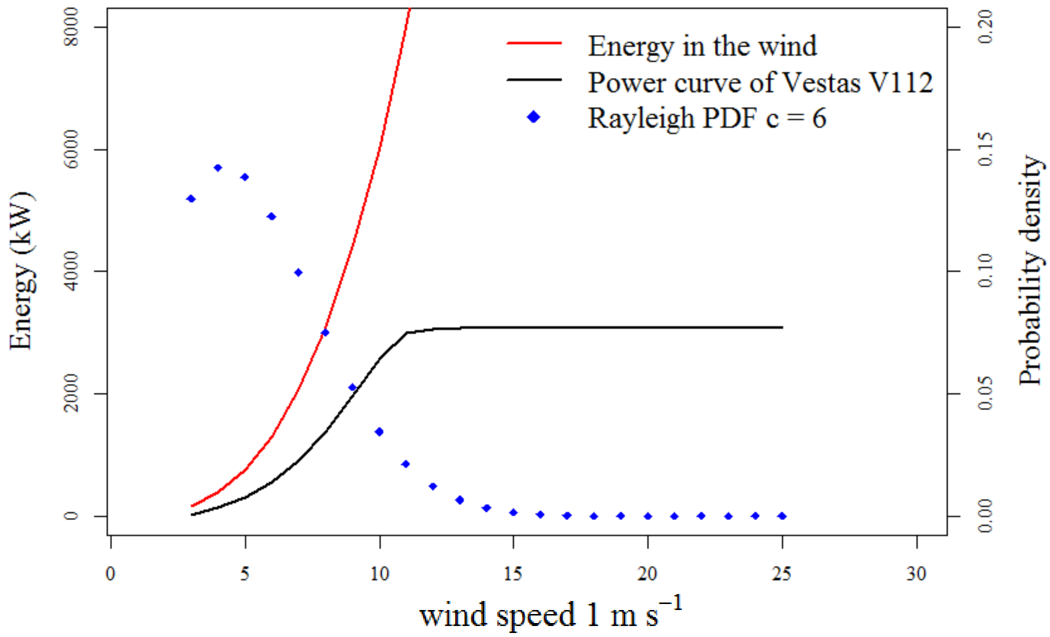


Figure 4: Power curve of the Vestas V112 onshore, the available Energy in the wind and the Rayleigh PDF with a c value of 6 (Windenergie im Binneland 2017)

### 3.4 Increasing wind speed with altitude

With an increase in height there is an increase in wind speed, which needs to be accounted for when calculating wind energy at a certain hub height. This adjustment can be calculated by incorporating the surface roughness, represented by the roughness length. One of the most common ways to describe the relationship between increasing height and increasing wind speed is by using the logarithmic height formula (Formula 2) (Hau 2006).

$$\bar{v}_H = \bar{v}_{ref} \cdot \frac{\ln \frac{H}{z_o}}{\ln \frac{H_{ref}}{z_o}} \tag{2}$$

$\bar{v}_H$ = mean wind velocity at elevation $H$ (m s$^{-1}$)

$\bar{v}_{ref}$ = mean wind speed at reference elevation $H_{ref}$

$H$ = height at turbine hub (90 m)

$H_{ref}$ = reference elevation at station (10 m)

$z_o$ = roughness length (m)

ln = natural logarithm (base $e$ =2.7183)

The logarithmic height formula is appropriate for the boundary layer closest to the ground and under the assumptions, of for instance, atmospheric stability and a good representation of the surface cover by the roughness length. Nevertheless it yields one source of error since the formula might underestimate wind speeds with increasing heights larger than 60 m (Hau 2006). The roughness length of a site should in general be computed by inspecting the surface cover at the site and its surroundings but can also be estimated by land cover classes (Silva et al. 2007). Table 4 shows the CLC classes, their codes and the proposed roughness length. The wind speed data for every station was calculated for 90 m hub height and based on the roughness length extracted from the CLC.

### 3.5 Weibull and Rayleigh PDF for wind speed

The actual wind speed frequency was calculated for each 1m s$^{-1}$ bin by incorporating values ±0.5 m s$^{-1}$ around each bin value (Masters 2013). The Weibull PDF can be calculated as follows:

$$f(v) = \frac{k}{c} \cdot \left(\frac{v}{c}\right)^{k-1} \cdot e^{-\left(\frac{v}{c}\right)^{k}} \quad (3)$$

$f(v)$ = Weibull PDF
$v$ = wind speed for 1m s$^{-1}$ bins
$k$ = shape parameter
$c$ = scale parameter

The scale and shape parameters can be estimated by different methods. Performance comparisons between the most common methods showed that most methods result in satisfying performances (Chang 2011; Carrillo et al. 2014; Bilir et al. 2015). Nevertheless, two studies suggested to use the maximum likelihood estimation since it performed best out of the different methods (Seguro and Lambert 2000; Chang 2011). The maximum likelihood method uses a considerable amount of iterations to calculate the best fit for the Weibull scale and shape parameters (Formula 4 and 5).

$$k = \left[\frac{\sum_{i=1}^{n} v_i^k \ln(v_i)}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln(v_i)}{n}\right]^{-1} \quad (4)$$

$$c = \left(\frac{1}{n} \cdot \sum_{i=1}^{n} v_i^k\right)^{1/k} \quad (5)$$

$v_i$ = wind energy per time step (m s$^{-1}$ h$^{-1}$)
$n$ = number of non-zero data points

Without detailed wind speed measurements at a site, the usual approach for a good representation is to use the Rayleigh PDF. It is a special form of the Weibull PDF with a fixed $k$ of 2 and a $c$ value, which in the case of the Rayleigh PDF can be calculated as follows (Masters 2013).

$$c = \frac{2}{\sqrt{\pi}} \cdot \bar{v} \cong 1.128 \cdot \bar{v} \tag{6}$$

$\bar{v}$ = average wind speed (m $s^{-1}$)

The Rayleigh PDF based on a $k$ =2 and $c$, which can be calculated as follows.

$$f(v) = \frac{\pi \cdot v}{2 \cdot \bar{v}^2} \cdot e^{-\frac{\pi}{4}\left(\frac{v}{\bar{v}}\right)^2} \tag{7}$$

### 3.6 Calculation of the annual wind energy potential

The power in the wind can be described by a mass flow at an assumed air density of 1.225 kg $m^{-3}$ moving at a wind speed through a cross sectional area of the rotor blade of a wind turbine (Formula 8) (Masters 2013).

$$P_w = 0.5 \cdot p \cdot A \cdot v^3 \tag{8}$$

$P_w$ = available energy in the wind (W)

$p$ = air density 1.225 kg $m^{-3}$

$A$ = cross sectional area 9852 $m^2$

In addition, an availability factor was added, which reflects for example times of maintenance, or other stand still times, where the turbine is out of order. An availability factor of 0.96 was considered suitable for this analysis (Hau 2006; Katsigiannis and Stavrakakis 2014; Siyal et al. 2015). The final calculation summed up the product of the Weibull PDF together with the available energy in the wind and the coefficient of power. The sum was then multiplied by the availability factor and the amount of hours per year to receive the annual yield from the wind turbine (Formula 9). The same was done with the Rayleigh PDF the observed wind speed frequency and the shape values based on the MIUU-model (Bergström and Söderberg 2008).

$$E_w = \eta \cdot t \cdot \sum (P_w(v) \cdot f(v) \cdot cp(v)) \quad (9)$$

$E_w$ = annual energy production (Wh)

$\eta$ = availability factor 0.96

$t$ = hours per year 8760

$cp(v)$ = coefficient of power for each wind speed bin of 1 m s$^{-1}$

### 3.7 Generalized Additive Model

The generalized additive model (GAM) by Hastie and Tibshirani (1990) was used to model the Weibull shape parameter based on the relationship between the shape parameter and other geographic variables. It is a more flexible model approach, which does not assume a linear relationship between the dependent and the explanatory variables. Smoothing functions were fitted to the data in a shape that resulted in the best fit (Wood 2006). A scatterplot analysis of the shape parameter and the explanatory variables indicated that an assumption of non-linearity was preferable over the assumption of linearity. Based on this, a GAM was used with the general model structure as follows (Hastie and Tibshirani 1990):

$$g(\mu_i) = x_i^* \theta + f_1(x_{1i}) + f_2(x_{2i}) + f_3(x_{3i}, x_{4i}) + ... \quad (10)$$

$\mu_i = \mathrm{E}(Y_i)$ and $Y_i$ ~ some exponential family distribution

$Y_i$ = response variable

$x_i^*$ = row of model matrix for any parametric model component

$\theta$ = corresponding parameter vector

$f_j$ = smooth function of the covariate $x_k$

$\mu_i$ is the average of the response variable and $Y_i$ are the individual responses. The smooth link function $g(\mu_i)$ is in general part of a family distribution. $x_i^*$ is a row of model matrix for any parametric model components and $f_j$ are smooth functions of the covariate $x_k$. The Weibull shape parameter calculated for the 165 stations was tested for normality with the Shapiro-Wilk test, the Kolmogorov-Smirnov test (K-S test) and the Anderson-Darling test. They all indicated that the distribution for the shape parameter was normal and rejected the hypothesis that the data did not follow a normal distribution. Based on that, the GAM model was built with a Gaussian family distribution. A link function is used as a connector between the mean of the assumed normal distribution and the linear predictor (Wood 2006). The residuals based on a log-link and on an identity-link were tested by the same normality tests. Only using the log-link resulted in normally distributed residuals. The variables latitude, longitude, elevation, slope, distance to water, surface roughness and the scale parameter were tested for correlation with the shape parameter but also with each other. The Spearman's rank correlation coefficient test was used since it does not assume a linear relationship. A forward model variable selection approach, starting with the strongest correlated variable was used to find the most suitable set of variables. A plot of the residuals and the fitted values indicates that there were not trends in the residuals. The previously used tests for normality supported that the residuals were normally distributed.

### 3.8 Evaluation

The hypotheses **$H_1$** "There is a considerable difference between using the Weibull distribution or the Rayleigh distribution for assessing the annual wind energy potential at a site." and **$H_3$** "Modeled Weibull parameters based on geographical variables result in a more accurate energy prediction than the Rayleigh PDF" were evaluated by the same steps, with only one additional step to test the **$H_3$** hypothesis.

The hypothesis **$H_2$** "There is a correlation between geographical variables and the Weibull shape parameter", was tested in two steps. Firstly, by the Spearman's rank correlation coefficient as mentioned in the model method section and secondly by building and evaluating a suitable GAM. The GAM was evaluated by the Akaike information criterion (AIC), the adjusted R-squared value and the generalized cross validation value (GCV) based on Golub et al. (1979).Firstly, the station data was split randomly into 75% (N=124) of the data as training data and 25% (N=41) as test data. The 75% input data were insuring that enough data was available for a reasonable model estimate. Secondly, the K-S test was used to test the null-hypothesis if the different PDFs were from the same distribution as the observed frequency distribution in the range of the cut-in and cut-out wind speeds (Corotis et al. 1978; Zhou et al. 2010; Truhetz et al. 2012; Jiang et al. 2017). The test is a nonparametric test of probability distributions, which tests if the input data is drawn from the same continuous distribution. The D-value of the test is the maximum vertical deviation between the two curves and averaged for all of the stations. The null-hypothesis is accepted with a 95% confidence interval if the D-value is below a critical level, which is calculated as follows (Lilliefors 1967, 1969).

$$H0_{0.95} = \frac{1.36}{\sqrt{n} + 0.12 + 0.11 \div \sqrt{n}} \quad (11)$$

$n =$ Number of bins for the probability distribution

Thirdly, the K-S test was also used to test if the model PDF, the Bergström and Söderberg (2008) PDF and the Rayleigh PDF were from the same distribution as the Weibull PDF at the 41 stations. This is done since the Weibull PDF was considered the best estimate for the observed wind speed distribution.

Fourthly, an evaluation of the model's sensitivity to input data was tested by splitting the station data in total 1000-times, instead of only once and calculating the technical annual energy potential at the stations. The mean, minimum, maximum and standard deviations of the 1000 model runs were plotted together with the energy potential based on the observations and the different PDFs. In addition to the model's sensitivity, the plot gave a first qualitative assessment of the accuracy of the different PDFs and made it possible to identify over- and underestimations. In addition to this more qualitative accuracy analysis, a quantitative accuracy analysis was performed. The root-mean-square-error (RMSE) and the mean absolute error (MAE) of the energy potentials at the stations were calculated based on the different PDFs.

Fifthly, the residuals of the technical energy potential at the stations based on the different PDFs and the observed potential were averaged and converted to percentage difference for each county in Sweden. This way, relative over- or underestimations in a more spatial sense might be detected.

Finally, the technical annual energy potential in Sweden for each 500*500 m grid cell was calculated based on the modeled PDF, the Rayleigh PDF and the Bergström and Söderberg (2008) PDF. The difference between the Rayleigh estimate and the model estimate and the Bergström and Söderberg (2008) estimate and the model estimate was calculated. Additionally, the percentage change was calculated. This value might give additional information about the relative differences between the PDFs and might help in identifying areas of high relative over- and underestimations.

# 4.0 Results

## 4.1 Correlation to geographical variables

The Spearman values of the correlation between the shape parameter and the latitude, the distance to water, the scale parameter and the elevation indicated a medium to strong relationship (Table 6). Surface roughness and slope showed almost no correlation. The only large correlation between the explanatory variables was between elevation and distance to water (0.91).

Table 6: Spearman's rank correlation coefficient (-1 – 1) between the Weibull shape parameter and the variables latitude, longitude, scale parameter, elevation, distance to water, surface roughness and slope, N=165

| **Spearman's rank correlation coefficient** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Variable** | Latitude | Longitude | Scale parameter | Elevation | Distance to water | Surface roughness | Slope |
| Shape | -0.63 | -0.22 | 0.46 | -0.44 | -0.59 | -0.06 | -0.01 |

## 4.2 GAM model results

The evaluation of the forward selection approach for the GAM models is displayed in Table 7. The best model (in bold) based on AIC, adjusted $R^2$ and GCV included the latitude, the longitude, the scale parameter and the elevation. A good model should have a high adjusted $R^2$, a low AIC and a low GCV score. Distance to water was excluded since it showed an overly high correlation with elevation and did not increase the adjusted $R^2$ as much as elevation did. All parametric coefficients and all smoothing terms were highly significant with a p value of ≤ 0.001.

Table 7: GAM models based on a forward variable selection approach and their goodness of fit, N=165.

| **Generalized Linear Model** | **AIC** | **Adj. R2** | **GCV** |
|---|---|---|---|
| Shape ~ f(Latitude) | -116.5 | 0.44 | 0.029 |
| Shape ~ f(Latitude)+Scale | -140 | 0.52 | 0.025 |
| Shape ~ f(Latitude)+Scale+f(Longitude) | -152 | 0.55 | 0.023 |
| **Shape ~ f(Latitude)+Scale+f(Longitude)+f(Elevation)** | **-172.5** | **0.62** | **0.020** |
| Shape ~ f(Latitude)+Scale+f(Longitude)+f(Elevation)+ Surface Roughness | -171 | 0.62 | 0.021 |
| Shape ~ f(Latitude)+Scale+f(Longitude)+f(Elevation)+Slope | -172.3 | 0.62 | 0.021 |

The predicted shape values were calculated out of an intercept of 0.62 and values added based on the modeled relationship between the shape parameter and the explanatory variables (Figure 5). Positive values on the y-axis increased the predicted shape values and negative number decreased it. The latitude added positive values in the south and high negative numbers the more north a location was. The residuals were mostly inside the 95% confidence band or at least close to it. The longitude added negative values in the west and slightly higher positive values in the east. The residuals showed a larger spread mostly outside the confidence interval and some even larger outliers. The scale parameter added mostly positive numbers the higher it got and was also the only linear relationship. However, the residuals for the lower values have a big spread and many outliers were detected. Low elevation adds negative values, which changed to positive values with elevations higher than 200m. The curve flattened towards higher elevation and started declining. Especially the lower elevations showed are large spread for the residuals.

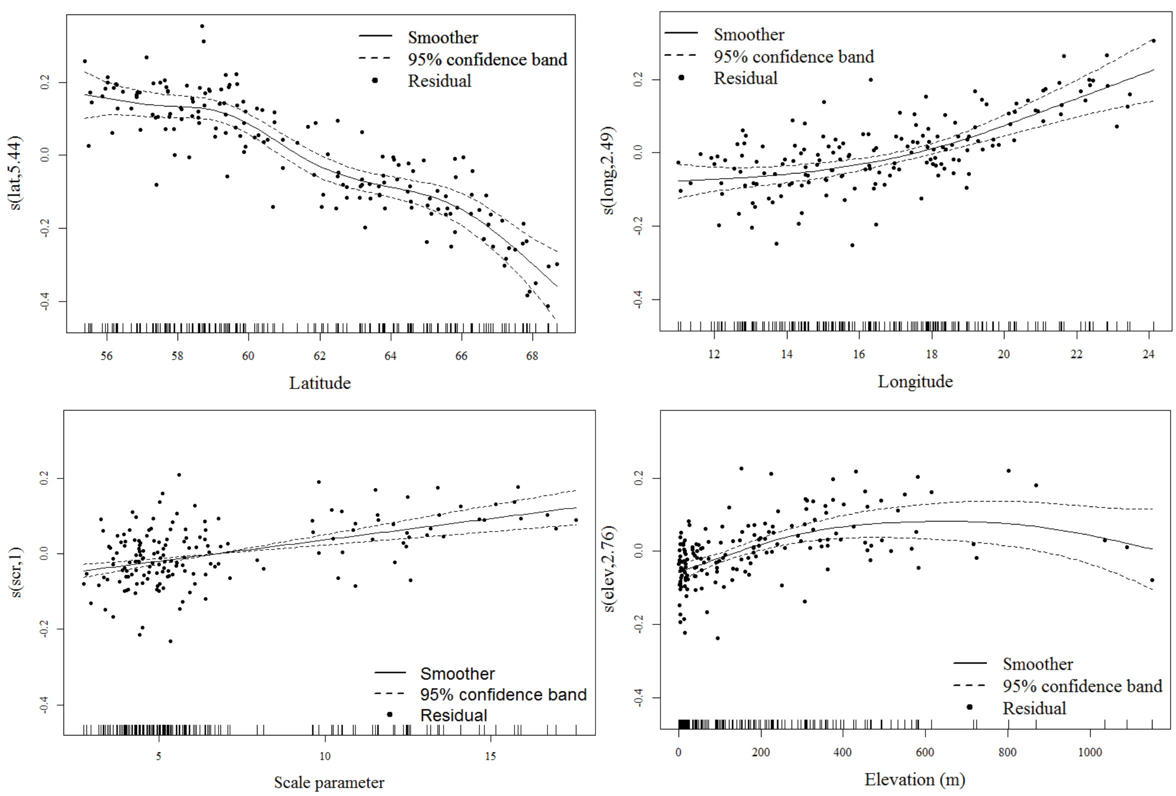


Figure 5: Smooth functions and residuals for the model variables latitude (A), longitude (B), scale (C) and elevation (D) for N=165 meteorological stations in Sweden

The final predicted shape values for Sweden are displayed in Figure 6. The southern third of the country and the coastal regions received mostly higher shape values in the range of 1.8 to 2.2. Shape values declined towards the north and the northwest and were the lowest in the most north-western areas of Sweden. In general were the values rather clustered and showed no large differences on a more local scale.

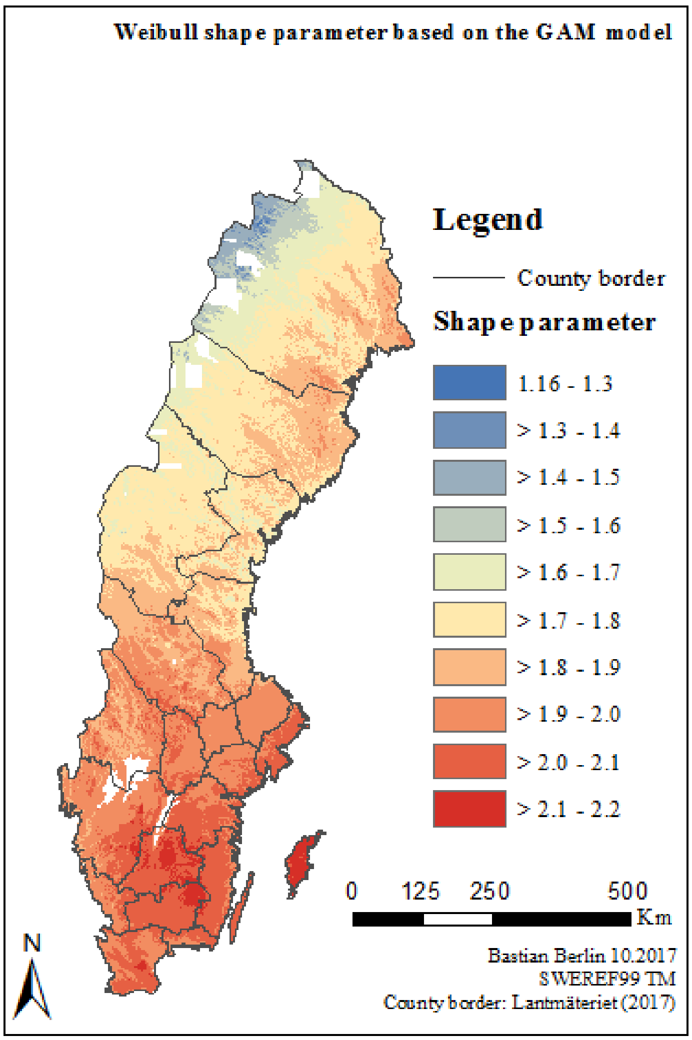


Figure 6: Modeled shape parameters for Sweden with a 500m resolution

### 4.3 Kolmogorov-Smirnov test of the PDFs

The K-S test was used for 41 random test stations, with the null-hypothesis that the PDFs are from the same distribution as the observed frequency with a 95% confidence. The Weibull PDF and the model PDF almost equally failed to reject the null-hypothesis for more than half of the stations. The null-hypothesis failed to be rejected for five stations fewer than the Bergström and Söderberg (2008) PDF than for the Weibull PDF. The Rayleigh PDF resulted in the least failures at the stations. The average D-value of the 41 stations was only below the critical value of 0.27 for the Weibull PDF and for the model PDF (Table 8).

Table 8: Mean Kolmogorov-Smirnov D-value and number of stations which are significantly (95%) similar to the observation frequency. N=41 random stations. Critical value = D < 0.27

| | **Probability density functions** | | | |
|---|---|---|---|---|
| **PDF** | Weibull PDF | Rayleigh PDF | Model PDF | Bergström PDF |
| **Mean D-value** | 0.25 | 0.31 | 0.26 | 0.29 |
| **No. of stations** | 24 | 16 | 23 | 19 |

The same test was performed to test the null-hypothesis that the PDFs are from the same distribution as the Weibull PDF since it was considered the best estimate for wind data. The null-hypothesis failed to be rejected for 40 out of 41 stations for the model PDF, 35 stations for the Bergström and Söderberg (2008) PDF and 35 stations for the Rayleigh PDF. The average D-value was 0.1 for the model PDF, 0.15 for the Bergström and Söderberg (2008) PDF and 0.18 for the Rayleigh PDF, which meant all average D-value led not to an rejection of the null-hypothesis.

### 4.4 Accuracy of the technical energy potential at the stations

The result of the model sensitivity analysis for input data and the technical energy potentials of the PDFs are displayed in Figure 6. The minimum and maximum values from the model runs, as well as the standard deviation envelope were close to the mean of the 1000-model-runs, which indicated low variation in output values based on differences in input values. Just very few stations were an exception to that and the minimum and maximum values were mostly not showing larger deviations than the Rayleigh PDF. Figure 6 also displayed a mainly good agreement between the modeled energy outputs and the observations, with a few peaks and troughs indicating a poor model fit at some of the stations. No strong indications of trends of under- or overestimations were detected. The annual energy potential based on the Weibull PDF was very close to the observations but showed small underestimations for the first 50 stations with the lowest observed annual energy output. Nevertheless, it resulted in the highest accuracy in comparison to the other PDFs. The Weibull PDF based on Bergström and Söderberg (2008) resulted in a mostly good fit for the first 50 stations but showed some larger overestimations for the stations 51 to 100 and a few extreme troughs for the stations 101 to 165, which had the highest observed energy output. The Rayleigh PDF resulted in the lowest agreement and in large underestimations in comparison to the observed energy potential for the stations 1 to 100. This improved towards the higher energy yields.

The RMSE and MAE values between the observed technical wind energy potential and the PDFs potentials are displayed in Table 9. The Rayleigh PDF RMSE was more than double and the MAE almost three-times as high as the Weibull PDF's. The model PDF showed also much lower values than the Rayleigh PDF but not as low as the Weibull PDF. The Bergström and Söderberg (2008) PDF resulted in the lowest accuracy of all of the PDFs.

Table 9: RMSE and mean absolute error for the technical annual energy potential (GWh) based on the observed wind speed frequency data and the calculations based on the Weibull PDF, the Rayleigh PDF, the model PDF and the Weibull PDF based on (Bergström and Söderberg 2008) for N=41 stations

| | **Weibull PDF** | **Rayleigh PDF** | **Model PDF** | **Weibull PDF (Bergström and Söderberg 2008)** |
|---|---|---|---|---|
| **Root-mean-square-error** | | | | |
| Energy potential (GWh) | 0.26 | 0.59 | 0.40 | 0.73 |
| **Mean absolute error** | | | | |
| Energy potential (GWh) | 0.17 | 0.43 | 0.27 | 0.52 |

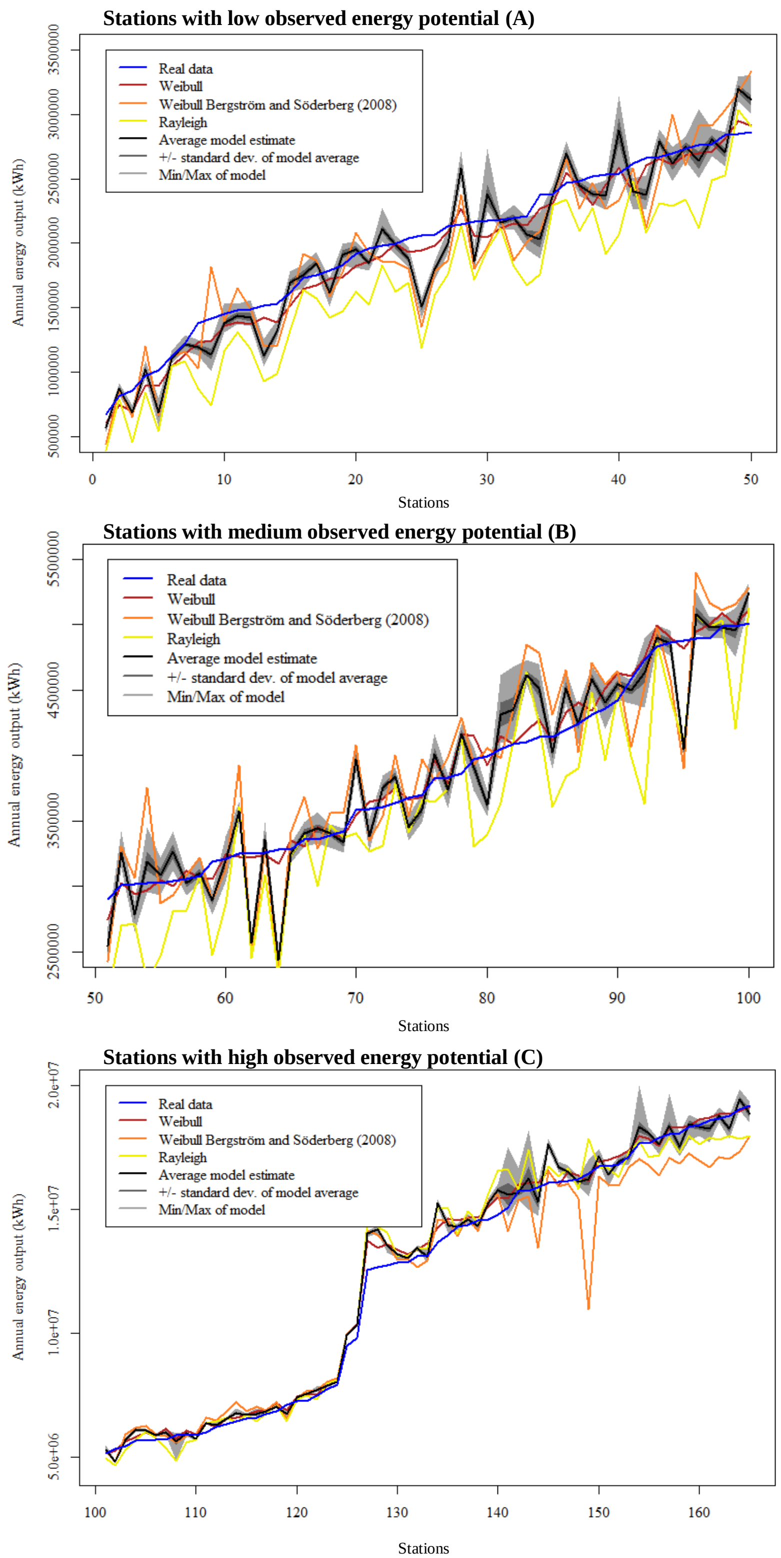


Figure 6: Model input sensitivity analysis based on 1000 model runs with a split in 75% train data (N=124) and 25% test data (N=41). The results (kWh) are compared with the potential based on the observed wind speed frequency (real data), the Weibull PDF, the Weibull PDF based on Bergström and Söderberg (2008) and the Rayleigh PDF for each of the 165 stations, in ascending order based on the observed energy potential (A-C)

### 4.5 County-level potential analysis based on the station data

The differences between the technical energy potential of the actual wind speed frequency and the calculations based on the Weibull PDF, the Rayleigh PDF, the model PDF and the Bergström and Söderberg (2008) PDF at the stations were averaged for each county in Sweden. Figure 7 shows the average difference in percent between the technical energy output of the observed wind speed frequency and the Rayleigh PDF for each county in Sweden. Negative values indicate an underestimation by the Rayleigh PDF and positive values overestimation. The map displays that almost two third of the country were greatly underestimated by the Rayleigh PDF with values ranging from -5 to -20.58%. The rest of the country, especially towards the south was mostly well-predicted with differences of ±5%. The map also displays the Weibull shape parameters based on the maximum likelihood estimation at the stations. It shows that most shape values in the southern parts of the country were close to the Rayleigh shape parameter, which included shape values of 1.9 to 2.1. Most shape values in the northern two-third were considerably lower than the Rayleigh shape parameter.

The average relative differences between the observed wind speed frequency and the Weibull PDF are displayed in Figure 8. No counties showed more than ±5% difference between the observations and the Weibull PDF. The range of the shape values was fairly high with the lowest value being 1.25 and the highest 2.38. Higher values occurred mostly in the southern third of the country and lower values in the rest of it. However there were some stations in the northern parts, which also had rather high values.

Figure 9 displays the average relative energy differences between the observed wind speed frequency and the model PDF. Most counties showed differences in the range of ±5%. There were only two counties in the central and central eastern part of Sweden with higher underestimations but these specific counties had also very few stations to take an average from. The modeled shape parameters resulted in similar values and spatial patterns than the shape parameters from the Weibull PDF. Nevertheless, the range of possible values was much shorter, with shape values from 1.42 to 2.29.

The average relative energy differences between the observations and the annual energy output based on Bergström and Söderberg (2008) is summarized in Figure 10. Most counties showed no more difference than ±5%. The same counties the model was underestimating were also underestimated by this PDF. Additionally, two counties in the central-west were higher overestimated. The shape parameters were generally lower, especially in the south, the west and also the far north. The range went from 1.0 to 2.0 and was much lower than the ranges from the Weibull PDF and the model PDF.

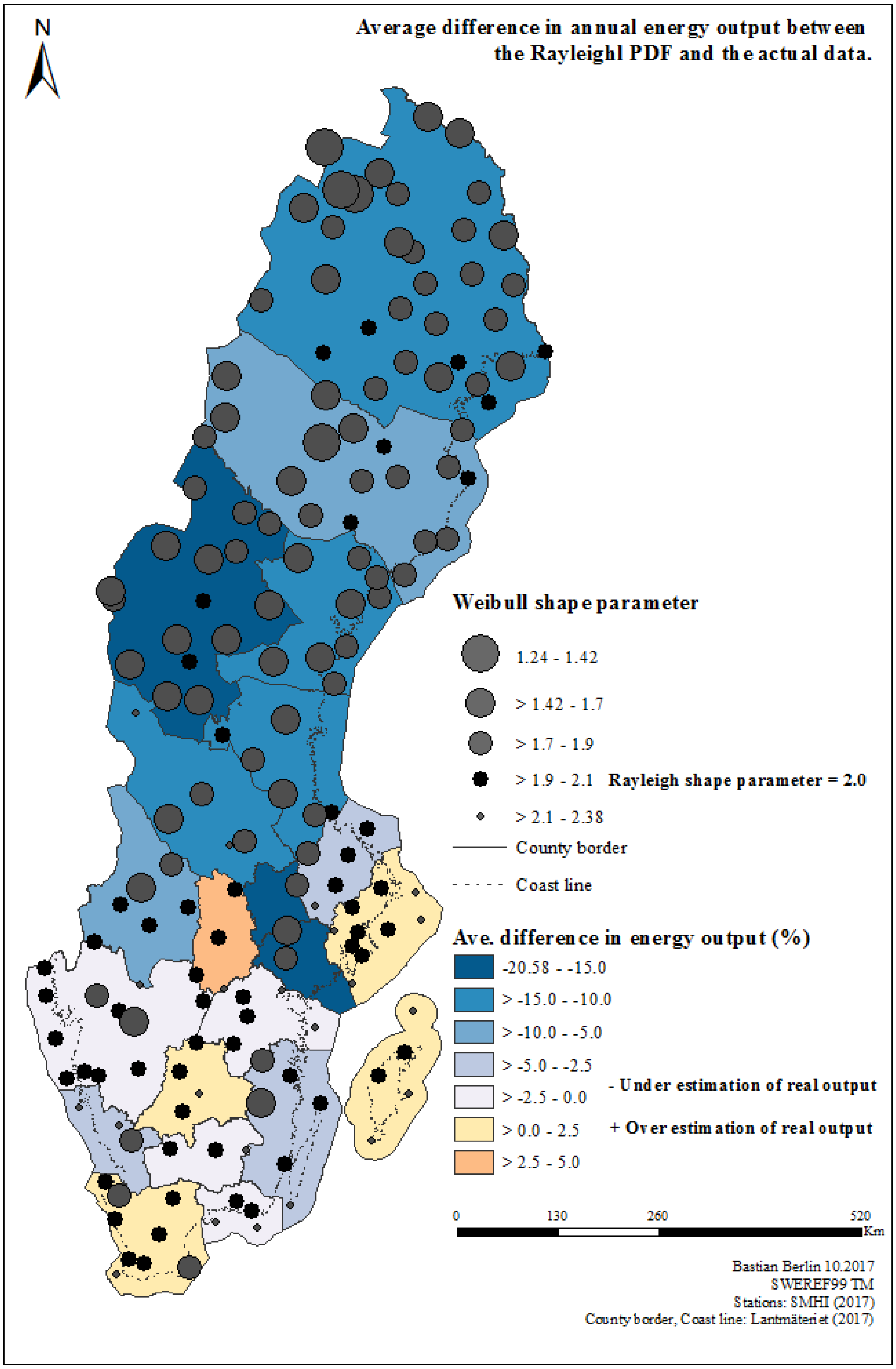


Figure 7: Average difference in annual energy output between the energy output based on the observed wind speed frequency and the Rayleigh PDF for each county in Sweden. In addition, the Weibull shape parameter is displayed

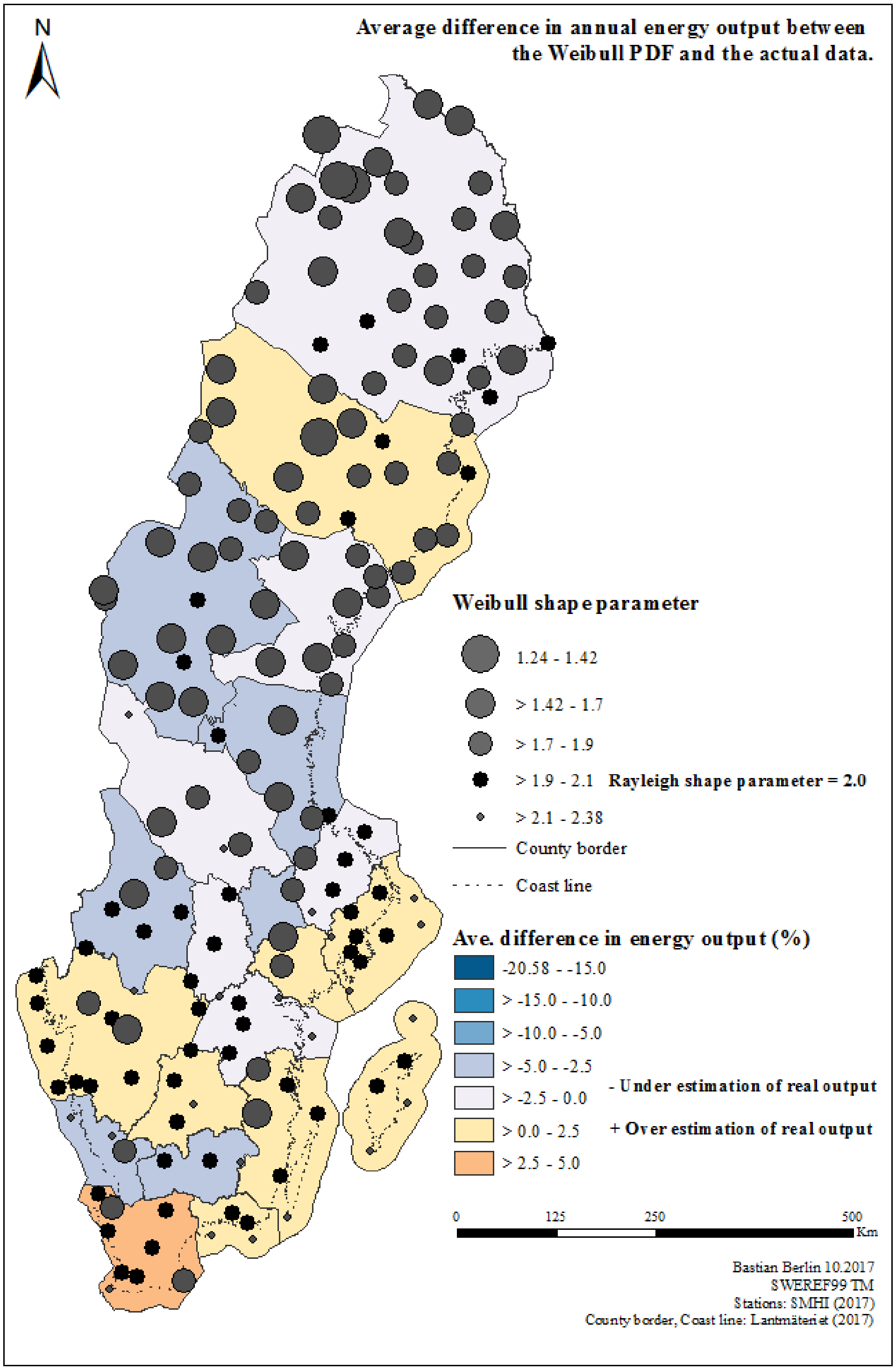


Figure 8: Average difference in annual energy output between the energy output based on the observed wind speed frequency and the Weibull PDF for each county in Sweden. In addition, the Weibull shape parameter is displayed

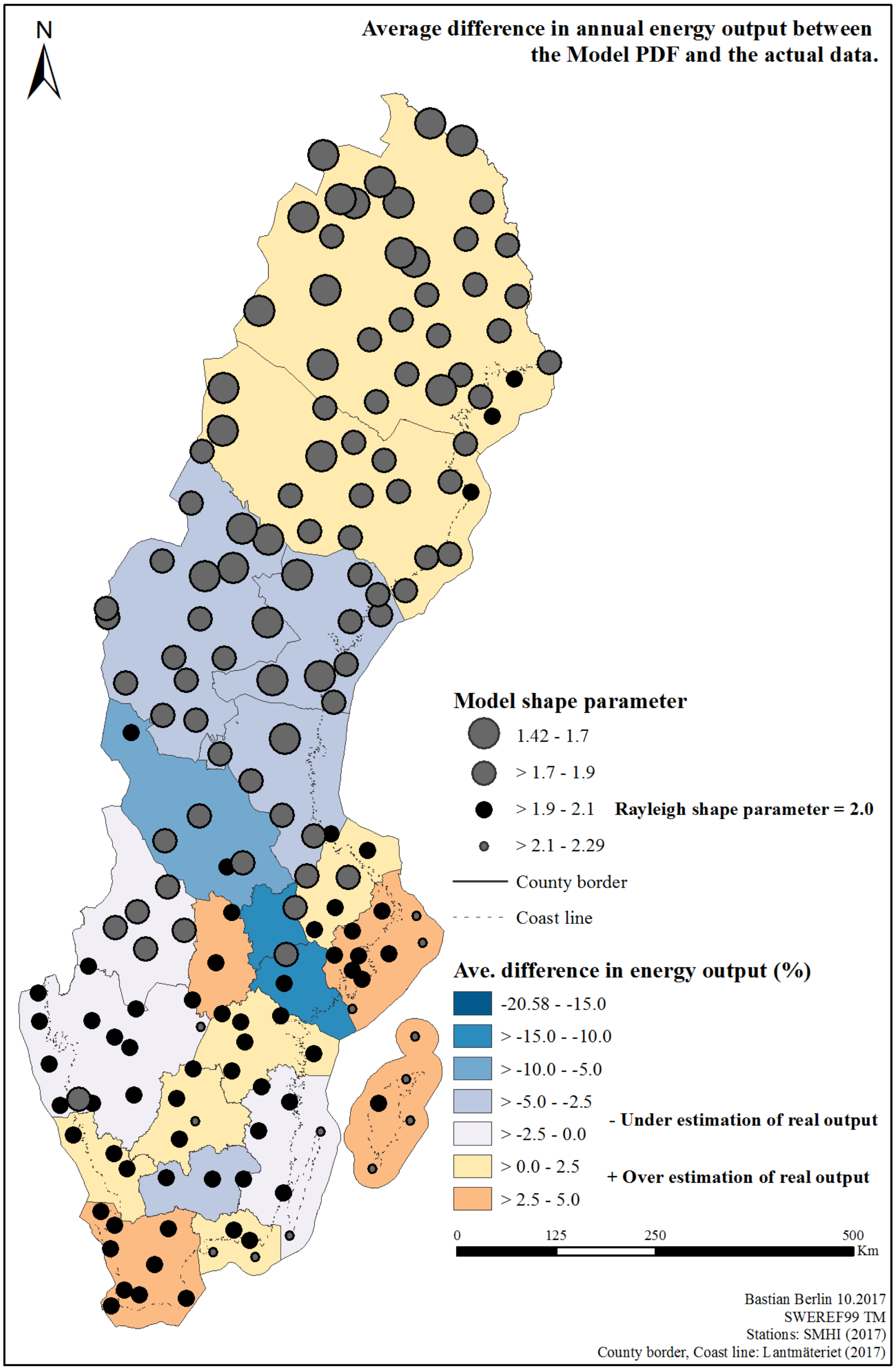


Figure 9: Average difference in annual energy output between the energy output based on the observed wind speed frequency and the model PDF for each county in Sweden. In addition, the modeled shape parameter is displayed

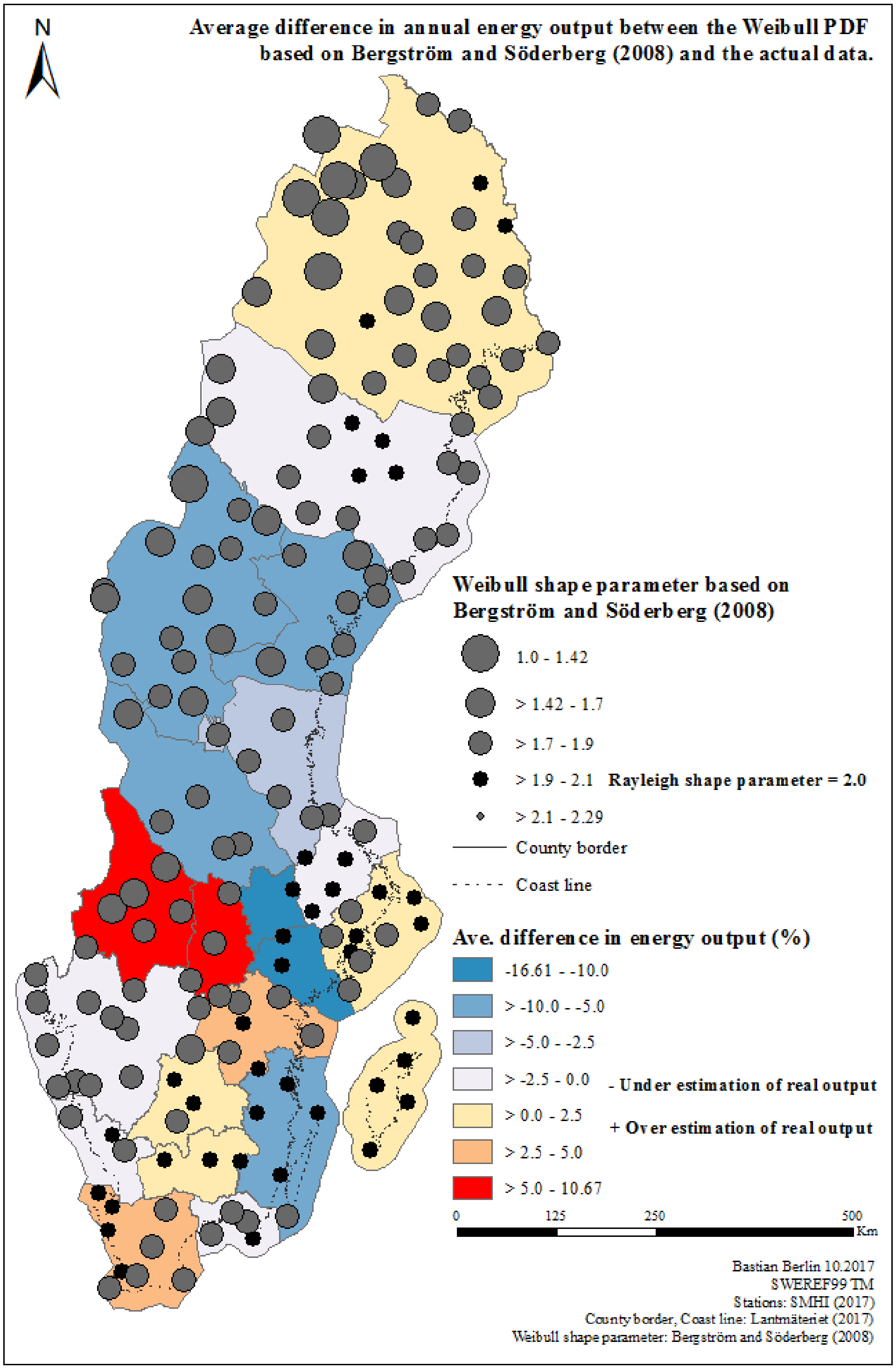


Figure 10: Average difference in annual energy output between the energy output based on the observed wind speed frequency and the Weibull PDF based on Bergström and Söderberg (2008) for each county in Sweden. In addition the Weibull shape parameter is displayed.

### 4.6 Technical wind energy potential for Sweden

The total technical annual energy potential for Sweden was 12589.5 TWh based on a 500 m resolution. The total annual energy output based on the Rayleigh PDF was 12292.6 TWh, which resulted in a difference between the approaches of 296.9 TWh. Without any data gaps or restrictions was the Rayleigh approach for this study resulting in 12787.1 TWh, which left a 484.5 TWh gap for missing data areas and areas such as large water bodies. The Bergström and Söderberg (2008) PDF resulted in a total of 12675.7 TWh, which is the highest out of the three approaches and 86.2 TWh more than the model predicted. The modeled annual wind energy output for Sweden is mapped in Figure 11. There appeared to be a division between the southern third and the rest of the country with high potentials in the south and generally lower potentials in the rest of the country. Nevertheless, some of the highest values occurred in the western mountains and likewise along the coast, the lakes "Vännern" and "Vättern" and the large islands Öland and Gotland. The lowest values are predominantly in-between the coast and the mountains of the northern two-thirds of the country.

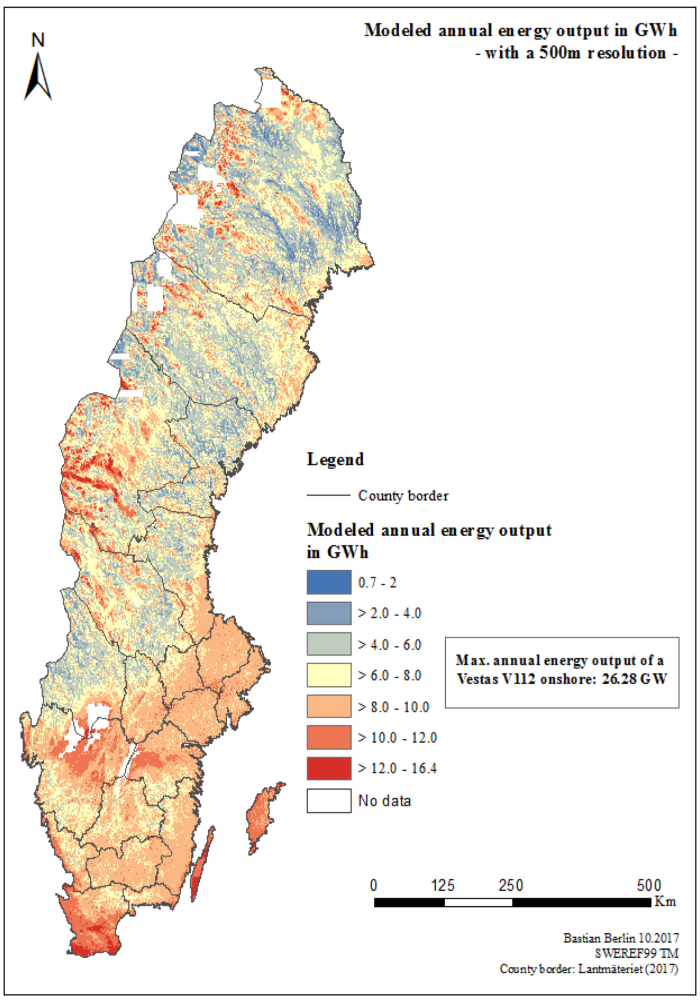


Figure 11: Modeled annual energy output in GWh for Sweden with a 500m resolution

The annual energy output from the model was subtracted by the Rayleigh PDF output and by the output based on the Bergström and Söderberg (2008) PDF to show the differences between the approaches for each cell (Figure 12). Positive numbers showed underestimations by the Rayleigh PDF or by the Bergström and Söderberg (2008) PDF. Negative numbers were underestimations. The green color in the map was chosen for differences of ±0.1 GWh, which were accepted as no considerable differences between the approaches. The calculated differences for the Rayleigh potential resulted in a clear division between the southern third, which was mostly well estimated by the Rayleigh PDF and the rest of Sweden. The northern two-thirds are mostly underestimated, with large underestimations of up to 1.0 GWh in the most northern parts and in the mountains. Very few cells displayed any overestimations. The differences between the model and the Bergström and Söderberg (2008) resulted in similar estimations for the south and along the coasts. Most overestimations were in the north and in the mountains in the west, mostly in the magnitude of -0.1 to -0.5 GWh. There were some smaller underestimations in some areas in the northern parts of Sweden but generally not higher than 0.5 GWh.

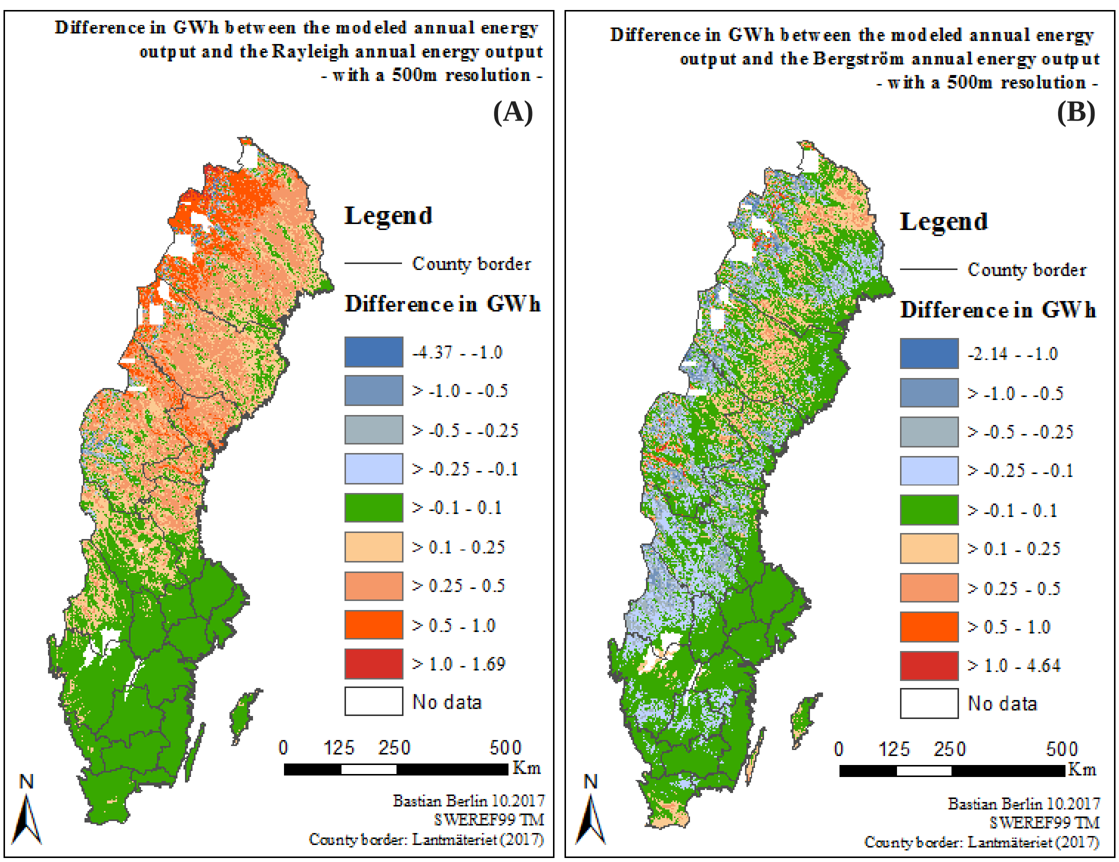


Figure 12: Differences in GWh between the modeled technical annual energy output and the Rayleigh output (A) and the output based on Bergström and Söderberg (2008) (B), with a 500m resolution for Sweden. Positive numbers show underestimation and negative number overestimations

Figure 13 displays the percentage change from the Rayleigh PDF potential to the model PDF potential and from the Bergström and Söderberg (2008) potential to the model potential. The values explain, by how much percentage of the Rayleigh output or the Bergström output, the energy output of the model, increased or decreased. This highlights how a certain absolute difference can have different impacts for cells based on their energy potential. The map on the left side of Figure 13 shows for example how underestimation of up to 1 GWh, like they occurred for large areas for the Rayleigh potential can result in changes of 5 – 30%. The largest changes resulted in the mountain areas with values of more than 30%. The percentage changes from the Bergström and Söderberg (2008) output were as high as -5 - -20% for large areas even though differences in these areas were mostly in the range of -0.1 - -0.5 GWh. Most of these areas had a small energy potential and got overestimated by the Bergström and Söderberg (2008) PDF. These small overestimations were still large relative changes compared to the model energy potential.

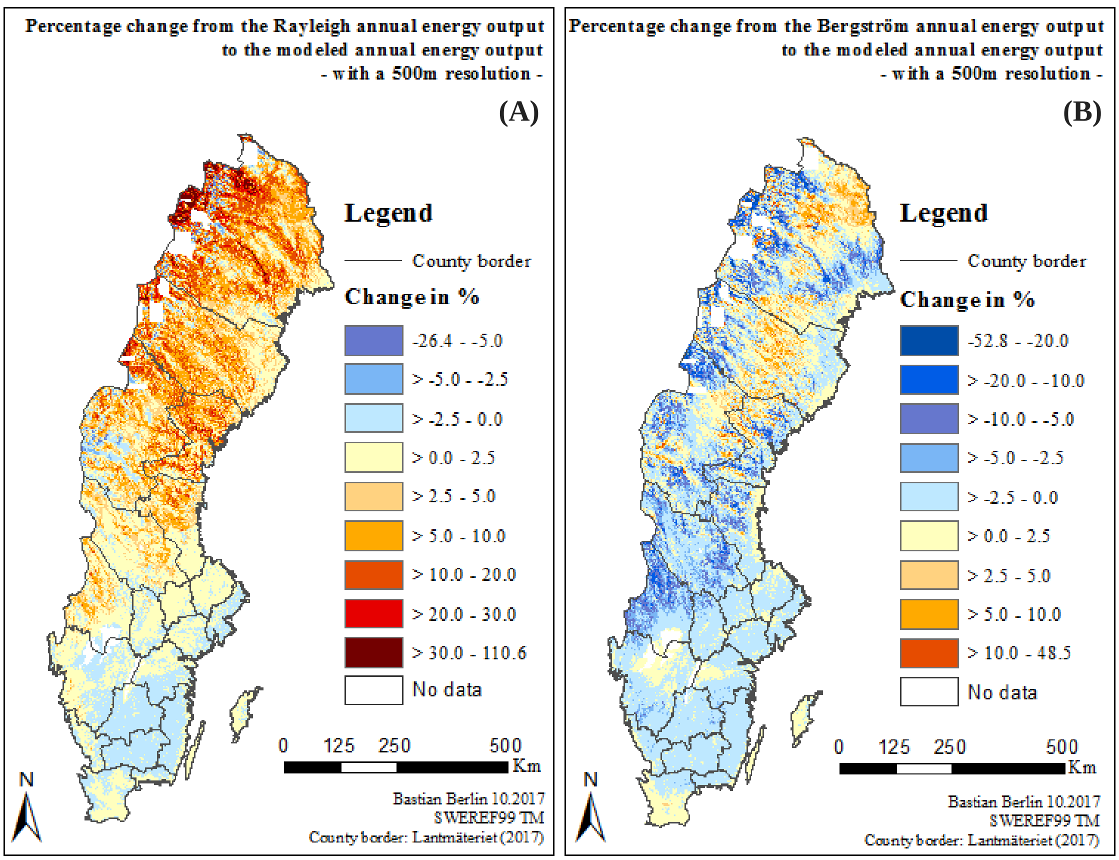


Figure 13: Percentage change from the Rayleigh annual energy output to the modeled energy output (A) and percentage change from the Weibull PDF based on Bergström and Söderberg (2008) to the model PDF (B), for Sweden with a 500m resolution

## 5.0 Discussion

This study showed that choosing between the Weibull PDF, the Rayleigh PDF, the Bergström and Söderberg (2008) PDF and the model PDF for assessing the wind energy potential for locations in Sweden had a considerable impact on the energy potential. For the case of Sweden, the Rayleigh PDF was only a good representation for certain parts of the country, mostly in the south. A GAM model was successfully used to model the shape parameter based on geographical variables. It improved the accuracy of the energy potential considerably in comparison to the other PDFs with the exception of the Weibull PDF based on station data.

### 5.1 Correlation to geographical variables

One of the purposes of this study was to analyze if the Weibull shape parameter could be modeled with geographical variables. For that, the hypothesis $\mathbf{H_2}$ was tested to analyze if there was any correlation between geographical variables and the Weibull shape parameter. The hypothesis was tested with the Spearman correlation test.

The test results showed medium to strong correlations but also no correlations at all for some variables. Latitude, elevation, the scale parameter and distance to water showed rather strong correlations, which was conform with literature. The correlation was not very strong to longitude, which might be because longitude was only a proxy for the distance to the mountains in the west. Maybe some form of Euclidean distance might have improved the correlation. There was no correlation to slope and surface roughness. It was surprising that there was no correlation to surface roughness since it is an important factor for local wind characteristics (Hau 2006). But not every roughness class was represented by the stations and in addition, the roughness classification by Silva et al. (2007) might have been too broad to capture all of the variation in land covers. Further, slope also showed almost no correlation, which could also be a representation problem by the stations. Most slope values of the stations were very low and the range of values was not very large. Additional data could have led to a higher correlation but also a larger matrix to calculate the slope could have had an impact. Distance to water was discarded after checking its correlation with elevation but it might be a better variable for study regions with small variation in elevation but with large water bodies in the surroundings. The results of the Spearman correlation test showed sufficient support for a correlation between some geographical variables and the Weibull shape parameter. Based on that, this study failed to reject the $\mathbf{H_2}$ hypothesis.

## 5.2 GAM model results

A GAM model was built based on the correlation between the shape parameters and the chosen geographical variables. The final GAM included latitude, longitude, elevation and the scale parameter, which were all highly significant and the GAM had an acceptable high adjusted $R^2$. The plot of the smooth functions showed mostly meaningful results with the latitude being the major impact on the model. The longitude lowered the shape parameter towards the mountains in the west, which is consistent with the more unstable weather conditions in mountainous regions. Somewhat contradictory to this was the influence of the elevation, since it increased the shape value with increasing elevation. The wind conditions along the coasts showed rather high average wind speeds and higher shape values were modeled at the coast. This made sense since coastal areas show occasional storms, which are captured by shape values around $k = 2$. The only existing shape values to compare with, were the ones based on the MIUU-model (Figure 14). In general, was the range of shape values based on the MIUU-model lower than the modeled shape values. Most GAM shape values of the cells were a bit higher with an exception to the area in the north east, where values were a lower. The modeled values had also a much more homogeneous spatial distribution than the MIUU-model values. However, the general trends seemed to be similar in most areas.

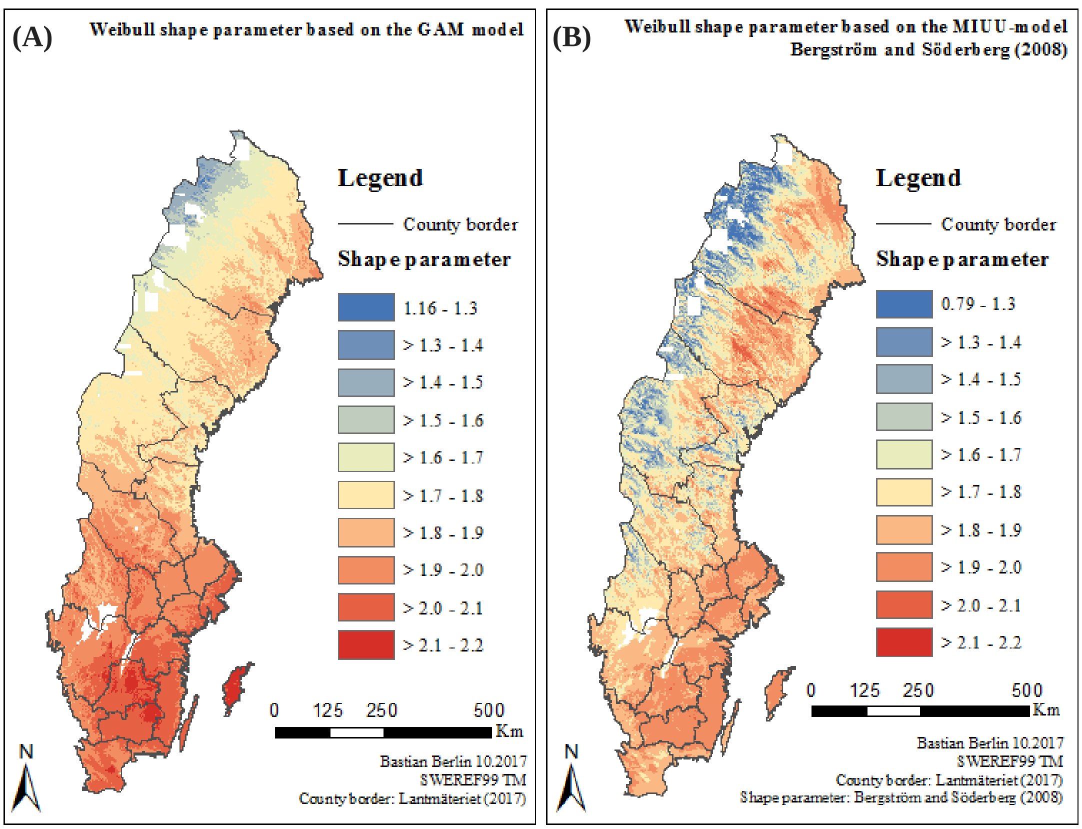


Figure 14: Modeled Weibull shape parameters based on the GAM model (A) and shape parameters based on the MIUU-model (Bergström and Söderberg 2008) (B)

Even though the GAM model seemed to have a sufficiently high adjusted $R^2$ value and similar trends as the MIUU-model, the residuals still had a rather large spread, which could not get explained by the model. Additional model improvements might decrease the residuals and improve the adjusted $R^2$ and the GCV values. One way to improve the model might be by incorporating additional variables, which did not get tested in this study. The aspect for example, since mountain ridges with certain shapes can increase wind speeds in far distances to the ridges (Hau 2006). Yet, the data values of the aspect will probably have similar representation issues as the slope and the surface roughness. In general this was also a problem for the scale parameter and the elevation The main improvements might probably be achieved by including more stations, especially when they add data to variables, which were not well represented.. Additional stations from very mountainous regions might be ideal to fill these gaps. But one problem with collecting additional station data could arise from the way the meteorological stations are set up and their purpose for weather and climate monitoring. It might be difficult to actually get station data from very steep slopes or more rare land cover classes.

### 5.3 Kolmogorov-Smirnov test of the PDFs

On the base of the cubed relationship between energy and wind speed, it was essential to calculate the PDFs as accurate as possible. The K-S test proved to be a useful way to test how significantly similar the different PDFs were to the observed frequency. The test for the stations showed that using the Weibull PDF resulted in considerably more station PDFs, which were significantly similar to the observed conditions than the Rayleigh PDF. Based on the results, it could also be confirmed that the model PDF resulted in almost the same amount of significantly similar stations than the Weibull PDF and considerably more stations than the Rayleigh PDF. The test was also used to analyze if the PDFs were significantly similar to the Weibull PDF since it was considered to be the best estimate. The result showed that the model PDF was significantly similar to the Weibull PDF except for one stations out of 41. So statistically the PDFs were almost similar.

It was surprising that only a few more than half of the Weibull PDFs were similar to the observed frequency. Reasons for this could be the mixed quality of the input data, the way of calculating the Weibull PDF itself or the general limitation of a model to capture every detail of the observations. However, the Weibull PDF and the model PDF proved to be superior over the Rayleigh PDF and based on the test should be favored for the process of modeling the observed frequency.

### 5.4 Accuracy of the technical energy potential at the stations

Many studies used the Rayleigh PDF to calculate the energy potential of areas instead of the Weibull PDF due to the lack of wind speed data (EEA. European Environment Agency 2009; Sliz-Szkliniarz and Vogt 2011; McKenna et al. 2014; Siyal et al. 2015). Based on this, the hypothesis **$H_1$** was tested, stating that there is a considerable difference between using the Weibull PDF or the Rayleigh PDF for assessing the annual wind energy potential at a site. Additionally, the hypothesis **$H_3$** was tested to evaluate if the GAM model PDF resulted in a considerably more accurate energy prediction than the Rayleigh PDF. The accuracy assessment was the first step to test these hypotheses. This evaluation was especially crucial since only a model, which improved the estimate of the energy potential considerably, would be effective to use for any potential analysis.

The sensitivity analysis showed that the model was mostly not very sensitive to input data, which indicated a good model performance. The Weibull PDF seemed to show the closest fir to the observations with basically no outliers. This supported that the Weibull PDF is indeed a good model for the probability of occurrence of wind speeds. The Rayleigh PDF was only a good representation for the highest energy potentials but the worst representation for the rest of the stations. This supports in addition to the K-S test, that the Rayleigh PDF was considerably less accurate than the Weibull PDF for most stations in Sweden. The model PDF performed not as good as the Weibull PDF but almost always better than the Rayleigh PDF. The Bergström and Söderberg (2008) PDF showed some strong outliers but performed for most stations as good as the model PDF. The outliers might indicate that the small amount of modeled data was not sufficient to predict a very accurate Weibull shape parameter for every station. It is however difficult to assess how large of an area in Sweden this might affect. The RMSE and the MAE values gave more support that the Weibull PDF has the highest accuracy and that the model PDF performed better than the other PDFs but not closely as good as the Weibull PDF did. The Rayleigh PDF had a higher accuracy than the Bergström and Söderberg (2008) PDF, which might be mostly connected to the outliers. This analysis showed as well that even though the PDFs had almost similar K-S test performances, that MAE and RMSE values showed considerable differences. This emphasized that it was important to also asses the accuracy of the energy potential and not only the accuracy of the PDFs themselves.

In other studies where the accuracy of the Rayleigh PDF and the Weibull PDF were compared, usually only the PDFs were compared and not the energy potential based on them (Zhou et al. 2010; Jiang et al. 2017). The problem with this was that there was no consideration for differences between errors for low wind speeds and errors for high wind speeds. However, a large error for high wind speeds results in an even larger error for energy potentials for the reason of the cubed relationship from wind to energy (Formula 8). Nevertheless, the general results from other studies were used to see if they are in line with the results from this study. A study of the wind energy potential of a region in southern turkey compared the use of the Rayleigh PDF and the Weibull PDF for one meteorological station but for different months. The Weibull PDF proved to be a better fit for monthly wind conditions than the Rayleigh PDF. The Weibull PDF also showed a considerably higher goodness of fit for the energy potential of the chosen station (Celik 2003). A comparison-study of methods to estimate different PDFs at four sites in China evaluated the goodness of fit of the Weibull PDF and the Rayleigh PDF. They were evaluated by the $R^2$, the RMSE and the K-S test. Each evaluation method resulted in a higher accuracy for the Weibull PDF than for the Rayleigh PDF (Jiang et al. 2017). At last, another study compared different PDFs by their goodness of fit for the wind conditions of five stations in North Dakota in the USA. The study showed that the Weibull PDF was a more accurate fit for wind conditions than the Rayleigh PDF (Zhou et al. 2010). The conclusion from this study, that the Weibull PDF was considerably more accurate than the Rayleigh PDF is supported by these other studies (Celik 2003; Zhou et al. 2010; Jiang et al. 2017).

The results showed altogether that there are rather large differences in the accuracy of the different PDFs. Nevertheless, certain sources of possible errors should also be considered. The evaluation of the PDFs was done by comparing to the observed wind speed frequency. Yet the frequency might have yielded a rather large uncertainty based on the different wind speed qualities. Additionally, more uncertainty might be based on the altitude correction for wind speeds based on the surface roughness classes. These might not always be representable of the real roughness conditions and add to the error in the frequency values. An improvement of more precise wind speed measurements and more knowledge about the true surface roughness might improve the accuracy of the observed frequency. More accurate observation might improve the accuracy of all of the PDFs.

The extent of the large differences in accuracy between the Weibull PDF and the Rayleigh PDF and the failure of the Rayleigh PDF to represent the wind conditions of a large share of the stations led to the failure to reject the $\mathbf{H_1}$ hypothesis. It should therefore always be preferred to use the Weibull PDF instead of the Rayleigh PDF. Based on the accuracy assessment of the stations, this study failed to reject the $\mathbf{H_3}$ hypothesis that modeled shape parameters result in a considerably more accurate energy prediction than the Rayleigh PDF. It is therefore recommended to use a GAM model to predict the shape values instead of only relying on the Rayleigh PDF. It is also recommended to improve the MIUU shape values to handle outliers better. This could mainly be achieved by modeling a longer time series of wind speed measurements. Finally only an analysis of the wind conditions and suitable PDFs can help in the decision if the Rayleigh PDF is appropriate for a location or the Weibull shape parameter needs to be modeled.

## 5.5 County-level potential analysis based on the station data

The county average of differences gave an indication of over- and underestimations in a more spatial sense. The maps showed that besides the southern counties, the Rayleigh PDF resulted in high underestimations for the rest of the counties. The Weibull PDF on the other hand showed the same range of very low under- and overestimations for all counties. There were only very few counties were the model PDF had larger over- or underestimations than the Rayleigh PDF. The model PDF showed very few larger over- or underestimations, which indicated that there were no spatial trends of over- and overestimations. The Bergström and Söderberg (2008) PDF showed some larger over- and underestimations in the center of Sweden but for the rest of Sweden no larger over- or underestimations. This analysis further supported the discussion of the previous section and especially underlined further that the Rayleigh PDF is probably not a good representation for rather large parts of Sweden.

## 5.6 Technical wind energy potential for Sweden

The energy potential prediction for the whole country based on the model was considered more accurate than the potential based on the Rayleigh PDF, due to the failure to reject the $\mathbf{H_3}$ hypothesis. A full accuracy assessment of the whole country was not possible since only the stations yielded a long enough wind speed time series to consider them the ground truth. It is however possible to compare Sweden's energy potential based on the GAM model with the potential based on the Rayleigh PDF.

The southern third of the country showed very few differences between the model and the Rayleigh potential but the other areas showed underestimations of 0.25 to 1.0 GWh. These differences resulted in percent changes of 5% to 30% for most areas. Similar differences were found in the technical energy potential analysis of Africa. It compared the use of the Rayleigh PDF and the Weibull PDF and resulted in a difference of 5% of the technical energy potential for the whole continent and maximums of up 100% at certain sites (Mentis et al. 2015).

The comparison of the technical energy potential for Sweden based on the model PDF with the Bergström and Söderberg (2008) PDF showed that large areas had very similar values and most other areas showed not very high deviations. The larger relative overestimations were mostly in areas with a low energy potential. Since energy potentials for most cells were very similar, this could be seen as another proof that the model worked well in estimating the energy potential. On the other hand this would also mean that besides the low accuracy assessment of the Bergström and Söderberg (2008) PDF at the stations, the MIUU-modeled shape values were probably rather accurate for most areas.

There are two known studies, which calculated the total technical energy potential of Sweden and were used for a comparison. Both studies only used the Rayleigh PDF to calculate the energy potential and they could therefore only be used to compare the estimate based on that PDF. Siyal et al. (2015) calculated the total technical energy potential for Sweden based on a 1 km resolution, with a similar wind turbine model than the one used in this study. The total potential was 7440 TWh for the whole country. The potential calculated by the Rayleigh PDF for this study was 12292.6 TWh for a 500 m resolution. The large differences are probably due to the different resolution and a slightly different turbine model, which might have let to the use of a different power curve. A study by the EEA. European Environment Agency (2009) calculated a total technical energy potential of about 5000 TWh for Sweden based on a 0.25° resolution and an 80 m hub height turbine model with a 2000 kW rated power yield. The results from this study and the other two indicated that calculations of the technical energy potential varied greatly depending on the turbine model and the cell size. All three technical energy predictions showed each only one possible scenario out of many. Different turbines are more or less favorable for certain wind conditions, based on the manufacturers choices (Burton et al. 2011). It is depending on the aim of the potential analysis to make the right choice of turbine model. The technical wind energy potentials analysis of an area is extremely depending on the turbine model and the resolution. It should therefore not to be considered the whole truth, but a specific scenario. An accurate assessment of the wind conditions would decrease the uncertainty of the theoretical energy potential on which all other potential predictions are build up. This would improve the different energy potential scenarios and be more helpful for decision makers. A detailed, high-resolution wind atlas is the recommended way to achieve this.

This study the study by Mentis et al. (2015) showed that there were considerable differences between using the Weibull or the Rayleigh PDF to calculate the energy potentials for areas. These large differences between the PDFs might have extensive consequences for the planning of wind turbines. A large share of the Swedish wind turbines were installed in the northern counties and it is therefore very important to predict the potentials in these areas as accurate as possible. Inaccurate predictions might slow down the so far rapid increase in newly installed wind turbines (SEA. Energimyndigheten 2016). The comparison between the model potential and the Bergström and Söderberg (2008) potential led to the conclusion that both models were probably suitable for most areas in Sweden and certainly considerably more suitable than the Rayleigh PDF. A meteorological model, which generates a long time series of wind data with a high accuracy, might be superior to the GAM model approach. Nevertheless, the GAM approach proved to be a suitable alternative to calculate reliable shape parameters.

## 6.0 Conclusion

The aim of this study was to investigate the impact on the annual energy potential in Sweden by using the different PDFs. The first hypothesis was mainly based upon the energy potential study by Siyal et al. (2015), who pointed out that for a better estimation of the energy potential, the Weibull PDF should be used instead of the Rayleigh PDF. The results showed clearly that for most meteorological stations in Sweden, there was a large difference in energy potentials between using the Weibull PDF or the Rayleigh PDF. The results of this study and other studies led to the failure to reject the $\mathbf{H_1}$ hypothesis that there is a considerable difference between using the Weibull PDF or the Rayleigh PDF for assessing the annual wind energy potential at a site (Celik 2003; Zhou et al. 2010; Jiang et al. 2017).

Testing the second hypothesis $\mathbf{H_2}$ led to a failure to reject the hypothesis that there is a correlation between geographical variables and the Weibull shape parameter. It was successfully tested that the variables latitude, longitude, elevation and the Weibull scale parameter could be used in a GAM to model the Weibull shape parameter for Sweden.

The accuracy of the model PDF based on the GAM was higher than the accuracy of the Rayleigh PDF and the Bergström and Söderberg (2008) PDF but not as high as the Weibull PDF modeled based on station wind speed data. A comparison between the energy potential of Sweden based on the Rayleigh PDF and the potential based on the model PDF resulted in high underestimation for large areas by the Rayleigh PDF. Based on the findings, this study failed to reject the $\mathbf{H_3}$ hypothesis that modeled Weibull parameters based on geographical variables result in a considerably more accurate energy prediction than the Rayleigh PDF. The predictions of the energy potential made by the GAM model at the stations were more accurate than the predictions by the Bergström and Söderberg (2008) PDF. However a comparison of the energy potentials for Sweden showed much lower differences between the predictions for most areas.

The Rayleigh PDF might increase the uncertainty of the wind energy potential of certain areas considerably and it is therefore recommended to use the Weibull PDF. It is necessary to analyze the local wind conditions either by measuring, using the suggested GAM model or modeling a sufficiently long time-series with a meteorological model. More understanding of the influences on the local wind conditions and more advanced models to predict the long-term wind conditions should be a major focus of future research.

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**Institutionen för naturgeografi och ekosystemvetenskap, Lunds Universitet.**
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