SELECTING OPTIMUM LOCATION AND TYPE OF WIND TURBINES IN ICELAND

May 2012
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Master of Science in Decision Engineering

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Selecting optimum location and type of wind turbines in Iceland

by

Kristbjörn Helgason

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Master of Science

Selecting optimum location and type of wind turbines in Iceland

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Abstract

In this research study, 48 locations around Iceland are studied along with 47 different wind turbines to indicate the potentials of wind power extraction using every combination of location and turbine.

The historical wind data from the locations are analyzed using the Weibull distribution and simulated to generate a representative year. Using the power curves of the 47 turbines, a model is constructed that calculates and compares three performance measurements for each turbine at each location. These measurements are: Expected annual energy output (in GWh), capacity factor (in % of maximum energy possible to generate) and cost of energy (c€/kWh).

In total, 2256 different combinations of locations and turbines are compared. The combination giving the lowest cost of energy is using a certain 3MW turbine at Garðskagaviti, and that combination is considered to be economically optimal. Additionally, Garðskagaviti is the location giving the best results for all the measures mentioned above.

In general, the study reveals relatively high energy output and capacity factors for numerous locations and turbines which indicates that wind power extraction could be feasible in Iceland compared to other countries. However, the cost calculations show that the cost per kWh of energy is still too high for the wind power source to compete with other renewable energy sources in Iceland, given the cost assumptions in this study.

Staðar- og tegundarval vindhverfla á Íslandi

Kristbjörn Helgason

Maí 2012

Útdráttur

Í þessu verkefni er skoðuð möguleg hæfni 47 mismunandi gerða vindhverfla til raforkuframleiðslu á 48 ólíkum stöðum á Ísland og mælikvarðar reiknaðir fyrir hverja samsetningu af tegund og staðsetningu.

Söguleg vindgögn eru greind með Weibull drefingu og sú greining notuð til að herma vind sem gefur dæmigert vind-ár á hverjum stað. Með því að láta þann vind verka á aflferil (e. power curve) hvers vindhverfils er smíðað líkan til að reikna þrjá mælikvarða á hæfni hvers hverfils á hverjum stað. Þessir mælikvarðar eru: vænt árs-orkuframleiðsla (mæld í GWh), nýtingarhlutfall (e. capacity factor, mældur í % af hámarksafli) og kostnaður á kílóvattstund framleiddrar orku (mældur í evru-sentum á kWh).

Samtals eru 2256 ólíkar samsetningar af staðsetningu og vindhverfli bornar saman. Sú samsetning sem skilar lægstum kostnaði á kWh, af þeim möguleikum sem skoðaðir eru, er að nota vissa gerð 3MW vindhverfils við Garðskagavita. Að auki kemur Garðskagaviti best út við skoðun allra mælikvarðanna.

Almennt sýna niðurstöður verkefnisins hátt nýtingarhlutfall og mikla orkufram-leiðslu fyrir margar staðsetninganna. Það ætti að benda til þess að Ísland henti vel til vindorkuframleiðslu miðað við önnur lönd. Hins vegar sýna útreikningar að framleiðslukostnaður á hverja kWh er enn of hár til að vin-dorka geti keppt við aðra orkugjafa á Íslandi, þar sem hann er í öllum tilvikum hærri en söluverð rafmagns hér á landi, m.v. forsendur kostnaðarútreinkninga.

This thesis is dedicated to my late father, Helgi Kristbjarnarson, who opened the world of science to me and made me the person I am.

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Chapter 1

Introduction

Like most countries, Iceland is faced with the challenge of how to meet the foreseeable increase in energy demand in the world. According to the International Energy Agency's Reference Scenario, global primary energy demand is expected to grow by 40% in the years between 2007 and 2030.

Iceland has its own energy demand forecast for the years 2011-2050, made by The National Energy Authority (Orkustofnun) in 2011. According to the forecast, primary energy demand will have increased by 7% in 2015, and by 94% in the next forty years. Energy demand is in close relation to changes in the volume of industrial production as well as population development. Moreover, usage can be expected to change and go hand-in-hand with progress in technology.

Iceland's energy use per capita is among the highest in the world, according to The National Energy Authority. Although the share of renewable energy sources in Iceland exceeds most other countries, the need is extreme to guarantee responsible and sustainable exploitation of those sources. There is no single solution to meeting the energy demand in Iceland. Instead, a combination of solutions is probably the answer. The interests of future generations need also to be kept in mind in the implementation of new energy policies, and the environment has to be left as unspoiled as possible. Therefore, more diversified usage of renewable energy sources in Iceland needs to be studied.

Wind power is currently one of the most cost efficient renewable energy sources available and the one of few that are available anywhere in the world, although some locations are more suitable for wind power production than other. The deciding factors on how much power can be produced at any location are the strength and distribution of the wind profile and how it matches to a particular wind turbine generator.

When choosing a location for a wind turbine, the wind profile of each prospective location needs to be studied, as well as which type of turbine best matches that wind profile. This process needs to be based on analysis of the stochastic element of wind for each location and the possible energy output of each turbine considered.

Each wind turbine type has a unique power curve which represents the turbine's optimal wind speed and the range of wind speeds that can drive the turbine. By comparing the mean wind speed of a location with a power curve, one can get a rough estimate of the potential power production at that particular location for that turbine. However, as the power curve is non-linear and wind is a highly stochastic element, the frequency distribution of the wind has to be taken into account to get a realistic estimate.

In this study the monthly wind profile of 48 different locations in Iceland are analyzed. This provides the necessary parameters to be able to conduct a simulation of future wind data for these locations. This simulated wind is run through 47 different wind turbine power curves.

Three performance measures are calculated for all turbines at each location:

- The amount of energy that each turbine is expected to produce annually.

- The capacity factor of each turbine, which gives the percentage of maximum possible energy generated by a turbine at a certain location. This indicates how well a turbine matches the location's wind profile.

- The cost of energy in cent€/kWh, calculated as the annual payment of the total cost of each turbine at each location divided by the annual energy production. This indicates which combination generates maximum energy relative to the setup and operating costs.

By finding the setup leading to the minimum cost of energy for each location, an economically optimal wind turbine is identified for each location. Thereby, the overall optimal pair of location and wind turbine can be identified.

The weather data used in this study were collected by The Icelandic Meteorology Office in the years 1998 to 2010. All locations selected to be included in the study have historical data of nine years or more and altitude of less than 330 meters above sea level.

Turbine data from most leading turbine manufacturers are retrieved, mainly from a dataset put together by the British Wind Power Program (*The WindPower Program*, n.d.). The data retrieved is combined into a database of 47 turbines that are used in this study.

Most of the largest wind parks in the world today are located off-shore. It has considerable advantages over on-shore locations, because of more stable wind and possibilities of less environmental impact. However, off-shore wind parks near Iceland are not likely to be constructed in near future, as costs are far higher than onshore, and not enough research has been done on their endurance and performance around Iceland. Therefore, this study will focus on on-shore locations.

Aim and objective

The aim of this study is to find optimum locations for wind turbines in Iceland and identify the optimum type of turbine to be used at each location. The objective is to build a model that calculates and compares performance measures of different combinations of locations and wind turbine types. The model identifies an optimum pair of wind turbine location and type out of the combinations considered. The optimum pair of location and type is considered to be the one that has the lowest cost of energy, based on simulation derived from historical wind data.

Additionally, the outcome of this study is compared to an extensive energy output estimation for the Búrfell area, which was conducted for Landsvirkjun (The National Power Company in Iceland) in 2011.

Motivation

In recent years, discussion about reduction in usable energy production options in Iceland has increased. There is not a general agreement on how much is left of usable hydropower, while most agree that geothermal energy needs to be studied further to determine its sustainability. Therefore, continuing research of other renewable energy sources in Iceland such as wind energy is of great importance.

In the process of choosing the most suitable location and type of wind turbine to be setup, many variables need to be considered. Each type of wind turbine has its specific wind speed working range, presented with the turbine's power curve. The location with the highest mean wind speed need not be the one generating the most energy on an annual basis and due to different power curves, the largest turbine might not even be the one that generates the most energy. However, the largest turbine can be assumed to be the most expensive one as the cost can be roughly estimated to increase linearly with the rotor diameter of the turbine.

Earlier studies on production of wind power in Iceland use either semi-annual or annual wind speed averages to estimate potential power at the location studied. Moreover, only one specific turbine is used to calculate the expected energy output in each of the studies, without considering the different characteristics of turbines.

Seasonal fluctuations in the wind make annual average wind speeds an imprecise parameter to base an energy calculations on. As an example, annual average wind speed can be high while certain months have mean wind speeds outside of the working wind speed range of a particular turbine and therefore leading to low efficiency of the turbine.

In this study the wind is analyzed and simulated on monthly basis which reveals large deviations in wind speeds between months. It also incorporates the difference of 47 turbines and estimates the cost and capacity factor of each one, giving an indication of which turbine might be the most suitable at each location.

Outline of the thesis

Chapter 2 describes the background of wind power and the state of the art. Literature is reviewed, both recent publications on wind power as well as classical definitions of wind and wind power measurements.

Chapter 3 describes the methods and data used in this study. The first part describes the data and the second and third part describe statistical methods for wind modeling. Next three parts describe methods used for simulation, energy calculation and cost analysis. Some limitations to the study are also listed.

Chapter 4 presents the results of the study. First, the results of the wind modeling and simulation are presented. Secondly, annual energy output estimates are presented. The last part presents the main results of this study, the efficiency and cost of energy for each location and turbine.

Chapter 5 concludes the work of this study, discusses the meaning of the results and portraits the most interesting findings. Moreover, a short summary of the contribution of the study is given and some future research suggested.

Chapter 2

Background and Literature Review

2.1 Wind power planning

Wind measurements and modeling

The deciding factors on the magnitude of the wind power that can be produced at any location, are the strength and distribution of the wind profile and how it matches to a particular wind turbine generator. Therefore, all wind power planning is based on wind measurements. This is for example stated in a recent study of the wind energy potential in Iran, where a team of researchers led by A. Keyhani analyzed long-term wind data on monthly basis to get an estimate of potential energy at a certain location (Keyhani et al., 2010).

Wind was first statistically modeled as a discrete random variable in 1951 (Sherlock, 1951), by using the Gamma distribution. In recent years the two parameter Weibull distribution has emerged as the most commonly used density function to model wind as it has been found to make a good fit to wide selection of wind data (Celik, 2004; Lun & Lam, 2000; Yeh & Wang, 2008).

The Weibull distribution, named after the Swedish scientist Waloddi Weibull, was first applied in 1933 (Rosin & Rammler, 1933). The distribution can be applied in various circumstances to describe the frequency of events, wind being one thereof. Keyhani and colleagues even go as far as stating that the Weibull distribution "is widely accepted for evaluating local wind load probabilities and can be considered almost a standard approach" (Keyhani et al., 2010).

Automatic weather observations have been made in Iceland since 1990 by the Icelandic Meteorology Office. In the current form of wind measurements, mean wind speed is recorded every ten minutes in more than 200 places around the country, as well as the highest gust speed in that same period (*Icelandic Meteorological Office*, n.d.).

All the automatic observations are taken at approximately ten meters above ground, while wind turbines operate at much higher altitudes. The projection of wind speed to higher altitudes is a well studied and documented process. The most widely used formula for the projection is the power law, described in i.e. (J.F. Manwell & Rogers, 2002) as

$$\frac{V(z)}{V(z_R)} = \left(\frac{z}{z_R}\right)^a \qquad\qquad (2.1)$$

where $V(z)$ is the wind speed at height z, $V(z_R)$ is the measured wind speed at height z_R, and a is the power law exponent, describing the terrain surface and stability of the air. The early works on the formula date back to 1968 where it is showed that $a = 1/7 \approx 0.14$, can be reasoned to be a typical value of the exponent (Schlichting, 1968).

Some studies in Iceland on wind speed varying with height have revealed values of the power law exponent for certain locations (Arason, 1998; Sigurðsson et al., 1999; J. Blöndal et al., 2011). The calculated values of the exponent range mainly between 0.08-0.16. Recent, unpublished studies by G. N. Petersen at Keflavik airport using weather balloons, show that the value of a=1/7 is reasonable for the area. Preliminary results of another recent unpublished study at the Búrfell area show a value near $a = 0.12$ for the exponent. That study uses recent and extensive wind measurements at different heights.

Wind power research in Iceland

Wind power has never been industrially extracted in Iceland, although some small turbines have been set up, mostly for private use. Despite that fact, some conditions such as mean wind speed and land availability are favorable in Iceland for large scale wind plants. The low cost of other available power sources, such as hydro and geothermal power, is probably the primary reason for the lack of effort in wind power usage in Iceland. However, in recent years the interest in wind power in Iceland has increased, following more emphasis on diversity in power production and sustainable use of natural power sources.

In a report from 2009 for the Ministry of Industry, some of the potentials of harvesting wind power in Iceland were identified and listed. The main potentials for Iceland were found to be (Sigurjónsson, 2009):

- Generate wind power in large scale to maximize efficiency and buildup of water reservoirs

- Construct small wind power turbines, where applicable, to lower the need of long distance transporting of electricity, thereby minimizing distribution costs

- Construct large scale wind power plants for electricity export, if plans of a submarine cable to Europe follow through

Landsvirkjun plans to construct two wind turbines in 2012 for research purposes. The turbines will be located near the hydro power plant at Búrfell, where extensive energy output estimation has been performed (Petersen & Björnsson, 2011). One of its aims is to research the possibilities of wind power to increase the efficiency and buildup of water reservoirs. That way more power could be extracted from the hydro power plants, providing base load electricity despite the stochastic behavior of wind power. (Landsvirkjun, 2012).

As these plans indicate, Landsvirkjun is increasing its emphasis on wind energy. At the company's Autumn meeting in 2011, the executive vice president of Research and Development, stated that wind is a realistic option with rising electricity prices, and that it might become competitive with hydro and geothermal power within ten years. In addition, if a submarine cable to Europe would become a realistic possibility in near future, it could create additional opportunities for utilization of wind power and development of the electricity system (Ó. G. Blöndal, 2011).

In the years 2010 and 2011, The Icelandic Meteorological Office and The University of Iceland collaborated in a wind power research for locations all around Iceland. The group projected wind speeds around Iceland up 90 meters and interpolated between locations. The correlation between locations was calculated in order to find places in which wind turbines can be installed to maximize total runtime of combined power plants. The calculations were based on mean winds of summer and winter from long-term wind data. Data for a few wind turbines were aggregated into one mean wind turbine, of class IEC 1a (J. Blöndal et al., 2011). In general, their findings show that overall efficiency can be increased by locating wind turbines in several different, uncorrelated locations.

A part of their study was to build a tool to automatically clean up corrupted wind data. When failures occur in automatic wind monitors, either wrong measurements are recorded

or measurements are missing. One of the reasons behind such deviations is that electrical fields can build up in the monitors and corrupt the measurements. Icing can also influence monitors, as well as other conventional failures in their mechanism. Due to the frequency of these errors, a tool for automatic cleanup process, as the one the research team constructed, is valuable for further use of wind data (J. Blöndal et al., 2011).

The process of matching wind turbines with specific wind profile is important to maximize the possible extraction of energy. One of few published papers on the topic is Abul'Wafa's paper about matching wind turbines with certain wind profile for deciding on wind farm location in Egypt. In his study, he presented a method for matching wind turbine generators to a site using turbine performance index in conjunction with minimum deviation ratio between the rated speed of wind turbine and optimal speed, resulting in minimum cost of energy (Abul'Wafa, 2011).

Specialized computer programs are widely used to estimate energy output of a wind turbine at a certain location. One of the best known in Europe is a program called WAsP (Mortensen & Laboratory, 2007). The program uses, the Weibull distribution to model wind, along with more detailed topography information and energy conversion calculations. It is capable of giving extensive energy calculations but it is proprietary with high license fees.

In 2011 The Icelandic Meteorology Office conducted an extensive energy study on the Búrfell area for Landsvirkjun, as the company is planning to install an experimental wind turbine in the area in 2012. The study uses WAsP and the result is a detailed estimation of possible energy generation at the location but the study uses only one type of turbine. The research shows that the power density at certain locations in the area can be expected to be as high as 975 W/m^2 and a high capacity factor can be achieved using the turbine studied (Petersen & Björnsson, 2011).

In 1985, the University of Iceland constructed a wind turbine in Grímsey, a small inhabited island in the North of Iceland, for the purposes of heating water for central heating. The turbine blades were damped by a hydraulic brake which again heated water with friction, that was used to heat up buildings in the proximity. The turbine broke down shortly after it was constructed and has not been used since. The turbine still stands, although it is in poor condition and will probably never run again. Two reports from 1985 and 2003 show that the use of wind power for central heating in Grímsey would be cost-effective. One of the main conclusions of the latter report is to state the importance of immediately conducting a technical review on the synergy of a diesel power generator and a wind turbine in Grímsey (Nefnd um sjálfbært orkusamfélag í Grímsey, 2003).

2.2   Wind energy and power

The basis of wind energy

The energy produced by a wind turbine is essentially the kinetic energy of the wind. In general, kinetic energy is described as $\frac{1}{2}mv^2$ where v is speed in m/s and m is the mass. In the case of wind, m can be described as the flow of air through a fixed area, A (for example the area that a particular wind turbine sweeps). In that case it is reasonable to redefine $m = \rho Avt$, where ρ is the density of the wind and t is the time interval of the wind flowing through the area. This leads to an equation for wind energy, E, and wind power, P (since by definition $P = E/t$):

$$E = \frac{1}{2}At\rho v^3 \tag{2.2}$$

$$P = \frac{1}{2}A\rho v^3 \tag{2.3}$$

From this it can be seen that the energy generated by a wind turbine is linearly related to the sweep area of the turbine's rotor and the density of the air but cubically related to the speed of the wind.

Due to fundamental laws of mass flow and energy conservation, no wind turbine can extract all the energy stored in the wind. In order for that to happen, the wind would come to a complete stop at the turbine blades and no more wind could arrive to pass the blades. At the other theoretical extreme the speed of the wind is unchanged by the blades and no energy is extracted. The maximum theoretical extractability was defined by Albert Betz in 1919 and proven to be $C_p = 16/27 \approx 59\%$. This is called the Betz limit and occurs when the ratio of the incoming wind, v_1 and the exiting wind v_2 is $\frac{v_2}{v_1} = \frac{1}{3}$ (J.F. Manwell & Rogers, 2002).

Calculation of wind power

There are several approaches to calculate the estimated power output of a wind turbine, given a wind profile and a power curve. The ideal way is to integrate the published power curve of the turbine and the probability distribution of the wind, over wind speeds from zero to infinity (J.F. Manwell & Rogers, 2002),

$$\bar{P}_w = \int_0^\infty P_w(v)p(v)\ dv \tag{2.4}$$

where v is the wind speed, $P_w(v)$ is the power curve function of the turbine and $p(v)$ is the Weibull density function of the wind at the location for that particular month. The outcome, $\bar{P}_w$, is the average wind turbine power which can then be multiplied with hours per year to get the annual energy output in kWh. This approach requires the power curve to be known as a continuous function of wind speed. In most cases only discrete values are known, so the function needs to be approximated from those values.

The integral in equation 2.4 can become very hard to solve, depending on the functions considered. One method of evaluating that type of integral is by using random numbers. The method is known as the Monte Carlo approach and is described by Sheldon M. Ross (2006, p. 42-45). The procedure of the method is:

- Let $g(x)$ be a function and $\theta = \int_0^1 g(x)\ dx$ be the integral to evaluate

- If U is a random number (uniform between 0 and 1), then $\theta = E[g(U)]$

- Thus, for k independent generations of U, by the strong law of large numbers,

$$\sum_{i=1}^k \frac{g(U_i)}{k} \to E[g(U)] = \theta \text{ as } k \to \infty \tag{2.5}$$

This method is used in various researches where stochastic simulation comes into play such as byValenzuela and Mazumdar (2000), who use it to evaluate power generation production costs and Kleywegt, Shapiro, and Homem-de-Mello (2002) who use it in stochastic discrete optimization.

The mean power output of a wind turbine, $\bar{P}_w$, can be estimated by using a Weibull random variable instead of a uniform random number and using $P_w(V_i)$ instead of $G(U_i$ in eq. 2.5. Here, V_i is the simulated wind value and $P_w(V_i)$ is the corresponding value on the power curve. The equation becomes

$$\bar{P}_w \approx \sum_{i=1}^k \frac{P_w(V_i)}{k} \tag{2.6}$$

for large k. In this case, each wind value V_i is generated by simulation, for each location, based on the calculated Weibull distribution of each month.

Wind Power Density

Wind power density (WPD) is a measure of the kinetic power available per square meter for certain wind speed. It is calculated by dividing the wind power, P, by the ares, A. This gives a measure which is only related to the wind speed, v, and the density of air, ρ, and is therefore a useful way to estimate the power available in the wind at a certain location.

$$\text{WPD} = \frac{P}{A} = \frac{1}{2}\rho v^3 \tag{2.7}$$

In 2004, A. N. Celik showed how to use the Weibull distribution to estimate the mean power density when he used the measure to show that a site in Southern Turkey presented poor wind characteristics. Moreover, he showed that the Weibull distribution provides better power density estimations than the more simple Rayleigh distribution (Celik, 2004).

Wind locations are classified by the American Wind Energy association (AWEA) according to its wind power density. "Areas designated as class 4 or greater are generally considered to be suitable for most wind turbine applications" (J.F. Manwell & Rogers, 2002, p. 67). Those sites show average wind speed of around 7.0-7.5 m/s at an altitude of 50 meters (J.F. Manwell & Rogers, 2002; *AWEA - Wind Energy FAQ*, n.d.).

Capacity factor

One of the most informative measures of how efficiently a wind turbine is functioning at a specific location is the Capacity factor (CF). It is defined as the ratio of the energy actually produced by a turbine at a given site and the maximum energy that the specific turbine can produce. Thus,

$$CF = \frac{\bar{P}_w t}{P_R t} = \frac{\bar{E}_{year}}{E_R} \tag{2.8}$$

where $\bar{P}_w$ is the mean power produced, P_R is the rated power of the turbine, t is any given time interval, $\bar{E}_{year}$ is the mean energy produced annually and E_R, is the maximum energy that the specific turbine can produce annually. (J.F. Manwell & Rogers, 2002, p. 63)

The Capacity factor is used in many cases where efficiency of turbines are compared such as by Celik (2003) and Chang and Tu (2007). Typical wind power capacity factors have been shown to be in the range 20-40%.

2.3 Modeling

Simulation

To determine an energy output of a wind turbine, some values of future wind speeds are needed. One way to estimate future wind speed is by simulating wind values from parameters based on statistical modeling of historical data from a particular location.

Values from a known probability density function (e.g. the Weibull function) can be simulated using, for example, the inverse transform method as described in Rubinstein and Melamed (1998) and Ross (2006). Mathematical programming languages, such as Matlab or R, have a built-in Weibull generating function, based on their random number generator, which is the approach used by many researchers.

The mean of the simulated values needs to approximate the mean of the historical data. Therefore, many simulation runs are needed for each set of parameters. One method for determining the number of simulation runs needed is described by Sheldon M.Ross. He lets S denote the standard deviation of the generated values, k the number of simulations and determines d as the acceptable standard deviation of the estimator. The method of determining k is to generate simulated values and check each time if $S/\sqrt{k} < d$. The estimate of the mean is then given by $\bar{X} = \sum_{i=1}^{k} X_i/k$ (Ross, 2006).

One method of reducing k, the number of iterations, is using Antithetic variables (Ross, 2006). The method is based on reducing the variance of the estimator by using negatively correlated random numbers with the inverse transform method of simulation. The method is described as:

1. Generate a random number U and use it to generate a random variable X using inverse transform.

2. Generate a new X using the random number $1 - U$.

3. Repeat 1 and 2, n times.

4. The mean of the X's is the estimator for the expected value of the random variable.

Cost analysis

The European Wind Energy Association (EWEA) is one of the leading organization in gathering data on cost of wind energy setups. The association regularly publishes fact sheets on the development of different cost factors, setting benchmarks for prices in the industry. According to their publication, capital costs of wind energy projects are dominated by the cost of the wind turbine. In 2006, the mean cost per kW of installed wind power capacity was from around € 1000/kW to € 1350/kW, although differing somewhat between countries. (EWEA, 2009a).

In recent years, the cost of wind turbines has dropped significantly following technical progress in the production as well as increase in supply and competition. The Bloomberg Corporation calculates a semi-annual Wind Turbine Price Index (WTPI) that reflects the prices of the latest turbine contracts. The latest edition reports that utility-scale wind power equipment prices hit a new low in the second half of 2011 and "contracts signed in the second half of 2011 for 2013 delivery fell to € 0.91m/MW ($1.21m/MW), down 4% from six months earlier and well off their five-year high of € 1.21m/MW in 2009". (Bloomberg, n.d.)

When comparing different turbines from many manufactures, a better estimate of the price is price per m^2 of swept rotor area. "Wind turbines are priced in proportion to their swept rotor surface area and generally speaking in proportion to roughly the square root of their hub height." (Krohn, Morthorst, & Awerbuch, 2009). No official number has been published by EWEA as a benchmark for the cost per rotor swept area. However, numbers from Denmark have been adopted by them for this use. The trend of this cost index is shown in figure 2.1 (from (Krohn et al., 2009)). The most recent price is around 460 € per swept rotor area, with the measure € $/m^2$. This is almost the same as the long-term average of the index.

EWEA also publishes benchmark prices for other cost factors such as operating and maintenance costs, connection costs and setup costs (EWEA, 2009b). These published values are regarded as viable for use in modeling and calculations as done by Abul'Wafa (2011).

Right axis: Investment costs divided by swept rotor area (€/m² in constant 2006 €). Left axis: Wind turbine capital costs (ex works) and other costs per kW rated power (€/kW in constant 2006 €).   Source: Risø DTU
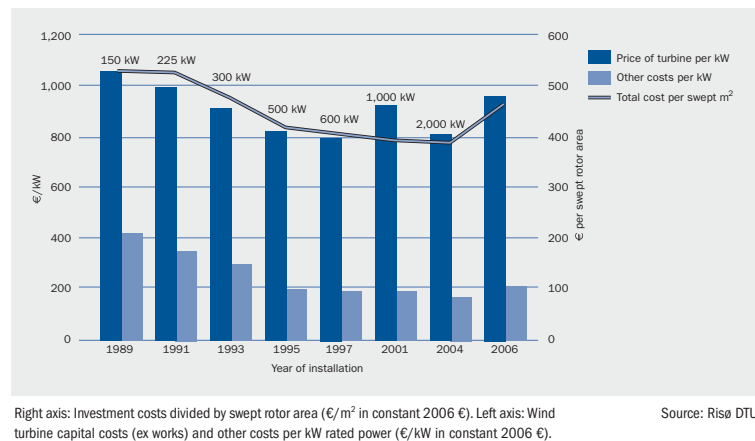
Figure 2.1: Trend of turbine prices in Denmark

Cost of transport of energy to the grid

All major electricity transmission lines in Iceland are owned and operated by Landsnet, a company owned by the state and some municipalities and operates under a concession arrangement. The electrical grid consists of 72 substations that connect the transmission lines that distribute on either 33kV, 66kV, 132 kV or 220 kV voltage. With increasing heavy industry in Iceland, the electrical grid in the vicinity of the industry has been forti-fied. This industry has accumulated in the South-West and the East of the country. As a result, the transmission lines and substations in these areas are most dense and powerful (Landsnet, 2011). Tariffs for transmission and ancillary services are published annually and are available online (Landsnet, 2012b).

The price of connecting the wind turbine to the grid is directly related to its distance from the nearest substation. According to Landsnet, the cost per kilometer of 132kV transmission lines is approximately $240,000$ €/km (100 mISK/2.6km). However 33kV line suffices for transmission of power below 10MW. The cost of 33kV is estimated to be 1/3 of that of 132kV or approximately $80,000$ €/km (*Landsnet | Kostnaður*, n.d.).

Chapter 3

Methods

This chapter starts by describing the data used in this study, then covers the methods used and ends on discussing some of the limitations of this study.

3.1 Data

3.1.1 Wind Data

This study uses data from weather stations located at altitudes below 330 meters above sea level that can supply at least nine years of measured data. This leads to a selection of 48 locations out of the 145 locations considered. All data were collected in the years 1998-2010.

Weather stations at more than 400 meters (including the turbine tower) are more susceptible to icing which reduces production, and are in general harder to access. Figure 3.1 shows a typical weather station at high altitude where icing has occurred. Using only locations with more than nine years of history reduces the risk of unusual periods in wind measurement overly affecting the results.

Figure 3.2 shows a map of the selected locations used in this study.

Use of raw weather data from a recent study made at the University of Iceland, was kindly permitted by the researchers, as well as access to a Matlab code to clean up the data (J. Blöndal et al., 2011). In this study, the code is run on the raw data from each selected weather station and the cleaned values are imported into R-programming language for further modeling.

Figure 3.1: A weather station at Skálafell, at altitude 771 m
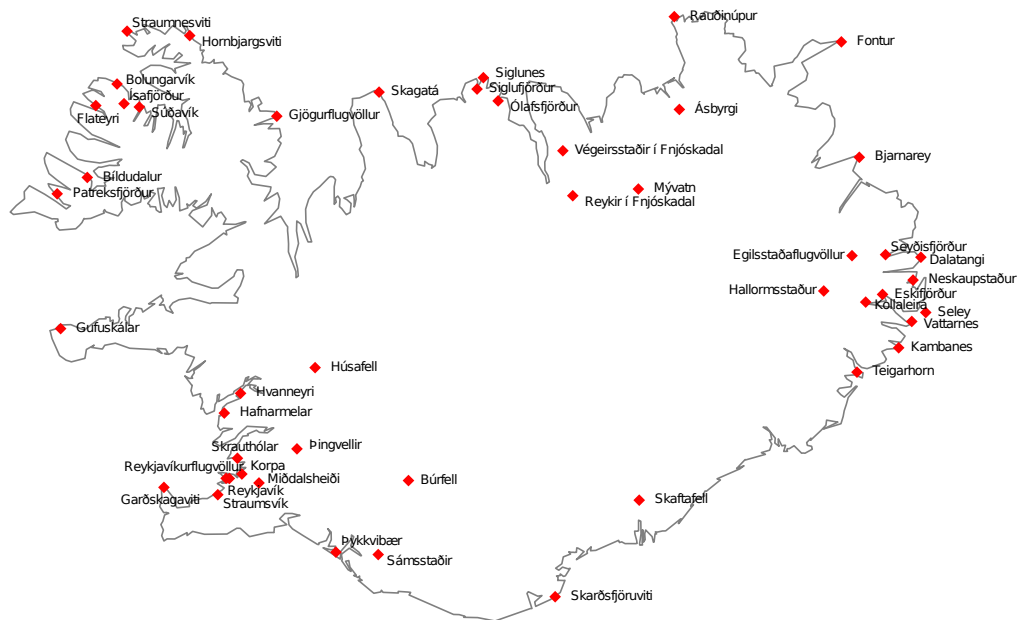
Figure 3.2: Locations of selected weather stations

3.1.2 Turbine Data

Turbine data of 47 turbines from most of the leading turbine manufacturers are used in this study. The data were retrieved mainly from a dataset put together by the British Wind Power Program (*The WindPower Program*, n.d.). The data consists of rotor size, cut-in speed, cut-out speeds and power output estimated for each integer value of wind speed. These values are represented in the power curve of each turbine where values for non-integer wind speeds are obtained by linearly interpolating between integer values.

Figure 3.3 shows all the curves aggregated to one plot which show wide span of power output considered. This gives an idea of the diversity of the turbines.

The power output presented in the power curves is representative at standard IEC conditions, i.e. for air density $\rho = 1.225$ kg/m^3. In this study, this particular air density is used for all locations. In reality, the air density varies with height and temperature but as maximum height difference in this study is around 300 meters this approximation is not very significant.
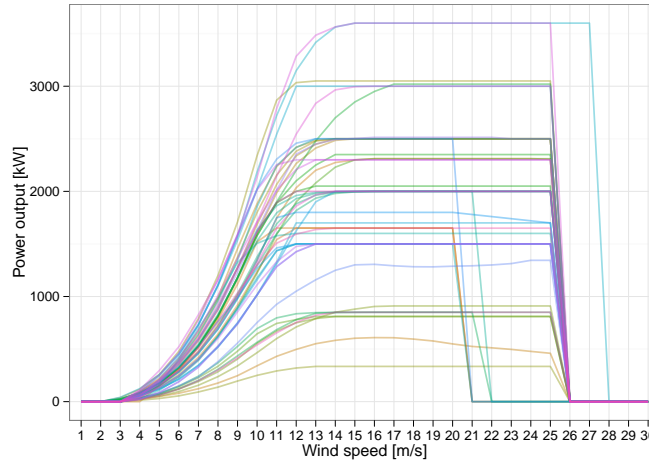
Figure 3.3: Power curves of all turbines used in the study

3.1.3 Electrical Grid Data

The layout of the electrical grid around Iceland limits the feasibility of certain locations for wind turbines as the generated energy needs to be put into the electrical grid, through its substations. Figure 3.4 shows the grid, the substations and the borders of six sections of Iceland. The rated flow through these borders determines how much of the produced power can be transmitted between sections.

Distances from weather stations to the nearest substation are calculated and used as a
parameter for estimating the cost of connecting each location to the electrical grid.
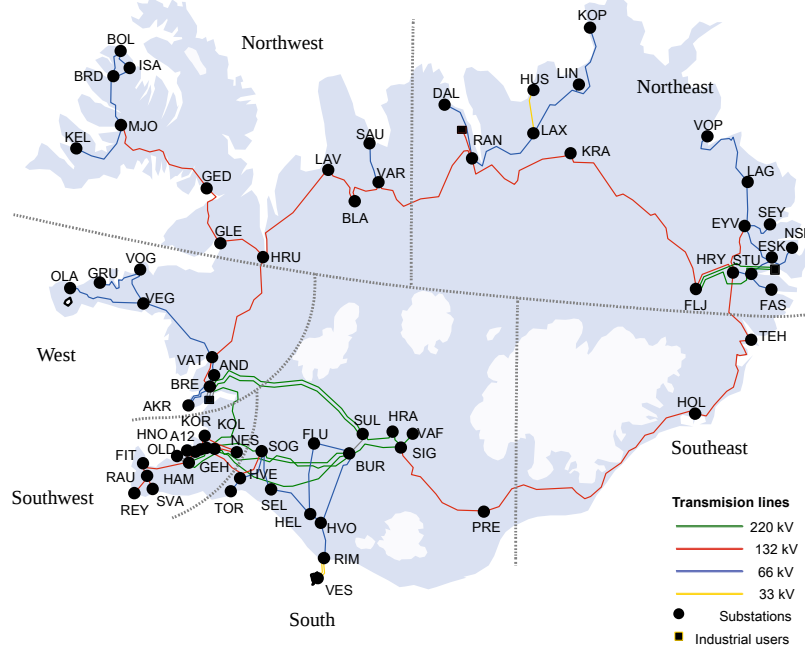
Figure 3.4: Layout of electricity grid and substations (Landsnet, 2012a)

3.2   Statistical Modeling of Wind

It has been shown that wind speed can be statistically modeled using Weibull distribution,
as discussed in section 2.1. The Weibull distribution has the following probability and
cumulative density functions,

$$f(x; \lambda, k) = \frac{k}{\lambda} \left(\frac{x}{\lambda} \right)^{k-1} e^{-(x/\lambda)^k} \tag{3.1}$$

$$F(x; k, \lambda) = 1 - e^{-(x/\lambda)^k} \tag{3.2}$$

for windspeeds $x > 0$, where $k > 0$ is the *shape* parameter and $\lambda > 0$ is the *scale*
parameter in m/s (Papoulis, 2002).

In this study, the wind data from each station is split into twelve bins, one for each month
of the year. The Weibull distribution is fitted to each monthly bin, using Maximum Like-
lihood Estimation in the R-programming language. As a result, one Weibull distribution
is generated for each month of the year for each station.

3.3 Projection of Wind Speed to Higher Altitudes

Wind speed measurements are projected up to the tower height of each turbine using the power law shown in equation 2.1.

The height, z, at which the turbine operates (height of tower) is normally at least as high as the diameter of the turbine's rotor (J.F. Manwell & Rogers, 2002). Therefore this study projects wind speed up to different height for each turbine i, that height being: $z_i = \text{rotor\_diameter}_i$

The power law exponent, a, needs to be determined for each location using measurements made at different altitudes. As detailed in section 2.1, research in Iceland have revealed values for the exponent mainly ranging from 0.08-0.16. Calculation of the exponent at Búrfell area has not been published but has been indicated to be close to $a = 0.12$.

The values of the power law exponent have to be approximated based on these earlier studies, as measurements of it are not available for the locations considered in this study (excluding Búrfell). It is assumed to be $a = 0.12$ for all locations. This value is around the mean of the results of the earlier studies. Moreover, using the same value as calculated for the Búrfell area gives the advantage of fair comparison. Inspection of the terrain surrounding each location could provide basis for adjustments of the value but that is outside the scope of this study, so no adjustments between locations can be justified.

Various examples of values of the power law exponent have been published, i.e. in Kaltschmitt et al. (2007) which are shown in table 3.1. As can be seen, the value used in this study ($a = 0.12$) is quite low compared to these values. This can however be justified by the fact that the terrain in Iceland is young and unvegetated as well as many of the locations being near an open coast.

Type of location	Power law exp.
Unstable air above open water surface:	0.06
Unstable air above flat open coast:	0.11
Neutral air above flat open coast:	0.16
Unstable air above human inhabited areas:	0.27

Table 3.1: Examples of power law exponents

3.4   Simulation of Wind Speed and Power

A simulation of future wind speeds is conducted using the Weibull parameters for each month at each location. Each simulated value is converted into simulated power output by using the corresponding value on the power curve of each turbine. The method of Antithetic variables is used to reduce number of iterations needed, as discussed in section 2.3. The process of simulation is described in the following steps:

1. Generate a random number, U_1 (uniform between 0 and 1) and also set $U_2 = 1 - U_1$

2. Use Inverse Transform to get two simulated wind speed values, $X_i = F(U_i, k_m, \lambda_m)$ where $F(x, k, \lambda)$ is the cumulative distribution Weibull function with the Weibull parameters, k and λ for month m.

3. Multiply X_i with $(z_j/10)^{0.12}$ (where z is the height of turbine j) and set $V_i = X_i \cdot (z_j/10)^{0.12}$ as a simulated value for wind at height z_j

4. Look up the power output corresponding to wind value V_i, on the power curve of turbine j and record it as P_i

5. Repeat steps $1-4$, k-times

6. The mean of the power outputs of the k runs gives the expected power output in month m for turbine j, $\bar{P} = \sum_{i=1}^{k} P_i / k$

The number of simulation runs, k, is decided such that the standard deviation of expected power output, S, is less than 0.2% of the rated power of the turbine, with 95% certainty. Ross (2006) gives the following equation to decide on k, using 95% certainty level

$$\frac{1.96S}{\sqrt{k}} < d \quad , \text{for } k > 100 \tag{3.3}$$

where d is the acceptable value of the standard deviation of the estimator (measured in kW). For a 2MW turbine, $d = 4$ and using eq. 3.3, the number k can be decided.

One value of k is estimated to use for all the simulations. Using one 2MW turbine, one 3MW turbine and one 1.25MW turbine, at a specific location for specific month gives a rage of k's. The resulting k's are all in the range of 40,000-50,000 iterations.

Therefore $k = 50,000$ is used when simulating data for each month for each weather station.

3.5   Energy calculation

All energy and efficiency calculations in the study assume 100% availability of the turbine, i.e. no downtime due to maintenance or malfunction is estimated.

3.5.1   Energy output

Each wind turbine has its unique power curve which represents the efficiency of its operation in various wind speeds. Appendix B shows the defining values for each of the turbines considered. Those are: Cut-in speed, cut-off speed and power output of operation for the certified wind speed range.

Since this study covers 47 different turbines for which only discrete power curve values are known, the energy output calculations are estimated using sums (equivalent to using the Riemann sum to estimate integrals). The wind speeds are generated by simulation based on the calculated Weibull distribution of each month. Each generated value represents wind speed over ten minute interval. The values on the power curve corresponding to each wind value are multiplied with the time interval of each wind value ($\frac{1}{6}$ of an hour to get a value in kWh). Those values are summed up to give an estimate of the average total energy generated each month and year, respectively,

$$\bar{E}_{month_j} \;=\; \frac{1}{N} \sum_{i=1}^{N} P_{w_i} \cdot \frac{1}{6} \cdot 24 \cdot D_j \tag{3.4}$$

$$\bar{E}_{year} \;=\; \sum_{j=1}^{12} E_{month_j} \tag{3.5}$$

where w_i is the ith simulated wind value, N is the total number of values simulated, P_{w_i} is the power curve value corresponding to the simulated wind and D_j is the number of days per month j.

This estimation of the average energy generated per year is calculated for each turbine at each location. The outcome is used to measure the cost of energy for each setup, which is comparable between different sizes, as is described in section 3.7.3.

3.5.2 Capacity factor

The capacity factor describes how well a wind turbine is utilizing the installed power at a specific location by stating the ratio between the power actually produced and the rated power of the turbine. In this study, it is used to give an indication of how well each turbine matches a specific location. The formula for the capacity factor is shown in equation 2.8

3.6 Distance from weather stations to substations

The cost of connecting a certain wind location to the energy grid needs to be estimated by calculating the distance from that location to the next substation of the energy grid.

All locations are provided in geographic longitude and latitude coordinates, in degrees. Distance between two points on a sphere is calculated by the great-circle distance

$$d = R \cdot \arccos(\sin \phi_1 \sin \phi_2 + \cos \phi_1 \cos \phi_2 \cos |\lambda_1 - \lambda_2|) \tag{3.6}$$

where R is the radius of the earth at Iceland's latitude, and ϕ_i, λ_i are latitude and longitude at points $i = \{1, 2\}$, respectively.

Earth's radius at the equator is $a = 6378.1$ km and at the poles $b = 6356.8$ km (Moritz, 2000). The latitude at the center of Iceland is approximately $\phi = 65°$N. Earth's radius at that latitude is calculated using ellipsoidal trigonometry

$$R = \sqrt{\frac{(a^2 \cdot \cos(\phi))^2 + (b^2 \cdot \sin(\phi))^2}{(a \cdot \cos(\phi))^2 + (b \cdot \sin(\phi))^2}} = 6361 \text{ km} \tag{3.7}$$

At each location, the distance d_i is the distance to substation i. By finding $\min d_i \; \forall i$, the distance to the next substation is calculated for all locations. The calculated distances are shown in appendix C.

3.7 Cost analysis

3.7.1 Setup and operational costs

The cost of turbines are considered to be proportional to the swept rotor area as suggested by the European Wind Energy Association in (Krohn et al., 2009) and (EWEA, 2009b). Price per rotor swept area is considered to be 460 €/m^2 which is the latest published value and close to a long-term mean, as shown in figure 2.1.

Other cost estimations used by EWEA in its cost of energy calculations is adopted in this study. These estimates are:

- - Operation and maintenance (O&M) costs are assumed to be 1.45 c€/kWh as an average over the lifetime of the turbine

- - The lifetime of the turbine is set at 20 years, in accordance with most technical design criteria

- - The discount rate is assumed to range from 5 to 10 % per annum. In the calculations, a discount rate of 7.5 % per annum is used

(EWEA, 2009b).

3.7.2 Connection cost

The cost per kilometer of 33kV connection line is estimated to be approximately 80,000€/km, as discussed in section 2.3. This line suffices for transmission of the power produced in all cases of this study as it never exceeds 3.6MW (for any single turbine). This is likely to rather be an overestimate than underestimate, specially for the smaller turbines.

Landsnet charges a fixed annual delivery fee of 4,317,536 ISK, approximately € 26,000 (Landsnet, 2012b). This fee is added to the operation cost in the cost of energy calculations.

Additionally, Landsnet charges for Ancillary Services and transmission losses per MWh. The current price is c€ 0.44 per kWh (77.4 ISK), which is added to the O&M costs in this study.

3.7.3 Cost of energy

The cost of energy (COE) is the total cost per kWh produced. It is calculated by discounting investment and O&M costs over the lifetime of the turbine and dividing it by the annual electricity production. Thus, the COE is calculated as an average cost over the turbine's lifetime .

J.F. Manwell and Rogers (2002) give the following equations for calculating COE when only cost is considered (not cash flow or any effect of selling price)

$$CRF = \frac{\text{annual\_payment}}{\text{present\_value}} = r/[1 - (1+r)^{-N}] \tag{3.8}$$

$$NPV_C = P_d + P_a \cdot Y\left(\frac{1}{1+r}, N\right) + C_{OM} \cdot Y\left(\frac{1+i}{1+r}, L\right) \tag{3.9}$$

$$Y(k,l) = \frac{k - k^{l+1}}{1 - k} \tag{3.10}$$

$$COE = \frac{NPV_c \cdot CRF}{\text{Annual\_energy\_production}} \tag{3.11}$$

where:
P_d = downpayment on system costs, estimated as 10%
P_a = annual payment on system costs = $(C_c - P_d) \cdot CRF$
CRF = capital recovery factor, based on the loan interest rate, b, rather than r
NPV_C = net present value of cost factors
Y = function to obtain the present value of a series of payments
b = loan interest rate, estimated 7.5%, in accordance with current gov. bond market
r = discount rate, estimated 7.5% as suggested by EWEA
i = inflation rate, 0%, no effect of inflation as constant prices are considered
L = lifetime of system, 20 years as suggested by EWEA
N = period of loan, 20 years as the lifetime of the system
C_c = capital cost of system, 460 €/m^2 × rotor_area + 80000 €/km×d_j
d_j = distance from location j to nearest substation
C_{OM} = annual O&M cost, 1.45 c€/kWh+0.44 c€/kWh+26000 €

The cost of energy can be used to estimate whether a certain wind turbine setup is economically feasible. If COE is higher than the sales price of the electricity, the construction is not feasible. Current sales price in Iceland, without transport, is 4.74 kr/kWh or around 3 c€/kWh (*OR.is / Prices / Rates*, 2012).

Sensitivity analysis or certainty estimates are outside the scope of this study. The COE is meant to be an indication to compare the different setup and not a full scale feasibility study. Nonetheless, two significant digits are used in the results, as they are justifiable when using the specific assumptions listed above.

3.7.4 Transmission losses

Loss in transmission is related to the distance of the transmission as well as characteristics of the line. Losses are described by Ohm's law as

$$P_l = IV_d = I^2 R \qquad (3.12)$$

where P_l is the power lost, I is the current in the transmission line, V_d is the voltage drop over the distance and R is the resistance of the line (typical value is 0.15 Ω/km). The current is $I = P/V$ where P is the power being transmitted and V the voltage of the power.

In the case of the biggest turbine (3.6MW), average capacity factor of 50% and typical distance (15 km) the loss is, $P_l = (1800kW/33kV)^2 \cdot 0.15\Omega/km \cdot 15km = 6.7$ kW, or only 0.4% of the average 1800 kW power transmitted. This is well within other uncertainty factors such as O&M costs or cost of the connection line, and therefore the cost of loss in transmission is omitted in this study.

3.8 Limitations

This study does not cover all the complex factors needed to be evaluated when deciding on locations for wind turbines. A few of those not covered, are listed below as limitations.

3.8.1 Wind measurements and locations

The selection of locations considered in this study is limited to weather stations which may not be the optimum locations for wind turbines. Moreover, those measurements are all made at altitudes of around 10m. More extensive wind measurements are needed to get a more detailed view of prospective locations.

The effect of the terrain surface on wind speeds have only been studied for a few locations in Iceland. In this study, that effect is approximated to be the same at all locations considered and thus overly simplifying the effect. This simplification is made due to lack of information on the terrain at each location. This has effect on the magnitude of wind when projected up to higher altitudes.

3.8.2 Turbine cost

The turbine market price is driven by individual quotes and a precise price for each turbine is hard to get without an actual bidding process. The prices used in this study are estimated prices using data from the European Wind Energy Association (EWEA, 2009a). Prices are assumed to be linearly related to the rotor diameter of the turbine. More precise prices are needed for a study like this to be used as ground for decision making.

The cost of operation and maintenance, is also approximated to be linearly related to power produced, using averages published by EWEA. These costs are to some extent locationally dependent and should therefore differ somewhat between locations and even countries. Due to the lack of experience of wind power usage in Iceland, no more detailed data is available.

3.8.3 Environmental issues

Environmental issues that should be addressed before permitting the setup of a commercial wind turbine include impacts on wildlife, habitat and other environmentally sensitive factors. A special concern for the habitats is noise and visual pollution, as a large turbine can be around 100 meters high and emit sound exceeding 100dB in its proximity. A wind turbine might pose a serious threat to many species of birds and their breeding areas.

The evaluation of those factors are beyond the scope of this study. Nonetheless, they are critical to further implementation of wind power in Iceland and need detailed research. The outcome of such research can affect heavily the process of locating of future wind power plants.

Chapter 4

Results

4.1 Wind Analysis and Simulation

To get a rough estimate of which locations could be feasible as a location for a wind turbine, average annual wind speeds are compared. Figure 4.1 shows the top ten locations with the highest annual mean wind speed. Bjarnarey has the highest annual mean wind speed over the period measured, 8.6 m/s in average.
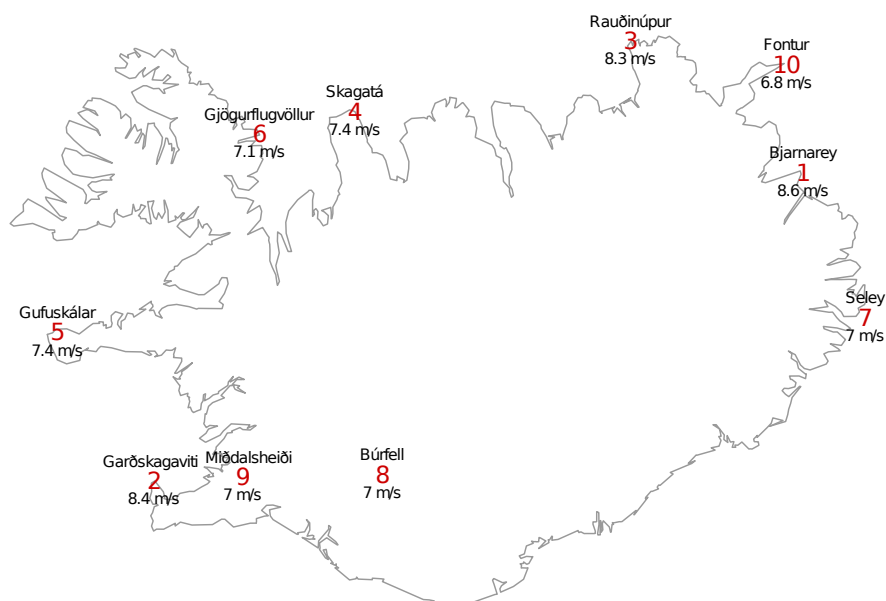
Figure 4.1: Top ten locations with the highest annual mean wind speed, ordered from 1 to 10
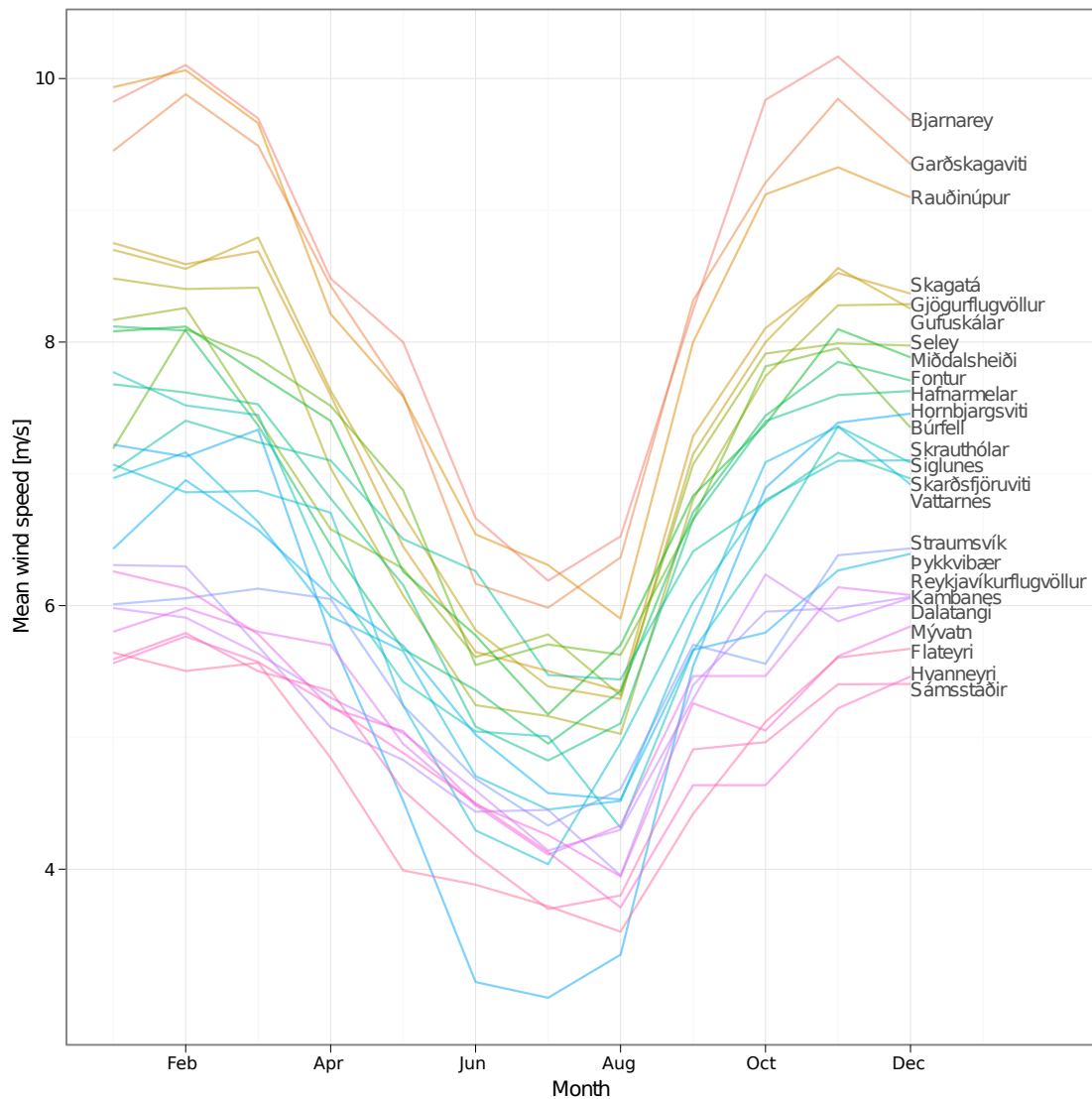
Figure 4.2: Mean wind speeds per month for top 25 stations

For a more detailed evaluation of the wind at each location, seasonal fluctuations need to be considered. Figure 4.2 shows the mean wind speed for each month at the 25 locations having overall highest wind speed. The data reveal strong seasonal fluctuations and that average wind speed is significantly lower in summer than in winter at all locations.
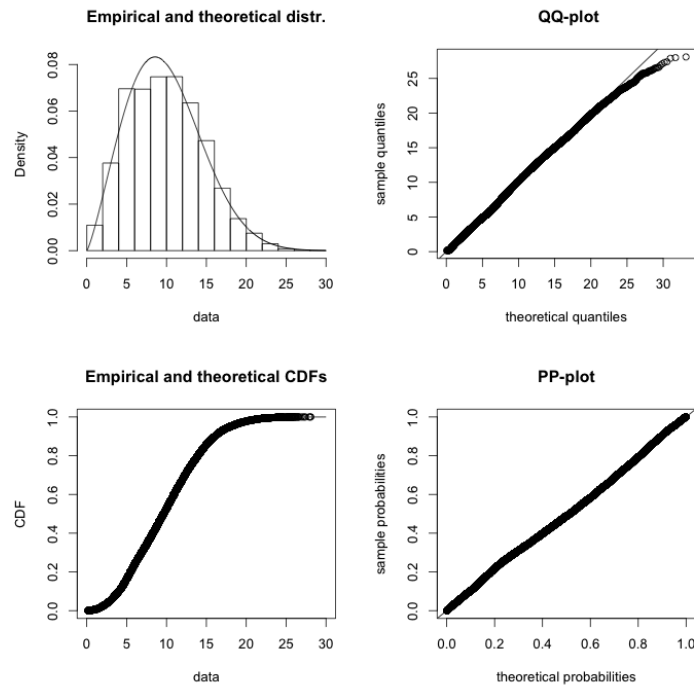
Figure 4.3: Example of a Weibull fit to measurements from Garðskagaviti in April

Analysis of the wind data generates Weibull distributions for each location, which are used in the simulation of the wind. Appendix A shows the resulting parameters of that analysis as means of the underlying data. The Weibull distributions make a good fit to the measurements as figure 4.3 shows an example of. Figure 4.4 shows the measurements, Weibull distribution and density of simulated data for one month at the location with the highest mean wind speed, Bjarnarey. It indicates that the density of the simulated values follows the Weibull density closely, as well as the measured data.
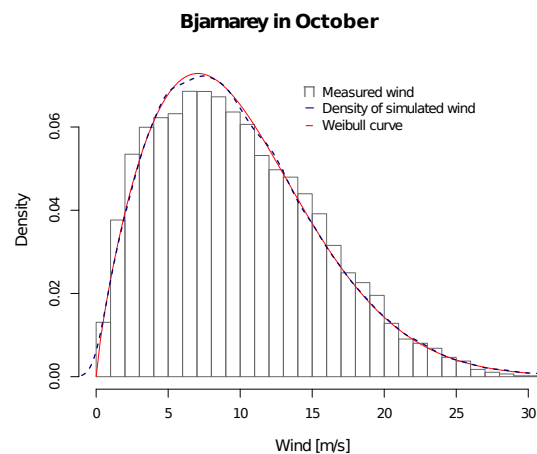
Figure 4.4: Example of measured and simulated wind and its Weibull curve

4.2   Annual Energy Output

Annual energy output for a representative year is calculated using the simulated wind and the power curves of each turbine.

Figure 4.5 shows the results after dividing it into bins of size $2-5$ GWh, where dark green shows the highest energy output. The order of the locations (on y-axis) are in the way that the mean annual energy output increases down. In the same way, the turbines (x-axis) are ordered in the way that the highest annual energy output increases to the left.

The ending of the names of the turbines indicate their power rating. The energy output generally increases with increase in rated power, as expected. The highest single annual energy output is at Garðskagaviti using Siemens_SWT_3.6MW, giving 18.1GWh for a representative year.
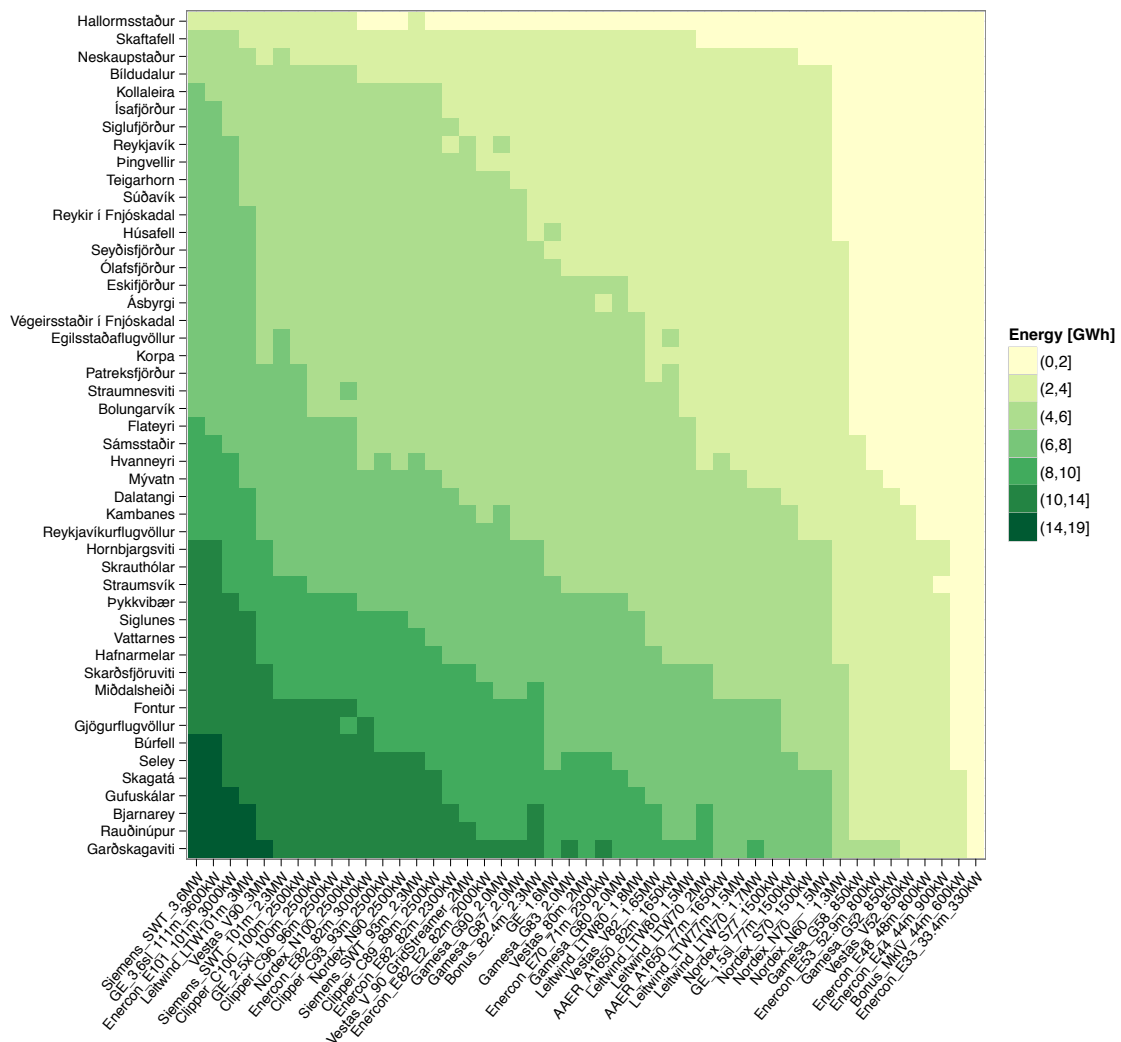
Figure 4.5: Annual energy output for all turbines and locations

4.3   Maximum Capacity Factor

Capacity factor (CF) is calculated for each turbine at each location to estimate which combination gives the highest efficiency of utilizing the installed power. The factor is given as percentage of maximum power output of each turbine.

Figure 4.6 shows the results after dividing it into bins of size 10%, where dark red shows the highest capacity factor. The order of the locations (on y-axis) are in the way that the mean the capacity factor increases down. In the same way, the turbines (x-axis) are ordered in the way that the highest mean capacity factor increases to the left. The ending of the names of the turbines indicate their power rating.

Garðskagaviti is the location giving the highest mean capacity factor over all the turbines and Hallormsstaður the lowest.
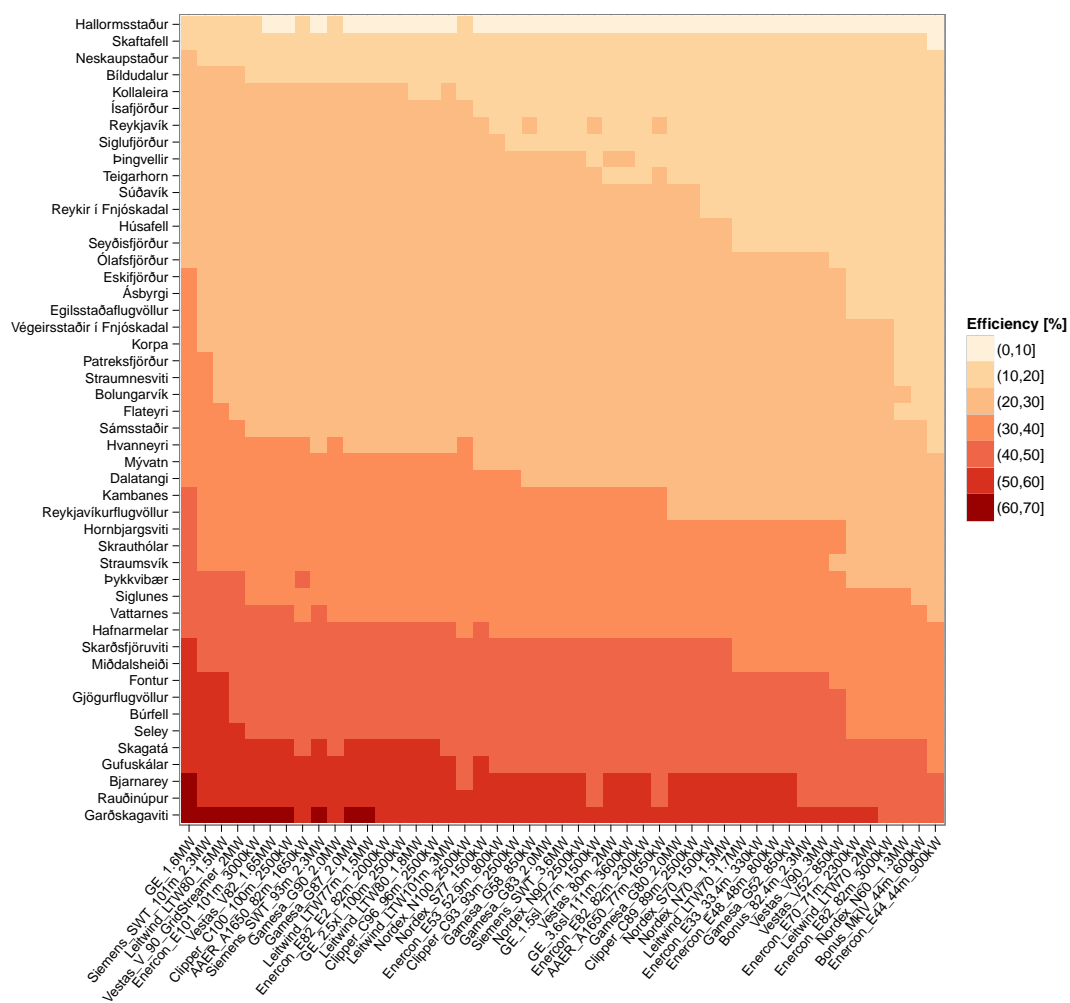
Figure 4.6: Capacity factors for all turbines at all locations
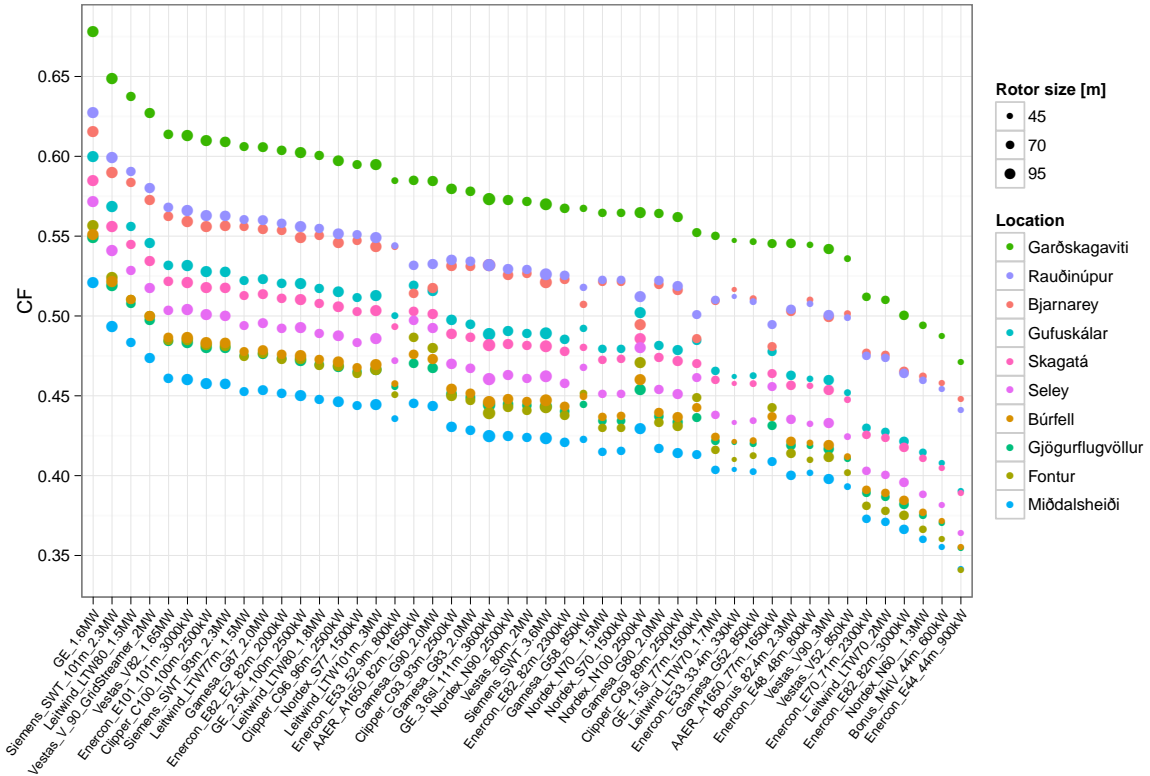
Figure 4.7: Capacity factors of all turbines for the ten locations
that have the highest capacity factors

Figure 4.7 shows the top ten locations that have the highest mean capacity factor. In this figure, a more precise value of the capacity factor of each turbine can be visualized.

The color of the dots indicates the location, and the size of the dots indicate the rotor diameter of each turbine. It can be seen that the efficiency roughly decreases with decreasing rotor size although some exceptions therefrom are visible. The most effective turbines tend to have relatively large rotor size compared to its rated power (rated power is shown in each turbine's name).

As figures 4.6 and 4.7 show, the turbine GE_1.6MW has the highest efficiency at all locations. This turbine is unusual in the way that, in spite of having a large rotor diameter of 101 meters, it is rated only 1.6MW. This rotor diameter is typical for a turbine rated around 2.5-3.0MW. Therefore, this turbine gives high efficiency but will have low power output compared to its setup cost. For this reason, this turbine is omitted in the next comparison, where locations having top ten capacity factors are mapped.
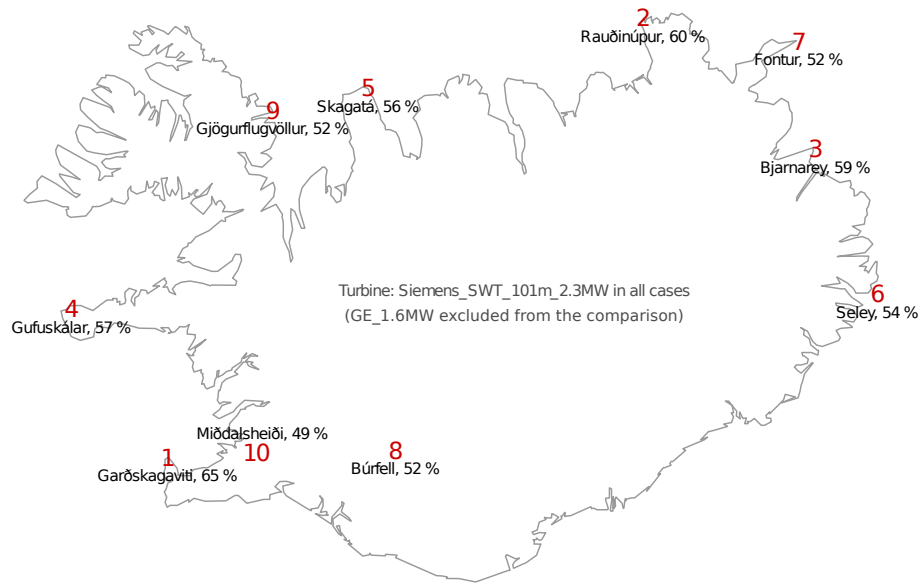
Figure 4.8: Top ten locations with the highest capacity factor,
ordered from 1 to 10

Figure 4.8 shows a map where the locations with the highest capacity factors (excluding the one that GE_1.6MW gives) are listed and ordered from one to ten, one being the highest. At all locations, the turbine which gives the highest capacity factor is Siemens_SWT_101m_2.3MW, which also has a very high rotor diameter (101m), but is rated 2.3MW.

A comparison between figures 4.8 and 4.1, where highest annual mean wind speed is ordered, shows that the same top ten locations are selected but the order differs somewhat. The main reason is different wind profiles at the locations and it emphasizes that average wind speed does not reveal all the potentials of a location for a wind turbine.

Generally, a capacity factor above 40% is regarded very good for wind turbine location. In that comparison, all ten locations listed in figure 4.8, have a very high capacity factor. Around half of all the locations can be regarded as good for wind turbine location in this sense.

4.4   Minimum Cost of Energy

The largest cost factor is in most cases the turbine cost. The exact cost of each turbine is not known but estimated as shown in section 3.7.1. However, if energy needs to be transmitted long distance from turbine to grid, the connection cost becomes a big factor as well. Appendix C shows the measured distances from each location to nearest grid substation.

Cost of energy (COE), measured in cent Euros per kWh (c€/kWh) is calculated dividing the annual payment of the discounted total cost estimated for each turbine with the annual energy output (shown previously in figure 4.5).

Figure 4.9 shows the cost of energy after dividing it into bins, where beige shows the lowest COE and dark blue the highest. The locations and turbines are ordered in such a way that the combinations having the lowest COE are in the lower left corner.

Garðskagaviti is the location giving the lowest mean cost of energy over all the turbines and Skaftafell gives the highest. The turbine that gives the lowest mean COE over all the turbines is Enercon_E101_101m_3000kW.

By looking at the locations on the y-axis of figure 4.9 it can be seen that the order differs a lot from the order in figure 4.6, where capacity factors are presented. This means that the turbine that have the highest capacity factors are not the one giving the lowest COE. The reason is that large rotor turbines generally have high capacity factor but as cost is related to rotor size, the capital cost is negatively affected by the large rotor.
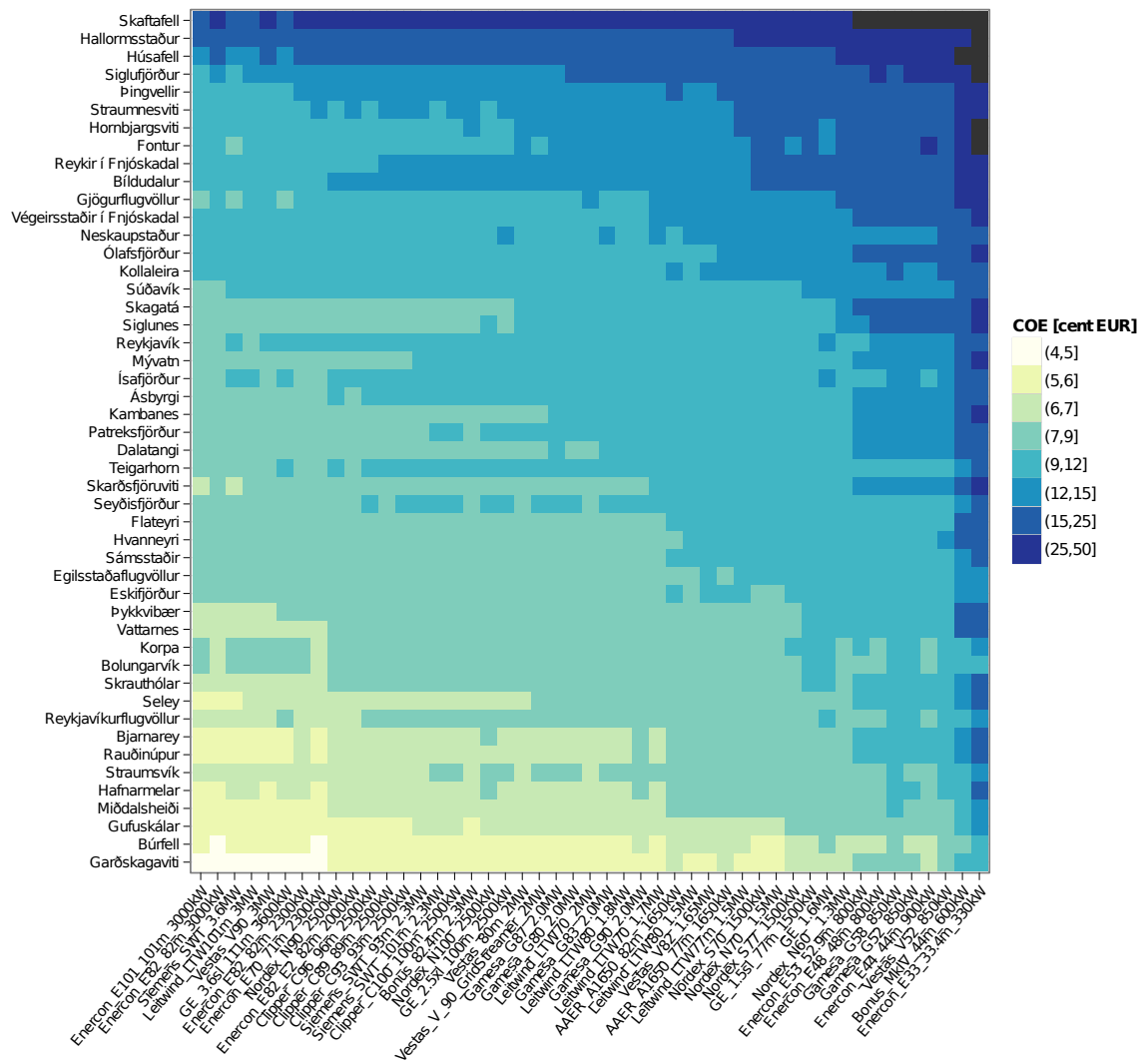
Figure 4.9: Cost of energy for all turbines at all locations
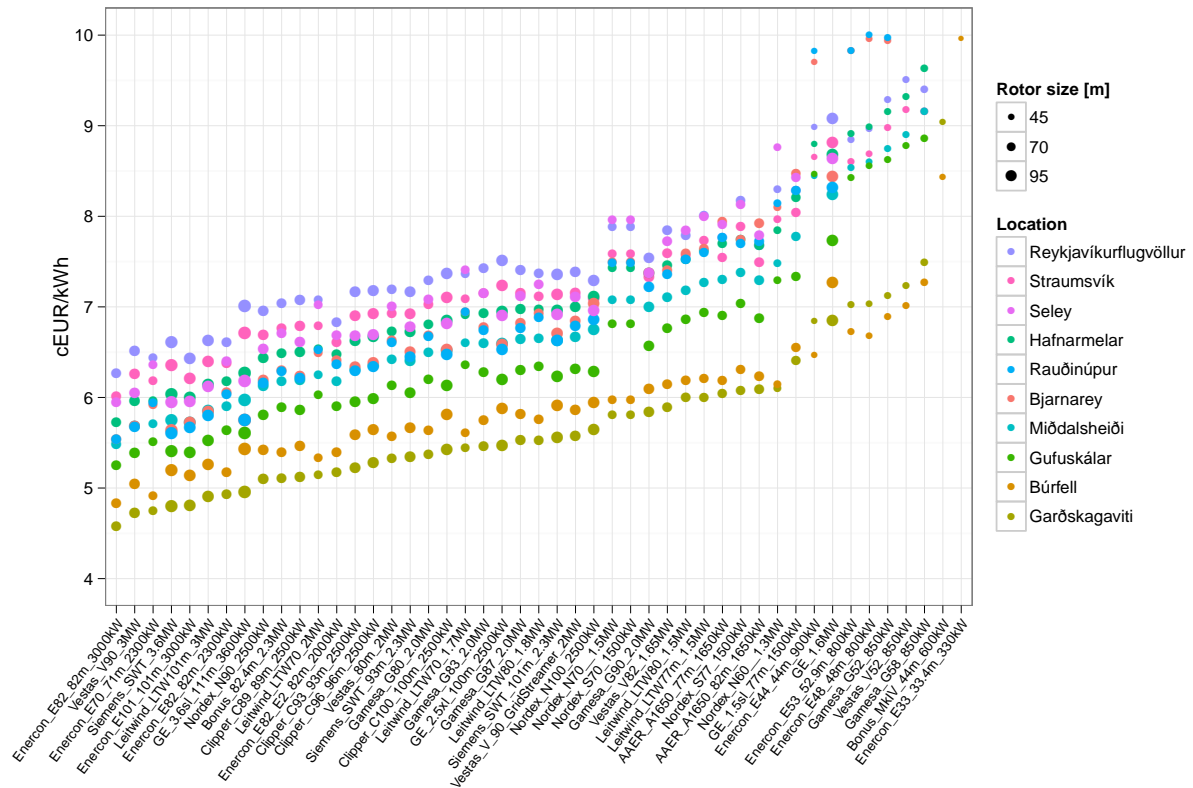
Figure 4.10: Cost of energy for all turbines at the ten locations
that give the lowest COE

Figure 4.10 shows the top ten locations that have the lowest mean cost of energy in figure 4.9. In this figure, more precise values of the COE can be visualized. The color of the dots indicate the location, and the size shows the rotor diameter of each turbine.

The turbine Enercon_E82_82m_3000kW, which is used at 82 meters height, gives the lowest COE for all five locations. However, the one giving lowest mean cost over all locations is used at 101 meter height (Enercon_E101_101m_3000kW) as stated before. This indicates that the higher energy output of the E101 does not compensate for its higher installation cost.

The combination giving the lowest cost of energy is Garðskagaviti and Enercon_E82_-82m_3000kW, having cost of 4.6 c€/kWh. The location giving the highest cost of energy is Skaftafell, which surpasses Hallormsstaður as the worst location due to longer distance to grid and therefore significantly higher connection cost.
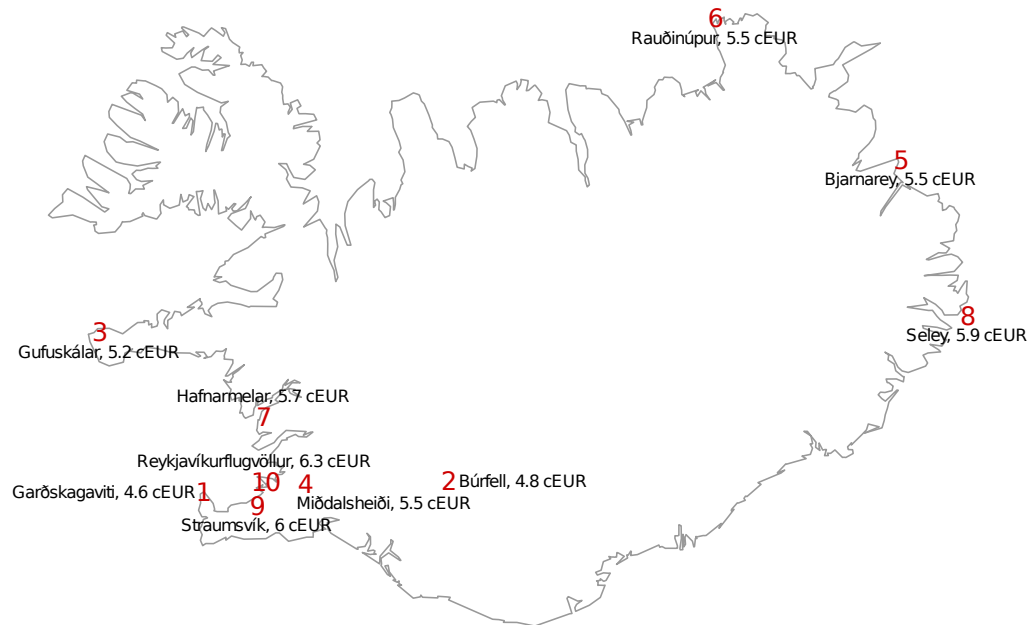
Figure 4.11: Top ten locations that give the lowest cost of energy

To visualize the locations giving the lowest mean COE, figure 4.11 maps the locations and the corresponding costs of energy. The turbine Enercon_E82_82m_3000kW gives the lowest COE for all the ten locations.

Comparing this figure to figures 4.1 and 4.8 shows that the selected locations differs somewhat. The relatively isolated locations, Gjögurflugvöllur, Fontur and Skagatá are replaced by locations in the South-West part of Iceland. The reason is that for locations far from the electricity grid, the connection cost becomes a large factor of the setup cost. Meanwhile, locations in the South-West part are more likely to be near a substation on the grid due to the density of the grid in the region.

4.5   Comparison to calculations at Búrfell

The results of this study can be compared to an extensive energy study performed at Búrfell for Landsvirkjun. That study uses a 660kW turbine. One of its conclusions is that annual energy production at the site is 2.3-2.5 GWh, depending on specific micro-location (Petersen & Björnsson, 2011). That translates to a capacity factor of 40-48%.

In this study, none of the turbines used are rated exactly 660kW. Comparable turbines are, however, Bonus_MkIV_44m_600kW and Enercon_E48_48m_800kW. Results for these turbines, and more, at Búrfell can be seen in table 4.1.

The energy output calculated in this study is on par with the energy output in the earlier study, but the capacity factors are lower. However, if bigger turbines are used, a higher capacity factor of up to 55% is achievable.

The turbine that gives the lowest cost of energy at Búrfell (4.6 c€/kWh) is Enercon_E82_-82m_3000kW. That turbine gives a capacity factor of 38% which is a lot lower than most of turbines listed below, but given it's high energy output compared to its rotor size, it still is the economically optimal for that location.

Turbine	Energy[GWh]	Capacity Factor	COE[c€/kWh]
Bonus_MkIV_44m_600kW	2.0	37.2%	8.4
Enercon_E48_48m_800kW	3.0	35.5%	6.7
GE_1.6MW	7.7	55.1%	7.3
Siemens_SWT_101m_2.3MW	10.5	52.2%	5.9
Leitwind_LTW80_1.5MW	6.7	51.0%	6.2
Vestas_V_90_GridStr._2MW	8.8	50.0%	5.9
Vestas_V82_1.65MW	7.0	48.7%	6.1
Enercon_E101_101m_3000kW	13.0	48.6%	5.1
Clipper_C100_100m_2500kW	10.6	48.3%	5.8
Siemens_SWT_93m_2.3MW	9.7	48.3%	5.7

Table 4.1: Results for 600-800kW turbines at Búrfell and all
turbines having CF higher than 48% at Búrfell

Chapter 5

Conclusions

5.1 Conclusions

Three measures of the performance of a combination of location and wind turbine type have been calculated, annual energy output, capacity factor (CF) and cost of energy (COE). A total of 2256 combinations of locations and turbines have been calculated and compared.

The results show that Garðskagaviti is the optimal location for a wind turbine in Iceland (out of the locations considerde), both in views of the highest efficiency in regards of capacity factor and when viewing the lowest cost of energy, 4.6 cEUR/kWh. This cost is however significantly higher than the sales price of electricity in Iceland which is around 3 c€/kWh, excluding transport.

Different turbines are selected as optimal, depending on if the objective is to maximize the capacity factor or minimize the cost of energy. For locations with high mean wind speeds the turbine Enercon_E82_82m_3000kW is the one giving the lowest cost of energy but for locations with lower wind speeds, the bigger Enercon_E101_101m_3000kW is the turbine giving the lowest cost. It is interesting that these are mainly the same turbines, differing only in rotor size.

As turbine cost is estimated to be linearly related to the rotor size, the Enercon_E82_82m-_3000kW has the advantage of having a high power rating but only medium sized rotor. That kind of turbine shows to be very cost efficient at locations where wind is strong and should be considered for that kind of installations.

The turbines with the lowest power rating generally give the highest cost of energy as annual cost are high relative to the low energy generation.

Distance of locations to the electricity grid play a significant role when looking at the
COE. This can be seen at a location such as Bjarnarey which has the highest annual mean
wind, the third highest overall capacity factor but drops to eighth in the minimum COE
due to high connection costs. The same applies to Rauðinúpur which also seems like
a favorable location, if not for the high connection cost. These location could however
be favorable for small scale power generation to be utilized in the proximity of the tur-
bine.

The cost of energy is in all cases significantly higher than the current sales price of energy
in Iceland, where lowest calculated COE is 4,6 c€/kWh while sales price is around 3
c€/kWh. Therefore, the production of wind power for direct sale is not currently feasi-
ble.

If plans of a submarine cable to Europe follow through, the scenario could be totally dif-
ferent as was pointed out by Sigurjónsson (2009). The sales price of electricity in the
European Union exceeds 10 c€/kWh in most countries, so wind power generation in Ice-
land could become feasible, depending on cost of transport and transmission losses.

The comparison to other calculations at Búrfell confirms the high capacity factors from
that studies. Furthermore, the COE calculations show that Búrfell has the second lowest
COE and thus makes the location even more feasible for wind generation. Therefore, the
choice of Landsvirkjun to construct their first wind turbine at the Búrfell area seems very
reasonable.

5.2   Summary of contribution

Wind measurements for 48 locations around Iceland have been statistically analyzed for
each month of the year. Such detailed analysis of these locations has not been published
earlier. The resulting Weibull parameters are presented in Appendix A. Using those
parameters, future wind is simulated.

The simulated wind is used along with the power curve of 47 different wind turbine types,
which were collected in this study. This gives energy output for each turbine at each
location.

To compare the 2256 different combinations of location and type, the Capacity Factor
and Cost of Energy have been calculated for each one and ordered accordingly. The
two performance measures give different perspectives on the quality of each location and
turbine type. The former does not incorporate the cost of different turbines or the cost of

utilizing each location. The latter one includes the estimated cost of turbine as well as the different costs of setting up turbines at each location. This calculations could be extended further as more information is gathered through research.

Capacity factors for a few turbines have earlier been studied in Iceland, in most cases based on annual or semi-annual mean wind speeds while this study bases the calculations on monthly analyzed Weibull data.

The Cost of Energy calculations result in cost per kWh for each turbine at each location. Building on these estimates, one can get a rough idea whether a particular turbine at a certain location is feasible or not. None of the combinations studied deliver energy at a feasible cost for the current Icelandic market, as production costs exceed the sale price of energy in all cases, given the assumptions used in the cost analysis.

5.3   Future Research

For successfully integrating wind power into the Icelandic energy market, the government needs to make a master plan for the utilization of wind power resources such as has been done for hydro and geothermal energy resources. The plan could detail e.g. a plan on what the share of wind power should ultimately become, what areas should be protected from wind power plants and what areas are suitable for wind power extraction.

Following such a plan, the locations for wind power plants could be optimized using relevant constraints. Such a research could implement the use of mixed integer linear programming which is known to be suitable for optimally locating different sources.

Before an implementation of a master plan is possible, more detailed wind profile measurements are needed, making measurements at different altitudes. The construction of a wind atlas for Iceland is in the makings, which is a huge contribution to this field of research.

The experimental construction of a wind turbine in the Búrfell area will give valuable information on the feasibility of wind power in Iceland. Operation and maintenance cost need to be studied along with availability percentage of such a large turbine in the harsh and windy Icelandic nature.

The environmental effects of wind turbine construction in Iceland need to be carefully researched for successful implementation of wind power in Iceland. In particular, the amount of noise and visual pollution as well as the possible negative impact on birds and wildlife need to be considered.

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Appendix A

Wind and Weibull parameters

Table A.1: Weibull parameters (k = shape and λ = scale)
and measured mean wind (μ)

Location	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	k	2.28	2.24	2.28	2.12	1.93	1.88	2.00	1.91	2.00	2.09	2.28	2.17
Garðskagaviti	λ	10.67	11.15	10.71	9.52	8.58	6.96	6.76	7.19	9.39	10.39	11.11	10.56
	μ	9.45	9.88	9.49	8.43	7.60	6.17	5.98	6.37	8.31	9.21	9.85	9.35
	k	1.69	1.53	1.63	1.63	1.55	1.52	1.41	1.46	1.54	1.46	1.65	1.57
Straumsvík	λ	6.74	6.71	6.79	6.71	5.79	5.12	4.68	5.03	6.30	6.13	7.14	7.17
	μ	6.01	6.06	6.13	6.05	5.24	4.68	4.33	4.61	5.70	5.56	6.38	6.43
	k	1.52	1.52	1.51	1.67	1.67	1.69	1.68	1.66	1.58	1.55	1.63	1.49
Reykjavík	λ	5.07	5.38	4.99	4.86	4.48	4.01	3.61	3.64	4.60	4.61	5.17	5.14
	μ	4.56	4.84	4.53	4.34	4.00	3.57	3.22	3.25	4.12	4.14	4.62	4.65
	k	1.57	1.53	1.58	1.69	1.61	1.65	1.66	1.60	1.61	1.47	1.67	1.53
Reykjavíkurflu	λ	6.43	6.61	6.42	6.35	5.50	4.99	4.58	4.82	6.09	6.02	6.84	6.73
	μ	5.80	5.98	5.80	5.70	4.95	4.48	4.11	4.33	5.47	5.47	6.14	6.08
	k	1.30	1.28	1.34	1.38	1.29	1.20	1.19	1.28	1.33	1.27	1.48	1.33
Korpa	λ	6.01	6.09	5.90	5.29	4.58	3.80	3.27	3.52	4.63	5.04	5.96	5.93
	μ	5.64	5.74	5.52	4.93	4.32	3.62	3.12	3.30	4.30	4.75	5.47	5.54
	k	1.41	1.53	1.20	1.73	1.59	1.66	1.50	1.46	1.62	1.66	1.72	1.51
Miðdalsheiði	λ	8.72	8.86	8.05	8.21	6.89	6.41	5.68	6.25	7.60	8.20	9.00	8.64
	μ	8.08	8.12	7.76	7.40	6.26	5.77	5.17	5.70	6.83	7.38	8.10	7.88
	k	1.32	1.17	1.21	1.26	1.22	1.21	1.20	1.20	1.34	1.19	1.30	1.27
Skrauthólar	λ	7.63	7.21	7.26	7.16	5.58	4.57	4.29	5.27	6.52	7.17	7.64	7.59
	μ	7.07	6.86	6.87	6.71	5.24	4.29	4.04	4.96	6.03	6.80	7.10	7.10
	k	0.85	0.84	0.90	1.02	1.08	1.14	1.14	1.00	1.00	1.00	0.98	0.85
Þingvellir	λ	4.08	4.29	4.58	4.61	4.53	3.94	3.50	3.36	4.16	4.50	4.54	4.10
	μ	4.36	4.59	4.75	4.57	4.42	3.79	3.37	3.37	4.16	4.51	4.58	4.38
	k	1.44	1.40	1.45	1.52	1.51	1.46	1.37	1.41	1.50	1.46	1.40	1.35
Hafnarmelar	λ	8.41	8.29	8.22	7.51	6.78	5.58	5.22	5.57	7.30	8.10	8.27	8.25
	μ	7.68	7.62	7.53	6.81	6.16	5.08	4.82	5.11	6.65	7.40	7.60	7.63
	k	1.58	1.56	1.62	1.85	1.80	1.92	1.79	1.73	1.61	1.65	1.62	1.53
Hvanneyri	λ	6.20	6.42	6.19	5.88	5.44	5.05	4.61	4.14	5.17	5.19	5.84	6.06
	μ	5.56	5.77	5.57	5.24	4.88	4.50	4.13	3.71	4.64	4.64	5.22	5.46
	k	2.02	1.84	1.94	2.03	1.83	1.89	1.85	1.77	1.83	1.91	1.91	1.90
Gufuskálar	λ	9.81	9.59	9.86	8.59	7.46	6.55	6.06	5.95	8.04	9.01	9.65	9.31
	μ	8.70	8.56	8.79	7.63	6.69	5.82	5.39	5.29	7.15	8.00	8.56	8.25

Table A.1 – continued from previous page

Location	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	k	1.32	1.31	1.32	1.31	1.28	1.28	1.22	1.23	1.34	1.32	1.44	1.35
Patreksfjörður	λ	6.36	6.04	6.19	5.20	3.91	3.71	3.40	3.54	4.65	5.36	6.40	6.35
	μ	5.89	5.60	5.72	4.81	3.64	3.45	3.19	3.32	4.27	4.93	5.81	5.85
	k	1.10	1.06	1.16	1.21	1.17	1.09	1.04	1.03	1.06	1.14	1.16	1.08
Bíldudalur	λ	4.94	4.79	4.95	3.96	3.44	2.90	2.63	2.56	3.73	3.87	4.53	4.74
	μ	4.79	4.69	4.73	3.75	3.29	2.83	2.60	2.54	3.67	3.72	4.32	4.62
	k	1.57	1.49	1.48	1.56	1.53	1.68	1.56	1.47	1.47	1.53	1.61	1.57
Flateyri	λ	6.25	6.05	6.10	5.37	4.41	4.32	4.10	3.87	4.83	5.66	6.23	6.27
	μ	5.64	5.50	5.57	4.85	3.99	3.88	3.72	3.53	4.42	5.12	5.61	5.67
	k	0.97	0.93	1.09	1.13	1.31	1.28	1.17	1.12	1.13	1.10	1.09	1.10
Ísafjörður	λ	4.89	4.63	5.07	4.10	4.01	3.51	3.21	2.99	3.83	4.40	4.89	4.82
	μ	4.93	4.74	4.92	3.95	3.73	3.29	3.07	2.88	3.68	4.26	4.75	4.67
	k	1.20	1.26	1.23	1.20	1.28	1.35	1.31	1.23	1.20	1.26	1.19	1.16
Súðavík	λ	5.18	5.44	5.61	4.48	4.25	3.63	3.34	3.26	4.17	4.83	5.17	5.19
	μ	4.89	5.07	5.27	4.23	3.95	3.33	3.09	3.05	3.92	4.50	4.90	4.96
	k	1.67	1.70	1.73	1.69	1.80	1.89	1.84	1.68	1.64	1.77	1.70	1.75
Gjögurflugvöll	λ	9.41	9.40	9.40	7.86	6.81	5.91	5.80	5.62	7.60	8.66	9.27	9.26
	μ	8.48	8.40	8.41	7.04	6.08	5.24	5.16	5.03	6.81	7.74	8.28	8.29
	k	1.32	1.25	1.25	1.17	1.39	1.29	1.21	1.21	1.31	1.34	1.30	1.33
Bolungarvík	λ	6.20	5.82	6.23	5.10	4.59	3.86	3.39	3.42	4.83	5.96	6.17	5.94
	μ	5.73	5.45	5.85	4.89	4.22	3.60	3.20	3.23	4.46	5.49	5.73	5.49
	k	1.53	1.54	1.53	1.40	1.30	1.24	1.27	1.27	1.36	1.56	1.58	1.59
Hornbjargsviti	λ	8.02	7.92	8.12	6.32	4.91	3.39	3.28	3.63	6.07	7.66	8.22	8.30
	μ	7.22	7.13	7.34	5.76	4.52	3.14	3.02	3.35	5.54	6.89	7.39	7.46
	k	1.49	1.38	1.45	1.46	1.37	1.37	1.43	1.43	1.35	1.48	1.34	1.50
Straumnesviti	λ	6.71	6.53	5.78	5.02	4.33	3.84	3.76	3.51	5.17	5.19	6.08	6.25
	μ	6.03	5.95	5.23	4.53	3.94	3.49	3.40	3.17	4.72	4.67	5.55	5.62
	k	1.15	1.16	1.22	1.40	1.39	1.41	1.33	1.16	1.20	1.10	1.16	1.19
Reykir í Fnjós	λ	5.14	5.30	5.20	5.05	4.49	4.10	3.83	3.31	4.08	4.06	4.81	5.24
	μ	4.94	5.07	4.92	4.65	4.15	3.79	3.56	3.17	3.87	3.94	4.60	4.98
	k	1.00	1.00	1.12	1.14	1.27	1.31	1.28	1.09	1.08	1.02	1.03	1.00
Végeirsstaðir	λ	5.35	5.50	5.76	5.34	4.99	4.54	4.23	3.59	4.50	4.67	5.11	5.42
	μ	5.35	5.50	5.55	5.14	4.68	4.24	3.96	3.50	4.39	4.64	5.07	5.42
	k	1.14	1.27	1.15	1.07	1.22	1.30	1.29	1.22	1.16	1.17	1.21	1.25
Ólafsfjörður	λ	5.70	5.61	5.32	4.35	3.94	3.93	3.96	3.45	4.39	4.88	5.51	5.47
	μ	5.47	5.22	5.08	4.26	3.72	3.68	3.70	3.27	4.18	4.64	5.18	5.10
	k	1.90	1.86	1.84	1.81	1.77	1.57	1.56	1.56	1.76	1.85	1.81	1.91
Skagatá	λ	9.86	9.66	9.77	8.54	7.24	6.30	6.15	5.97	8.19	9.13	9.58	9.43
	μ	8.75	8.59	8.69	7.60	6.45	5.65	5.50	5.35	7.29	8.11	8.52	8.37
	k	1.13	1.19	1.09	1.06	1.18	1.26	1.15	1.08	1.06	1.06	1.11	1.11
Siglufjörður	λ	5.58	5.43	5.00	3.92	3.56	3.29	3.11	2.77	3.92	4.42	5.07	4.89
	μ	5.36	5.14	4.85	3.84	3.37	3.09	2.98	2.70	3.84	4.33	4.89	4.72
	k	1.48	1.46	1.49	1.44	1.59	1.65	1.58	1.18	1.17	1.43	1.46	1.44
Siglunes	λ	8.55	8.26	8.20	6.79	5.98	5.59	5.54	4.50	5.91	7.04	8.07	7.76
	μ	7.77	7.52	7.45	6.20	5.42	5.05	5.01	4.31	5.66	6.44	7.36	7.09
	k	0.94	1.07	1.15	1.25	1.28	1.24	1.19	1.11	1.11	1.16	1.09	1.11
Hallormsstaður	λ	3.01	3.37	3.15	3.29	2.90	2.31	2.13	1.98	2.23	2.89	2.95	3.19
	μ	3.07	3.29	3.01	3.09	2.71	2.18	2.02	1.91	2.16	2.76	2.87	3.08
	k	1.34	1.26	1.11	1.01	1.08	1.15	1.09	1.00	1.09	1.13	1.20	1.28
Seyðisfjörður	λ	6.01	6.07	5.14	4.23	4.09	3.53	3.06	2.89	3.93	4.61	5.30	5.37
	μ	5.56	5.69	4.97	4.21	4.00	3.39	2.97	2.89	3.82	4.43	5.02	5.01
	k	1.28	1.33	1.41	1.31	1.29	1.21	1.21	1.16	1.31	1.28	1.38	1.33
Dalatangi	λ	6.44	6.41	6.15	5.71	5.36	4.81	4.35	4.47	5.70	6.63	6.42	6.57
	μ	5.98	5.91	5.64	5.30	5.03	4.60	4.14	4.30	5.29	6.24	5.88	6.06

Table A.1 – continued from previous page

Location	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	k	1.25	1.14	1.29	1.46	1.68	1.76	1.64	1.49	1.44	1.38	1.29	1.11
Egilsstaðaflug	λ	5.25	5.13	5.15	5.46	5.36	5.11	4.76	4.29	4.83	5.13	4.87	4.79
	μ	4.91	4.93	4.82	4.99	4.83	4.59	4.30	3.91	4.41	4.72	4.53	4.65
	k	1.16	1.15	1.30	1.48	1.64	1.72	1.56	1.47	1.49	1.38	1.21	1.27
Mývatn	λ	6.53	6.38	6.21	5.74	5.62	5.03	4.73	4.35	5.80	5.50	5.94	6.24
	μ	6.26	6.13	5.78	5.22	5.05	4.49	4.26	3.95	5.26	5.05	5.62	5.84
	k	1.77	1.78	1.81	1.64	1.56	1.53	1.62	1.57	1.62	1.80	1.88	1.84
Bjarnarey	λ	11.04	11.34	10.90	9.47	8.89	7.35	6.93	7.28	9.21	11.06	11.45	10.90
	μ	9.82	10.10	9.70	8.48	8.00	6.66	6.19	6.53	8.24	9.84	10.17	9.68
	k	1.42	1.50	1.35	1.47	1.49	1.50	1.45	1.31	1.23	1.20	1.32	1.48
Ásbyrgi	λ	6.05	6.23	5.61	5.24	4.71	4.14	3.79	3.56	4.34	4.75	5.29	5.81
	μ	5.55	5.67	5.20	4.81	4.29	3.78	3.48	3.32	4.09	4.51	4.91	5.32
	k	1.90	2.01	1.91	1.93	1.84	1.93	1.81	1.71	1.88	1.89	1.96	1.91
Fontur	λ	9.13	9.12	8.29	7.28	6.37	6.03	5.53	5.96	7.55	8.35	8.83	8.64
	μ	8.12	8.09	7.37	6.46	5.67	5.36	4.95	5.35	6.71	7.44	7.85	7.71
	k	1.88	2.00	1.99	1.88	1.90	1.92	1.91	1.41	1.67	1.91	1.70	1.70
Rauðinúpur	λ	11.21	11.37	10.90	9.25	8.56	7.37	7.09	6.37	8.92	10.28	10.36	10.05
	μ	9.93	10.06	9.66	8.21	7.59	6.54	6.31	5.90	8.00	9.12	9.33	9.10
	k	1.51	1.47	1.41	1.43	1.47	1.37	1.31	1.25	1.41	1.56	1.47	1.48
Teigarhorn	λ	5.24	5.26	4.86	4.68	4.57	3.62	3.13	3.26	4.51	5.30	5.46	4.99
	μ	4.72	4.77	4.44	4.27	4.16	3.33	2.90	3.05	4.12	4.78	4.95	4.51
	k	1.50	1.55	1.50	1.55	1.62	1.53	1.46	1.44	1.45	1.55	1.58	1.57
Kambanes	λ	6.97	6.98	6.28	5.61	5.36	4.90	4.87	4.31	5.89	6.57	6.65	6.72
	μ	6.31	6.30	5.69	5.08	4.83	4.44	4.45	3.95	5.40	5.95	5.98	6.07
	k	1.04	1.02	0.98	0.97	1.11	1.09	1.02	0.94	0.95	1.00	1.00	1.02
Kollaleira	λ	4.78	4.76	4.24	4.05	4.07	3.49	2.90	2.84	3.59	4.23	4.66	4.41
	μ	4.72	4.73	4.27	4.09	3.95	3.40	2.88	2.91	3.66	4.23	4.66	4.39
	k	1.23	1.17	1.19	1.10	1.17	1.17	1.13	1.05	1.06	1.23	1.22	1.22
Eskifjörður	λ	5.51	5.68	5.22	4.69	4.85	4.16	3.52	3.46	4.19	5.27	5.52	5.32
	μ	5.16	5.40	4.94	4.54	4.61	3.96	3.38	3.39	4.10	4.95	5.19	4.99
	k	1.68	1.64	1.60	1.44	1.34	1.23	1.16	1.08	1.36	1.80	1.77	1.74
Vattarnes	λ	7.79	7.98	7.37	6.49	6.12	4.99	4.65	4.63	6.35	7.95	8.26	7.76
	μ	6.97	7.16	6.63	5.92	5.66	4.71	4.45	4.52	5.85	7.09	7.36	6.92
	k	1.38	1.35	1.31	1.28	1.44	1.34	1.26	1.23	1.27	1.39	1.39	1.37
Neskaupstaður	λ	4.79	4.70	4.34	3.74	3.46	3.20	2.93	2.74	3.55	4.25	4.54	4.36
	μ	4.37	4.32	4.01	3.48	3.15	2.96	2.74	2.58	3.31	3.88	4.14	4.00
	k	1.78	1.89	1.82	1.77	1.81	1.73	1.66	1.75	1.81	1.88	1.95	1.91
Seley	λ	9.18	9.30	8.34	7.39	7.06	6.30	6.47	5.97	7.95	8.90	9.01	8.98
	μ	8.17	8.26	7.42	6.58	6.28	5.61	5.78	5.32	7.07	7.91	7.99	7.97
	k	1.48	1.60	1.60	1.84	1.80	1.85	1.66	1.42	1.50	1.58	1.62	1.58
Skarðsfjöruviti	λ	7.74	8.25	8.08	7.98	7.30	7.04	6.10	5.89	7.07	7.55	8.01	7.74
	μ	7.02	7.40	7.24	7.10	6.51	6.26	5.47	5.44	6.41	6.79	7.16	6.96
	k	1.76	1.70	1.72	1.69	1.69	1.49	1.80	1.81	1.73	1.73	1.78	1.79
Þykkvibær	λ	7.22	7.72	7.30	6.68	6.29	5.42	5.11	5.07	6.35	6.48	7.02	7.18
	μ	6.43	6.95	6.57	6.07	5.70	5.02	4.58	4.53	5.66	5.80	6.27	6.39
	k	1.31	1.36	1.35	1.48	1.37	1.39	1.47	1.40	1.34	1.31	1.37	1.22
Sámsstaðir	λ	6.04	6.28	5.97	5.89	4.97	4.47	4.06	4.15	5.31	5.36	5.86	5.71
	μ	5.59	5.79	5.50	5.35	4.60	4.11	3.70	3.80	4.91	4.96	5.40	5.41
	k	1.58	2.02	1.71	1.96	1.75	1.64	1.58	1.36	1.48	1.69	1.79	1.70
Búrfell	λ	7.93	9.04	8.74	8.40	7.64	6.12	6.27	6.06	7.26	8.64	8.89	8.19
	μ	7.19	8.10	7.88	7.52	6.88	5.55	5.71	5.63	6.65	7.82	7.95	7.35
	k	0.83	0.88	0.90	1.03	0.96	0.92	1.04	0.80	0.95	0.88	0.83	0.81
Skaftafell	λ	3.34	3.50	3.39	3.63	2.97	2.52	2.18	1.87	2.80	3.42	3.30	3.08
	μ	3.63	3.71	3.54	3.59	3.01	2.59	2.15	2.02	2.86	3.62	3.59	3.39

Table A.1 – continued from previous page

Location	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	k	1.22	1.23	1.28	1.40	1.48	1.45	1.38	1.33	1.32	1.26	1.21	1.20
Húsafell	λ	5.40	5.63	5.23	4.75	4.54	4.03	3.71	3.37	4.50	4.38	5.06	5.39
	μ	5.08	5.28	4.87	4.35	4.12	3.67	3.40	3.12	4.15	4.07	4.75	5.08

Appendix B

Turbines

Table B.1: Turbine parameters and power in kW at 1-11 m/s

	rotor	cutout	cutin	1	2	3	4	5	6	7	8	9	10	11
AAER_A1650_77m_1650kW	77.0	20.0	3.0	0.0	0.0	0.0	57.0	141.0	258.0	422.0	642.0	919.0	1237.0	1541.0
AAER_A1650_82m_1650kW	82.0	20.0	3.0	0.0	0.0	0.0	71.0	173.0	316.0	516.0	781.0	1117.0	1520.0	1651.0
Bonus_82.4m_2.3MW	82.0	25.0	4.0	0.0	0.0	0.0	0.0	153.7	301.2	479.4	731.4	1008.0	1346.1	1745.6
Bonus_MkIV_44m_600kW	44.0	25.0	3.0	0.0	0.0	0.0	23.0	48.0	80.0	123.0	177.0	247.0	341.0	431.0
Clipper_C100_100m_2500kW	100.0	25.0	3.0	0.0	0.0	0.0	96.0	221.0	412.0	669.0	993.0	1456.0	1882.0	2235.0
Clipper_C89_89m_2500kW	89.0	25.0	3.0	0.0	0.0	0.0	58.0	154.0	301.0	522.0	801.0	1162.0	1603.0	1985.0
Clipper_C93_93m_2500kW	93.0	25.0	3.0	0.0	0.0	0.0	58.0	184.0	353.0	581.0	875.0	1272.0	1684.0	2066.0
Clipper_C96_96m_2500kW	96.0	25.0	3.0	0.0	0.0	0.0	88.0	206.0	382.0	632.0	971.0	1375.0	1801.0	2154.0
Enercon_E101_101m_3000kW	101.0	25.0	2.5	0.0	0.0	37.0	118.0	258.0	479.0	790.0	1200.0	1710.0	2340.0	2867.0
Enercon_E33_33.4m_330kW	33.0	25.0	2.5	0.0	0.0	5.0	13.7	30.0	55.0	92.0	138.0	196.0	250.0	292.0
Enercon_E44_44m_900kW	44.0	25.0	1.0	0.0	1.4	8.0	24.5	53.0	96.0	156.0	238.0	340.0	466.0	600.0
Enercon_E48_48m_800kW	48.0	25.0	1.5	0.0	2.0	12.0	32.0	66.0	120.0	191.0	284.0	405.0	555.0	671.0
Enercon_E53_52.9m_800kW	52.0	25.0	1.5	0.0	2.0	14.0	38.0	77.0	141.0	228.0	336.0	480.0	645.0	744.0
Enercon_E70_71m_2300kW	71.0	25.0	1.5	0.0	2.0	18.0	56.0	127.0	240.0	400.0	626.0	892.0	1223.0	1590.0
Enercon_E82_E2_82m_2000kW	82.0	25.0	1.5	0.0	3.0	25.0	82.0	174.0	321.0	532.0	815.0	1180.0	1612.0	1890.0
Enercon_E82_82m_2300kW	82.0	25.0	2.5	0.0	0.0	25.0	82.0	174.0	321.0	532.0	815.0	1180.0	1580.0	1890.0
Enercon_E82_82m_3000kW	82.0	25.0	2.5	0.0	0.0	25.0	82.0	174.0	321.0	532.0	815.0	1180.0	1580.0	1900.0
Gamesa_G52_850kW	52.0	25.0	3.5	0.0	0.0	0.0	27.9	65.2	123.1	203.0	307.0	435.3	564.5	684.6
Gamesa_G58_850kW	58.0	21.0	2.5	0.0	0.0	9.7	31.2	78.4	148.2	242.7	368.8	525.3	695.0	796.6
Gamesa_G80_2.0MW	80.0	25.0	3.5	0.0	0.0	0.0	66.3	152.0	280.0	457.0	690.0	978.0	1296.0	1598.0
Gamesa_G83_2.0MW	83.0	25.0	3.5	0.0	0.0	0.0	65.1	152.4	285.2	470.8	715.8	1024.8	1377.4	1690.8
Gamesa_G87_2.0MW	87.0	25.0	3.5	0.0	0.0	0.0	78.6	181.2	335.4	549.8	831.5	1174.8	1528.3	1794.7
Gamesa_G90_2.0MW	90.0	21.0	2.5	0.0	0.0	21.3	84.9	197.3	363.8	594.9	900.8	1274.4	1633.0	1863.0
GE_1.6MW	100.0	25.0	3.5	0.0	0.0	0.0	38.0	154.0	405.0	693.0	986.0	1323.0	1506.0	1578.0
GE_1.5sl_77m_1500kW	77.0	20.0	3.5	0.0	0.0	0.0	32.0	107.0	230.0	391.0	616.0	895.0	1178.0	1435.0
GE_2.5xl_100m_2500kW	100.0	25.0	3.5	0.0	0.0	0.0	55.0	182.0	391.0	645.0	955.0	1345.0	1855.0	2245.0
GE_3.6sl_111m_3600kW	111.0	27.0	3.5	0.0	0.0	0.0	98.0	244.0	451.0	732.0	1110.0	1574.0	2184.0	2721.0
Leitwind_LTW101m_3MW	100.0	25.0	2.5	0.0	0.0	41.0	124.0	257.0	456.0	735.0	1101.0	1537.0	2019.0	2543.0
Leitwind_LTW70_1.7MW	70.0	25.0	3.0	0.0	0.0	0.0	58.0	120.0	213.0	344.0	519.0	742.0	1018.0	1327.0
Leitwind_LTW70_2MW	70.0	25.0	3.0	0.0	0.0	0.0	57.0	120.0	214.0	347.0	524.0	749.0	1012.0	1309.0
Leitwind_LTW77m_1.5MW	77.0	25.0	3.0	0.0	0.0	0.0	61.0	135.0	248.0	406.0	619.0	877.0	1158.0	1435.0
Leitwind_LTW80_1.5MW	80.0	25.0	3.0	0.0	0.0	0.0	77.0	184.0	330.0	527.0	761.0	993.0	1268.0	1462.0
Leitwind_LTW80_1.8MW	80.0	25.0	3.0	0.0	0.0	0.0	80.0	163.0	287.0	460.0	691.0	986.0	1346.0	1749.0
Nordex_N100_2500kW	99.0	20.0	3.0	0.0	0.0	0.0	50.0	211.0	429.0	725.0	1111.0	1583.0	2023.0	2306.0
Nordex_N60__1.3MW	60.0	25.0	3.5	0.0	0.0	0.0	25.0	78.0	150.0	234.0	381.0	557.0	752.0	926.0
Nordex_N70__1.5MW	70.0	25.0	3.5	0.0	0.0	0.0	24.0	87.0	190.0	329.0	520.0	750.0	1016.0	1284.0
Nordex_N90_2500kW	90.0	25.0	3.0	0.0	0.0	0.0	43.0	181.0	374.0	599.0	877.0	1230.0	1626.0	2011.0
Nordex_S70_1500kW	70.0	25.0	3.0	0.0	0.0	0.0	24.0	87.0	190.0	329.0	531.0	736.0	1016.0	1284.0
Nordex_S77_1500kW	77.0	25.0	3.0	0.0	0.0	0.0	44.0	131.0	244.0	400.0	600.0	854.0	1111.0	1331.0
Siemens_SWT_101m_2.3MW	101.0	25.0	3.5	0.0	0.0	0.0	102.0	252.0	462.0	774.0	1163.0	1583.0	2014.0	2254.0
Siemens_SWT_93m_2.3MW	93.0	25.0	3.5	0.0	0.0	0.0	59.0	200.0	400.0	678.0	1011.0	1361.0	1712.0	2012.0
Siemens_SWT_3.6MW	107.0	25.0	3.5	0.0	0.0	0.0	113.0	296.0	523.0	827.0	1159.0	1594.0	2135.0	2788.0
Vestas_V90_3MW	90.0	25.0	3.5	0.0	0.0	0.0	77.0	190.0	353.0	581.0	886.0	1273.0	1710.0	2145.0
Vestas_80m_2MW	80.0	25.0	3.5	0.0	0.0	0.0	66.0	166.0	288.0	473.0	709.0	1000.0	1316.0	1651.0
Vestas_V_90_GridStreamer_2MW	90.0	25.0	3.5	0.0	0.0	0.0	92.0	213.0	377.0	610.0	925.0	1271.0	1612.0	1896.0
Vestas_V52_850kW	52.0	25.0	3.5	0.0	0.0	0.0	19.0	60.0	120.0	200.0	300.0	417.0	539.0	654.0
Vestas_V82_1.65MW	82.0	25.0	3.5	0.0	0.0	0.0	38.0	144.0	307.0	510.0	762.0	1035.0	1300.0	1507.0

Table B.2: Turbine power output in kW at 12-28 m/s

turbine.shortname	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
AAER_A1650_77m	1651	1651	1651	1651	1651	1651	1651	1651	1651	0	0	0	0	0	0	0	0
AAER_A1650_82m	1651	1651	1651	1651	1651	1651	1651	1651	1651	0	0	0	0	0	0	0	0
Bonus_82.4m_2.	2035	2200	2274	2299	2311	2311	2311	2311	2311	2311	2311	2311	2311	2305	0	0	0
Bonus_MkIV_44m	497	551	583	603	609	608	595	577	549	525	512	497	478	460	0	0	0
Clipper_C100_1	2419	2485	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	0	0	0
Clipper_C89_89	2265	2412	2485	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	0	0	0
Clipper_C93_93	2338	2448	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	0	0	0
Clipper_C96_96	2382	2478	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	0	0	0
Enercon_E101_1	3034	3050	3050	3050	3050	3050	3050	3050	3050	3050	3050	3050	3050	3050	0	0	0
Enercon_E33_33	320	335	335	335	335	335	335	335	335	335	335	335	335	335	0	0	0
Enercon_E44_44	710	790	850	880	905	910	910	910	910	910	910	910	910	910	0	0	0
Enercon_E48_48	750	790	810	810	810	810	810	810	810	810	810	810	810	810	0	0	0
Enercon_E53_52	780	810	810	810	810	810	810	810	810	810	810	810	810	810	0	0	0
Enercon_E70_71	1900	2080	2230	2300	2310	2310	2310	2310	2310	2310	2310	2310	2310	2310	0	0	0
Enercon_E82_E2	2000	2050	2050	2050	2050	2050	2050	2050	2050	2050	2050	2050	2050	2050	0	0	0
Enercon_E82_82	2100	2250	2350	2350	2350	2350	2350	2350	2350	2350	2350	2350	2350	2350	0	0	0
Enercon_E82_82	2200	2480	2700	2850	2950	3020	3020	3020	3020	3020	3020	3020	3020	3020	0	0	0
Gamesa_G52_850	780	841	848	849	850	850	850	850	850	850	850	850	850	850	0	0	0
Gamesa_G58_850	836	847	849	850	850	850	850	850	850	850	0	0	0	0	0	0	0
Gamesa_G80_2.0	1818	1935	1980	1995	1999	2000	2000	2000	2000	2000	2000	2000	2000	2000	0	0	0
Gamesa_G83_2.0	1882	1964	1990	1998	1999	2000	2000	2000	2000	2000	2000	2000	2000	2000	0	0	0
Gamesa_G87_2.0	1931	1981	1995	1999	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	0	0	0
Gamesa_G90_2.0	1960	1990	1998	2000	2000	2000	2000	2000	2000	0	0	0	0	0	0	0	0
GE_1.6MW	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	0	0	0
GE_1.5sl_77m_1	1500	1500	1500	1500	1500	1500	1500	1500	1500	0	0	0	0	0	0	0	0
GE_2.5xl_100m_	2418	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	0	0	0
GE_3.6sl_111m_	3148	3417	3563	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	0
Leitwind_LTW10	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	0	0	0
Leitwind_LTW70	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700	1700	0	0	0
Leitwind_LTW70	1625	1900	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	0	0	0
Leitwind_LTW77	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	0	0	0
Leitwind_LTW80	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	0	0	0
Leitwind_LTW80	1800	1800	1800	1800	1800	1800	1800	1800	1800	1780	1760	1740	1720	1700	0	0	0
Nordex_N100_25	2458	2500	2500	2500	2500	2500	2500	2500	2500	0	0	0	0	0	0	0	0
Nordex_N60__1.	1050	1159	1249	1301	1306	1292	1283	1282	1288	1292	1300	1313	1344	1344	0	0	0
Nordex_N70__1.	1426	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	0	0	0
Nordex_N90_250	2354	2450	2493	2503	2514	2514	2514	2514	2514	2514	2514	2500	2500	2500	0	0	0
Nordex_S70_150	1426	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	0	0	0
Nordex_S77_150	1476	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	0	0	0
Siemens_SWT_10	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	0	0	0
Siemens_SWT_93	2208	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	0	0	0
Siemens_SWT_3.	3285	3485	3564	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	0	0	0
Vestas_V90_3MW	2544	2837	2965	2995	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	0	0	0
Vestas_80m_2MW	1860	1968	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	0	0	0
Vestas_V_90_Gr	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	0	0	0
Vestas_V52_850	754	822	850	850	850	850	850	850	850	850	850	850	850	850	0	0	0
Vestas_V82_1.6	1593	1637	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650	0	0	0

Appendix C

Distance from location to nearest substation

Table C.1: Distance from weather stations to nearest substation in km

	Station	Distance	Substation
2738	Bolungarvík	0.4	Bolungarvík
1479	Korpa	0.8	Korpa
5981	Eskifjörður	1.2	Eskifjörður
5872	Teigarhorn	1.4	Teigar
5990	Neskaupstaður	1.4	Neskaupstaður
2642	Ísafjörður	2.0	Ísafjörður
4180	Seyðisfjörður	2.3	Seyðisfjörður
4271	Egilsstaðaflugvöllur	2.4	Eyvindará
1475	Reykjavík	2.8	Hnoðraholt
6430	Búrfell	4.5	Búrfell
1477	Reykjavíkurflugvöllur	4.5	Hnoðraholt
1473	Straumsvík	5.2	Öldugata
2631	Flateyri	6.1	Breiðadalur
5975	Kollaleira	6.3	Stuðlar
6222	Sámsstaðir	6.3	Hvolsvöllur
1779	Hvanneyri	7.4	Vatnshamar
2646	Súðavík	7.8	Ísafjörður
4614	Ásbyrgi	8.1	Lindabrekka
2319	Patreksfjörður	8.1	Keldeyri
1578	Skrauthólar	8.6	Korpa
4060	Hallormsstaður	9.0	Hryggstekkur

Table C.1 – continued from previous page

	Station	Distance	Substation
1673	Hafnarmelar	10.1	Vatnshamar
1483	Miðdalsheiði	10.7	Geitháls
1453	Garðskagaviti	11.6	Fitjar
2428	Bíldudalur	11.7	Keldeyri
3658	Ólafsfjörður	13.3	Dalvík
1919	Gufuskálar	14.1	Ólafsvík
6208	Þykkvibær	14.3	Hella
4193	Dalatangi	14.4	Neskaupstaður
4300	Mývatn	15.4	Krafla
5988	Vattarnes	15.5	Fáskrúðsfjörður
5885	Kambanes	16.3	Fáskrúðsfjörður
3477	Végeirsstaðir í Fnjóskadal	19.4	Rangárvellir
3380	Reykir í Fnjóskadal	20.2	Rangárvellir
5993	Seley	20.4	Neskaupstaður
1596	Þingvellir	20.8	Nesjavallavirkjun
4472	Bjarnarey	23.5	Vopnafjörður
4912	Rauðinúpur	23.5	Kópasker
3752	Siglufjörður	25.5	Dalvík
3754	Siglunes	28.9	Dalvík
6176	Skarðsfjöruviti	29.5	Prestbakki
2941	Straumnesviti	31.2	Bolungarvík
3720	Skagatá	46.4	Sauðárkrókur
2862	Hornbjargsviti	48.3	Bolungarvík
6802	Húsafell	48.4	Hrútatunguvegur
6499	Skaftafell	57.6	Prestbakki
2692	Gjögurflugvöllur	62.9	Geiradalur
4867	Fontur	70.6	Vopnafjörður

Appendix D

Computer Codes

```r
# Load packages
library(fitdistrplus)
library('R.matlab')
library('zoo')
library('chron')
library('reshape')
library('RgoogleMaps')
library('RSvgDevice')
library('Hmisc')
library("mixdist")
library(ggplot2)
library('ffbase')
library('xtable')
library(mapdata)
library(RSQLite)
install.packages('directlabels')
library('directlabels')

## importa stödvum og laga nöfn á theim
stodvar <-
read.delim("~/Documents/MATLAB/FINAL/wep/sta.stod_leidr",stringsAsFactor=FALSE)
stodvar$EIG <- factor(stodvar$EIG)
selected <- readMat('~/Dropbox/Skoli_vor2012/FINAL/DATA/HIwind/selected.mat')
selected <- as.numeric(selected$selected)
lowstodvar <- stodvar[stodvar$STOD %in% selected,]
lowstodvar$NAFN <- trim(lowstodvar$NAFN)
lowstodvar$NAFN <- gsub(' ','_', lowstodvar$NAFN)
lowstodvar$NAFN <- trim(lowstodvar$NAFN)

## Breyti hnitum svo thau séu í tugabrotum í vectorum
hnitasplit <- gsub("'","",lowstodvar$BREIDD)
hnitasplit <- strsplit(as.character(hnitasplit),"°")
hnitasplit <- unlist(hnitasplit)
hnitasplit <- matrix(as.numeric(hnitasplit),ncol=2,byrow=TRUE)
hnitasplit[,2] <- hnitasplit[,2]/60
breidd2 <- hnitasplit[,1]+hnitasplit[,2]


hnitasplit <- gsub("'","",lowstodvar$LENGD)
```

```r
hnitasplit <- strsplit(as.character(hnitasplit),"°")
hnitasplit <- unlist(hnitasplit)
hnitasplit <- matrix(as.numeric(hnitasplit),ncol=2,byrow=TRUE)
hnitasplit[,2] <- hnitasplit[,2]/60
lengd2 <- (hnitasplit[,1]+hnitasplit[,2])*-1

##------------ Connect to SQLite database
drv <- dbDriver("SQLite")
con <- dbConnect(drv,'~/Documents/winddatabase')
dbListTables(con)
dbDisconnect(con)
# ---------   Database import, bara gera í fyrsta skiptid
drv <- dbDriver("SQLite")
consql <- function(db) {
  dbcon <- dbConnect(dbDriver("SQLite"),file.path('~/Documents/',db))
  return(dbcon)
}
con <- consql('winddatabase')

for (i in selected) {
  tablename <- paste('table',i,sep='_')
  windfile <- paste('~/Documents/MATLAB/wep/M-Files/OUT/gogn/',i,'.txt',sep='')
  stodin  <- read.delim(windfile,header=FALSE,sep='\t',

colClasses=c('NULL','integer','integer','integer','integer','integer','numeric'))
  names(stodin) <- c('year','month','day','hour','minute','wind')
  dbWriteTable(con,tablename,stodin, row.names=FALSE,overwrite=TRUE)
  rm(stodin)
  gc()
}

#---------- Function to get one station
getOneStation  <- function(con,station) {
  q <- paste('SELECT * FROM table',station,sep='_')
  result <- dbGetQuery(con,q)
  return(result)
}

#----------  Function: Weibull per manud per stod
monthWeibull <- function (p) {
  manstod <- einstod[einstod$month==p,"wind"]
  fit.einstod.man <- fitdist(einstod[einstod$month==p,"wind"]+0.0001,
'weibull',method='mle')
  print(plot(fit.einstod.man))
  month <- c(fit.einstod.man$estimate, 'sd'=fit.einstod.man$sd,
mu=mean(manstod),sigma=sd(manstod))
  month <- c(unlist(month[1:6]),aic_value=fit.einstod.man$aic)
  return(month)
}

#------ Load one station into memory at a time and analyze
windList <- list()
windMatrix <- matrix(ncol=7,nrow=12)
colnames(windMatrix) <- c('shape','scale','sd.shape','sd.scale','mu','sigma',
'aic_value' )
```

```r
con <- dbConnect(drv,'~/Documents/winddatabase')

for (i in 1:nrow(lowstodvar)){
  windtable <- paste('table',lowstodvar$STOD[i],sep='_')
  einstod <- dbReadTable(con,windtable)
  cat("Station:",lowstodvar$STOD[i],lowstodvar$NAFN[i],"\n")
  windMatrix <- t(sapply(1:12,monthWeibull))
  windList[[lowstodvar$NAFN[i]]] <- windMatrix
  einstod <- NULL
}
names(windList) <- trim(names(windList))
copy.windList <- windList
copy.windMatrix <- windMatrix

#Get AVG wind speed for each oation
windAvg <- data.frame('Station'=c(1,1),'Mean.wind'=c(1,1))
for (i in 1:nrow(lowstodvar[,])){
  s <- lowstodvar$NAFN[i]
  w <- as.numeric(dbGetQuery(con,paste('SELECT AVG( wind ) FROM
table',lowstodvar$STOD[i],sep='_')))
  windAvg[i,] <- c(s,w)
}

#set medalvind í töflu
windAvg$Mean.wind <- round(as.numeric(windAvg$Mean.wind),2)
windAvg  <- cbind(windAvg,lengd2,breidd2)
windOrdAvg <- windAvg[order(windAvg$Mean.wind,decreasing=TRUE),]
#mesti medalvindur:
maxwind <- ceiling(max(sapply(windList[1:49],function(x) x[,5])))

#melta töfluna til ad plotta í ggplot, fyrir hverja station
plotMeanWind <- function(st){
  a <- data.frame(sapply(windList[st],function(x) x[,5]))
  names(a) <- names(windList)[st]
  b <- melt.data.frame(a)
  #Plotta medalvind mánada fyrir n stödvar
  rtext <- data.frame(x=12,y=as.numeric(a[12,]),label=as.character(names(a)))
  gg <- ggplot()+xlim(c(1,13.9))+#ylim(c(1.8,maxwind))+
    geom_line(data=b,aes(x=1:12, y=value,col=variable),alpha=0.5,size=0.6)+
    labs(x='Month',y='Mean wind speed [m/s]')+
    scale_color_discrete(b$variable,h=c(10,360),h.start=90, l=57)+
    scale_x_date(format = "%b") +
    theme_bw()+opts(legend.position='none')

  print(gg)
}
top25 <- order(windAvg$Mean.wind,decreasing=TRUE)[1:25]
plotMeanWind(top25)
ggsave('fig/meanWind1_25low.pdf',width=9,height=7)

plotMeanWind(order(windAvg$Mean.wind,decreasing=TRUE)[26:49])
ggsave('fig/meanWind26_49.pdf',width=9,height=9)


#---------SIMULATION------
daysinmonth <- c(31,28,31,30,31,30,31,31,30,31,30,31)
```

```r
n=50000
st <- 33
mon <- 12

simulateWind <- function(st,mon,n) {
  sh.wei <- windList[[st]][mon,1]
  sc.wei <- windList[[st]][mon,2]
  p <- runif(n)
  weisim <- qweibull(p=p,shape=sh.wei,scale=sc.wei)
  return(weisim)
}

simulateWindAnti <- function(st,mon,n) {
  sh.wei <- windList[[st]][mon,1]
  sc.wei <- windList[[st]][mon,2]
  p <- runif(n/2)
  p  <- c(p,1-p)
  weisim <- qweibull(p=p,shape=sh.wei,scale=sc.wei)
  return(weisim)
}

simulateEnergy <- function(tur,mon,wind) {
  cutin <- turbines['cutin',tur]
  cutout <- turbines['cutout',tur]
  simwind1 <- wind*powerLaw[tur]
  simwind <- data.frame(weib=simwind1, round.down=floor(simwind1),
round.up=ceil(simwind1))
  simwind[simwind$weib>30,] <- 0
  simwind <- cbind(simwind,pdn=turbines[simwind$round.down+3,tur],
                   pup=turbines[simwind$round.up+3,tur])
  simwind$pdiff <- simwind$pup-simwind$pdn
  simwind$pdiff[simwind$pdiff<0] <- 0
  simwind$totpow <- with(simwind,pdn+weib %% 1 * pdiff)
  simwind$totpow[simwind$weib<cutin] <- 0
  simwind$totpow[simwind$weib>cutout] <- 0
  #MWh framl í mánudinum:
  monenergy <- mean(simwind$totpow)*24*daysinmonth[mon]/1000
  return(monenergy) #list(weisimall,monenergy)) simwind$totpow)
}


#---plot simulation
bjar <- getOneStation(con,lowstodvar$STOD[lowstodvar$NAFN=='Bjarnarey'])
bjarNov <- bjar[bjar$month==12,]
mon=10
st=32
weisim <- simulateWind(st,mon,50000)
weisim2 <- data.frame(variable='Simulated wind', wind=simulateWind(st,mon,50000))
WindBjar <- data.frame(variable='Measured wind',wind=bjarNov$wind)
WindSimCom <- rbind(weisim2,WindBjar)
histname <- paste(lowstodvar$NAFN[st],'in',month.abb[mon])
pdf('fig/SimWeiHist.pdf',width=7,height=6)
hist(bjar$wind[bjar$month==10],main=histname,xlim=c(0,30),ylim=c(0,0.075),cex.main=1,
     xlab='Wind [m/s]',freq=FALSE, border='grey40',breaks=seq(0,40,1),
cex.lab=1.2,cex.main=1.4)
x=seq(0,30,0.1)
```

```r
curve(dweibull(x,scale=windList[[st]][mon,2], shape=windList[[st]][mon,1]),add=TRUE,
col='red')
points(density(weisim), type='l',col='navy',lty='dashed',lwd=1.6)
legend(x=14,y=max(density(weisim)$y),legend=c('Measured wind','Density of simulated
wind',
      'Weibull curve'),cex=1,pch=c('l','-','_'), col=c('grey40','navy','red'),
box.col='white')
dev.off()
rm(bjar)

############## Power and energy simulation ###########

simulatePowerMonth <- function(st,mon,n) {
  wind <- simulateWind(st,mon,n)
  #simulate power for all turbines
  powergen <- sapply(1:ncol(turbines),simulateEnergy,mon=mon,wind=wind)
  #cat(month.abb[mon],'-')
  return(powergen)
}


simulateYear <- function(st,n) {
  cat(st,'-')
  tmp <- sapply(1:12,simulatePowerMonth,st=st,n=n)
  tmp <- cbind(tmp,rowSums(tmp))
  return(tmp)
}


#simulate all stations for n instances
simEnAllStations <- vector(mode='list',length=48)
for (i in 1:48) simEnAllStations[[i]] <- matrix(nrow=47,ncol=13)
timestamp()
simEnAllStations <- lapply(1:48,simulateYear,n=50000)
timestamp()

names(simEnAllStations) <- lowstodvar$NAFN
#copy.simEnAllStations <- simEnAllStations

simAllUnlist <- sapply(simEnAllStations[1:48],function(x) x[,-13])
#simAllUnlist50 <- sapply(simEnAllStations50000[1:48],function(x) x[,-13])
#simAllUnlist5 <- sapply(simEnAllStations500[1:48],function(x) x[,-13])
plot(density(simAllUnlist),lty=1, col='red')
points(density(simAllUnlist50),type='l',lty=2, col='green')
points(density(simAllUnlist5),type='l',lty=3)


############### Annual Energy calculations: ##########
#Reikna annual energy output fyrir allar location
energyAll <- data.frame('station'=c(),'turbine'=c(),'energy'=c())

for(i in lowstodvar$NAFN) {
  en1 <- as.vector(x=simEnAllStations[[i]][,13])+turbines[4,]
  en1 <- t(en1/1000) #from MWh to GWh
  en1 <- en1[order(en1,decreasing=TRUE),]
  en1df <- data.frame(turbine=factor(names(en1),ordered=FALSE),energy=en1)
  energyAll <- rbind(energyAll,cbind(names(simEnAllStations[i]),en1df))
  row.names(energyAll) <- NULL
```

```r
}
names(energyAll)[1] <- 'station'

energyMeanAll <- sapply(lowstodvar$NAFN,function(x)
mean(energyAll$energy[energyAll$station==x]))
energyMeanOrdNames <- names(sort(energyMeanAll,decreasing=TRUE))
energyMeanTur <- sapply(names(turbines),function(x)
mean(energyAll$energy[energyAll$turbine==x]))
energyMeanOrdTur <- names(sort(energyMeanTur,decreasing=TRUE))
energyMax <-
data.frame(station=energyAll$station[order(energyAll$energy,decreasing=TRUE)],
                    energy=round(sort(energyAll$energy,decreasing=TRUE),1))

##-#-#-# #-Plot heatmap of annual energy for al stations
fill_factor <- cut(round(energyAll$energy,1), breaks=c(0,2,4,6,8,10,14,19))
ggplot(data=energyAll)+
  geom_tile(aes(station,turbine,fill=fill_factor))+theme_bw()+
  opts(axis.text.x=theme_text(hjust=1, vjust=1,
angle=50,size=8.5),axis.text.y=theme_text(size=9,hjust=1))+
  scale_fill_brewer(name='Energy [GWh]',palette='YlGn')+
  scale_y_discrete(name=' ', limits=energyMeanOrdTur)+
  scale_x_discrete(name=' ',limits=energyMeanOrdNames)+coord_flip()
ggsave('fig/energyAllOrd.pdf',width=10.3,height=9.5)

##############    CF calculations:  ###########
#Reikna capacity factor fyrir allar location
cfAll <- data.frame('station'=c(),'turbine'=c(),'cf'=c())

for(i in lowstodvar$NAFN) {
  cf1 <- as.vector(x=simEnAllStations[[i]][,13])/turbines[34,]
  cf1 <- t(cf1)
  cf1 <- cf1[order(cf1,decreasing=TRUE),]
  cf1df <- data.frame(turbine=factor(names(cf1),ordered=FALSE),CF=cf1)
  #cf1df <- cf1df[-c(55,64),]
  #cf1df <- droplevels(cf1df$turbine)
  pdf(paste('fig/CapFactor2/cf',names(simEnAllStations[i]),'.pdf',sep=' '),7,7)
  color=as.numeric(turbines['rotor',match(cf1df$turbine,names(turbines))])
  print(ggplot(data=cf1df) + xlab('Turbines') + ylab('Capacity factor') + theme_bw()+
    geom_point(aes(x=turbine,y=CF, color=color),size=3)+
    opts(title=paste('Efficiency of turbines at ',names(simEnAllStations[i])))+
    scale_color_continuous(name='Rotor size [m]',breaks=seq(20,100,by=15), low =
"yellow",high = "red") +
    scale_x_discrete(limits=rev(names(cf1)))+
    scale_size(guide = 'none')+coord_flip()+opts(axis.text.y = theme_text(size =
8,hjust=1)))
  dev.off()
  cfAll <- rbind(cfAll,cbind(names(simEnAllStations[i]),cf1df))
  row.names(cfAll) <- NULL
}
names(cfAll)[1] <- 'station'

cfMeanAll <- sapply(lowstodvar$NAFN,function(x) mean(cfAll$CF[cfAll$station==x]))
cfMeanOrdNames <- names(sort(cfMeanAll,decreasing=TRUE))
cfMeanTur <- sapply(names(turbines),function(x) mean(cfAll$CF[cfAll$turbine==x]))
cfMeanOrdTur <- names(sort(cfMeanTur,decreasing=TRUE))
```

```r
##-#-#-# #-Plot heatmap of all CF for al stations
fill_factor <- cut(round(cfAll$CF*100), breaks=seq(0,70,10))
ggplot(data=cfAll)+
geom_tile(aes(station,turbine,fill=fill_factor))+theme_bw()+
opts(axis.text.x=theme_text(hjust=1, vjust=1,
angle=50,size=8.5),axis.text.y=theme_text(size=9,hjust=1))+
scale_fill_brewer(name='Efficiency [%]',palette='OrRd')+
scale_y_discrete(name=' ', limits=cfMeanOrdTur)+
scale_x_discrete(name=' ',limits=cfMeanOrdNames)+coord_flip()
ggsave('fig/cfAllOrd.pdf',width=10.3,height=9.5)

### Tek út 5 hæstu, set upp í töflu og plott saman á graf
top5cf <- cfMeanOrdNames[1:5,drop=TRUE]
cfTop5 <- subset(cfAll,subset=station %in% top5cf)
cfTop5$station <- cfTop5$station[,drop=TRUE]
levels(cfTop5$station) <- top5cf
colcf <- as.numeric(turbines['rotor',match(cfTop5$turbine,names(turbines))])

ggplot(cfTop5)+geom_point(aes(x=turbine,y=CF, color=colcf),size=2.5)+
  facet_grid(station ~ .)+
  scale_color_continuous(name='Rotor size [m]',breaks=seq(20,100,by=15), low =
"yellow",high = "red")+
  scale_x_discrete(name=' ',limits=unique(cfAll$turbine))+
  scale_size(guide = 'none')+theme_bw()+
  opts(axis.text.x = theme_text(size =
8,angle=53,hjust=1,vjust=1),legend.position='top')
ggsave('fig/cfTop5.pdf',width=8,height=10)

# Geri töflu yfir 10 stadi med Hæst CF, plottad á kort í mapplots.R
top10cf <- cfMeanOrdNames[1:10,drop=TRUE]
cfTop10all <- subset(cfAll,subset=station %in% top10cf)
cfTop10all$turbine <- as.character(cfTop10all$turbine)
cfTop10all$station <- as.character(cfTop10all$station)
cfTop10 <- sapply(top10cf, function(x) subset(cfTop10all,
                subset= CF==max(CF[station==x][CF[station==x] !=
max(CF[station==x])])))
cfTop10 <- data.frame(t(cfTop10), row.names=NULL)
cfTop10$CF <- as.numeric(cfTop10$CF)
cfTop10 <- cfTop10[order(cfTop10$CF, decreasing=TRUE),]
cfTop10$breidd <-as.numeric(sapply(cfTop10$station,function(x)
lowstodvar$breidd2[lowstodvar$NAFN==x]))
cfTop10$lengd <-as.numeric(sapply(cfTop10$station,function(x)
lowstodvar$lengd2[lowstodvar$NAFN==x]))


#install.packages('geosphere')
require(maptools)

kmldata <- getKMLcoordinates(
  '~/Dropbox/Skoli_vor2012/FINAL/DATA/LandsnetTengivirki/TengivirkiLandsnets2.kml',
ignoreAltitude=TRUE)
tengivirki <- matrix(unlist(kmldata),ncol=2,byrow=TRUE)

station.longlat <- data.frame(lengd2,breidd2)
row.names(station.longlat) <- lowstodvar$STOD
```

```r
tengivirki.longlat <-
data.frame(long=as.numeric(tengivirki[,1]),lat=as.numeric(tengivirki[,2]))

#tmp <- read.clipboard.csv(header=FALSE,as.is=TRUE)
#tmp <- sub("\n+.*",'',tmp$V1)
#dput(tmp)
tengivirki.nofn <- c("Öldugata", "Vopnafjörður", "Varmahlíð", "Vatnshamar",
                     "Vestmannaeyjar", "Vegamót", "Vogaskeið", "Grundarfjörður",
                     "Ólafsvík", "Glerárskógafjall", "Hrútatunguvegur", "Geiradalur",
                     "Keldeyri", "Mjólká", "Ísafjörður", "Breiðadalur", "Bolungarvík",
                     "Blanda", "Laxárvatn", "Sauðárkrókur", "Rangárvellir", "Dalvík",
                     "Húsavík", "Laxá", "Krafla", "Lindabrekka", "Lagarfossvirkjun",
                     "Eyvindará", "Seyðisfjörður", "Neskaupstaður", "Eskifjörður",
                     "Fáskrúðsfjörður", "Fljótsdalur", "Stuðlar", "Hryggstekkur",
                     "Teigar", "Hólar", "Sigalda", "Vatnsfell", "Hrauneyjafoss",
                     "Prestbakki", "Sultartangi", "Búrfell", "Hvolsvöllur", "Hella",
                     "Flúðir", "Selfoss", "Hveragerði", "Nesjavallavirkjun", "Rimakot",
                     "Sog", "Hamranes", "Svartsengi", "Reykjanes",
                     "Fitjar", "Rauðimelur", "Korpa", "Hnoðraholt", "Geitháls",
                     "A12", "Akranes","Kópasker")
tengivirki <- cbind(tengivirki,' '=tengivirki.nofn)

#This function computes the distance on the surface of the earth between two points
#point1 and point2, each of the form (Longitude, Latitude)
geodetic.distance <- function(point1, point2) {
  R <- 6370
  p1rad <- point1 * pi/180
  p2rad <- point2 * pi/180
  d <-
sin(p1rad[2])*sin(p2rad[2])+cos(p1rad[2])*cos(p2rad[2])*cos(abs(p1rad[1]-p2rad[1]))
  d <- acos(d)
  R*d
}

detect.distance.tonext <- function(point) {
  dist <- vector()
  for(i in 1:nrow(tengivirki)) dist[i] <-
geodetic.distance(point,tengivirki.longlat[i,])
  mindist <- min(unlist(dist))
  minnafn <- tengivirki[which.min(unlist(dist)),3]
  result <- data.frame(dist=mindist,'tengivirki'=minnafn)
  return(result)
}

#keyra detect.dist yfir allar stödvar
shortest.dist <- apply(station.longlat,1,detect.distance.tonext)
shdistframe <- data.frame(shortest.dist)
mintengivirki <- t(as.vector(shdistframe[grep('.tengivirki',names(shdistframe))]))
row.names(mintengivirki) <- gsub('.tengivirki','',row.names(mintengivirki))
row.names(mintengivirki) <- gsub('X','',row.names(mintengivirki))
mindisttoteng <- t(as.vector(shdistframe[grep('.dist',names(shdistframe))]))
row.names(mindisttoteng) <- gsub('.dist','',row.names(mindisttoteng))
mintenging <- data.frame(mintengivirki,mindisttoteng,'Station'=lowstodvar$NAFN)
names(mintenging)[1:2] <- c('Substation','Distance')
minTafla <- xtable(mintenging[order(mintenging[,2]),c(3,2,1)],digits=1,
                   tabular.environment='longtable',floating=FALSE)
```

```r
print.xtable(minTafla,file='~/Dropbox/Skoli__vor2012/FINAL/THESIS/MScThesis/tables/minDistTable.txt')

shdist <- unlist(shortest.dist,recursive=FALSE)
shdist <- shdist[seq(1,length(shdist),2)]
tmp <- data.frame('dist'=unlist(shortest.dist))
shortestdist <- subset(tmp,grepl(".dist",row.names(tmp)))

######## Cost of energy  #############
### Constants
r=0.075; b=0.075; infl=0
N=20; L=20
CRF=r/(1-(1+r)^(-N))
k1=1/(1+r)
k2=(1+infl)/(1+r)

### Functions
#capital cost
CcFun <- function(stnum,tur) {

460*(turbines['rotor',tur]/2)^2*pi+80000*mintenging$Distance[rownames(mintenging)==stnum]
}
#Annual production in kWh
annual.kWh <- function(stnum,tur) {
  stname <- lowstodvar$NAFN[lowstodvar$STOD==stnum]
  simEnAllStations[[stname]][tur,13]*1000
}
#Present value of series of payments
Y <- function(k,l) {(k-k^(l+1))/(1-k)}

#Cost of energy, leverized
COELfun <- function(stnum,tur) {
  Cc=CcFun(stnum,tur)
  OMc=annual.kWh(stnum,tur)*0.0189+26000
  Pd=0.1*Cc
  Pa=(Cc-Pd)*CRF
  NPVc <- Pd+Pa*Y(k1,N)+OMc*Y(k2,L)
  COEL <- NPVc*CRF/annual.kWh(stnum,tur)
  return(COEL)
}

COELallTur <- data.frame('turbine'=names(turbines))
COELall <- list()

for(i in lowstodvar$STOD) {
  stname <- lowstodvar$NAFN[lowstodvar$STOD==i]
  COELallTur$COE <- sapply(1:ncol(turbines),COELfun,stnum=i)
  COELall[[stname]] <- COELallTur
}

COELallUnlist <- sapply(COELall[1:48],function(x) x[,2])
rownames(COELallUnlist) <- names(turbines)
COELmelt <- melt(COELallUnlist)
names(COELmelt)[1:2] <- c('turbine','station')

coeMeanAll <- sapply(lowstodvar$NAFN,function(x)
mean(COELmelt$value[COELmelt$station==x]))
```

```r
coeMeanOrdNames <- names(sort(coeMeanAll,decreasing=FALSE))


coeMeanTur <- sapply(names(turbines),function(x)
mean(COELmelt$value[COELmelt$turbine==x]))
coeMeanOrdTur <- names(sort(coeMeanTur,decreasing=FALSE))

###-#-# Plot heatmap showing all locations and turbines
fill_factor <- cut(round(COELmelt$value*100,2), breaks=c(4,5,6,7,9,12,15,25,50))
ggplot(data=COELmelt)+
  geom_tile(aes(station,turbine,fill=fill_factor))+theme_bw()+
  opts(axis.text.x=theme_text(hjust=1, vjust=1,
angle=50,size=8.5),axis.text.y=theme_text(size=9,hjust=1))+
  scale_fill_brewer(name='COE [cent EUR]',palette='YlGnBu', na.value = 'grey20')+
  scale_y_discrete(name=' ',limits=coeMeanOrdTur)+
  scale_x_discrete(name=' ',limits=coeMeanOrdNames)+coord_flip()
ggsave('fig/coeAllOrd.pdf',width=10.3,height=9.5)


### Tek út 5 hæstu, set upp í töflu og plott saman á graf
top5coe <- coeMeanOrdNames[1:5,drop=TRUE]
coeTop5 <- subset(COELmelt,subset=station %in% top5coe)
coeTop5$station <- coeTop5$station[,drop=TRUE]
levels(coeTop5$station) <- top5coe

#rada turb eftir cost röd í tilviki gardskagavita
coeTurbOrd <- subset(coeTop5,subset=station==top5coe[1])#,select=turbine[order(value)])
coeTurbOrd <- with(coeTurbOrd,turbine[order(value)])

#library('gtools')
#colcoe <-
quantcut(as.numeric(turbines['rotor',match(coeTop5$turbine,names(turbines))]),
q=seq(0,1,by=0.2))
colcoe <- as.numeric(turbines['rotor',match(coeTop5$turbine,names(turbines))])

ggplot(coeTop5)+geom_point(aes(x=turbine,y=value*100,
color=colcoe),size=2.5)+ylim(c(4,10))+
  facet_grid(station ~ ., scale='free_y')+#coord_trans(y="log10")+
  scale_color_continuous(name='Rotor size [m]',breaks=seq(20,100,by=15), low =
"yellow",high = "red")+
  scale_x_discrete(name=' ',limits=coeTurbOrd)+
  scale_y_continuous(name='Cost of energy, cent EUR/kWh')+
  #scale_y_log10()+
  scale_size(guide = 'none')+theme_bw()+
  opts(axis.text.x = theme_text(size = 8,angle=53,hjust=1,vjust=1),
      legend.position='top', plot.margin=unit(c(0.5,0.5,0.5,0.8), "cm"))
ggsave('fig/coeTop5.pdf',width=8.2,height=10)


# Geri töflu yfir 10 stadi med lægstu COE, plottad á kort í mapplots.R
top10coe <- coeMeanOrdNames[1:10,drop=TRUE]
coeTop10all <- subset(COELmelt,subset=station %in% top10coe)
with(COELmelt,unique(station[order(value)]))
coeTop10all$turbine <- as.character(coeTop10all$turbine)
coeTop10all$station <- as.character(coeTop10all$station)
coeTop10 <- sapply(top10coe, function(x)
subset(coeTop10all,subset=value==min(value[station==x])))
coeTop10 <- data.frame(t(coeTop10), row.names=NULL)
coeTop10$value <- as.numeric(coeTop10$value)
```

```r
coeTop10 <- coeTop10[order(coeTop10$value),]
coeTop10$breidd <-as.numeric(sapply(coeTop10$station,function(x)
lowstodvar$breidd2[lowstodvar$NAFN==x]))
coeTop10$lengd <-as.numeric(sapply(coeTop10$station,function(x)
lowstodvar$lengd2[lowstodvar$NAFN==x]))

################# gera töflu um Búrfell
asd <- cfAll[cfAll$station=='Búrfell',]
asd$CF <- round(asd$CF*100,1)
asdf <- energyAll[energyAll$station=='Búrfell',]
asdfa <- COELmelt[COELmelt$station=='Búrfell',]
asdfa$value <- asdfa$value*100
asdfasdf <- merge(asdf,asd)
burfTurb <- merge(asdfasdf,asdfa)
burfTurb <- burfTurb[order(burfTurb[,4],decreasing=TRUE),]
print(xtable(burfTurb[,-1],digits=1),include.rownames=FALSE)

####### Turbines
#Define folder and file names
tfolder <- '~/Dropbox/Skoli__vor2012/FINAL/DATA/turbines/'
tfiles <- read.csv(file.path(tfolder,'turbines.csv'),stringsAsFactors=FALSE)

#Load turbine files to data.frame
trows <- c('rotor','cutout','cutin',seq(1,30,1))
turbines <- data.frame(row.names=trows)
turbnames <- c()
for (i in 1:nrow(tfiles)){
  turbi <- scan(file.path(tfolder,tfiles[i,1]), what=character(), n=35)#, skip=1)
  turbnames[i] <- turbi[1]
  turbi <- as.numeric(turbi[-c(1,3)])
  turbines[,i] <- turbi;
}


#Clean up names of turbines
turbnames <- gsub("\\(.*","",turbnames)
turbnames <- gsub("\\Class.*","",turbnames)
turbnames <- gsub("General Electric",'GE ',turbnames)
turbnames <- trim(turbnames)
for (i in c(" ","\\-","\\+","\\/",'Liberty')){
  turbnames <- gsub(i,'__',turbnames)
}
names(turbines) <- turbnames
turbines['maxMWhYr',] <- apply(turbines[4:33,],2,max)*24*365/1000 #max. GWh possible
omitTurbines <- c(1:5,8,9,12,17:22,60,61,73:78,81:85,92:98)
turbines <- turbines[,-omitTurbines]
omitTurbines <- c(19:21,32,45:48,56)
turbines <- turbines[,-omitTurbines]

siemens <- grep('Siemens__SWT__2.3',names(turbines))
names(turbines)[siemens[1]] <- 'Siemens__SWT__101m__2.3mW'
names(turbines)[siemens[2]] <- 'Siemens__SWT__93m__2.3mW'
rm(siemens)

names(turbines) <- gsub('mW','MW',names(turbines),ignore.case=TRUE)
names(turbines) <- gsub('kw','kW',names(turbines),ignore.case=FALSE)
```

```r
names(turbines) <- gsub('kWn','kW',names(turbines),ignore.case=FALSE)

turbnames <- names(turbines)

# Plot rotor sizes of turbines
qplot(as.numeric(turbines['rotor',order(turbines['rotor',])]),x=1:length(turbines),
      xlab='index of turbine', ylab='Rotor diameter in meters')+theme_bw()

#Rotor size listed
turbines['rotor',order(turbines['rotor',],decreasing=TRUE)]
#sleppa theim sem eru yfir 112m og undir 20m
turbines <- subset(turbines, select=(turbines[1,]>20 & turbines[1,]<112))
#sleppa úreltum týpum
turbines <- turbines[,-c(50,51)]
turbines <- turbines[,-grep('Suzlon',names(turbines))]
names(turbines) <- gsub('___','__',names(turbines))
names(turbines) <- gsub('\\mW__.*','mW',names(turbines))
turbnames <- names(turbines)
#lista nöfn framleidenda
names(turbines) <- gsub('Vesta_','Vestas__',names(turbines))
producer <- strsplit(names(turbines), split='__')
unique(sapply(producer,function(x) x[1]))

##########@powerlaw factors
powerLaw <- (turbines['rotor',]/10)^0.12

#########@plotta power curve
turbMelt <- melt(turbines[4:33,])
x <- factor(row.names(turbines)[4:33],levels=1:30)
#par(oma=c(rep(3,4)))
ggplot()+geom_line(aes(x=x,y=turbMelt$value, group=turbMelt$variable,
                      color=turbMelt$variable), alpha=0.4,size=0.6)+
theme_bw()+xlab('Wind speed [m/s]')+ylab('Power output [kW]')+
scale_color_hue(guide='none',h=c(30,340),l=57)+opts(legend.postion='none')
ggsave('fig/powercurves.pdf',width=7,height=5)
```