Feasibility of a wind farm at Sandvíkurheiði

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Feasibility of a wind farm at Sandvíkurheiði

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30 ECTS thesis submitted in partial fulfillment of a Magister Scientiarum degree in Environmental Engineering

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Reykjavik, May 2016
Abstract

Electricity production with wind power has been increasing in the world in the last few years. The first wind turbines were raised at Búrfell, Southern Iceland in 2012 and a growing number of studies focusing on wind power in Iceland have been released. The goal of this study is to estimate the wind resource, costs, environmental impacts and the possible electricity generation of an Enercon E-44 wind turbine at Sandvikurheiði in eastern Iceland. Data from a meteorological station owned by The Icelandic Road Administration was used for all calculations and estimations. Levelized Cost of Electricity (LCOE) analyses were made and a short environmental impact assessment was made. A possible wind farm at Sandvikurheiði was compared to current wind turbines in Iceland and a Norwegian wind farm in order to compare Icelandic conditions to those in Europe. The results indicate that Sandvikurheiði might be a good location for a wind farm. The average capacity factor for an Enercon E44 wind turbine is estimated to be 41.6% for the whole year which is higher than in most other places. Seasonal variations in the capacity factor are high which is not optimal. It is higher during winter than during summer.

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1 Introduction

1.1 Motivation and site selection

Iceland is a windy place. With decreasing prices of wind power technology (IRENA, 2012) and recent and possible future increases in electricity prices in Iceland harvesting the wind power in Iceland is becoming a feasible option (Landsvirkjun, 2014a).

The cost of electricity generated by wind power has been declining rapidly in recent years. Wind power could become one of the main techniques to produce electricity in Iceland. Wind turbines at Búrfell have yielded good results (Landsvirkjun, 2014a) and they have sparked interest for wind farms elsewhere in Iceland. The wind production numbers from the wind turbines at Búrfell indicate that Iceland might be a good location for wind farms a marketing opportunity for Icelandic green electricity to Europe.

According to forecasts the electricity demand will increase in Iceland in the future (Landsvirkjun, 2014a). This increase in demand has to be met by new power plants. A big portion of these power plants will have to harness renewable energy if increase in renewable energy goals that the European Union have set are to be reached. (European Commission, 2014). According to the International Renewable Energy Agency (IRENA, 2013) wind power is the cheapest renewable option. Installed wind power capacity has increased fast in recent years, and is expected to keep growing.

There are a lot of unharnessed options for both hydro- and geothermal power in Iceland but due to environmental impacts they are not as viable as they might seem to be. As a result, wind power has emerged as an alternative option.

When choosing a location for a wind farm the main thing to look for is wind speed. Wind speed influences the generated energy more than any other factor. The higher the wind speed the more energy is in the wind. Surface roughness is also a factor that has to be considered when location is selected. Low surface roughness is optimal, because the lower the roughness the more the wind speed increases with height.

According to Icelandic wind atlas, the heath Sandvíkurheiði located in the eastern part of Iceland is one of the windiest places in Iceland. (Nawri et.al, 2013) The landscape at Sandvíkurheiði is also good for a wind farm.

In order to evaluate a location for wind power production weather data is needed. Weather data can be obtained from forecast models or measurements stations. Forecasts are not completely accurate and measurements are better. Weather measurements above the ground, at turbine hub height are optimal, but wind measurements from lower altitudes can be projected to higher altitudes.

The longer weather data timeseries the better, if the timeseries is long chances are bigger that the measured wind speed is in accordance to the long time wind speed average.

The Sandvíkurheiði region was chosen for this study due to five different reasons.
• According to wind atlas made by Veðurstofa Íslands (IMO) this region is windier than most other low mountain regions in Iceland, see Figure 1. Parts of Sandvíkurheiðið are yellow, which indicates average wind speed of 10 m/s – 12 m/s.

• There is a lack of electricity in the northeastern part of Iceland and limited amount of electricity can be transported between the western part and the eastern part of Iceland. If more electricity is needed in the eastern part, new power plants have to be built in the region or a new transmission line between the different parts would need to be built. (Landsnet, 2014)

• The region is accessible. There is a road going through the region and it’s close to villages. The road makes it easier to access the region when estimating it’s feasibility and service can be obtained from the villages nearby.

• The region is not high above ground level. Most of the windiest regions in Iceland are high above ground level. Higher regions can cause problems to wind turbines, some of the regions are covered by glaciers, where it is not possible to install wind turbines. Icing would likely be a problem in other regions high above ground level.

• The last reason is that the region is closer to Europe than most other windy regions in Iceland. If a subsea cable ever connects Europe and Iceland it would be optimal to have the power projects supplying the cable as close to it as possible. The cable end point would most likely be in eastern Iceland.
1.2 Objective

In this study the estimated power output for a wind turbine in a wind farm at Sandvíkurheiði is calculated and the wind resource is mapped. This study is the first step in the process of building a wind farm. If the results are favorable further steps can be made and wind farm can eventually be built.

The following are the defined objectives of the study:

- Estimating the wind resource at Sandvíkurheiði.
- Carrying out a feasibility study for a wind farm at Sandvíkurheiði.
- Estimating the effects that a wind farm would have on its environment
1.3 Outline of thesis

In Chapter 2 an overview of electricity production with wind power and other power plants is given for both Europe and Iceland. At last the main environmental impacts of wind power are described. An overview of a possible subsea cable connecting Iceland to Europe is given.

Chapter 3 describes the methods used to estimate the power output of a wind turbine. It does also give a short overview of the cost of energy and it describes the wind turbine power curve.

Chapter 4 presents all the results in the study. The calculation of the wind resource is presented first. The power output of the wind turbine is presented as well as the estimated cost of the electricity generated by the wind turbine. The environmental impacts of the wind farm are estimated.

Chapter 5 summarizes the work of this study. An overview of the contribution in this study is given and lastly future research is suggested.
2 Background and literature review

2.1 Electricity production in Europe

In 2012 the European Union produced around 3.086TWh of electricity. 52% of that electricity was supplied by conventional thermal power plants, 27% were supplied by nuclear power and 21% was produced by renewable sources. Hydropower dominates the renewable electricity production, with around 57% of the production. 29% is produced with wind power and around 14% is produced with other renewable sources. These sources are mainly solar power and biomass energy. (Eurostat, 2012)

In 2007 the European Union set environmental targets that have to be met by 2020. These targets consist of three key objectives. These objectives are 20% reduction of greenhouse gases emission compared to 1990 levels, 20% improvement in energy efficiency and increasing the share of renewable energy to 20% of the total energy consumed. (European Commission, 2014)

Figure 2. shows the renewable share of total electricity production in each of the 28 European union countries and Norway and Turkey in 2012. In some of the target of 20% of electricity generated with renewable sources has already been reached. Other countries are still far away from reaching the targets. The electricity generated by renewable sources does not need to be generated in the country of consumption and electricity produced in Iceland and transported with a submarine cable to the place of consumption can count towards the 20% goal. (Eurostat, 2013)

Figure 2: Share of renewables in electricity production for different European countries (Eurostat, 2013)

The electricity prices for industry vary within Europe. Eurostat collects information on the electricity price for industry in the European Union. The price was converted from Euros to USD using the December 2014 conversion rate of 1.24 in order to enable an easier comparison to other prices.
Figure 3 shows electricity prices including transport for industrial customers for 2013. (Eurostat, 2014). The electricity prices are different in the countries, the lowest in France, 0.0956 USD/kWh and highest in Ireland, 0.1650 USD/kWh.

![Price of electricity for industries](image)

**Figure 3:** Industrial electricity prices in European countries (Eurostat, 2014)

### 2.2 Wind power production in Europe

At the end of 2013 the total installed wind power capacity in the European Union was 107.3GW. Historical data for wind power capacity is shown in Figure 4.

The wind power capacity has increased in recent years. The installed capacity was almost 10 times more in 2013 than in 2000. In recent years the installed wind power capacity has increased more than any of the other power sources installed in the European Union.
Figure 4: Installed wind power capacity (GW) in the European Union (European Wind Energy Association (EWEA), 2014)

Figure 5. shows the share of wind power amongst the European Union countries. The most installed capacity is in Germany and Spain. These two countries have more than half of the installed capacity in the European Union. (EWEA, 2014)
2.4 Electricity production in Iceland

In 2012 a total of 17,549 GWh of electricity were produced in Iceland. Almost all of this electricity was produced with renewable sources: 12,337 GWh were produced by hydro power plants, 5,210 GWh were produced by geothermal power plants. In contrast, only 2.8 GWh were produced by burning fuel. The fuel burners are mainly used for backup power generation when power lines cannot transmit the electricity due to weather or if the transmission system is not working correctly due to other reasons (Hagstofa Íslands, 2014).

2.5 Wind power production in Iceland

Electricity production by wind power has never been a big industry in Iceland. Until recently the energy in the wind has mainly been harvested by owners of summer houses and farms. Those turbines are smaller than 100 kW and most of them are not connected to the national electricity grid.

In January 2013 Landsvirkjun raised two industry scale wind turbines at Hafíð in Búrfell. The wind turbines are E-44 turbines made by Enercon. According to Landsvirkjun’s annual
report 2013 the operation of the wind turbines has gone well and they have produced more energy than originally expected (Landsvirkjun, 2014a).

Studies have been done regarding wind power in Iceland. A study in 2012 estimated which places in Iceland were most suitable for wind power. The study also used turbine data for different turbines in order to try to find optimal wind turbine for Icelandic conditions. The results indicate that there are number of places in Iceland with annual wind speeds suitable for wind farms. The best location was Garðskagavíti, in the southwestern part of the country. Sandvíkurheiði was not included in this study (Helgason, 2012).

In 2013 a report was made on the wind energy potential in Iceland. This report introduces a wind atlas for the whole country. Wind measurements and models were made to estimate the wind speed at different heights. This wind atlas can be used as a first step in wind power planning (Nawri et al., 2013).

2.6 Marketing opportunity for Icelandic Green Electricity in Europe

Recently ideas about connecting the Icelandic electricity market with the European market with a high voltage direct current (HVDC) subsea cable have been surfacing. The cable would most likely cause increase in power prices in Iceland which will make some electricity generation projects feasible that are not feasible in the current environment.

Landsvirkjun has been doing a research on connecting Iceland to mainland Europe. The proposals are to connect to Norway, UK or Germany. The different options can be seen in Figure 6. Most of the focus has been on a cable to the UK. That cable length would be around 1,200 kilometers. The transport capacity of the cable has not been decided yet. It could be from 200 MW to around 1200 MW (Landsvirkjun, 2014a).
Landsvirkjun offers 0.043 USD/kWh to industrial consumers. Price data from other electricity producers is not available but the price should be on the same level as the Landsvirkjun prices (Landsvirkjun, 2014a). If a cable would be built the price of the electricity would increase. The UK government has guaranteed prices for energy made from various types of renewables. For onshore wind power their price guarantee is 95 – 100 Pounds/MWh (UK. Gov, 2014). That is around 150USD/MWh, which is considerably higher than electricity prices in Iceland. The costs of transporting the electricity to the UK are high and they do need to be taken into account. There will be costs of using the cable and there will be losses in the cable.

A HVDC cable producer losses in 1200 kilometer cable would be around 7.5%. A 2000MW subsea cable does cost around 1.6 million dollars for each kilometer. In addition to that converter station to convert the electricity from AC to DC and reverse would need to be built. One in Iceland and another one in the UK. Each converter station costs around 170 million dollars. That would make the total cost of the cable 2.3 billion dollars. If all the capacity of the cable would be used and a discount time of 20 years the rental price for using the cable would be at least 0.007 USD/kWh (Siemens, 2014).

If GBP/USD conversion rate (1.57) from December 2014 is used, the price available to the producer, after paying for cable rent would be from 0.149 USD/MWh to 0.156 USD/MWh. These prices are considerably higher than the current Icelandic prices.
2.6 Technical considerations for wind turbines

2.6.1 Capacity factor and Cp

A capacity factor of a wind turbine is the ratio of the actual power production to the maximum power production that is the rated output of the turbine multiplied by total number of hours during the period in question.

Capacity factor is often used to compare the energy production of a wind turbine or wind farm for different periods. It is also used to compare two different wind farms and to evaluate proposed wind farms.

Cp factor is the ratio of energy that a wind turbine extracts from the wind to the energy available in the wind. Cp for wind turbines varies with wind speed. The theoretically highest Cp achievable is 59.3% (J. F. Manwell., 2009).

2.6.3 Wind turbine power curve

The power curve of a wind turbine describes how much power the wind turbine can extract at different wind speeds. A line of the Cp for different wind speeds is also often included in the power curve. The producer of the wind turbine measure the produced power output at different wind speeds and use those measurements to generate the power curves. The actual power output of a wind turbine at a given wind speed is often different from the power curve due to different turbulence and pressure. Each wind turbine has its own power curve, the one for Enercon’s E44 turbine is shown in Figure 7. Enercon does not provide data for wind speeds over 35 m/s but the turbine has storm control and it does produce electricity up to 34 m/s. Production was estimated to be 900 kW up to 30 m/s and 0 kW for higher wind speeds.
Figure 7: Enercon E-44 power curve (Enercon, 2014)

The power curve is generated under standard conditions, when the air density is 1.225 kg/m$^3$. The air density varies with height and temperature, but since power curves are not generated for different air densities it is hard to estimate the power production under nonstandard conditions (Manwell., 2009).

2.6.4 Turbulence

Turbulence is quasi random movements causing vertical mixing in the flow. The intensity of the turbulence depends on the wind speed, and the neighboring surface.

Turbulence causes random movements which lead to increased pressure on different parts of the blades and leads to increased wear. Turbulence can also cause lower electricity yield. Even though turbulence decreases the electricity yield it is a secondary factor when choosing a location for a wind turbine. Wind speed is more important (Holton G., 2004).

2.6.5 Wind Turbine Generator Classes

The International Electro Technical Commission (IEC) have made standards for wind turbines. The IEC 61400 is a class of standards regarding wind turbines. These standards consider various aspects of a wind turbine. Most of them are not related to this thesis but the IEC 61400-1 is. It splits different wind turbines into various classes depending on wind speed and turbulence intensity at the turbines site (ISO/IEC 61400, 2005). The wind turbine
classes are important when selecting a wind turbine for a specific location. The wind turbine classes are shown in Table 2.1.

Table 2.1: IEC 61400-1 Wind class standards

<table>
<thead>
<tr>
<th>Wind Class/Turbulence</th>
<th>Annual average wind speed at hub height (m/s)</th>
<th>Extreme gusts. (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ia High wind – Higher Turbulence 18%</td>
<td>10.0</td>
<td>70</td>
</tr>
<tr>
<td>Ib High wind – Lower Turbulence 16%</td>
<td>10.0</td>
<td>70</td>
</tr>
<tr>
<td>Ila Medium wind – Higher Turbulence 18%</td>
<td>8.5</td>
<td>59.5</td>
</tr>
<tr>
<td>Iib Medium wind – Lower Turbulence 16%</td>
<td>8.5</td>
<td>59.5</td>
</tr>
<tr>
<td>IIIa Low wind – Higher Turbulence 18%</td>
<td>7.5</td>
<td>52.5</td>
</tr>
<tr>
<td>IIIb Medium wind – Lower Turbulence 16%</td>
<td>7.5</td>
<td>52.5</td>
</tr>
<tr>
<td>IV Lowest wind</td>
<td>6.0</td>
<td>42.0</td>
</tr>
</tbody>
</table>

2.7 Environmental Impacts

A wind farm, has just like any other type of big power plant has environmental impacts on the region it is built in.

The environmental impacts can be split into positive and negative effects. The main positive effects are: Benefits for people living in the region and limited CO\textsubscript{2} emissions. The main negative effects are: Noise pollution, visual impact, moving shadows and impact on birds and other wildlife.

2.7.1 Benefits for people in the region

A wind farm mainly has positive effects on the community next to it. When the farm is being constructed a lot of jobs are created in the region and after the construction period some of those new jobs stay in the region. New infrastructure, such as roads and power lines are built which can be beneficial to the community. On the other hand the negative effects affect the community next to the farm more than other communities. The locals are more likely to encounter the noise and visual pollution (Koundouri et al, 2009).
2.7.2 CO₂ emissions

A wind farm emits less CO₂ than a traditional thermal power plant. Wind turbines do not need fuel and do therefore not emit any CO₂ when in operation. Some CO₂ is however emitted when the wind turbine is manufactured, when it is being transmitted to the farms location and during maintenance of the turbine. If a wind farm is built instead of a thermal power plant or if a wind farm replaces an old thermal power plant then the CO₂ emission of the particular region decreases.

Guezuraga et al (2011) estimated the CO₂ emitted for a wind turbine during its whole lifecycle. They found that the total emitted CO₂ for 1 MW wind turbine in Europe is anywhere from 1000 – 1400 tonnes during the turbines lifetime.

2.7.3 Noise pollution

When the blades of a wind turbine rotate around its axis they generate unwanted noise. This noise can be up to 40dB 30 meters away from the turbine. If the wind farm is in a residential area the noise pollution can have negative impacts on the inhabitants. If the wind farm is located in a recreational region the people enjoying the region might be impacted by the noise pollution. The noise pollution can also have effects on wildlife in the region. Noise pollution from wind turbines has decreased in recent years and it is not considered to have big environmental effects any more (Pedersen E et al, 2007).

2.7.4 Visual impact

Wind turbines are big structures and they do have a great visual impact on the region they are built in. A beautiful view might be lost if wind turbines are in the region. The region where the wind farm is located might become less attractive for people enjoying the view in the region (Harding G, Harding P, Wilkins A, 2008).

2.7.5 Moving shadows

When the sun shines on a rotating wind turbine rotating shadows form on the ground. If the wind farm is located in uninhabited region the rotating shadows will have limited negative effect on people. If the wind farm is located in a residential region it can have negative effects on the inhabitants. The moving shadows can cast through a window or cast onto a place where people are enjoying the sunshine. The rotating shadows are mainly a problem when the sun is low in the horizon and the shadows are long. It is possible to limit the negative effects of the moving shadows by turning the turbine off when moving shadows might cause disturbance to the inhabitants in the region.(Harding G, Harding P, Wilkins A, 2008).

2.7.6 Impacts on wildlife

A rotating wind turbine blade can kill birds flying in the swept area of the wind turbine. It is mainly a problem with migrating birds and at some places a lot of birds have been killed by this. (Everaert & Stienen, 2007) A wind farm might also have negative effects on other wildlife, especially during construction. The environment in the region changes a lot and the animals might be forced to migrate elsewhere. (Drewitt and Langston, 2008) The impact that a wind farm has on reindeers has been studied. Wind farms do not have significant effect on reindeers passing the region (Colman, J. et.al, 2012).
3 Methods

3.1 Sandvíkurheiði

Sandvíkurheiði is a mountain region in northeast Iceland. Its area is about 200 km². The region consists mainly of swamps and small lakes. On Figure 8 a map of the region is showed. Sandvíkurheiði and the neighboring villages are marked on the map.

Figure 8: Map of Sandvíkurheiði (Landmælingar Íslands)
The top height of Sandvíkurheiði is around 200 meters above sea level. (Land Survey of Iceland, 2014) There is little wildlife in the region. In the summer farmers living in neighboring regions release sheep which can walk freely in the region. Apart from the sheep the wildlife consists of birds, fox and reindeers.

There are no inhabitants at Sandvíkurheiði and it is not used to grow crops. There is a paved road in the middle of the region. The road connects the neighboring villages of Vopnafjörður and Bakkafjörður. (Landmælingar Íslands)

On the picture below (Figure 9) the typical vegetation at Sandvíkurheiði can be seen, moss fields with rocks in between.

Figure 9: Typical landscape at Sandvíkurheiði

### 3.2 Meteorological data

The wind data used in this study was obtained from the Icelandic Road Authority (Vegagerðin). Vegagerðin has operated a weather station at central Sandvíkurheiði since 1997. It is 275 meters above sea level. Figure 10 is an image of the station. The weather station records wind speed and wind direction at 6 meters asl. The weather station also records temperature and humidity at 2 meters asl. It records data every three seconds. 10 minute and 1 hour average values are calculated. 1 hour values were used in this study. The weather station does not have a barometer so no air pressure is measured.
In this study wind and temperature data from January 1st 1998 until December 31st 2013 was used to estimate the wind resource. The data yield for this period was 99.95% which is considered to be very good. The missing data consists of few single measurements and two whole days in December 2013. Typical data values are shown in Figure 11. x axis shows hours since the first measurements. The values are the first hours in the data series.

Figure 10: The weather station at Sandvíkurheiði
Figure 11: Sample of the meteorological data used

The nearest weather station which measures barometric pressure is at Dalatangi. The data for the barometric pressure at Dalatangi, used to estimate different pressure effect on the power curve was obtained from Veðurstofa Íslands. There has been a weather station at Dalatangi since 1938. Hourly barometric pressure data for the period from 1961 to 1990 was used in this study.

The energy in the wind increases with increasing pressure. The temperature of the air does also impact the energy in wind. With increasing temperature the energy decreases. Wind turbine power curves are simulated in an environment at a constant barometric pressure and temperature. However in normal conditions barometric pressure and temperature varies, both with time and elevation.

The wind speed is the most important factor when considering power production with wind turbines. The average wind speed was calculated for the whole period as well as well for each year and each month.

The 6 meter wind speed is not used when considering the wind power potential. The average wind speed at hub height has to be estimated. Using the wind power profile law, (Equation 3.1) the wind speed was projected up to 50 meters. 50 meters was chosen because that is a common hub height for smaller wind turbines.
3.3 Wind Characterization

3.3.1 Wind profile power law

Wind is caused by pressure difference in the atmosphere. Wind flows from regions where pressure is high to regions where pressure is lower. The wind is affected by the Coriolis force. The Coriolis force is caused by rotation of earth. In the northern hemisphere the Coriolis force rotates the wind clockwise. The wind caused by the pressure gradient and the Coriolis force is called geostrophic wind Holton wrote a book on atmospheric physics. According to his book the wind blowing high up in the troposphere is the geostrophic wind. Close to earth the wind is impacted by the surface and it decreases with decreasing height (Holton G., 2004).

Most wind measurements are taken at 10 meter above the ground or lower. Wind turbines are however higher above the ground. A method is therefore needed to project the wind speed up to higher altitudes. The wind profile power law projects the wind speed to different altitudes. The law is introduced in Equation 3.1.

\[
\frac{V(z)}{V(z_R)} = \left( \frac{z}{z_R} \right)^\alpha \tag{3.1}
\]

Where \( V(z) \) is the wind speed at height \( z \), \( V(z_R) \) is the measured wind speed at height \( z_R \), \( \alpha \) is the power law coefficient, the power coefficient \( \alpha \) describes the surface roughness of the ground and the stability of the air next to the measurement point ((Burton D., Jenkins T., 2011).

The value of \( \alpha \) varies highly with location, surface roughness and the stability of the air. The higher the value of \( \alpha \), the more does the wind speed increase with height. Alfa is generally higher where surface roughness is high and or the stability of the atmosphere is high. Several studies have been done regarding the value of \( \alpha \) have been carried out in Iceland. \( \alpha \) of between 0.12 and 0.18 was estimated in urban Reykjavik based on wind speeds between 1986 and 1996 (Arason Þ., 1998). \( \alpha \) of 0.11 was estimated in Reyðarfjörður in 1999. (Sigurðarson F., 1999)

The surface roughness at Sandvikurheiði is lower than in the urban environment in Reykjavik and higher than in the marine environment at Reyðarfjörður. Houses and other infrastructure increase the surface roughness, while sea is not rough. The roughness coefficient should then be lower at Sandvikurheiði than the average value for Reykjavik and it should be higher at Sandvikurheiði than in Reyðarfjörður. A value of 0.13 was used for all calculations in this study.

3.3.2 Weibull distribution

The Weibull distribution can be used to model wind speed. Wind speed can also be modeled with the Gumble distribution. The Weibull distribution has the following coefficients:

\[
f(v) = \frac{k v^{k-1}}{c} e^{-\frac{v^k}{c}} \tag{3.2}
\]
v is a discrete random variable, \( f(v) \) is wind speed, \( k \) is the shape parameter of the Weibull curve and \( c \) is the scale parameter of the curve. The cumulative distribution probability function of the Weibull distribution is the following:

\[
F(v) = 1 - e^{-\frac{v}{c}^k}
\]  \( (3.3) \)

If the \( k \) and \( c \) coefficients are known the probability density function of the Weibull distribution can be used to estimate the power output of a wind turbine, if the power curve of the turbine is known. The \( k \) and \( c \) coefficient can be estimated by iterating over equation 3.2.

In order to calculate power output using \( k \) and \( c \) one has to generate many discrete random variables. For each of the random variables the wind speed is calculated and the power output is found from the wind turbine power curve. (Johnson, Norman L.; Kotz, Samuel; Balakrishnan, N., 1994). If \( c \) and \( k \) has been calculated, measurements are not needed to estimate production.

### 3.3.3 Wind Energy

The energy in the wind can be described by Equation 3.4.

\[
P = \frac{1}{2} \rho A V^3
\]  \( (3.4) \)

\( \rho \) is power output in watts, \( \rho \) is the air density, \( A \) is the swept area of the turbine blades in square meters and \( V \) is the wind speed in m/s. Wind turbines can only harvest a part of the total energy available in the wind. If the turbine would harvest all of the energy in the wind the air would be standstill after the turbine and air would accumulate downwind of the turbine. That is not possible. Albert Betz derived the Betz law in 1919. A wind turbine can extract no more than 59.3% of the energy available in the wind. (J. F. Manwell., 2009)

The amount of electricity produced by a wind turbine was calculated with Equation 3.5 (J. F. Manwell., 2009)

\[
P = \frac{1}{2} \rho A V^3 C_p
\]  \( (3.5) \)

\( C_p \) is the ratio of the power extracted by the turbine of the total power in the wind. The monthly and annual average power production were estimated based on the 17 year timeseries of wind speeds for the E-44 wind turbine with 50 meter hub height.

In order to calculate the average power output each hourly value in the wind data series was converted into estimated power output. Average was then taken of the values to generate monthly and yearly means.
The air pressure has an effect on the energy in the wind so air pressure measurements would be useful. The density of air was calculated based on measured barometric pressure of the atmosphere and the temperature according to Equation 3.6.

\[ \rho = \frac{P}{RT} \]  
(3.6)

Where \( P \) is the barometric pressure in Pascals, \( R \) is the gas constant for dry air equal to \( \frac{287}{K_e R} \) and \( T \) is the temperature in Kelvin. (Holton G., 2004)

To account for change in pressure and temperature with height and time, the barometric pressure change with height follows.

\[ P(Z) = P(0)e^{-\frac{Zg}{RT}} \]  
(3.7)

\( Z \) is the height above sea level, \( g \) is gravitational acceleration and \( P(Z) \) is pressure at height \( Z \). These equations can be used to estimate the density of air at different temperatures and pressures at various heights. (Holton G., 2004)

Graphs are plotted, showing the effect that different barometric pressure and temperature has on the air density.

Average power output was calculated for each month of the year. Every wind value was converted into energy generation using the power curve shown in Figure 2.9, and then summed up. It is also possible to use the Weibull coefficients and generate a number of discrete random variables and convert to wind values. If the measurement period is long the outcome of the two different methods should be almost identical.

### 3.4 Levelized cost of energy (LCOE)

The Levelized Cost of Energy (LCOE) was used to compare Sandvíkurheidi power plant to plants at other locations. By definition, LCOE is the break even price of energy for the producer, calculated as.

\[ LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \]  
(3.8)

LCOE is the producers cost of generating one kWh, \( I_t \) is the investment cost, \( M_t \) is the maintenance cost, \( F_t \) are the fuel expenditures, \( E_t \) is the electricity generation, \( r \) is the discount rate and \( n \) is the lifetime of the system. (IRENA, 2012)

In the LCOE formula the total benefits during the power plants lifetime are summed up and divided by the total costs of setting up and running the power plant during its lifetime.

### 3.5 Wake effect

When a wind turbine extracts power from the wind it slows the wind down downstream of the turbine. The wind speed decrease is most next to the turbine and then gradually decreases when the distance increases. This decrease of the wind speed is the wake effect.
The wake effect has been studied in order to estimate the optimal spacing between wind turbines. When the area for the wind farm is big compared to the wind farm the optimal solution is to have as much space between turbines as possible. If there is not a lot of space for the wind farm a common solution is to have the spacing between turbines 6 times the rotor diameter of the turbine. If the wind blows mainly from one or two directions the spacing should only be three diameters of the turbines rotor. (González et.al, 2013)

Wind farm of 50 MW and 200 MW Enercon E-44 turbines were drawn onto a map of Sandvíkurheiði using 6 times the diameter in the frequent wind direction and 3 times the diameter in less frequent directions.
4 Results and Discussion

4.1 The wind characteristics at Sandvíkurheiði

The wind direction data was analyzed by plotting annual and seasonal wind roses. A wind rose shows how a wind direction is distributed at a particular location. The wind rose is one of the tools used to plan a wind farm. The spacing between wind turbines can be less if the wind does not frequently blow in the direction of the spacing.

The wind rose for Sandvíkurheiði is presented on Figure 12. It shows that the wind blows mainly from three different directions. The northwestern sector is the most frequent sector. The eastern sector and the southwestern sector are also frequent. Other sectors are not frequent. A good alignment of the wind farm would be to place the wind turbines in the N-S and E-W directions. That would allow a short gap between wind turbines in the N-S direction and a bigger gap between the wind turbines in the E-W directions.

![Wind rose at Sandvíkurheiði for the period from 1998 to 2013](image)

**Figure 12:** Wind rose at Sandvíkurheiði for the period from 1998 to 2013

The wind rose for the summer months (Jun – Aug) is similar to the one for the whole year. The southwestern direction is less frequent while the northwestern and eastern directions are more common in summer. The wind rose for the winter months is more uniform.
Different sectors are more common than during summer months. The wind direction during summer months does also vary within the day, eastern directions are more common during the daytime but northwestern directions are more common during the night time. In the winter time diurnal changes do not occur. Figure 13 shows the wind rose for the summer and winter months.

![Wind rose for summer and winter months](image)

**Figure 13:** Wind rose at Sandvíkurheiði for the summer months (left) and winter months (right) from 1998 to 2013

Figure 14 shows the monthly average wind speed for the 16 years from 1998 - 2013. The average wind speed exhibits seasonal variations. The wind speed is highest during the winter months and lowest during the summer months. It is possible to split the year in three well defined periods. The winter, with high wind speeds is from October until March, the summer with low wind speeds is from June until August and it is the transition period spring and fall, April, May and September with moderate average wind speeds. These three periods will be used in the remaining of the report. The average wind speed for the whole year is 7.10 m/s.
Figure 14: The average wind speed at Sandvíkurheiði at 6 meters

The wind speed at 50 meters was calculated using Equation 3.1. Figure 15 shows the average wind speed at 50 meters. The average wind at 50 meters is higher than the wind speed at 6 meters. The average speed for the winter period is 10.69 m/s, the average wind speed in the transitional period is 8.90 m/s and 7.16 m/s during the summer period. The average wind speed for the whole year is estimated to be 9.35 m/s. The discussed results are shown in Table 4.1.

Table 4.1: Average wind speeds at 50 meters

<table>
<thead>
<tr>
<th>Period</th>
<th>Annual average wind speed at 50 meters (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>7.2</td>
</tr>
<tr>
<td>Winter</td>
<td>10.7</td>
</tr>
<tr>
<td>Transitional</td>
<td>8.9</td>
</tr>
<tr>
<td>All year</td>
<td>9.3</td>
</tr>
</tbody>
</table>
Figure 15: The average wind speed at Sandvíkurheiði at 50 meters

Figure 16 shows the Weibull distribution for the 6 meter wind at Sandvíkurheiði. The blue bars are the ratio of the actual wind speed and the green line is the Weibull distribution. The Weibull distribution fits the wind speed well. Wind speeds from 3 m/s to 6 m/s are the most common while the frequency decreases with higher wind speed. All available wind speed data was used to generate the Weibull distribution. It was made by calculating c and k coefficients from Equation 3.2. The cumulative distribution was then calculated by Equation 3.3.
The Weibull distribution for the summer months differs from the one for the whole year. It can be seen in Figure 17. Lower wind speeds are more frequent while wind speeds above 20 m/s are almost non-existing. According to these results the electricity production would be less during the summer months.
Figure 17: Weibull distribution for the 50 meter wind during summer

The Weibull distribution just as the wind speed varies within the season. The $c$ and $k$ factor for each period of the year can be seen in Table 4.2.

<table>
<thead>
<tr>
<th>Period</th>
<th>$c$ factor</th>
<th>$k$ factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>6.08</td>
<td>1.68</td>
</tr>
<tr>
<td>Winter</td>
<td>9.18</td>
<td>1.64</td>
</tr>
<tr>
<td>Transitional</td>
<td>7.75</td>
<td>1.64</td>
</tr>
<tr>
<td>All year</td>
<td>7.98</td>
<td>1.58</td>
</tr>
</tbody>
</table>

The $c$ factor is related to the mean wind speed but the $k$ factor describes the shape of the curve. The $c$ factor corresponds well to the wind measurements. The $k$ factor is similar in all the periods and the curve does therefore look similar in all the periods.

Extreme wind speeds are important when estimating the wind resource at a certain location. Some wind turbines in wind class I stop producing electricity at wind speeds around 30 m/s. Wind turbines do also have a maximum gust rating. If higher gusts happen the wind turbine might break down or even collapse (Wang J et.al, 2015).
Wind speeds above 30 m/s are rare at Sandvíkurheiði. In the 16 year period in question the estimated wind speed at 50 meters was over 30 m/s for 767 hours. That is around 0.55% of the time. Figure 18 shows the frequency of extreme wind speeds for each month of the year. Extreme wind speeds are most frequent during the winter months, especially in January. In January extreme winds occur 1.7% of the time, or about half a day each year.

Figure 18: Frequency of wind speeds over 30 m/s

The weather station at Sandvíkurheiði does not record extreme gusts and it is therefore not possible to see if the wind speeds do ever pass extreme gust values. Gust coefficient can be used to estimate gust at given time. Gust coefficient do vary with location and wind direction and it is hard to estimate the gust coefficient if no measurements have been made.

4.2 Power output

When the estimated wind speed at Sandvíkurheiði is compared to Table 2.1 it can be assumed that the wind resource at Sandvíkurheiði is in wind class I. The average wind speed is above 10 m/s. Gust measurements were not available. Since there are no measurements of turbulence intensity it is not possible to know if it is in wind class Ia or Ib. Wind turbine for class I should therefore be chosen for the energy output simulation. Enercon E44 wind turbine has been used with good success at Búrfell and will in this study be used for calculations. The E44 turbine has a rotor diameter of 44 meters and its rated power is 900kW. (Enercon)
The monthly average power output estimated by taking average of the hourly values is portrayed in Fig. 19. It shows that the is highest during the winter time and lowest during summer time as the wind measurements suggested.

![Figure 19: The average power output for every month](image)

The average for each of the three periods was calculated. The production is lowest during the summer period, but higher during the transitional period and highest during winter time. The average production in winter is 82% more than in the summer time. The results are summed up in Table 4.3.

<table>
<thead>
<tr>
<th>Period</th>
<th>Average Production</th>
<th>Capacity Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>254 kW</td>
<td>28.2%</td>
</tr>
<tr>
<td>Winter</td>
<td>463 kW</td>
<td>51.5%</td>
</tr>
<tr>
<td>Transitional</td>
<td>367 kW</td>
<td>40.8%</td>
</tr>
<tr>
<td>Total year</td>
<td>387 kW</td>
<td>43.0%</td>
</tr>
</tbody>
</table>
### 4.2.2 Sensitivity to wind power law coefficient

The average power output varies greatly with wind speed. The estimated wind speed at 50 meters is uncertain, the $\alpha$ value from Equation 3.1 could be higher or lower and or the wind measurements at Sandvíkurheiði incorrect. A 10% increase in the $\alpha$ value in Equation 3.1 causes an increase of wind speed of 0.5% to 1%. The $\alpha$ coefficient could well be overestimated or underestimated by 10%. The anemometer at Sandvíkurheiði could yield results that are a little higher or lower than the correct wind. It is unlikely that the error is bigger than 2%.

To account for the possible error, likely values for the wind speed were used to calculate likely high and low power outputs. The result can be see in Table 4.4. The likely values are generated with the wind speed 3% higher and 3% lower than the original wind speed.

**Table 4.4:** Sensitivity analysis on monthly average power output at Sandvíkurheiði for Enercon E-44 at 50 meters

<table>
<thead>
<tr>
<th></th>
<th>Average production</th>
<th>Capacity factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>375 kW</td>
<td>41.7%</td>
</tr>
<tr>
<td>Mean</td>
<td>387 kW</td>
<td>43.0%</td>
</tr>
<tr>
<td>High</td>
<td>398 kW</td>
<td>44.2%</td>
</tr>
</tbody>
</table>

Figure 20 shows the annual generation for one Enercon E44 wind turbine with 50 meter hub height. The annual generation would have been highest 3.588MWh in 2004 and lowest 3.100MWh in 2010. The average annual production would have been 3.354MWh. The production in 2004 is 16% higher than in 2010. 16% difference is not a lot and the electricity generation would be rather equal for the different years.

The annual electricity production at Sandvíkurheiði does also vary. A bar plot for the annual variations for the estimated annual generation is presented in Figure 20.
The estimated electricity generation values might be too high. Maintenance is needed and during maintenance the wind turbine needs to be stopped, and it will not produce electricity while it is stopped.

Both the capacity factor and the average production for a wind farm at Sandvíkurheiði is high. These values indicate that the wind resource at Sandvíkurheiði is good for wind power production.

### 4.3 Sensitivity to Barometric pressure

At standard conditions the density of air is 1.25 kg/m$^3$. At Sandvíkurheiði the barometric pressure is generally lower than 1013 hPa and the temperature above 20° C are rare at Sandvíkurheiði.

The average barometric pressure at Dalatangi is shown in Figure 21. The monthly average pressure at Dalatangi is higher during the summer than during the winter, the difference is less than 2%. The average barometric pressure at Dalatangi is 1007.0 hPa, with a general range from 940 hPa to 1040 hPa.

Figure 20: Estimated annual electricity generation at Sandvíkurheiði
The temperature at Sandvíkurheiði also changes within the year. The temperature is low during winter time and high during summer time. The overall mean temperature is 1.9°C. The temperature rarely goes below -20°C or above 15°C. Equation 3.7 was used to estimate the average pressure. The average pressure at Sandvíkurheiði at 200 meters above sea level was calculated to be 976 hPa.

Figure 22 shows density of air for different temperatures at a pressure of 976 hPa. Equations 3.6 and 3.7 were used to calculate the density. As expected the density decreases with increasing temperature. The density equals 1.25 kg/m³ (standard conditions) when the temperature is -1.1°C.
Figure 22: Density of air at various temperatures at constant pressure

Figure 23 shows the density of air for different pressures at a constant temperature of 1.9°C. The density increases almost linearly with decreasing pressure. The density equals the standard 1.25 kg/m³ when the pressure is 988.3 hPa.
Figure 23: Density of air at various pressures at constant temperature

The density at the average conditions at Sandvíkurheiði, when the temperature is 1.9°C and pressure is 976 hPa is 1.241 kg/m\(^3\). The density at the average conditions is 0.8% less than at the standard conditions. The density at Sandvíkurheiði is usually within 5% of the standard condition density. Figure 24 shows the average density for each month of the year.

Most of the time the air density is close to the standard density. Electricity yield should be similar to the yield the power curve gives. Therefore electricity generation values do not need to be corrected because of air density variations.
Using Equation 3.5, the levelized cost of electricity for a wind farm at Sandvíkurheiði is calculated. If a lifetime of 20 years, production cost of 2 million USD per installed megawatt, operation cost of 15 USD/MWh, discount rate of 5% per year and electricity production of 3.354 MWh is assumed the LCOE of the wind farm at Sandvíkurheiði would be 0.062 USD/kWh (IRENA, 2014).

It is hard to estimate all the factors determining the LCOE for a wind turbine. Installation cost varies with the type of wind turbine and hub height, operation costs vary in different countries and wind farms and using one weather station at 6 meters will not get a really accurate estimate of the capacity factor. In order to see how changes in these factors would affect the LCOE a sensitivity analysis was made. The sensitivity analysis can be seen in Figure 25.

To generate the sensitivity analysis, different values for each parameter up to 30% more and down to 30% less than the estimated value. That forms four different lines that can be plotted to make a sensitivity analysis.
Changes in the electricity production affect the LCOE more than any of the other factors. Changes in the production costs would also change the LCOE considerably. Operation costs and discount rate have less impact on the LCOE.

Changes in electricity production and therefore wind speed, since wind speed and electricity production is the most important factor in the LCOE. Changes in the other factors do impact the LCOE, but not as much as the electricity production does.

A LCOE of 0.06USD/kWh is low for electricity generation by wind power. Most wind farms have a considerably higher LCOE. 0.06 USD/kWh is high for an Icelandic power plant. As discussed in previous sections Landsvirkjun delivers power to new customers for 0.054 USD/kWh, which is lower than the LCOE estimated for a wind farm at Sandvikurheidi. A wind farm at Sandvikurheidi would not be competitive in today’s energy market in Iceland.

However this price could compete with the price in Europe's energy markets, as shown in Figure 3. the average industry prices are higher than 0.06USD/kWh in all of the countries in the comparison. If a subsea cable were to connect Iceland to mainland Europe the electricity prices would likely rise towards the European ones and a wind farm at Sandvikurheidi could become economically feasible.
4.5 Comparison to Búrfell wind farm

Since there is only one wind farm in Iceland, comparison is difficult. Landsvirkjun made the capacity factor of the two wind turbines at Búrfell available in their annual report so it is possible to compare the calculated capacity factor at Sandvíkurheiði with the actual capacity factor at Búrfell. Capacity factor was calculated by diving average production by maximum production.

Figure 26 shows comparison of capacity factor between Búrfell values and 2013 values at Sandvíkurheiði. The average capacity factor over the year is higher at Sandvíkurheiði than at Búrfell. It is 41.60%.

![Figure 26: Comparison of capacity factor in Búrfell and Sandvíkurheiði 2013 measurements (Landsvirkjun, 2014a)](image)

According to these results a wind turbine located at Sandvíkurheiði would yield more electricity than a wind turbine at Búrfell. The difference is greatest 76% in the month of July. The series of data available from Búrfell is only a little over one year long and errors in capacity factor estimation are therefore high. On the other hand, these are based on actual production, whereas the Sandvíkurheiði values are theoretical estimates.

Figure 27 shows the capacity factor both for Búrfell and Sandvíkurheiði. The wind turbines at Búrfell were not in operation until January 21st and therefore the Búrfell bar for January only contains data for the last 10 days of the month. It should also be noted that the hub height of the wind turbines at Búrfell is 55 meters while the estimations for Sandvíkurheiði...
are for hub height of 50 meters. When looking at the whole year, the capacity factor is higher at Sandvikurheidi, 41.6% than at Búrfell where it is 40%.

Figure 27: Comparison of capacity factor in Búrfell and Sandvikurheidi (Landsvirkjun, 2014a)

Such a comparison could be questionable since it compares only one year of data at Búrfell and 16 years of estimations at Sandvikurheidi. There are some variations in wind speed and electricity production in different years. Therefore it can be useful to compare the 2013 estimations of capacity factor at Sandvikurheidi to the actual 2013 capacity factor at Búrfell.

4.6 Comparison to European wind farms

Since it is hard to obtain capacity factor data for individual wind farms, average capacity factor for European and North American wind farms was used for the comparison. Average capacity factors for selected countries can be seen in Figure 28.
The capacity factor is much higher at Sandvíkurheiði than any of the average capacity factors in other countries. Comparing the capacity factor of an individual wind farm to the average capacity factor of a whole country is not really accurate but it gives some idea of where the wind farm at Sandvíkurheiði stands against other wind farms.

### 4.7 Wind farm layout

A possible layout for a 50 MW wind farm at Sandvíkurheiði consisting of E-44 turbines is shown in Figure 29. The purple dots represent wind turbines. This location at the heath was chosen because it is close to the road and less amount of lakes than in nearby regions. The most frequent wind direction is northwestern direction followed by eastern and southwestern directions. Northern and southern directions are infrequent. According to these results the wind farm layout was set N-S and E-W. The spacing between turbines in the E-W direction was set to 6 times the rotor diameter of an E-44 turbine that equals 264 meters. The spacing between the turbines in N-S direction is 3 times diameter or 132 meters.
Figure 29: Wind farm layout for a 50 MW wind farm

The wind farm takes up a little part of all the region. There would be room for a bigger wind farm. A 200 MW wind farm can be seen in Figure 30.
There would be enough room for a 200 MW wind farm. The maximum size depends on the definition of the Sandvíkurheiði area but a 1000 MW wind farm could easily fit in the region. When the layouts were made the landscape, apart from lakes were not taken into consideration. It might not be possible to raise a wind turbine in the middle of a steep hill and the size of an eventual farm would therefore be bigger.
4.8 Environmental impact of a wind farm at Sandvíkurheiði

The wind farm at Sandvíkurheiði may positively impact on the community next to the wind farm, especially in the towns of Vopnafjörður and Bakkafjörður. There will be new jobs, mainly during the construction of the wind farm but also afterwards. The road connection between the two towns may be improved after the construction.

A wind farm at Sandvíkurheiði would most likely not be installed instead of a thermal power plant, at least not in Iceland. It might however come instead of a thermal power plant somewhere else in the world. Then the wind farm would have positive effects on CO\textsubscript{2} emission in the world.

Grams of CO\textsubscript{2} emitted for each produced kWh is a measurement frequently used to compare pollution of different power plants. If the turbine produces 3300MWh/year and it’s lifetime CO\textsubscript{2} release is 1400 tonnes the CO\textsubscript{2}/kWh release would be 21 grams.

The release from a coal fired power plant is around 850 grams CO\textsubscript{2}/kWh. (Raghuvanshi et al, 2005) The CO\textsubscript{2} release from a wind farm would therefore be around 2.5% of what a coal fired plant would release.

In current situation noise pollution would most likely not be a big problem at Sandvíkurheiði. The region is to date not used as a recreational area, as it is in a remote part of the country. If there would be a population increase at Bakkafjörður, Vopnafjörður or elsewhere in the neighborhood use of the region for recreational purposes would likely increase.

The region is a big wasteland. There is a view towards the sea and the mountains inland. In most of the region the view is not blocked by anything. If there was a wind farm built in the region some part of the view would be blocked by the wind turbines. The view after the change can be seen in Figure 31. Some people driving the road might not like the new view.
Figure 31: Possible future view at Sandvíkurheiði

Sandvíkurheiði is far north and during winter time the sun shines low over the horizon. When the sun is low above the horizon the shadows get longer than when the sun is high above the horizon. During winter time there would therefore be big areas in the region impacted by shadow flickering. People in cars driving the road through the region could be impacted by the shadow flickering if wind turbines were built close to the road. If the wind farm was built further away from the road the shadow flickering would likely cause less disturbance.

Due to little vegetation it is not likely that there is a lot of wildlife in the region. Reindeers live in the eastern part of Iceland and could pass through the region. Birds and fox live in most places in Iceland and likely also at Sandvíkurheiði. Sheeps are released in most remote parts of Iceland, and likely at Sandvíkurheiði.

Birds might get killed by the rotating blades, but it is hard to estimate weather birds would fly into the turbines in big quantities. According to a presentation at a conference held by Landsvirkjun wind turbines at Búrfell have not had any impact on bird life, and they do in general not have a lot of impacts on bird life where there is not a lot of migrating birds. (Landsvirkjun, 2014b) There were no studies found about the amount of migrating birds in the region. Other wildlife consists mainly of reindeers, foxes and sheeps. At construction time the reindeers and foxes might get disturbed due to people and machines in the region. Once the construction time is over the reindeers should still cross the region. No studies were found that focus on the effects a wind farm has on sheeps and fox so it is hard to estimate how those animals would react to a wind farm.
4.9 Wind farm challenges at Sandvíkurheiði

Iceland is a remote country, and since wind turbines are not produced in Iceland they would have to be shipped from other parts of the world. Technicians that know how to raise a wind farm might not be available in Iceland and they might need to be imported as well.

The nearest big harbor is at Reyðarfjörður, some 140 km away. The wind turbines would most likely be shipped to Reyðarfjörður and will need to be transported from there. The road from Reyðarfjörður is good and no tunnels or bridges in the way. Transportation from Reyðarfjörður to Sandvíkurheiði should not cause problems.

The geology of the region was not considered in this study. The geology of the region is an important factor for the foundations of a wind turbine. In addition to that concrete is needed for the foundations. It is optimal to obtain the materials for the concrete as close to the wind farm as possible in order to keep costs low.

There is not any electrical grid at Sandvikurheiði. The nearest grid connection is at Vopnafjörður. Vopnafjörður and Bakkafjörður are an end station of the electrical grid and the electrical lines are low voltage. Changes in the transmission system depend on how big eventual wind farm would be. For a big wind farm a new higher voltage and current transmission line to either Vopnafjörður and Bakkafjörður would have to be built. In any case a line would be necessary to connect the wind farm to Vopnafjörður and Bakkafjörður. The costs associated with the new transmission line depend on the size of the wind farm.

4.10 Comparison to Hitra wind farm

One way to compare a wind farm in Sandvikurheiði to foreign wind farms is to look at a fairly new wind farm located in similar conditions to those at Sandvikurheiði. The wind farm at Hitra in Norway has those characteristics. Hitra is an island outside of the western coast of Norway. The wind farm is on top of a hill in about 200 meters agl. It is close to the North Atlantic Ocean and there is little or no vegetation at the wind farms location. The conditions are therefore similar to those at Sandvikurheiði and Hitra wind farm should be a good comparison for a wind farm at Sandvikurheiði. A picture of a part of the wind farm and its surroundings can be seen in Figure 32.
The wind farm at Hitra is amongst the biggest ones in Norway. There are 24 Vestas turbines at Hitra. Each of those has a capacity of 2.3MW and a hub height of 70 meters. The annual average wind speed is 8m/s which is higher than in most other wind farms in Europe. The average capacity factor of Hitra wind farm is 31% (Statkraft, 2014).

The wind speed at Hitra is lower than the wind speed at Sandvíkurheiði. The capacity factor at Hitra is also lower than the estimated capacity factor at Sandvíkurheiði. Sandvíkurheiði seems to be a better location for a wind farm than Hitra when wind speed and capacity factors are compared.
5 Conclusions

5.1 Discussion

The results show that a wind farm at Sandvíkurheiði would have higher capacity factor and it would produce more electricity than similar wind farms in Europe. Due to high wind speeds the hub height of turbines at Sandvíkurheiði could be lower than in most European wind farms. This could lead to lower costs of original investment in the turbines.

The levelized cost of energy is 0.062 USD/kWst which is lower when compared to wind farms in Europe. However due to cheap power from big hydro power- and geothermal power plants in Iceland the wind farm would not be feasible with current electricity prices. If electricity prices rise in Iceland or if a subsea cable to Europe will be built the project would likely become economically feasible.

The project would not have great impact on the environment. The view and unspoiled wilderness at Sandvíkurheiði will be disrupted but the project would have close to no other environmental effects.

The average wind speed in different countries gives a general picture of wind power production in Europe and North America. The conditions at most of these wind farms differ a lot from the conditions at Sandvíkurheiði. Most of the wind farms in these averages are located inland, hundreds or thousands of kilometers from the sea while Sandvíkurheiði is close to the ocean where wind speed is most often higher than inland. Many wind farms in the average are old. Old wind farms do not yield as good capacity factor as new ones due to recent technological improvements.

5.2 Summary of contribution

The aim of this study was to estimate the wind power potential at Sandvíkurheiði. Wind measurements were used to estimate the wind resource at Sandvíkurheiði. Both the wind speed and wind directions were examined. No analysis of the wind resource at Sandvíkurheiði has been published before.

The capacity factor and electricity production were estimated both for each year and every month of the year. The year was also split into three different categories. Capacity factors and electricity production has been estimated in Iceland before, but this seems to be the first study that studies Sandvíkurheiði.

The levelized cost of energy for a wind farm at Sandvíkurheiði was estimated. Some studies have researched LCOE of wind power in Iceland, but none of them have included Sandvíkurheiði.

An insight was given into environmental impacts of a possible wind farm. Currently, there are no published studies have discussed environmental impacts of a wind farm in Iceland before but some studies have short chapters on environmental impacts of wind power, none of them at Sandvíkurheiði though.
5.3 Future research

Even though the conditions for a wind farm seem to be ideal at Sandvíkurheiði further research is needed. Using measurements from a 6 meter wind mast is not enough to determine the wind resource. A wind mast higher than 10 meters, 50 or 60 meters would have to be put up. The new mast would have to collect measurements for some time before the wind resource can be estimated with a great level of accuracy.

Turbulence in the wind has effects on the output of a wind turbine. Turbulence intensity has not been estimated. In order to estimate the turbulence the wind speed and would have to be measured at higher frequency at hub height.

The landscape at Sandvíkurheiði has not been examined with regards to wind turbines. A geographical study is necessary to see how the landscape would affect potential wind turbines. The landscape might consist of hills that are too steep for wind turbines. The landscape can also have effects on both wind speed in the region and the turbulence in the wind. The geology of the area will also have to be analysed.

The cost of energy calculations are based on numbers from Europe and both the installation cost and operation cost could be different from mainland Europe. The cost analysis did not consider hub height, lower mast should cost less than a high mast.

Connection to the electrical grid from Sandvíkurheiði has not been researched. Transmission lines would need to be built and their costs will have to be added to LCOE.
References


