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Site analysis for complementary wind turbines in Iceland

Master's Thesis within the Sustainable Energy Systems program

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Department of Energy and Environment
Division of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2016

MASTER’S THESIS

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Cover:
The cover figure is taken at the Búrfell area in a field trip in March 2016. It presents one of the two turbines already erected in Iceland. ©Harpa Sif Gísladóttir

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ABSTRACT

As a result of increased focus on climate change, the installed global capacity of wind power has increased rapidly in recent years. The problems connected to the intermittency of wind power production have become clearer and the demand for regulating power increased. An interesting solution is to use hydro power to even out the production fluctuations.

In Iceland, electricity is mainly produced by hydro and geothermal power plants. Therefore, it is of great interest to implement wind power to this hydro dominated power system. In 2013 two wind turbines were erected close to the hydro power plant Búrfellsvirkjun for research purposes. The turbines have proven to have a very high capacity factor and there is a plan to build a wind power park with up to 70 turbines in the area. In this thesis the focus is on finding a feasible location for wind power production to complement the planned production at Búrfell.

The meteorological data required to conduct this analysis is collected from the Meteorological Agency of Iceland. Time series containing the hourly average wind speed at each considered location are gathered.

Correlation of wind speeds at considered locations to the wind speed at Búrfell is calculated. Negative correlation of wind speeds between two areas indicates that by placing wind turbines in those two areas it is possible to even out the fluctuations in the wind power production. Many time steps are considered as the wind speeds and behavior of the wind differs between those time steps. The annual power production at the considered locations is estimated using the Weibull probability distribution of wind speeds. Additionally, the wind speed time series are used to calculate the historical power production at each considered location and find the correlation to calculated production at Búrfell. The locations resulting in negative correlation of wind speed and/or production are further analyzed and compared to the calculated production at Búrfell.

Höfn í Hornafirði is the most favorable location with regard to the negative correlation of wind speed and power production for many time steps. Additionally, this location is estimated to have high enough capacity factor to have the possibility to complement the planned production at Búrfell. However, the vulnerability of the results to the estimated roughness length is of great concern.

The results of this thesis show that it is difficult to predict the interactions of wind power production at different locations. The correlation of wind data does not provide good enough indication of the interaction and it is important to evaluate the production level as well.

Key words: Site analysis, wind power, wind speed correlation, wind power correlation, saving regulating power.

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Harpa Sif Gísladóttir, Reykjavík, May 2016.

Terms and abbreviations

Symbol	Explanation
A	Rotor area of wind turbine $[m^2]$
B	Data set B
C	Data set C
c	Scale factor of the Weibull probability distribution
$Cov(B, C)$	Covariance of data set B and C
CF	Capacity factor
Cp	Power coefficient
E	Energy $[Wh]$
E_T	Energy output from a wind turbine $[Wh]$
$E_{T,maximum}$	Maximum theoretically possible energy output from a wind turbine $[Wh]$
$F(v)$	Cumulative Weibull distribution function of wind speeds
f_j	Number of occurrences in a bin j
HVDC	High voltage direct current
i	Index referring to data or variables
j	Index referring to data or variables
m_j	Midpoint of bin j
N	Wind speed bins
Nb	Number of bins
N_{data}	Number of entries in a data set
k	Shape factor of the Weibull probability distribution
P	Power $[W]$
P_{rated}	The rated power of a turbine $[W]$
P_T	Power output from a turbine $[W]$

Symbol	Explanation
$P_T(v)$	Power curve of a turbine $[W]$
$\overline{P_T}$	Average power from a turbine $[W]$
P_w	Power carried by the wind $[W]$
t	Time $[h]$
TSO	Transmission system operator
v	Air velocity $\left[\frac{m}{s}\right]$
$\bar{v}$	Long term wind speed average $\left[\frac{m}{s}\right]$
v_{rated}	The rated velocity for which a turbine is designed $\left[\frac{m}{s}\right]$
v_{ref}	The reference velocity at height z_{ref}
v_z	Wind speed at height z
WPD	Wind power density $\left[\frac{W}{m^2}\right]$
z	Height above sea level $[m]$
z_{ref}	Reference height above sea level $[m]$
z_0	Surface roughness length $[m]$
α	Power law coefficient
$\Gamma(x)$	Gamma function of variable x
ρ_a	Air density $\left[\frac{kg}{m^3}\right]$
$\rho(B, C)$	Correlation coefficient of data sets B and C
$\rho(v)$	Weibull probability distribution of wind speeds
μ_i	Mean of a data set i
η_T	Efficiency of a wind turbine
$\eta_{mechanical}$	Mechanical efficiency of a wind turbine
σ_i	Standard deviation of variable or data set i

1 Introduction

This chapter covers the background to wind energy and the problems with increased penetration of intermittent sources. The power production mix in Iceland is introduced as well as the aim of the thesis. Finally the method and its limitations are discussed.

1.1 Wind as a renewable energy source

The global energy demand is expected to grow by one third by 2040 and electricity is expected to make up almost a quarter of the total energy demand. As the focus on mitigating climate change increases, renewable energy sources become more vital (International Energy Agency, 2015).

In 2014 the total global capacity of renewable power was 1712 GW, thereof 369 GW of installed capacity was wind power. The share of installed wind capacity has grown fast in recent years and is expected to keep growing as it is the cheapest renewable option available (Renewable Energy Policy Network for the 21st century, 2015).

Despite the fast growth of the technology in recent years, utilization of wind power is not a new concept. The first wind mills appeared in the years 500 – 900. In the beginning wind mills were used to grind grain and pump water. Later, wind mills were developed and used to drive mechanical devices. However, in the early 20th century the wind mill technology was used to develop wind turbines for electricity production. In the mid-20th century many experimental wind turbines were built. As more economically feasible options to produce electricity were available, utilizing wind for power production did not become a standard way to produce electricity. The oil crisis in the late 80’s as well as political instruments, such as feed-in tariffs and tax discounts, for wind turbine development projects created the necessary conditions needed for the technology to become competitive (Blöndal Á. , 2001). For the last decades, the capacity of a single wind turbine has increased from 10kW up to 8MW. The Vestas V164 8 MW offshore wind turbine, which was installed in 2014 for testing in Denmark, is currently the biggest turbine producing electricity (Philips, 2014).

As installed capacity of wind power increases, the problems connected to the intermittency of wind become clearer. Wind turbines produce electricity while the wind is blowing. Therefore, if the wind does not blow there is no electricity production. The electricity consumption in today’s society varies within the day and these variations are met by controllable electricity production units. However, as the penetration of wind energy in the system increases it becomes more difficult to match the production to the consumption. This imbalance creates problems for the electricity grid. There are few options available and under development to solve this problem. Solutions such as energy storage, demand site management or load curtailment are all being considered. An interesting solution to this problem is using hydro power, where it is available, to even out the fluctuations in the wind generation (Steen, Goop, Göransson, & Nursebo, 2014).

1.2 Electricity production in Iceland

In Iceland, electricity is mainly produced by geothermal and hydro power plants. Geothermal power plants contribute to roughly 29% of the total electricity produced and hydro power plants 71% of the production. Other energy sources account for a much smaller part of the energy mix for electricity production (Orkustofnun, 2015).

As the demand for electricity in Iceland is expected to grow by 1,4% per year for the period from 2015 – 2050, there is a need for increased power production. Iceland is an islanded power system which means that all demand must be met with production within the country. Therefore, as wind power implementation is becoming cheaper and possible locations to utilize hydro power get fewer, the interest in empowering the wind in Iceland has increased (Orkustofnun, 2015).

Iceland has favorable conditions to utilize wind for power production. The wind speeds onshore are similar to offshore wind speeds in other geographical areas. The roughness of the surface is generally low which results in more even wind speeds and less turbulence. However, utilizing wind for power production in Iceland does not have a long history. In the early twentieth century small wind turbines were used to power summerhouses and farms in areas not connected to the national grid. Since the beginning of the 21st century the feasibility of implementing larger wind turbines and wind farms connected to the grid has been researched (Vindur og vindorka, 2012).

In Iceland it is of special interest to use the interaction between hydro power production, with annual variations, and wind power production with intraday variations. The maximum inflow to a hydro dam and therefore the maximum power output is available during summer. During winter less inflow can be expected to dams due to frozen waters. These fluctuations can be well correlated to the wind which blows heavily during winter but less during summer (Landsvirkjun, 2012).

The biggest power production utility in Iceland, Landsvirkjun, installed two 900 kW wind turbines in 2013 for research purposes. Those turbines were installed in an area called Hafið close to the hydro power plant Búrfellsvirkjun in the southern part of Iceland. The research aim was to investigate the feasibility of a wind power park in Icelandic conditions, including the effect of volcanic ash, snow, icing and sand. The erected wind turbines have proven to have a capacity factor of 44% which is higher than the world's average capacity factor of 23% (Ritstjórn Kjarnans, 2015). However, it must be kept in mind that the erected turbines in Iceland are new and therefore more efficient than old turbines which are included in the world average. Additionally, Iceland has high average wind speed and the wind resource is very good.

Due to the promising result from the research installments the future outlook is to build a wind power park with up to 70 wind turbines, close to the site of research called Búrfellslundur.

Despite the increased interest in wind power the connected cost is still considerably higher than the current electricity prices in Iceland. The cost of the two installed wind turbines in Iceland is 45 $/MWh while the current cost for hydro and geothermal power are 34$/MWh and 38$/MWh respectively. Therefore, it is still not economically feasible to invest in large scale wind farms (Skúlason, 2014). However, with a possible connection to Europe through a subsea HVDC link to England, electricity prices will likely increase. Therefore, implementing large scale wind farms will become more feasible (Landsvirkjun).

1.3 Aim

The focus of this thesis is on finding a suitable geographical location for wind power production. The production at the feasible location should complement the current and planned production at Hafið and Búrfellslundur. That is, the installed wind turbine at the possible site should produce electricity while there is less production from turbines at Búrfellslundur or there should be production at both locations simultaneously. This is done in order to maximize the synergetic effects of the wind production so the instalments will even out each other’s fluctuations as well as to simplify the control of the wind power production within the system as a whole. This can help to decrease the effects of intermittency on the grid as well as maximizing the efficiency of the hydro power plants and meet the increase in electricity demand.

High capacity factors are expected at the Búrfell area. It is important that the complementing production does not decrease the capacity factor of the cumulative production significantly. That is the cumulative annual production should not be significantly less than if all the production is placed at Búrfell.

1.4 Limitations

The quality of the data used for this research is good and it is not considered as a limiting factor for the validity of the research. The calculation method used to predict the possible production at the considered locations is well accepted. However, there are programs available such as WAsP or Windpro that could give more accurate results than the calculation methods used in this research.

For this research the wind direction and turbulence at the considered locations are not considered. The wind speed is used to judge the feasibility of the location. Including the wind direction and turbulence in this analysis would make the results more accurate.

The research is conducted for one turbine model and the results may differ if other models are considered. It is a macro scale site analysis and therefore further analysis are needed in order to validate the feasibility of the proposed locations. No economic factors are considered and that must be kept in mind while evaluating the results.

The grid connection is taken into consideration briefly when the feasibility of locations is judged. However, the effects of integrating wind power production to the grid are not evaluated or considered in this research.

1.5 Outline of the thesis

In Chapter 2 the theory and literature needed to conduct this research are reviewed.

In Chapter 3 the methodology of the research is introduced as well as the data and modelling described.

In Chapter 4 the results are presented.

In Chapter 5 the time series for feasible locations are analyzed and compared to the Base Case.

In Chapter 6 the results are summarized, a feasible energy system for wind power production discussed and sensitivity analysis presented.

In Chapter 7 the conclusions drawn from the research are presented and suggestions made for further research.

2 Wind energy and site selection

This chapter covers the theoretical background and concepts used in this thesis.

2.1 Operation and technical background of a wind turbine

The theoretical possible energy that can be derived from wind at certain velocity is expressed as (Manwell, McGowan, & Rogers, 2009):

$$E = \left(\frac{1}{2}\right) A\rho_a v^3 t \tag{1}$$

The power possible to derive from the wind is equal to the energy per time and is thus proportional to the wind velocity in the power of three (Manwell, McGowan, & Rogers, 2009). It can be expressed as:

$$P = \left(\frac{1}{2}\right) A\rho_a v^3 \tag{2}$$

The wind power per unit area is called the wind power density (WPD) (Manwell, McGowan, & Rogers, 2009). It is expressed as:

$$WPD = \frac{P}{A} = \left(\frac{1}{2}\right) \rho_a v^3 \tag{3}$$

Wind power density can be used to qualitatively evaluate the magnitude of wind resources. A wind power density greater than $400\ \frac{\mathrm{W}}{\mathrm{m}^2}$ at 10m above ground is considered to indicate a good wind resource (Manwell, McGowan, & Rogers, 2009).

The power coefficient of a wind turbine is the ratio of power extracted by the turbine to the total power contained in the wind and is expressed as:

$$Cp = \frac{P_T}{P_w} \tag{4}$$

A wind turbine cannot absorb all kinetic energy from the wind since that would cause the air to come to a complete stop. This limit on the power output of a turbine is called the Betz limit (Manwell, McGowan, & Rogers, 2009). The Betz limit is expressed as:

$$Cp_{maximum} = \frac{16}{27} \tag{5}$$

The theoretical maximum power of a turbine is when a turbine is assumed to be 100% efficient. That is there are no mechanical, frictional or thermodynamic losses in the turbine (Manwell, McGowan, & Rogers, 2009). The efficiency of a wind turbine can be expressed as:

$$\eta_T = \left(\frac{P_T}{\frac{1}{2}\rho_a A v^3}\right) \tag{6}$$

Thus the power output of a turbine can be calculated using the equation below:

$$P_T = \frac{1}{2}\rho A v^3 C p \eta_{mechanical} \quad (7)$$

2.2 Design of wind turbine

Wind turbines are designed to have a certain rated power, P_{rated}, which is generated at a wind speed v_{rated}. Therefore, the rated power of a turbine is important when selecting a suitable turbine for a particular site. The value of the rated power and velocity is selected by the turbine manufacturer. Turbines are often designed for a rated velocity of 12-15 m/s. The reason for not designing turbines for higher velocities is that wind speeds seldom reach this level and the extra cost of construction is not feasible compared to the possible gains. Wind turbines are designed in such a way that at a certain wind velocity the turbine will shut down or slowly decrease the production. This stop velocity is at 25m/s for most turbines (Bruhn, Lorensson, & Svensson, 2009). Turbines with high wind ride through do not come to a complete stop when the wind speed reaches 25m/s but gradually decrease production before coming to a stop. This allows turbines to operate in a more stable way at high wind speeds (Siemens, 2012).

It can be seen by the theoretical formulations presented in Section 2.1 that the power output increases by a factor of three with increased wind speed. However, due to the design of the turbine, when the rated velocity is reached so is the maximum power output. Therefore at this point the design of the turbine starts to limit the power output. This stresses the fact that for every instalment the right turbine, given local conditions, must be chosen in order to maximize the potential power output at the location.

2.3 Wind resource analysis using historical wind data

As theoretical formulations in Section 2.1 indicate, the wind speed is of high importance for the power output of a wind turbine. Wind speed is highly variable and varies both with time and location. Meteorological data provide mean wind speeds for ten minute or hourly intervals. This data can be used to calculate the potential production from a wind turbine. The data collected is measured at 10m height above ground. For analysis, the data must be converted to the exact height of the turbine hub (Manwell, McGowan, & Rogers, 2009). This conversion can be expressed by the following equation:

$$\frac{v_z}{v_{ref}} = \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)} \quad (8)$$

Another equation commonly used to project wind speed to higher altitudes is:

$$\frac{v_z}{v_{ref}} = \left(\frac{z}{z_{ref}}\right)^{\alpha} \quad (9)$$

Statistical analysis is a commonly used method when analyzing wind data. This results in probability distribution of wind speeds which can be used to calculate possible power output of a turbine. The Weibull probability density function is a well-accepted function used for wind data analysis (Manwell, McGowan, & Rogers, 2009). The probability density function can be expressed as:

$$\rho(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{10}$$

Additionally the cumulative distribution function can be expressed as:

$$F(v) = 1 - \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{11}$$

Using equation 10 the average velocity can be expressed as:

$$\bar{v} = c\Gamma\left(1 + \frac{1}{k}\right) \tag{12}$$

Where the gamma function is expressed as:

$$\Gamma(x) = \int_{0}^{\infty} e^{-t} t^{x-1} dt \tag{13}$$

The variance of the Weibull distribution of wind speeds can be evaluated by:

$$\sigma_v^2 = \bar{v}^2 \left(\frac{\left(\Gamma\left(1 + \frac{2}{k}\right)\right)}{\Gamma^2\left(1 + \frac{1}{k}\right)} - 1 \right) \tag{14}$$

To approximate the shape factor, k, and the scale factor, c, there are several methods available. The analytical approach is a good approximation for $1 < k < 10$ (Manwell, McGowan, & Rogers, 2009). It is expressed as:

$$k = \left(\frac{\sigma_v}{\bar{v}}\right)^{-1{,}086} \tag{15}$$

Using the calculated value for the shape factor, k, and solving equation 12 the scale factor c can be found using the following expression:

$$c = \frac{\bar{v}}{\Gamma\left(1 + \frac{1}{k}\right)} \tag{16}$$

For a given power curve $P_T(v)$ the average power from a turbine at a location with probability density function $\rho(v)$ for the wind speeds can be found using (Manwell, McGowan, & Rogers, 2009):

$$\overline{P_T} = \int_{0}^{\infty} P_T(v)\rho(v)dv \tag{17}$$

The integral can be replaced by a summation over the N bins being considered.

Capacity factor (CF) is used to measure how efficiently a wind turbine is functioning at certain location. It is defined as the ratio between energy actually produced by turbine at a given site and maximum possible energy if the turbine would produce at maximum power for all hours of the year (Wagner & Mathur, 2009):

$$CF = \frac{E_t}{E_{t,maximum}} \tag{18}$$

2.4 Correlation of data sets

Linear correlation of data sets can be calculated using the correlation coefficient which is a measure of the linear dependence of the two data sets. For data sets of N_{data} observations the correlation coefficient can be explained as:

$$\rho(B,C) = \left(\frac{1}{N-1}\right) \sum_{i=1}^{N_{data}} \left(\frac{\overline{B_\iota - \mu_B}}{\sigma_B} - \frac{\overline{C_\iota - \mu_C}}{\sigma_C}\right) \tag{19}$$

This relationship can also be expressed using the covariance of the data sets as:

$$\rho(B,C) = \frac{Cov(B,C)}{\sigma_B \sigma_C} \tag{20}$$

High correlation coefficient indicates positive linear relationship between data sets, correlation coefficient close to zero indicates low linear relationship between sets and that there is no clear linear trend in the behavior of the data. Negative correlation coefficient indicates that there is a negative linear relationship between data sets (Upton & Cook, 2014).

2.5 Site selection criteria

The siting of a wind turbine or wind farm is often divided into five stages. Those stages are identification of suitable geographic areas, selecting feasible sites, preliminary evaluation of the feasible sites, final site evaluation and micro siting (Manwell, McGowan, & Rogers, 2009).

The identification of suitable geographic areas is based on finding areas with high average wind speeds. The characteristics of the turbine determine the minimum useful wind speed. This stage is followed by an identification of potential windy areas where installation of wind turbines appears to be practical. Topographical and ecological considerations as well as computer modelling can be used to evaluate the wind resource. The preliminary evaluation of sites is carried out by ranking the feasible sites in order of economic potential. The ownership of the land must be taken into consideration when economically evaluating possible sites. The most viable sites are examined further for environmental impact and social acceptance issues as well as operational problems. This evaluation results in candidate sites which serve as the best possible sites to install wind power production. For these sites a more comprehensive study of the wind resource must be carried out. These studies should identify the wind shear and turbulence at the site in addition to wind speeds and wind direction. After analysis of these measurements the most feasible site is selected. Once a site is selected, micro siting analysis must be carried out where the exact siting of the wind turbine as well as the energy production must be determined. This is done with computer programs which model the wind field and the interactions between turbines. As the complexity of the terrain increases and the available data decreases the modelling becomes less accurate (Manwell, McGowan, & Rogers, 2009).

The process to carry out a comprehensive site analysis for possible wind power production can be both expensive and time consuming. The data that must be gathered and the measurements carried out are extensive. Therefore, the initial stages of the process are very important as they come at lower cost than the later stages and can be carried out with data often available by the Meteorology Agency (Manwell, McGowan, & Rogers, 2009). In this thesis the first two stages of a site analysis will be carried out.

2.6 Selection of locations to be considered for analysis

The locations chosen for consideration in this analysis are shown in Figure 1. These locations are selected due to large availability of data from the anemometers at these sites. Additionally most of the selected anemometers are owned and operated by the Meteorology Agency of Iceland.

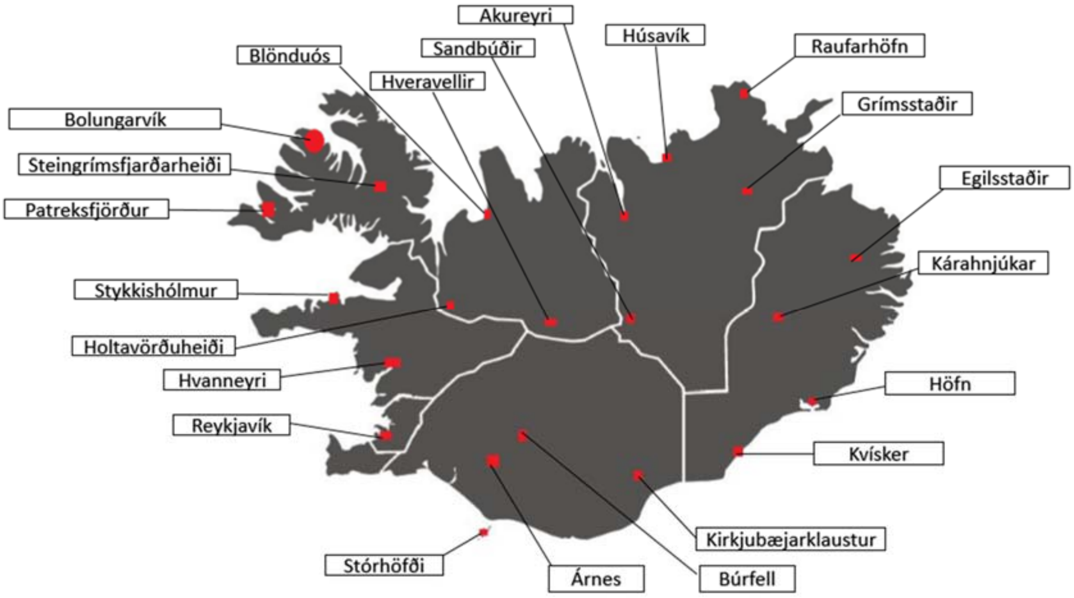


Figure 1. Locations selected for the analysis.

2.6.1 Proximity to the national grid

Most of the locations considered are close to the national grid except the anemometers located in the highlands. The proximity to the grid is important since the grid connection of an onshore wind farm is approximated 9-14% of the total cost of the wind farm (IRENA, 2012). Implementing a wind farm close to the grid decreases the cost for cabling and doing so decreases the total cost of grid connection.

The national grid is operated by a governmentally owned company Landsnet. The grid is operated at 220kV but has the opportunity to operate at 400kV if more power is to be transferred in the grid. There are some bottlenecks present in the grid and the transmission capacity of the ring connected grid is 100MW. Therefore, it is clear that distributed electricity production is the key for an operational electricity system in Iceland (Orkustofnun, 2015). It is of interest to implement wind power production at areas connected to the grid with low transmission limits to decrease the pressure on the grid and meet the local demand using the interaction between hydro- and wind power (Þorleiksson, 2013).

An overview of the national grid is shown in Figure 2.

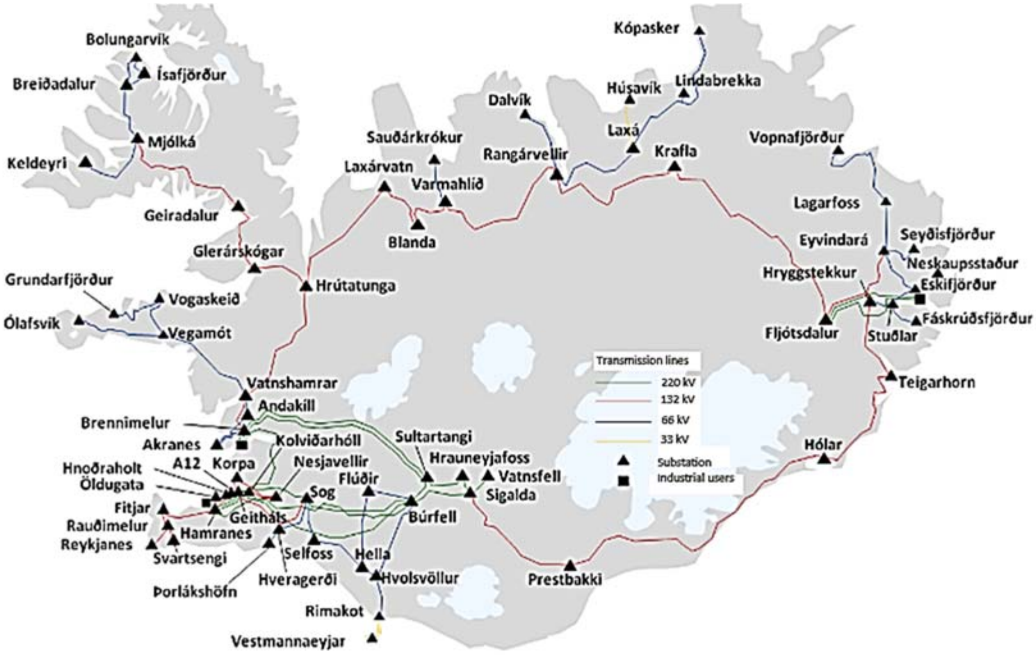


Figure 2. The transmission network in Iceland (Orkustofnun).

In the TSO’s future outlook there are plans on expanding the transmission network (Landsnet, 2014). This expansion is of interest when conducting a site analysis for wind power. New configurations of the grid may decrease the cost of producing electricity from wind at locations which currently are not economically feasible. The possible configurations are shown in Figure 3.

Figure 3. Possible and probable expansions of the national electricity grid (Landsnet, 2014).

2.6.2 Feasible wind profile for electricity production

The first step in selecting locations for possible wind power production is considering the wind profile of the possible locations. Figure 4 shows annual average wind profiles for Iceland in 50m height above the surface. The areas of interest have average wind speeds of 7 m/s or higher.

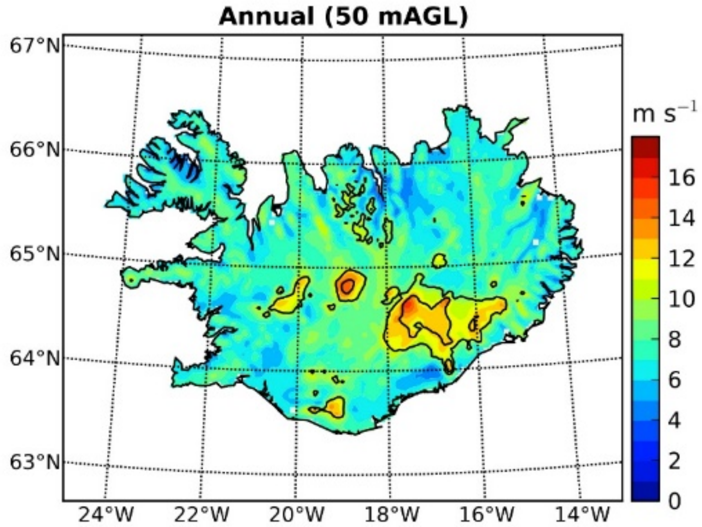


Figure 4. Annual average wind speeds in 50m height above surface level (Veðurstofa Íslands, 2012).

The wind power density explained by equation 3 in Section 2.1 is a good indicator of wind resources. The average annual wind power density at 50m height is shown in Figure 5. As explained in Section 2.1 WPD above $400\frac{W}{m^2}$ indicates good wind resources.

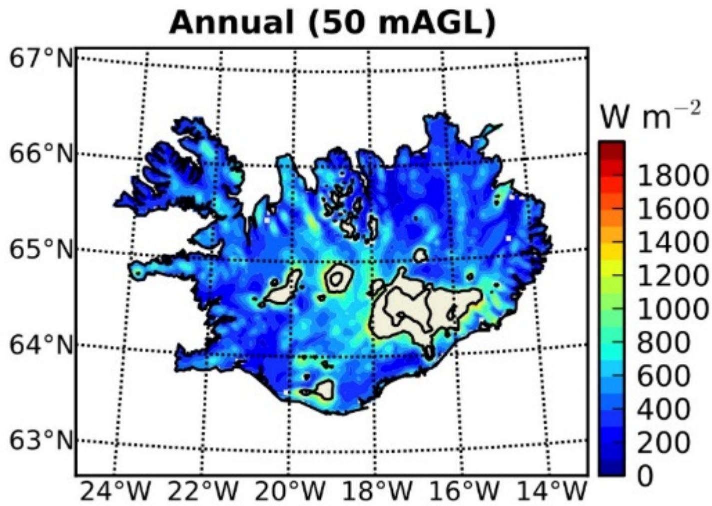


Figure 5. Annual average wind power density at 50m above surface level (Veðurstofa Íslands, 2012).

Considering Figure 2 - Figure 5 the locations selected are feasible for further analyzing.

3 Method

Meteorological data retrieved from the Meteorological Agency of Iceland is imported to Matlab© for calculation and analysis purposes. The data consists of station names, wind speeds, wind direction and general information about the weather stations.

The names of measurement stations and their corresponding information are stated in Table 10 in Appendix 1.

To analyze the data different time scales are considered. The time steps taken are hourly, daily, weekly, monthly, seasonal and yearly averages. This number of time steps are considered because correlation between data as well as average wind speeds can significantly differ between different time scales.

The correlation of the raw wind data and power production for each anemometer location are calculated. The data and results are compared to measurements from an anemometer and calculated power production at the location of current installation.

The analysis is based on historical data. Therefore, the future potential of wind power production is estimated by calculating the Weibull distribution of the historical time series. The Weibull probability distribution of wind speeds is used to calculate the potential power output from a turbine at each of the considered locations.

The historical hourly wind speed time series at each of the considered locations are used to calculate the power production. The wind speed time series are combined with the turbine power curve and the production time series calculated. This production is compared between locations in order to better understand the interaction between locations.

For parts of the study, for calculation and presentation purposes Excel is used.

3.1 Wind data

The wind data collected consists of measurements from 22 anemometers scattered around the country as shown in Figure 1 in Chapter 2, Section 2.6.

The measurements were collected between the years 2006-2016. However, some anemometers have not been operational for the whole period and therefore the data sets collected are not all of the same length as shown in Figure 6. Due to this the different lengths of data sets are taken into consideration when analyzing the data and when comparing two stations the common measurement points are selected.

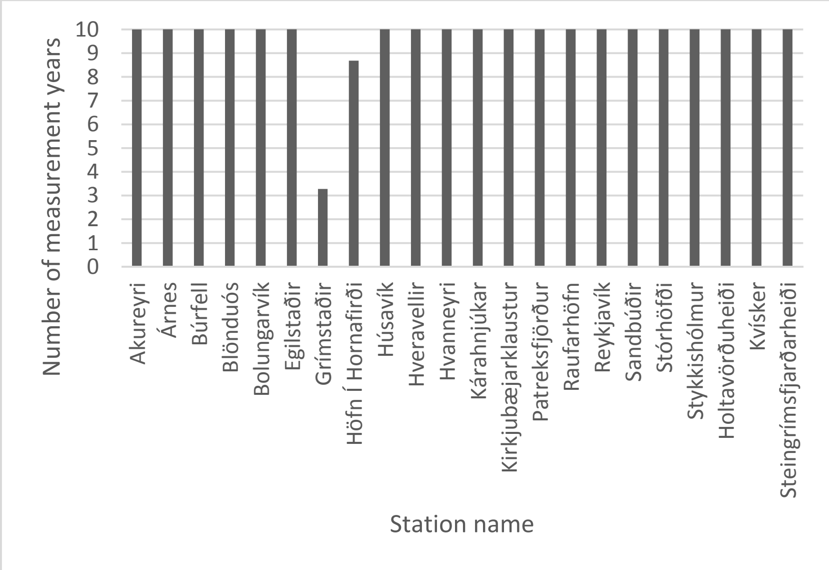


Figure 6. Number of years of collected data.

The dataset consists of the average wind speed for the last ten minutes of measurements for every hour. This is considered to be fair enough estimate on the hourly average data.

3.1.1 Quality analysis of data

The data collected has been cleaned by the Meteorology Agency. Due to this the time interval of measurements are not even for all anemometers. The data set includes some corrupted data points that either are not available in the original data set or get corrupted when the data set is imported to Matlab©. For further analysis those corrupted measurement points are removed. As the cleaning process results in missing data points, Figure 7 shows the data that should be theoretically available in comparison to the collected data as well as the cleaned data set. The theoretically available data consists of all hourly measurements for the years of operation of the anemometer.

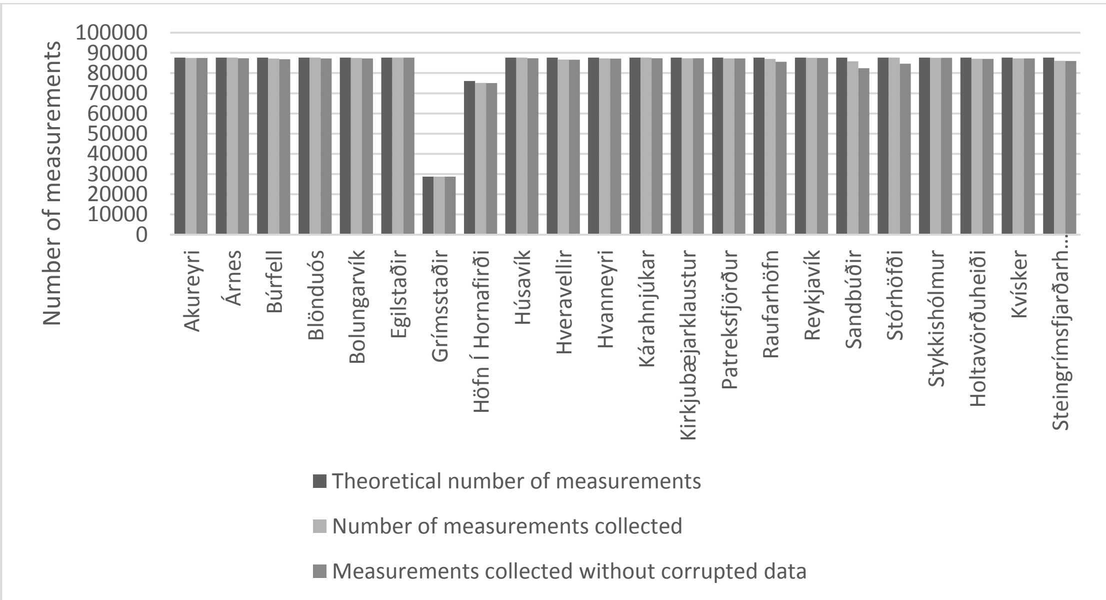


Figure 7. Number of collected data points for hourly measurements compared to theoretical available data as well as data sets without corrupted data.

The number of corrupted data points differ between seasons as well as stations. The seasonal difference is shown in Figure 8. The figure presents number of corrupted data as well as the percentage of corrupted data compared to total collected data per month. As can be seen the highest number of corrupted data points are detected during the winter and spring months but fewer during summer. This can be due to icing that can occur on the measuring devices. This is as well the reason for higher number of corrupted data points from measurement devices located at high altitudes (Blöndal & Birgisson, 2010).

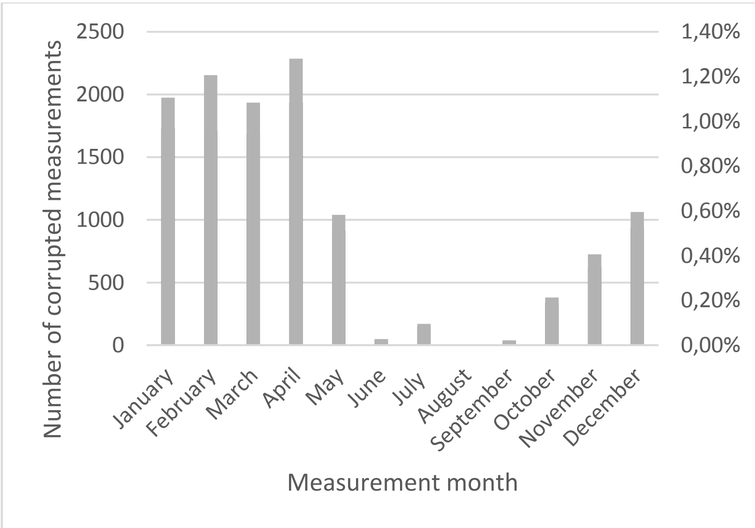


Figure 8. Number of corrupted data points per month.

Figure 6 - Figure 8 indicate that the quality of the data is rather high as few data points are lost in comparison to those collected. Therefore, after considering the quality of data no location is excluded from the analysis.

3.2 Wind speed correlation between locations

The wind speed profiles at considered locations are compared to the wind speed profile at Búrfell which is the baseline for this analysis. The wind speeds are compared at various time steps i.e. for hours, days, weeks, months, seasons and years. The wind data is compared considering time of measurement. The data is sorted in such a way that the same measurement points are taken for each station. For hourly comparison the hourly mean speed for every hour with available measurements for the years 2006-2016 is compared. For bigger time steps the wind speeds are averaged over the considered time.

The analysis of seasons is presented in Table 1.

Table 1. Months considered in a season.

Winter	December, January and February
Spring	March, April and May
Summer	June, July and August
Autumn	September, October and November

The seasons are compared as a whole in order to detect any seasonal trends as well as intra-season comparison is carried out.

While comparing yearly averages the last value of the data set is excluded as it only includes one measurement for the first hour of 2016. This must be excluded as if it is included the analysis becomes skewed.

To compare the data the correlation between data sets is calculated as Equation 19 in Chapter 2, Section 2.4 explains.

The correlation between locations is calculated in order to find any connection of behavior of wind in different locations. Negative correlation indicates that placing wind turbines in those two areas can even out the fluctuations in production as the synergetic effects of the turbines can even out the production profile. This decreases the intermittency of the production. Neutral correlation indicates that controlling the fluctuation of the production by using synergetic effects of wind turbines becomes difficult. Positive correlation indicates that the wind is behaving similarly at the two compared locations and there is a positive linear connection of the wind behavior. This results in a situation where both wind turbines will be producing electricity at the same time. Positive correlation can decrease the need for other power sources when the wind blows heavily, therefore, the wind power generation can supply higher share of the total power demand. While negative correlation can result in decreased need for regulating power as the turbines even out each other fluctuations. Therefore, negative correlation can help decrease the need for hydro power and maximize the efficiency of the hydro reservoirs. The power can be saved in the reservoirs and sold when it is most efficient. Negative correlation is of interest in this analysis and can help decreasing the effects of intermittent production on the grid.

3.3 Projecting velocity to hub height

The wind speed changes with height. Therefore, higher velocity is expected with increased height. The magnitude of the increase in speed is dependent on the roughness length of the terrain, thus over rough landscape the wind speed measured close to ground will increase more with height than over smooth surface (Manwell, McGowan, & Rogers, 2009).

For this analysis turbines with hub height of 70m, 80m and 90m are considered. The average as well as hourly measured wind speeds are projected to the height of the hub. Equation 9 in Chapter 2, Section 2.3 is commonly used to calculate the projected velocity with the power law coefficient,(α), equal to 1/7 (Blöndal & Birgisson, 2010). For this analysis the CORINE[1] factor for each location is determined using the ArcMap software. Using this factor the roughness length of the terrain can be found in the literature (Silva & Guedes). Therefore, the surface roughness length is determined independently for every location. It is necessary to validate the roughness length determined by the CORINE factor as for some locations the factor is misleading. Therefore, the program Google Earth Pro is used to visually analyze the validity of the roughness length found using the CORINE factor. After adjusting the roughness length where it is needed the calculations using the common value for alpha and the locational based roughness length using Equation 8 in Chapter 2, Section 2.3 are compared. Overall, calculating the projected wind speeds using Equation 9 with $\alpha = \frac{1}{7}$ underestimates the increase in wind speeds compared to Equation 8. However, as the

[1] Coordination of Information on the Environment, uniformed European terrain classification system.

velocity increase is highly dependent on the roughness length, overestimating it can give misleading results of the feasibility of a location.

The height of anemometers as well as the roughness length at each location are presented in Table 10 in Appendix 1. For the anemometers with unknown height it is assumed to be 10m. The anemometer height is used as the reference height when the wind speeds are projected to hub height.

3.4 Modelling of wind power production

To calculate the predicted power output at a considered location the power curve must be modeled. In this section the modelling of the power curve is described as well as how the power production is calculated from the known wind data.

3.4.1 Modelling the power curve of a turbine

The turbine used for this analysis is the ENERCON E-101 E2 3500kW wind turbine. The hub height of the turbine is 74m. However, for calculations 70m, 80m and 90m hub heights are considered.

In Iceland the roughness length of the terrain is usually low. The average roughness length has been estimated 3cm (Nawri, Petersen, Björnsson, & Jónasson, 2012). Low roughness length indicates that a stable wind profile is reached at lower altitudes than for higher roughness lengths (Ragheb, 2015). Therefore, higher turbines are not considered in this analysis.

The power curve for the considered turbine is modeled in Matlab©. The power outputs of the turbine at wind speeds 1 - 25 m/s are known and presented in Table 11 in Appendix 2. The cut off speed of the wind turbine is 25 m/s. The power curve of the turbine is given for standard air density of 1,225 kg/m^3. In order to find the power output of the turbine in between the published values of the power output the curve must be interpolated. This is done using cubic spline data interpolation. This results in a continuous function for the power curve shown in Figure 9. This function is used to calculate the power output of the turbine for every occurring wind speed. In comparison Figure 10 presents the published power curve of the ENERCON E-101 turbine.

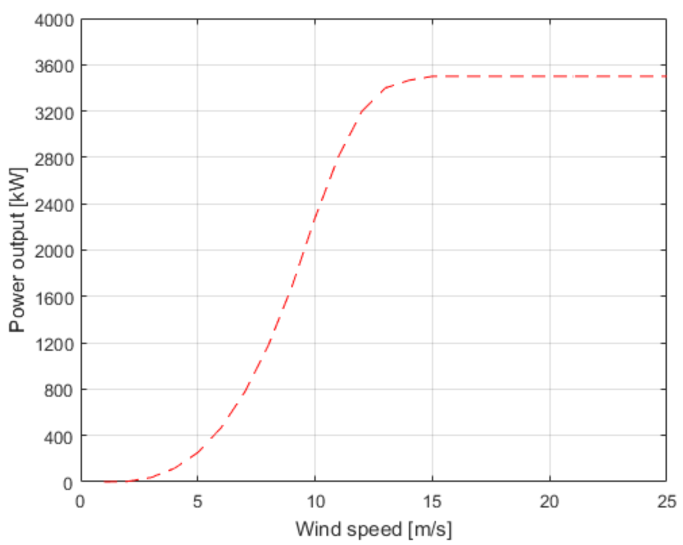


Figure 9. Simulated power curve of the ENERCON E-101 E2 3500kW turbine.

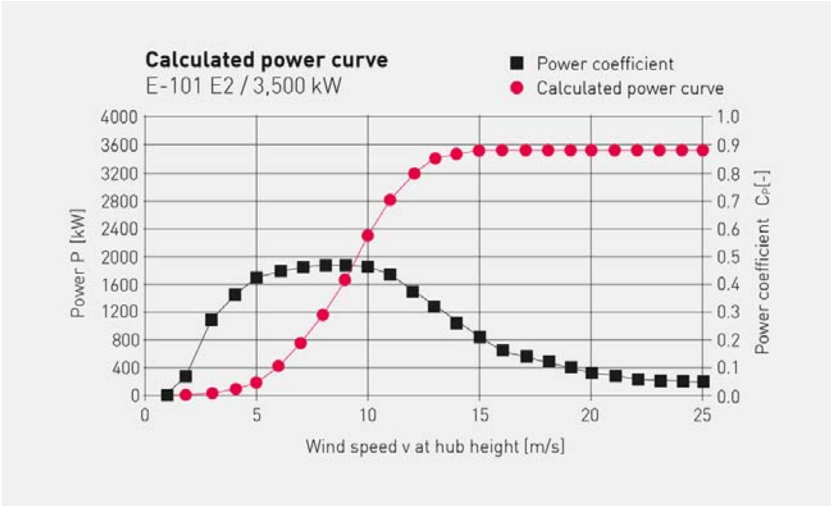


Figure 10. Published power curve of the ENERCON E-101 E2 3500kW turbine (ENERCON)

3.4.2 Statistical modelling of power production

To estimate the possible power output from a wind turbine at a location the Weibull distribution of wind speeds is calculated. The shape factor, k, and scalar factor, c, are calculated both using a built in function in Matlab© as well as the analytic approach presented by Equations 15 and 16 in Chapter 2, Section 2.3. The difference between methods is small and for simplicity the built in function is used for calculations.

The probability density function for the Weibull distribution is calculated using Equation 10 in Chapter 2, Section 2.3. This probability density function is compared to the real measured data and the quality of the fit estimated.

The power production at a location is calculated using the probability distribution of wind speeds. This is combined with the power curve in order to get the probability of certain power output from the turbine. The energy produced by the turbine is calculated by summing the power produced over a period of time. The capacity factor for all locations is calculated using equation 18 in Chapter 2, Section 2.3.

3.4.3 Power production of a turbine considering historical data

The correlation of power production between locations is of interest. In order to calculate the correlation of power production between locations, the power output at each location is calculated using the wind speed time series. The production is calculated by combining the wind speed data with the simulated power curve and by doing so finding the power output for every hour. The power production calculated using the time series is compared to the calculated power production at Búrfell.

The historical production at a location is compared to the production at Búrfell in order to estimate how often the turbines will be complementing each other, how often the turbines produce simultaneously and how often no production is at both locations. Production intervals are considered and it is estimated how often over the measurement time each production interval is detected at the locations separately or while implementing turbines at both locations.

4 Results

This chapter covers the results of the analysis of wind speeds as well as the calculated power production at each considered location.

4.1 Average wind speeds

The average detected wind speed for a location gives an important indication of the wind resources at that location. The average wind speeds at anemometer height as well as the considered hub heights are presented in Table 2.

Table 2. Average wind speeds for the considered locations. The shaded cells represent locations considered infeasible for wind power production.

Locations	Average wind speeds at anemometer height [m/s]	Average wind speeds at hub height of 70m [m/s]	Average wind speeds at hub height of 80m [m/s]	Average wind speeds at hub height of 90m [m/s]
Akureyri	3,86	6,52	6,70	6,86
Árnes	5,28	7,05	7,17	7,28
Búrfell	7,04	9,39	9,56	9,70
Blönduós	5,31	7,08	7,20	7,31
Bolungarvík	4,40	7,24	7,44	7,61
Egilsstaðir	4,55	5,71	5,79	5,86
Grímsstaðir	6,19	8,27	8,41	8,54
Holtavörðuheiði	7,56	10,10	10,27	10,43
Húsavík	3,97	5,27	5,36	5,44
Hvanneyri	4,71	6,39	6,50	6,61
Hveravellir	7,50	9,76	9,93	10,07
Höfn Í Hornafirði	6,28	10,19	10,47	10,71
Kárahnjúkar	6,58	8,77	8,92	9,06
Kirkjubæjarklaustur	5,00	6,67	6,79	6,89
Kvísker	5,64	7,91	8,05	8,17
Patreksfjörður	4,69	7,73	7,93	8,12
Raufarhöfn	5,09	7,93	8,12	8,29
Reykjavík	4,01	6,59	6,77	6,93
Sandbúðir	8,70	10,92	11,07	11,20

Locations	Average wind speeds at anemometer height [m/s]	Average wind speeds at hub height of 70m [m/s]	Average wind speeds at hub height of 80m [m/s]	Average wind speeds at hub height of 90m [m/s]
Steingrímsfjarðarheiði	7,66	10,23	10,40	10,56
Stórhöfði	10,77	14,30	14,55	14,77
Stykkishólmur	5,51	8,57	8,78	8,97

It is commonly accepted that locations with average wind speeds higher than 5,1m/s at approximately 10m height are feasible for wind power production (NREL). However, considering the results presented in Table 2, locations resulting in average wind speeds below 8 m/s at 90m hub height are judged infeasible. This is due to the fact that these locations are not likely to have high enough capacity factor to make the instalment profitable, considering the low price of electricity in Iceland. Patrekfjörður has average wind speed at anemometer height below 5,1m/s. However, as this is a mountainous area the roughness factor at this location is estimated to be high, therefore, the average wind speed increases significantly with increased height.

Stórhöfði has very high wind speeds and therefore seems to be a very feasible location for wind power production. However, the data used for the analysis for this location is from an anemometer located at the southernmost tip of an island, on a steep hill close to the seaside. Therefore, the hourly average wind speed is likely highly affected by extreme wind situations which do not last for enough time to utilize for power production. Additionally, this part of the island is lacking important infrastructure needed to implement wind turbines. Therefore, wind integration would be more expensive than at other considered locations. In order to further examine the possibility for wind power production on this island other anemometers located more inland should be considered. However, this is not done for this research.

Considering the IEC 61400-1 standard, a class I wind turbine is designed to withstand an annual average wind speed of 10 m/s at hub height (IEC, 2005). Therefore, locations resulting in average wind speeds higher than 11m/s are not considered. Locations with average wind speeds of 10 -11m/s are considered further but it has to be kept in mind that the wind speed is relatively high.

Due to the aforementioned arguments, the shaded locations in Table 2 will not be considered for further analysis.

For all feasible locations the calculated WPD at the anemometer height, presented in Table 10 in Appendix 1, is higher than $400\ \frac{\mathrm{W}}{\mathrm{m}^2}$ which as mentioned in Chapter 2, Section 2.6 indicates good wind resources.

4.2 Correlation between wind data

The correlation of data from feasible locations and Búrfell is calculated and compared. Table 3 presents the correlation between wind speeds at the feasible locations for the hourly, daily, weekly, monthly and yearly comparison. Table 4 presents the correlation for the seasons. The green colored cells represent the most negative correlation for every time step, the red cells represent the most positive correlation for every time step and the yellow cells the most neutral correlation.

Table 3. Correlation between locations for hourly, daily, weekly, monthly and yearly wind speeds average data.

Locations	**Average wind speeds at anemo-meter height [m/s]**	**Locations**	**Average wind speeds at anemo-meter height [m/s]**	**Hourly data**	**Daily data**	**Weekly data**	**Monthly data**	**Yearly data**
Grímsstaðir	6,19	***Búrfell***	7,04	-0,01	-0,02	-0,08	-0,12	-0,85
Holtavörðuheiði	7,56	***Búrfell***	7,04	0,07	0,10	0,26	0,44	0,67
Hveravellir	7,50	***Búrfell***	7,04	0,17	0,25	0,31	0,60	0,67
Höfn í Hornafirði	6,28	***Búrfell***	7,04	-0,05	-0,08	-0,16	-0,38	0,25
Kárahnjúkar	6,58	***Búrfell***	7,04	0,12	0,17	0,28	0,66	0,56
Kvísker	5,64	***Búrfell***	7,04	0,15	0,24	0,53	0,84	0,79
Patrekfjörður	4,69	***Búrfell***	7,04	0,13	0,18	0,36	0,74	0,70
Raufarhöfn	5,09	***Búrfell***	7,04	0,10	0,16	0,33	0,70	0,38
Steingrímsfjarðar heiði	7,66	***Búrfell***	7,04	0,06	0,09	0,23	0,43	0,75
Stykkishólmur	5,51	***Búrfell***	7,04	0,13	0,18	0,28	0,42	0,85

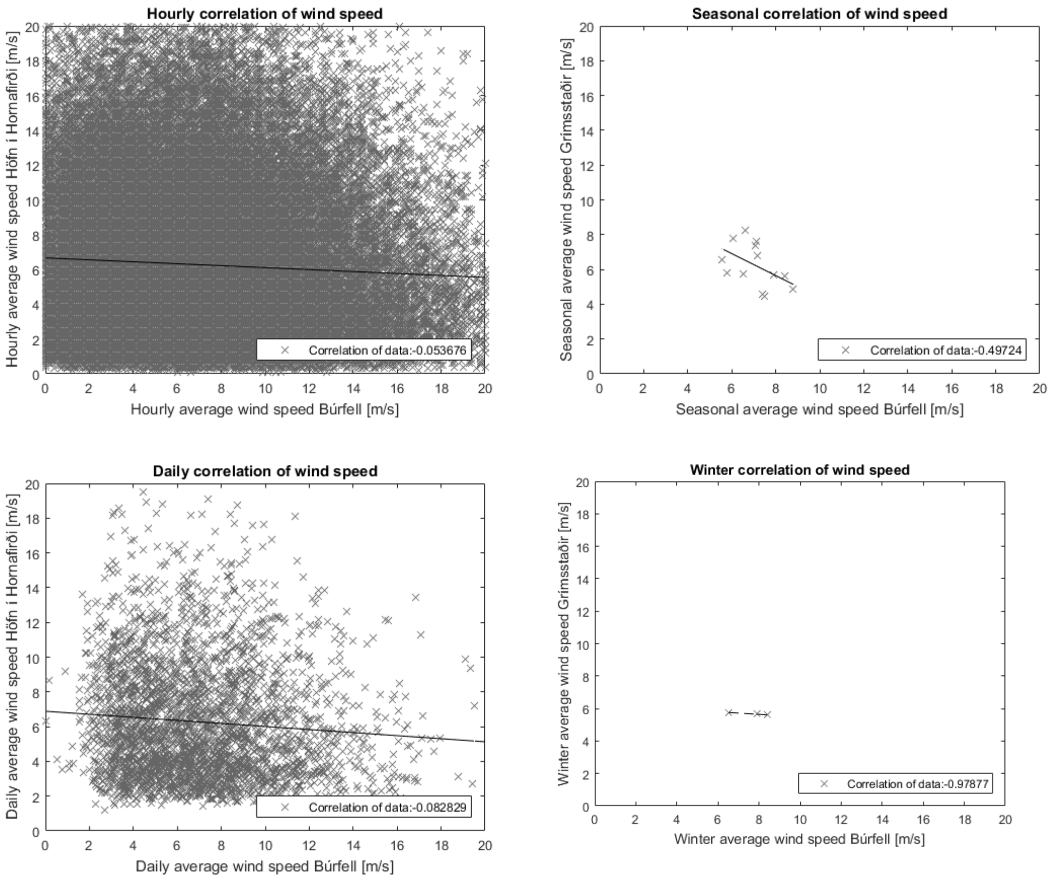
Table 4. Correlation between locations considering the seasonal average wind speeds.

Location	**Average wind speeds at anemo-meter height [m/s]**	**Location**	**Average wind speeds at anemo-meter height [m/s]**	**Seasonal data**	**Winter**	**Spring**	**Summer**	**Autumn**
Grímsstaðir	6,19	***Búrfell***	7,04	-0,50	-0,98	-0,86	0,61	0,92
Holtavörðuheiði	7,56	***Búrfell***	7,04	0,70	0,03	0,57	0,80	0,47
Hveravellir	7,50	***Búrfell***	7,04	0,73	-0,04	0,83	0,73	0,42
Höfn í Hornafirði	6,28	***Búrfell***	7,04	-0,49	-0,09	0,10	0,73	-0,38
Kárahnjúkar	6,58	***Búrfell***	7,04	0,78	0,22	0,70	0,22	0,15
Kvísker	5,64	***Búrfell***	7,04	0,92	0,55	0,71	0,90	0,94
Patreksfjörður	4,69	***Búrfell***	7,04	0,90	0,73	0,47	0,96	0,89
Raufarhöfn	5,09	***Búrfell***	7,04	0,79	0,24	0,67	0,68	0,50

Location	Average wind speeds at anemo-meter height [m/s]	Location	Average wind speeds at anemo-meter height [m/s]	Seasonal data	Winter	Spring	Summer	Autumn
Steingrímsfjarðarheiði	7,66	***Búrfell***	7,04	0,57	-0,35	0,59	0,92	0,85
Stykkishólmur	5,51	***Búrfell***	7,04	0,68	0,16	0,74	0,84	0,73

To better understand the correlation between locations, Figure 11, Figure 12 and Figure 13 show the locations with the lowest, most neutral and highest correlation to Búrfell respectively for all time steps considered. The wind speeds at anemometer height at the considered locations are plotted with respect to the wind speed at Búrfell. The correlation is very small when the data points are many. The correlation increases with decreased number of data points. Therefore, the highest correlations, both positive and negative, are detected for yearly and intra seasonal comparison.

Figure 11 presents the most negative resulting correlation when considering all the feasible locations and Búrfell for all considered time steps. No negative correlation is detected for the summer season comparison. The locations resulting in the most negative correlation for all time steps are Höfn í Hornafirði and Grímsstaðir.



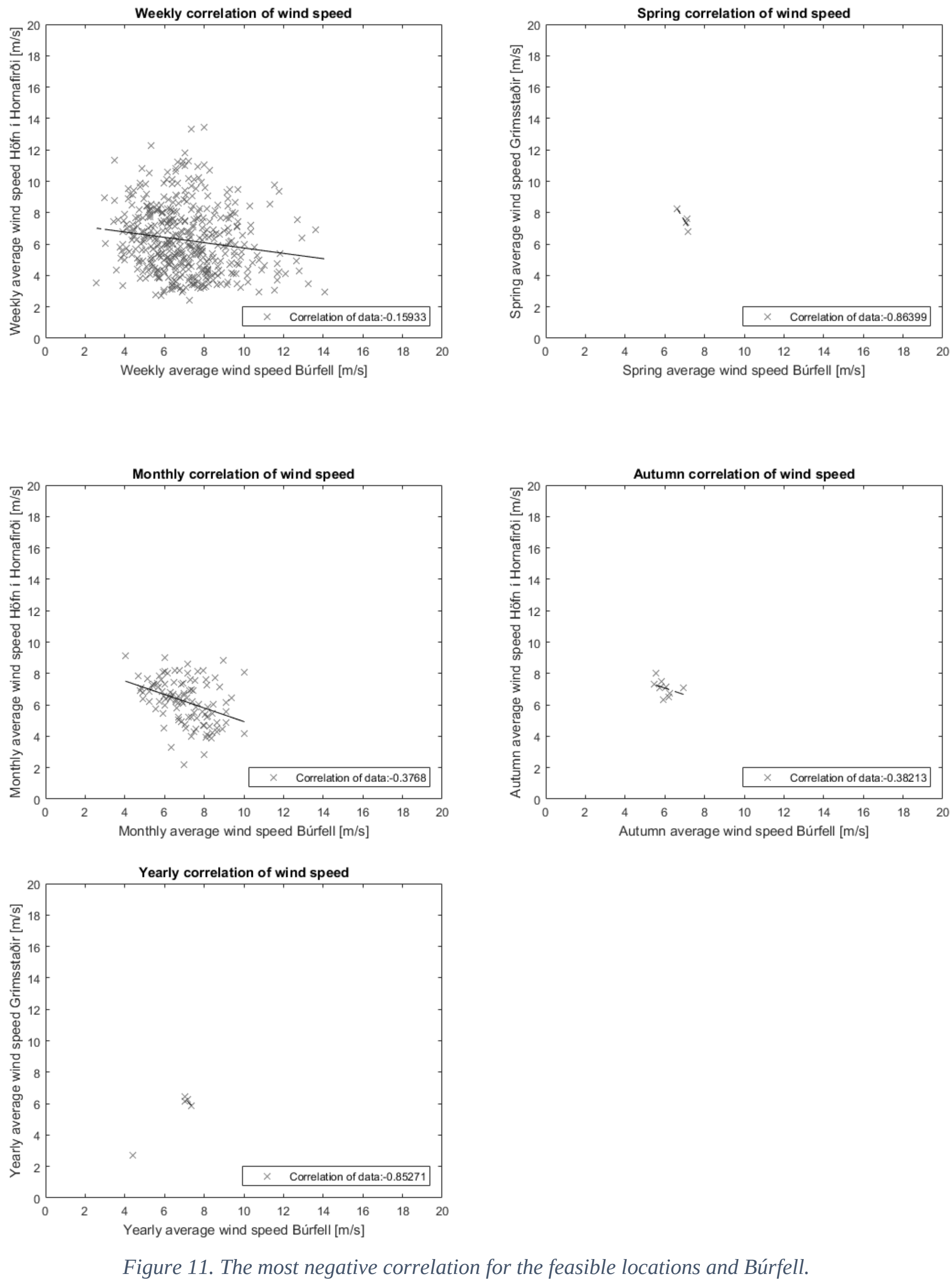
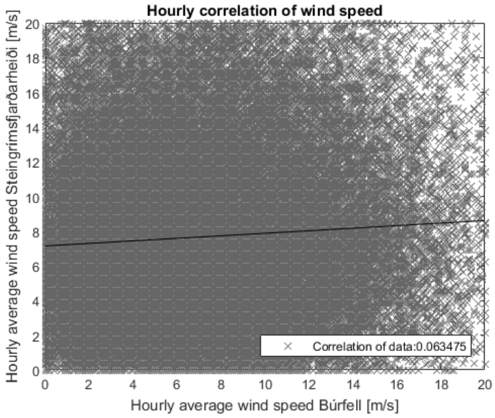
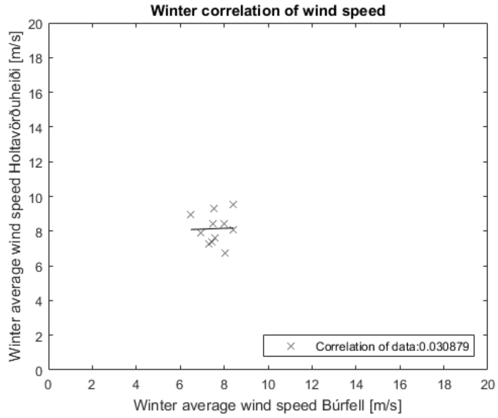
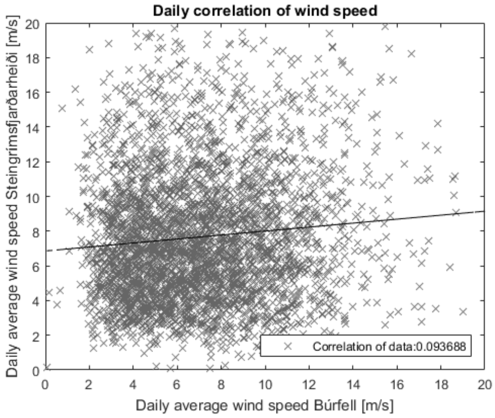


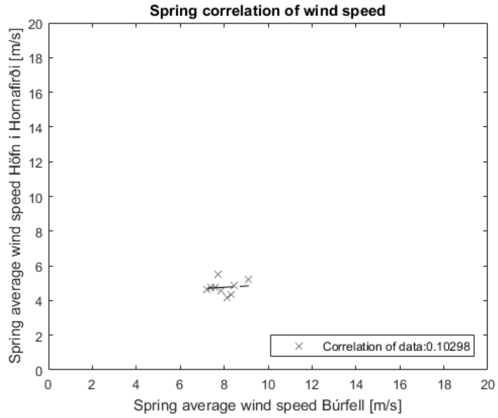
Figure 11. The most negative correlation for the feasible locations and Búrfell.

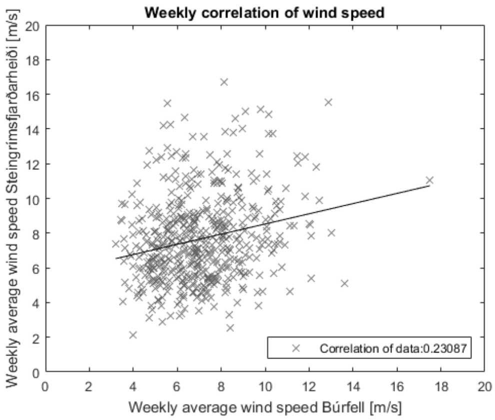
Considering Figure 12 there is not a clear trend as to which locations have the most neutral correlation to Búrfell. The correlation varies as well as the location resulting in the most neutral correlation. The seasonal comparison results in no correlation below 0,5 which is considered neutral for this study.

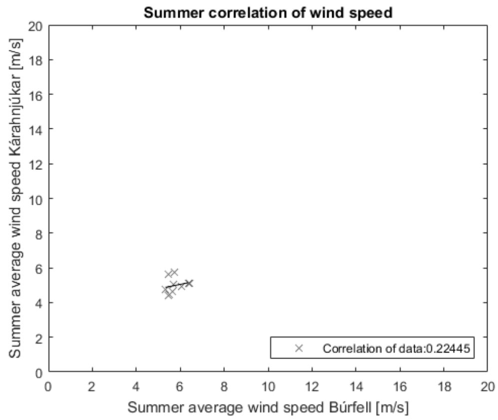

Hourly correlation of wind speed
Hourly average wind speed Steingrimsfjarðarheiði [m/s]
Hourly average wind speed Búrfell [m/s]
Correlation of data:0.063475

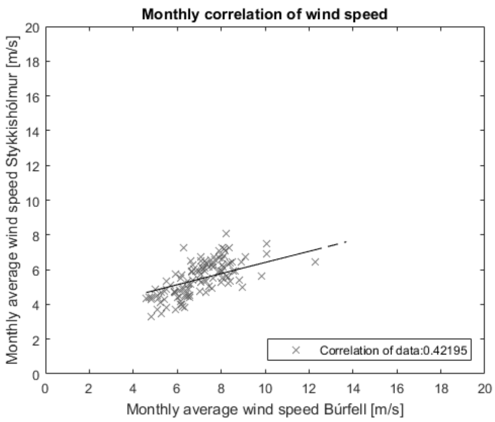

Winter correlation of wind speed
Winter average wind speed Holtavörðuheiði [m/s]
Winter average wind speed Búrfell [m/s]
Correlation of data:0.030879

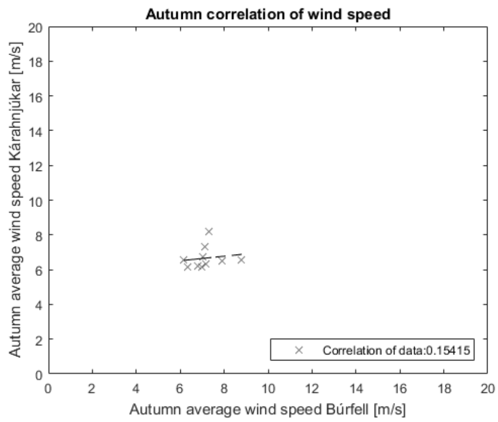

Daily correlation of wind speed
Daily average wind speed Steingrimsfjarðarheiði [m/s]
Daily average wind speed Búrfell [m/s]
Correlation of data:0.093688


Spring correlation of wind speed
Spring average wind speed Höfn í Hornafirði [m/s]
Spring average wind speed Búrfell [m/s]
Correlation of data:0.10298


Weekly correlation of wind speed
Weekly average wind speed Steingrimsfjarðarheiði [m/s]
Weekly average wind speed Búrfell [m/s]
Correlation of data:0.23087


Summer correlation of wind speed
Summer average wind speed Kárahnjúkar [m/s]
Summer average wind speed Búrfell [m/s]
Correlation of data:0.22445


Monthly correlation of wind speed
Monthly average wind speed Stykkishólmur [m/s]
Monthly average wind speed Búrfell [m/s]
Correlation of data:0.42195


Autumn correlation of wind speed
Autumn average wind speed Kárahnjúkar [m/s]
Autumn average wind speed Búrfell [m/s]
Correlation of data:0.15415

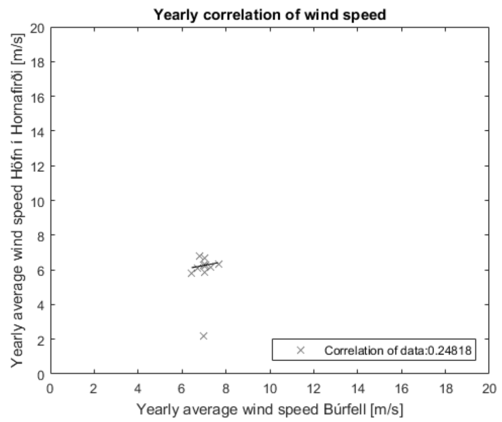
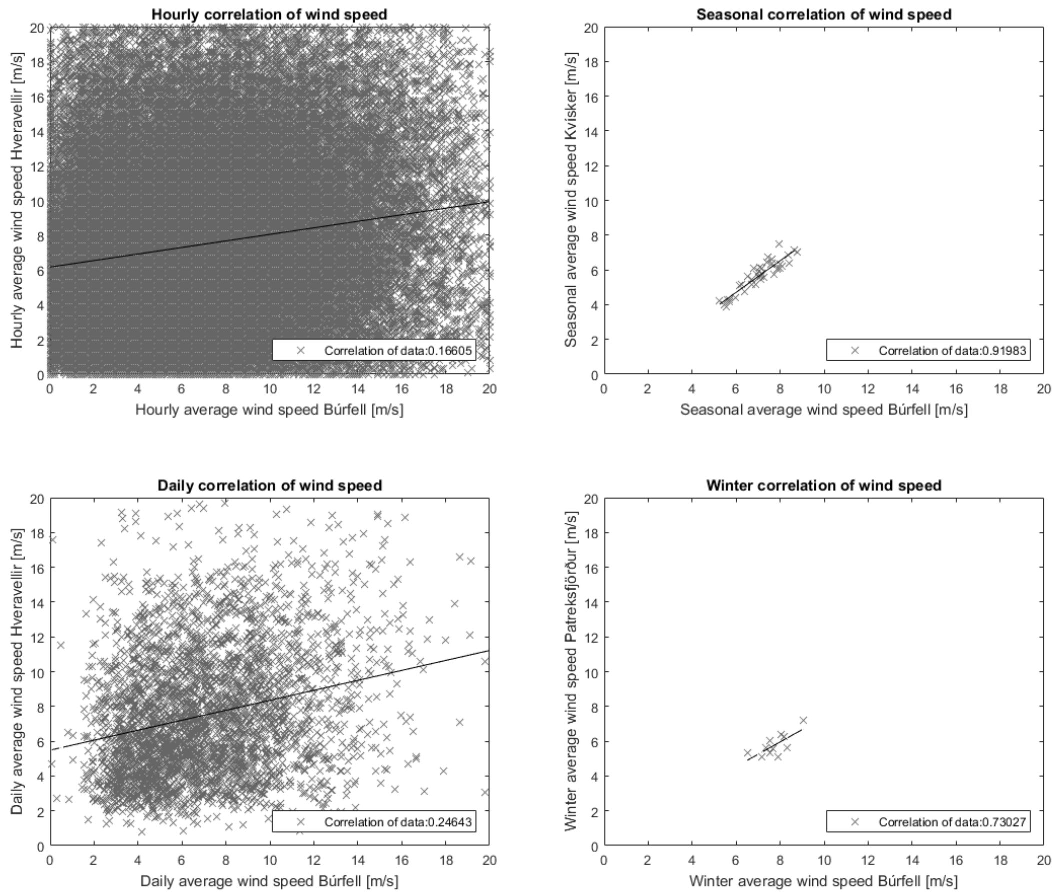


Figure 12. The most neutral correlation for the feasible locations and Búrfell.

Figure 13 shows the comparison of wind speeds between locations and Búrfell resulting in the highest correlation. The highest correlation is highly variable as the lowest value is a rather neutral correlation of 0,17 for the hourly comparison of data. The highest correlation is 0,96 for the summer comparison. The wind speed profile of Kvísker most often results in the highest correlation to the wind speed measured at Búrfell.



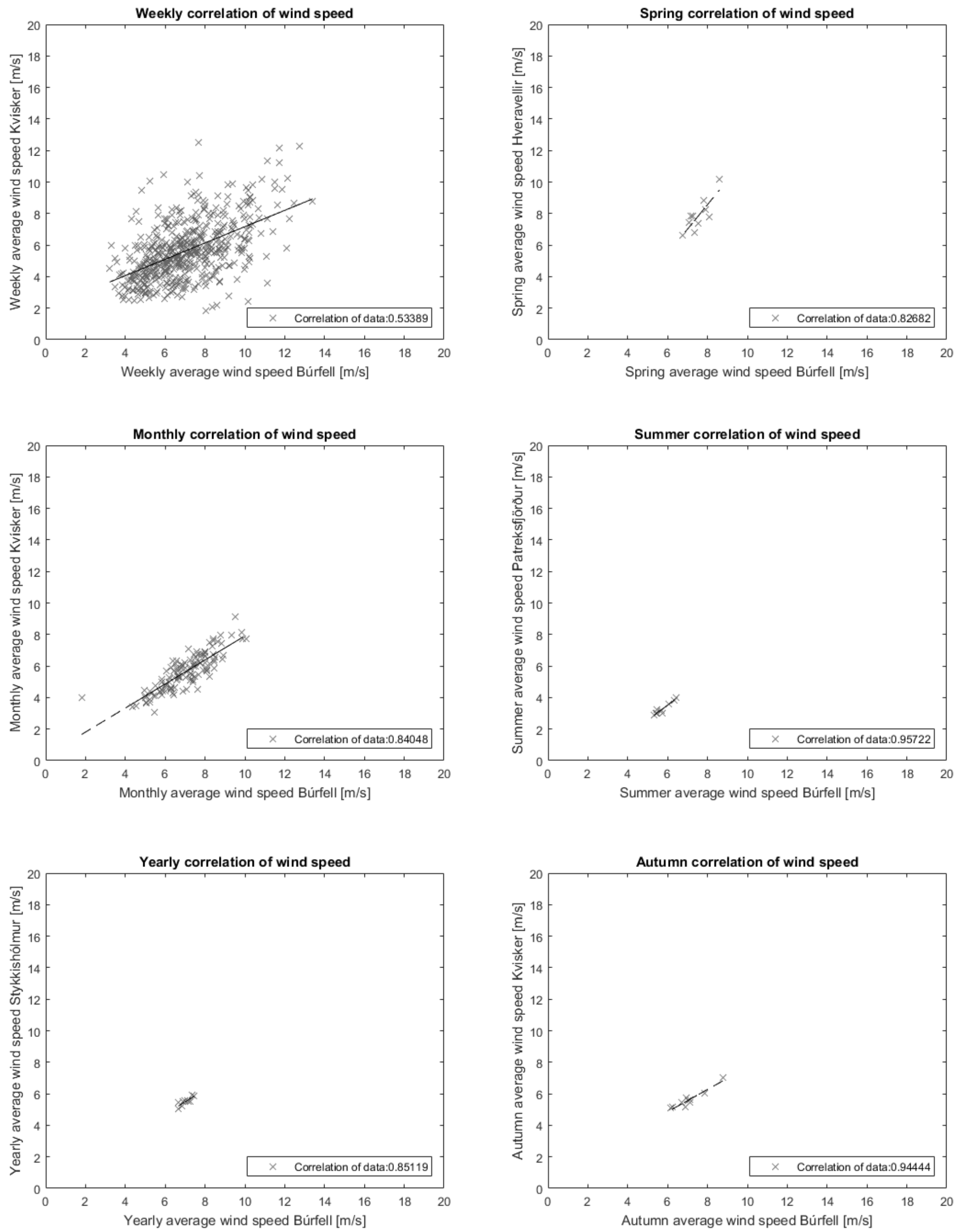


Figure 13. The highest correlation for the feasible locations and Búrfell.

When analyzing the data in Table 3 and Table 4 the result is that for most of the time steps the wind speed profile at Höfn í Hornafirði has negative or close to neutral correlation to the wind speed profile at Búrfell. The highest correlation occurs during summer and is 0,73. Since it is considered more important to have the synergetic effects of the wind turbines during winter in order to even out production and save hydro power this does not decrease the possible feasibility for power production at Höfn í Hornafirði. The wind speed measured at Grímsstaðir has negative correlation to the wind speed measured at Búrfell for many time steps. The highest correlation of 0,92 occurs for the autumn season.

4.3 Weibull parameters and probability distribution of wind speeds

The Weibull parameters for all locations are presented in Table 5. Where, k is the shape factor of the probability distribution and c is the scale factor. Increased value of k indicates that the probability distribution curve has a sharper peak. This means that there is a less wind speed variation at the location. Higher value for the scale parameter indicates more wind speed variation and a flatter curve (Manwell, McGowan, & Rogers, 2009).

Table 5. Weibull shape and scale factor for the feasible locations.

Location	***k***	***c***
Búrfell	1,74	10,92
Grímsstaðir	1,52	9,54
Holtavörðuheiði	1,66	11,74
Hveravellir	1,64	11,29
Höfn Í Hornafirði	1,50	11,90
Kárahnjúkar	1,57	10,23
Kvísker	1,49	9,07
Patreksfjörður	1,31	8,85
Raufarhöfn	1,73	9,38
Steingrímsfjarðarheiði	1,68	11,90
Stykkishólmur	1,73	10,09

The Weibull fit for all the locations considered represents the real data fairly accurately. The Weibull fit for Búrfell is shown in Figure 14 and Figure 15 shows the fit for Höfn í Hornafirði as a comparison.

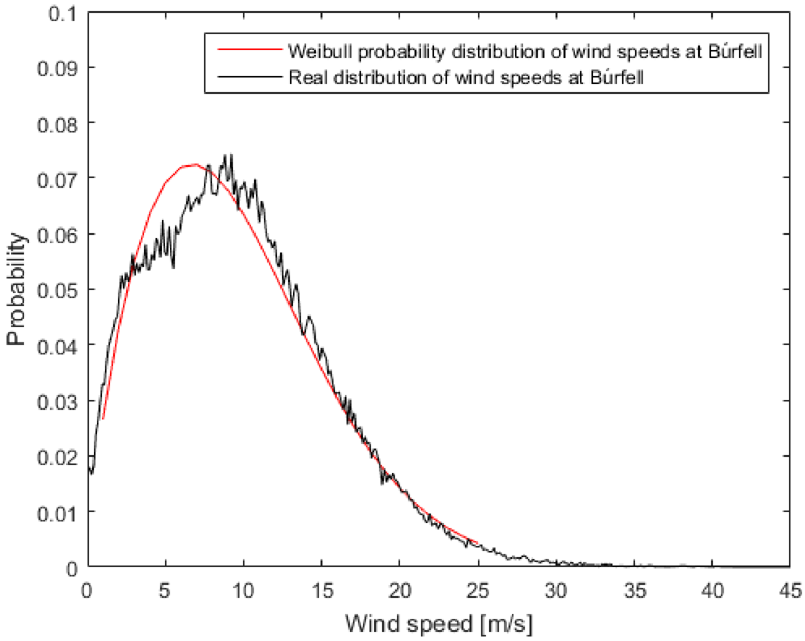


Figure 14. Comparison of the Weibull probability density function to the distribution of real measured data at Búrfell.

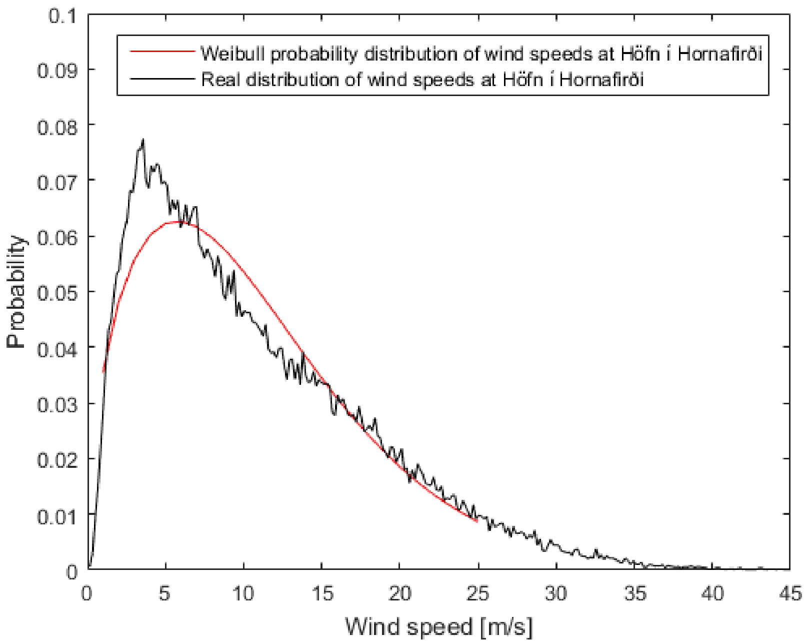


Figure 15. Comparison of the Weibull probability density function to the distribution of real measured data at Höfn í Hornafirði.

4.4 Power production and capacity factor

The possible and predicted annual power production as well as the capacity factor at the considered locations is presented in Table 7. This production is calculated as described in Chapter 3, Section 3.4 using the Weibull distribution of wind speeds. However, air pressure and temperature are not taken into account.

In order to verify the calculation method used, the annual production for the two ENERCON E-44 turbines already installed at the Búrfell area is calculated using the

Weibull probability function. This calculated annual production is compared to the real annual production published by Landsvirkjun (Landsvirkjun). This comparison is shown in

Table 6. As can be seen the calculations are close to the observed values.

Table 6. Calculated annual power for already installed turbines compared to real annual power output.

	Calculated production and capacity factor from the two installed turbines	**Production and capacity factor from the two installed turbines**
Annual production [GWh]	6,53	6,70
CF	0,41	0,42

Table 7 presents the predicted annual production and capacity factor for a turbine with hub height of 70m, 80m and 90m at each considered location. The highest annual production as well as capacity factor occurs at Steingrímsfjarðarheiði. All of the locations considered have high capacity factors.

Table 7. Predicted annual production and capacity factor for ENERCON E-101 E2 3,5MW turbine at each location.

	Hub height 70m		***Hub height 80m***		***Hub height 90m***	
Locations	**Annual Power [GWh]**	**CF**	**Annual Power [GWh]**	**CF**	**Annual Power [GWh]**	**CF**
Búrfell	14,67	0,49	14,92	0,49	15,14	0,49
Grímsstaðir	12,19	0,40	12,42	0,41	12,61	0,41
Holtavörðuheiði	15,33	0,50	15,53	0,51	15,70	0,51
Hveravellir	14,80	0,48	15,01	0,49	15,19	0,50
Höfn Í Hornafirði	14,56	0,47	14,81	0,48	15,01	0,49
Kárahnjúkar	13,27	0,43	13,50	0,44	13,69	0,45
Kvísker	11,47	0,37	11,70	0,38	11,90	0,39
Patreksfjörður	10,64	0,35	10,94	0,36	11,19	0,37
Raufarhöfn	11,99	0,39	12,39	0,40	12,74	0,42
Steingrímsfjarðarheiði	15,60	0,51	15,80	0,52	15,96	0,52
Stykkishólmur	13,20	0,43	13,59	0,44	13,92	0,45

4.5 Correlation of power production

The correlation of power production is evaluated by calculating the power production at each location using historical data. Figure 16 presents the correlation between production at each location and the production at Búrfell for all time steps considered in this analysis. The correlation is more clearly presented in Table 12 - Table 13 in Appendix 3. The correlation of production is similar to the wind correlation as Grímsstaðir and Höfn í Hornafirði result in negative correlation to Búrfell for most of the time steps considered. Hveravellir, Steingrímsfjarðarheiði and Holtavörðuheiði result in negative correlation to Búrfell for the winter season.

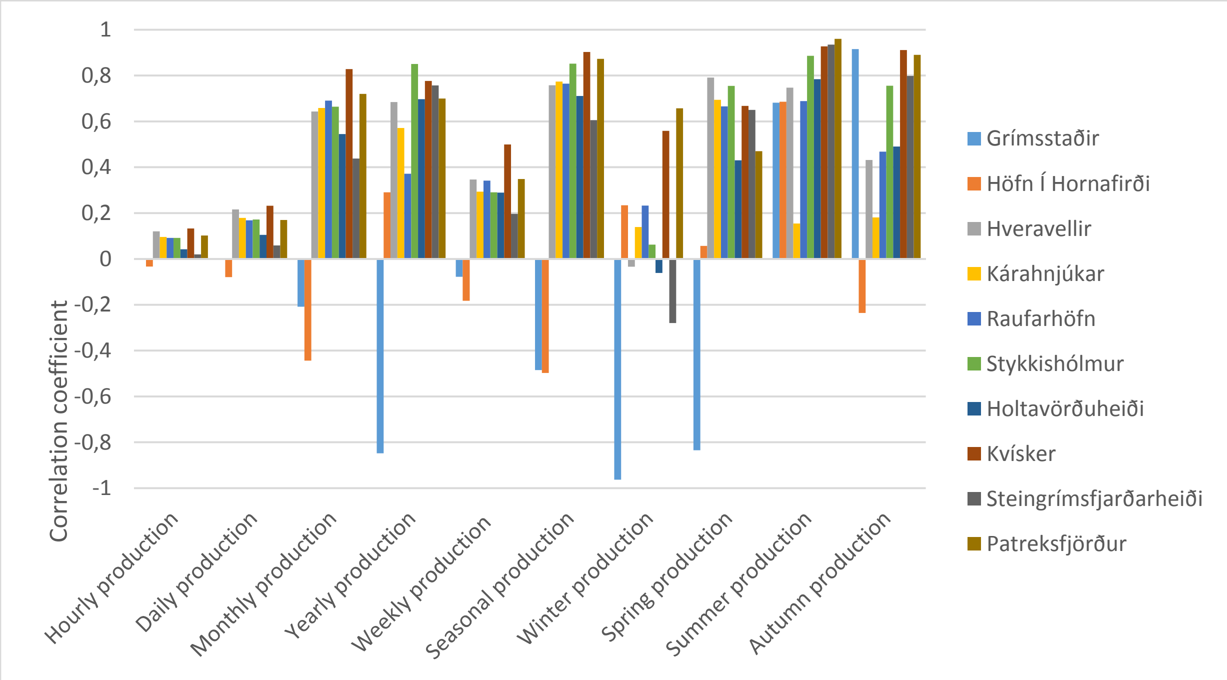


Figure 16. Correlation of production between locations for all time steps considered.

The predicted total annual production as well as the capacity factor if two turbines with 90m hub height are installed at separate locations can be seen in Table 8. This is calculated using the Weibull probability function for wind speeds at each location. The highest combined production results at Steingrímsfjarðarheiði while the lowest combined production is when a turbine is placed at Patreksfjörður.

Table 8. Annual production and capacity factor for two installed turbines.

		Annual power production [GWh]	**CF**
Búrfell	*Búrfell*	30,27	0,49
Grímsstaðir	*Búrfell*	27,83	0,45
Holtavörðuheiði	*Búrfell*	30,82	0,50
Hveravellir	*Búrfell*	30,29	0,49
Höfn Í Hornafirði	*Búrfell*	30,10	0,49
Kárahnjúkar	*Búrfell*	28,83	0,47
Kvísker	*Búrfell*	26,98	0,44

		Annual power production [GWh]	CF
Patreksfjörður	*Búrfell*	26,30	0,43
Raufarhöfn	*Búrfell*	27,78	0,45
Steingrímsfjarðarheiði	*Búrfell*	31,10	0,51
Stykkishólmur	*Búrfell*	29,07	0,47

For the locations resulting in negative correlation to Búrfell, for wind speed and/or production, the wind speed time series are analyzed further in Chapter 5. The locations being considered are Grímsstaðir, Holtavörðuheiði, Hveravellir, Höfn í Hornafirði, and Steingrímsfjarðarheiði. The aim of the analysis in Chapter 5 is to estimate if and how the production at the second location complements the production at Búrfell by considering both wind speeds and production profiles.

5 Time series analysis of feasible locations

In this chapter the time series for the locations resulting in negative correlation to Búrfell are considered. The historical wind data is used to calculate and evaluate the possible power output. The amount of data available for each location was presented in Chapter 3, Section 3.1. Five cases are considered, A, B, C, D and E. Those cases are when one turbine is located at Búrfell and other at location resulting in negative correlation of wind speed or production to Búrfell for some of the time steps considered. The cases are presented in Table 9.

Table 9. Cases considered in Chapter 5

Case	**Location 1 - Location 2**
Base Case	*Búrfell - Búrfell*
Case A	*Búrfell - Grímsstaðir*
Case B	*Búrfell - Holtavörðuheiði*
Case C	*Búrfell - Hveravellir*
Case D	*Búrfell - Höfn í Hornafirði*
Case E	*Búrfell - Steingrímsfjarðarheiði*

The comparison between sites is carried out for the turbine presented in Chapter 3, Section 3.4 with 90m hub height. When analyzing the production it is assumed that a 3,5MW turbine is installed at both locations resulting in an installed capacity of 7MW.

In the following sub-sections it is evaluated how often the turbines at different locations operate simultaneously, how often they complement each other and how often neither produces electricity. The hourly wind speed time series are used for the analysis.

For this analysis the Base Case must be presented. Figure 17 shows for how long time of the measurement time there is production at Búrfell. This figure indicates that there is an opportunity to improve the production profile since there is no production for 8% of the measurement time.

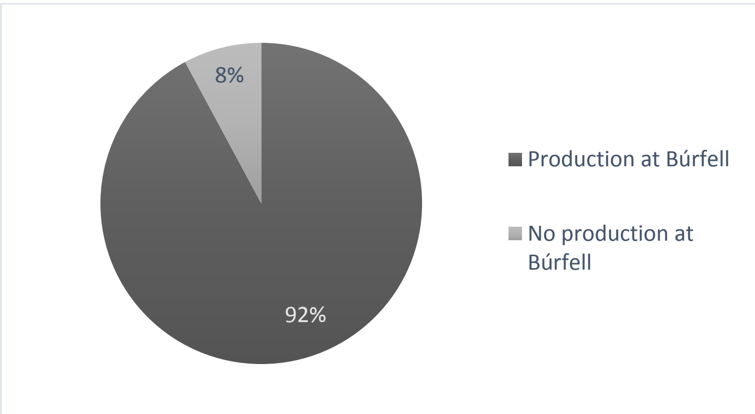


Figure 17. Production at Búrfell.

Figure 18 shows that for 16% of the measurement time there is full production detected at Búrfell. By locating turbines at different locations the hours of full production may increase. Two turbines located at Búrfell exceed the rated power of one turbine for 49% of the time considered. This will likely increase if turbines are located at different locations.

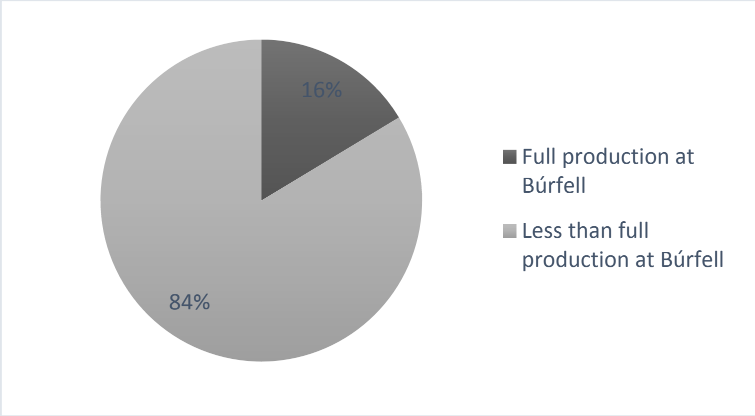


Figure 18. Full production at Búrfell

In the following sub-sections the cases presented in Table 9 are analyzed and it is evaluated if the production profiles complement the Base Case in such a way that less regulating power is needed.

5.1 Case A

The location of Grímsstaðir and Búrfell are presented in Figure 19. The wind speed profiles at Grímsstaðir have negative correlation to the wind speed profiles at Búrfell for all time steps considered except for the summer and autumn comparison. The most negative wind speed correlation, -0,98, occurs for the winter season comparison. Negative correlation for power production is detected for all time steps except hourly, daily, summer and autumn comparison. The most negative correlation of power production, -0,96, occurs for the comparison of winter production profiles. The highest correlation both for wind speed and power production occurs for the autumn comparison.

Possible production at these two locations as well as the interaction between them are considered in sub-sections 5.1.1 – 5.1.2.

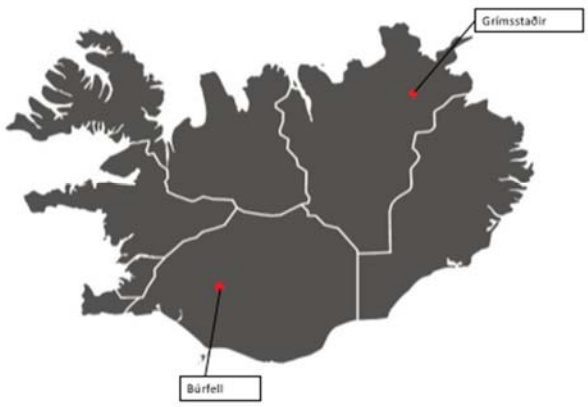


Figure 19. Map showing the location of Grímsstaðir and Búrfell.

5.1.1 Production at Grímsstaðir and Búrfell

The calculated historical production levels at Grímsstaðir and Búrfell are compared in Figure 20. The figure shows how often certain production levels are detected as a percentage of the whole historical data set. The production for Grímsstaðir, Búrfell and the combined production are compared. As can be seen the production levels 0-10 % and 90-100% are the most often detected production levels for Grímsstaðir. These production levels stand for 46% of the total production series considered. The production at Búrfell is most often 90-100% of the rated power. The combined production is most often 40-60% of the installed capacity. This indicates that for 34% of the time the cumulative production is 2,8 - 4,2MWh/h.

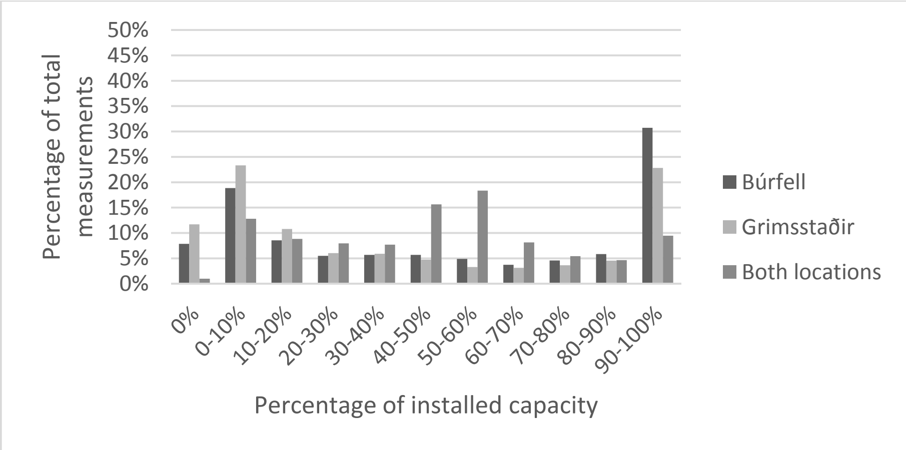


Figure 20. The percentage of each capacity level over the measurement time for Grímsstaðir and Búrfell.

In order to better understand how often the locations are helping even out each other's fluctuations it is examined how often one place has production while the other has no production. As shown in Figure 21, Grímsstaðir and Búrfell complement each other for 18% of the time series considered. For 81% of the time there is production at both locations while for 1% there is no production.

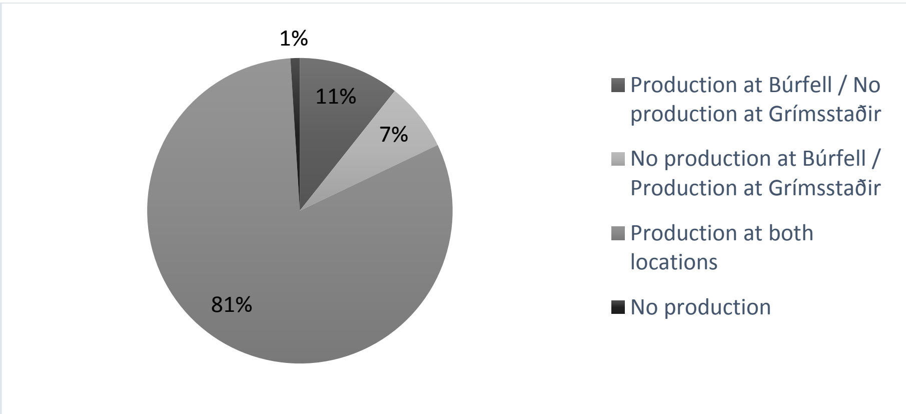


Figure 21. Comparison of the production at Búrfell and Grímsstaðir.

The highest production levels that can be reached are when both turbines are producing at rated power. In Figure 22 it is compared how often full production levels are detected. For 73% of the time there is less than full production and for 2% both locations are producing at rated power. For 15% of the time there is full production at Búrfell while there is less production at Grímsstaðir. For 10% of the considered time series there is full power production at Grímsstaðir while there is less production at Búrfell. The level of full production can be compared to the Base Case. The full production level there is 16% while for the combination of Búrfell and Grímsstaðir both locations produce at full power simultaneously for 2% of the time. However, there are more hours where some full production is detected than for the Base Case. By distributing the production one turbine can be producing at rated power while the other is not. The cumulative production at Grímsstaðir and Búrfell exceeds the rated power of one turbine for 49% of the time considered. This is a similar level as for the Base Case.

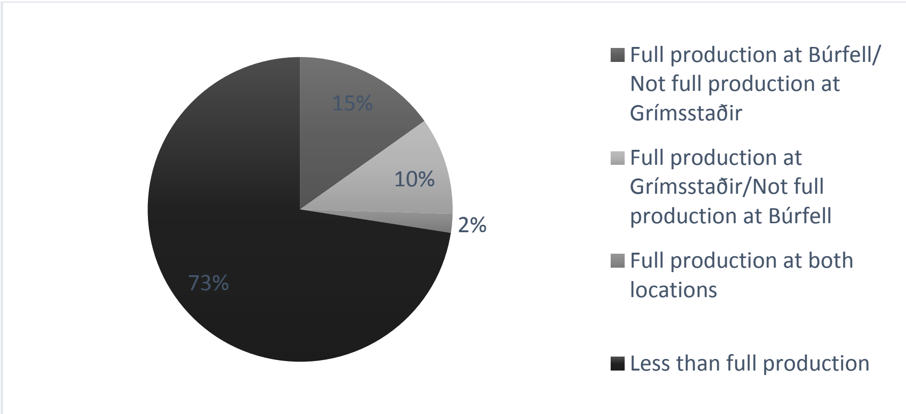


Figure 22. Comparison of how often full production levels are reached at Búrfell and Grímsstaðir.

If a turbine is located at Grímsstaðir the production there exceeds the production at Búrfell for 41% of the time series considered. The total average increase in production is 0,95MWh/h.

5.1.2 Production profile for Búrfell and Grímsstaðir

The monthly production levels at the two locations are compared in order to evaluate if some seasonal variations can be detected and the production variability between years evaluated. Comparing the monthly production levels of Grímsstaðir and Búrfell the interaction between productions at different locations can be seen. The turbine located at Búrfell has a higher production level than the one located at Grímsstaðir for most of the months considered, as presented in Figure 23.

The seasonal variations in the production are clearly presented in the figure. The highest production levels are observed during winter and significant production drop is detected during summer. The monthly production profile is not identical for the years considered, however, some clear trends can be seen. Figure 23 presents that the production at Búrfell has higher monthly average production than Grímsstaðir for almost every month considered. The production level at Grímsstaðir is too low to help even out the production at Búrfell at monthly level.

The red curve in Figure 23 represents the aggregated production profile for the two locations. It can be seen that the aggregated profile is lower than if two turbines are located at Búrfell for almost all the months considered.

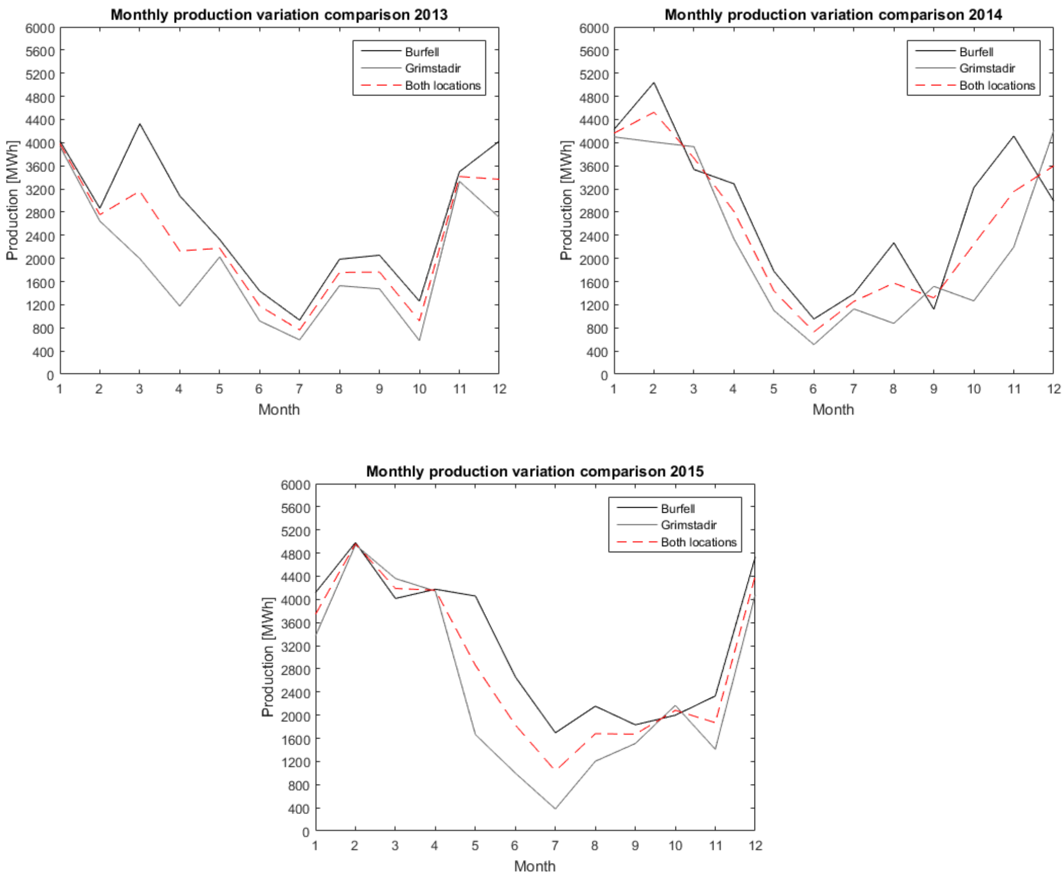
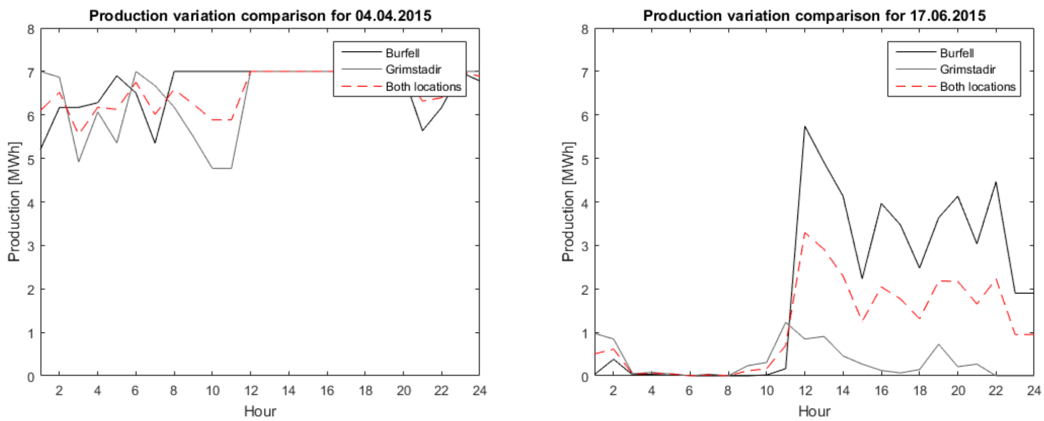


Figure 23. Comparison of monthly production levels at Grímsstaðir and Búrfell for 2013-2015.

To investigate the behavior of the production at smaller time steps several days of the year 2015 are considered. The production profiles for Búrfell and Grímstaðir as well as the aggregated profile are considered for one randomly selected day per season. The days are randomly chosen, however, it is assured that measures are available for all hours of the selected days. Figure 24 shows that the aggregated production level is smoother and the variations between hours decrease. However, the overall aggregated production is less than if both turbines are placed at Búrfell.



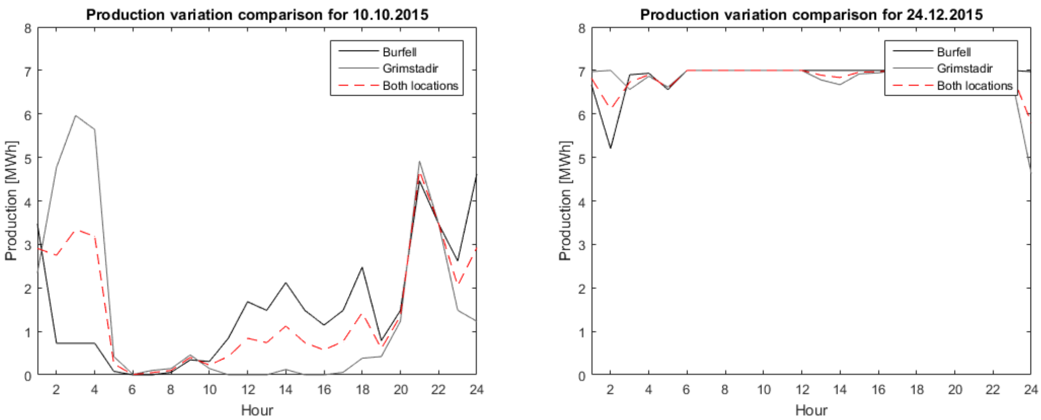


Figure 24. Intraday production comparison for Grímsstaðir and Búrfell.

5.2 Case B

The locations of Holtavörðuheiði and Búrfell are presented in Figure 25. The wind speed correlation of Holtavörðuheiði and Búrfell are close to neutral or high for all time steps considered. Negative correlation of power production is detected for winter production comparison. Though the negative correlation is close to neutral the interaction of these two locations is of interest due to the high cumulative annual production and capacity factor estimated. The highest correlation detected for those two locations is during summer.

Possible production at these two locations as well as the interaction between them are considered in sub-sections 5.2.1 and 5.2.2.

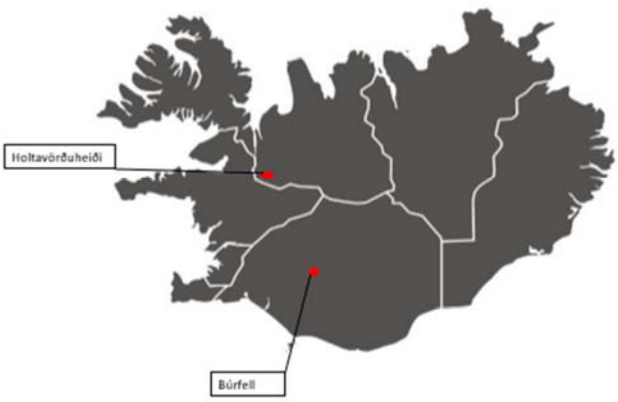


Figure 25. Map showing the location of Holtavörðuheiði and Búrfell.

5.2.1 Production at Holtavörðuheiði and Búrfell

Figure 26 presents the production profile for Holtavörðuheiði and Búrfell. The production level most often detected is 90-100% for both locations. For the combined production the most common production level is 40-60%, this production level is detected for 32% of the time considered. This indicates that for 32% of the time the cumulative production is 2,8 - 4,2MWh/h.

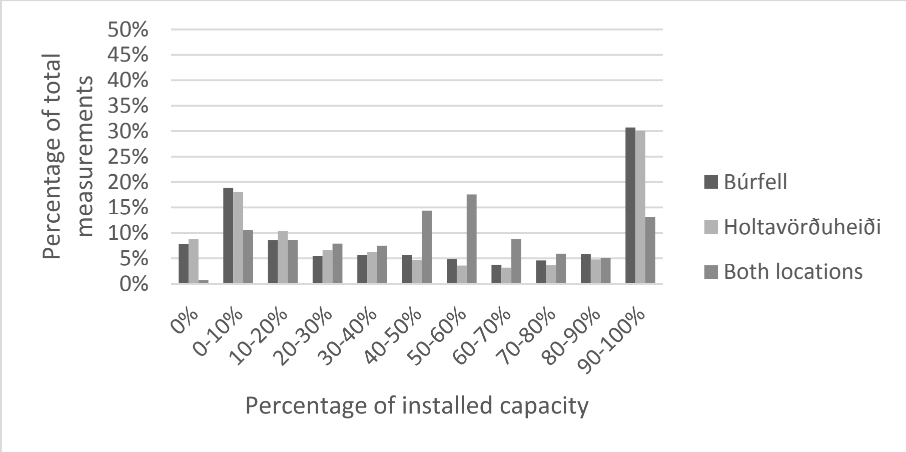


Figure 26. The percentage of occurrences of each capacity level over the measurement time for Holtavörðuheiði and Búrfell.

As can be seen in Figure 27, for 15% of the time the locations complement each other while for 84% of the time there is production at both locations. The level of no production decreases by 7% compared to the Base Case.

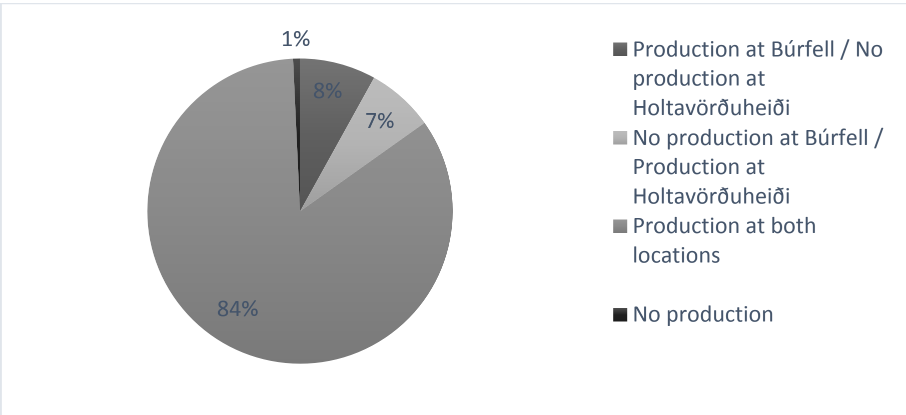


Figure 27. Comparison of the production at Búrfell and Holtavörðuheiði.

There is full production at one or both of the locations for 31% of the time considered as can be seen in Figure 28. For 3% of the time there is full production at both locations resulting in 7MWh/h production. This is less than if both turbines are placed at Búrfell. The cumulative production at Holtavörðuheiði and Búrfell exceeds the rated power of one turbine for 53% of the time which is a 4% increase compared to the Base Case.

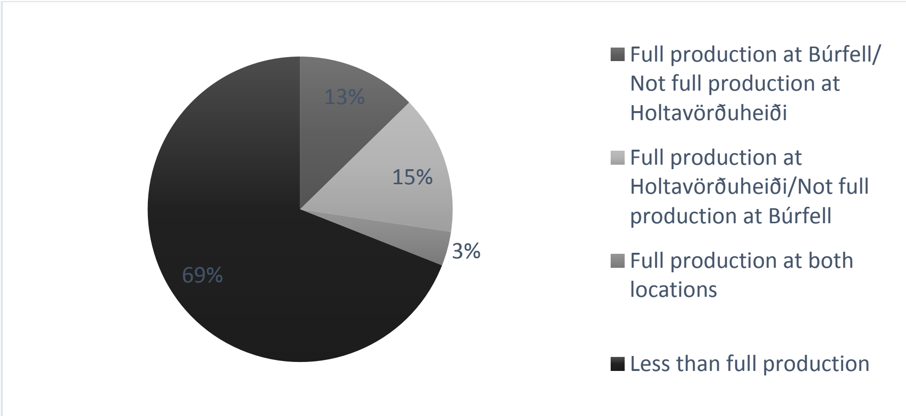


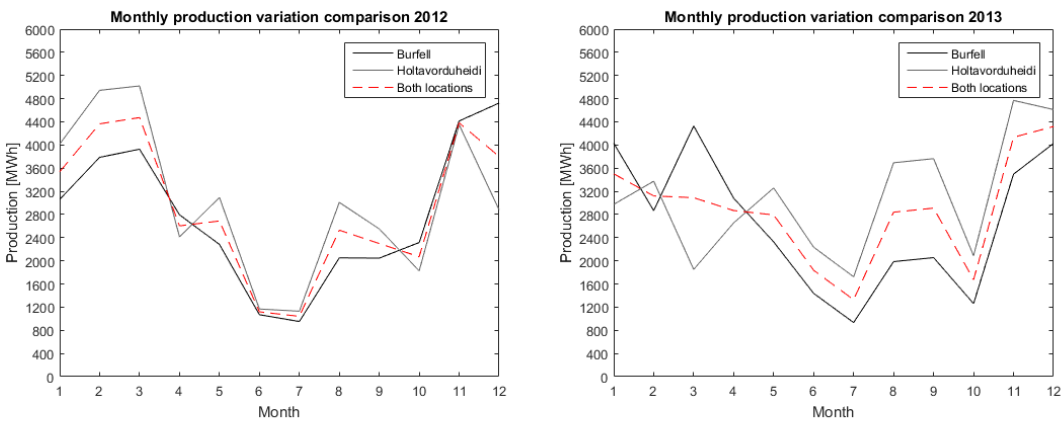
Figure 28. Comparison of how often full production levels are reached at Búrfell and Holtavörðuheiði.

There is higher production from a turbine located at Holtavörðuheiði than at Búrfell for 47% of the time. The average increase in production by placing a turbine at Holtavörðuheiði is 1,16MWh/h.

5.2.2 Production profile for Holtavörðuheiði and Búrfell

The monthly production profiles for 2012-2015 are presented in Figure 29. The seasonal variations can be seen as well as the overall trend of the production at both locations. The production profile of the locations is not identical for the years considered. However, the trend and magnitude of production can be seen.

The production profiles for two turbines located at Búrfell or Holtavörðuheiði are shown. The aggregated production if one turbine is placed at the two locations is shown by the red curve. As can be seen the aggregated production profile is smoother than if the turbines are placed at the same location. By placing one turbine at Holtavörðuheiði the production for the most of the months considered increases compared to placing both at Búrfell.



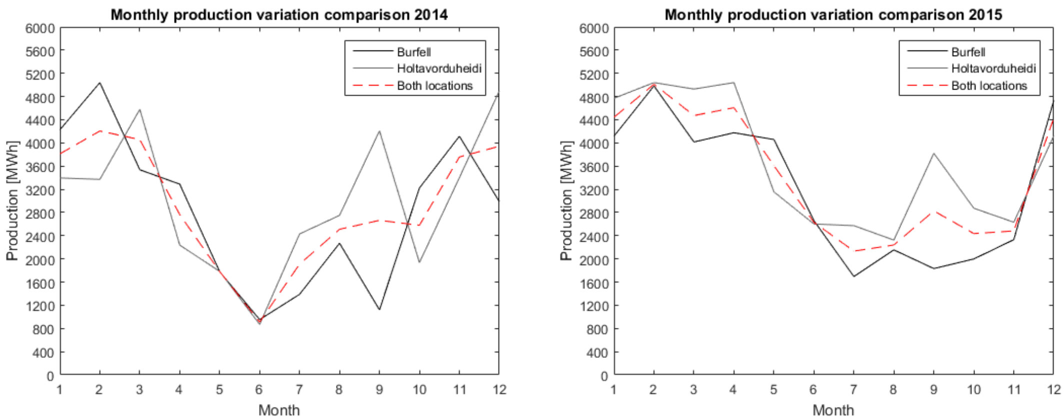


Figure 29. Comparison of monthly production levels at Holtavörðuheiði and Búrfell for 2012-2015.

To evaluate the effect of locating complementary turbines at Holtavörðuheiði on a smaller timescale the hourly production profile is examined. The hourly production profile for one day per season for the year 2015 is shown in Figure 30. As can be seen the aggregated production profile is smoother than if turbines are placed only at Búrfell. The higher production levels at Holtavörðuheiði compensate for lower production levels at Búrfell.

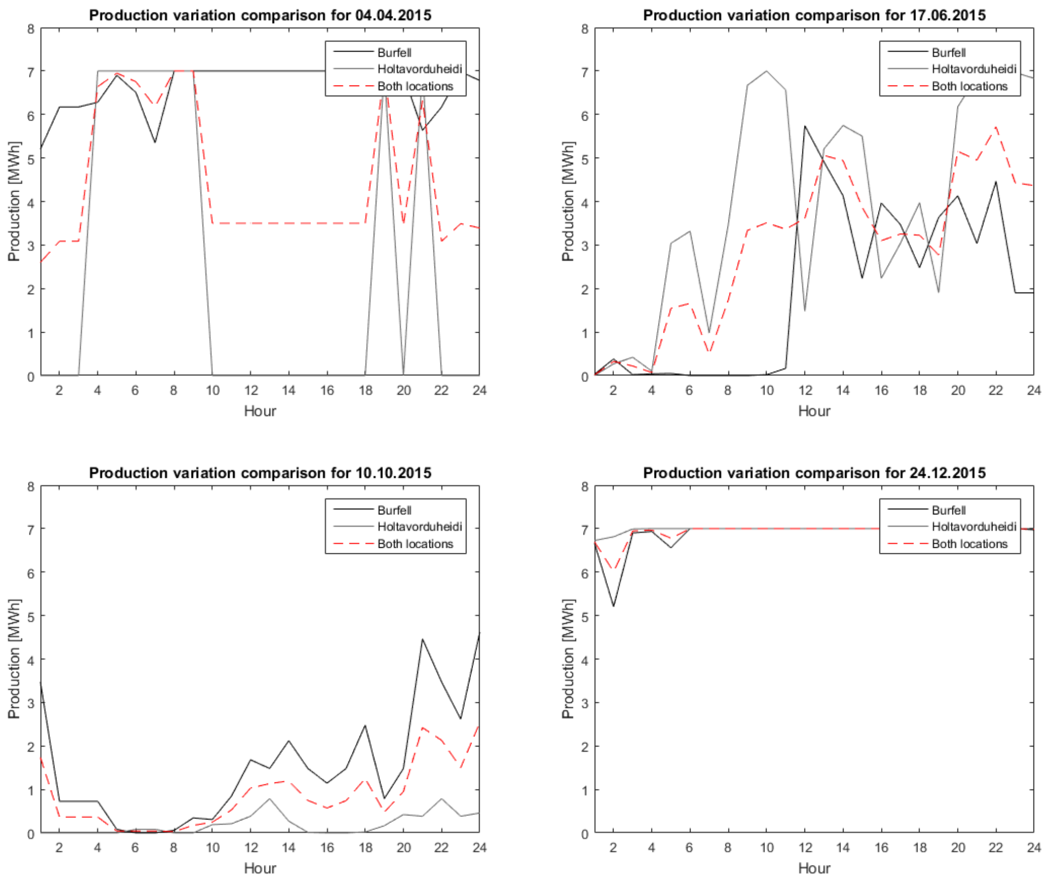


Figure 30. Intraday production comparison for Holtavörðuheiði and Búrfell.

5.3 Case C

The locations of Hveravellir and Búrfell are presented in Figure 31. For the wind speed and production comparison a negative correlation is observed for winter comparison.

For other time steps considered positive correlation is detected. Despite the rather neutral correlation of wind speeds and power production between those locations the interactions are of interest due to the high estimated annual production and capacity factor.

Possible production at these two locations as well as the interaction between them are considered in sub-sections 5.3.1 and 5.3.2.

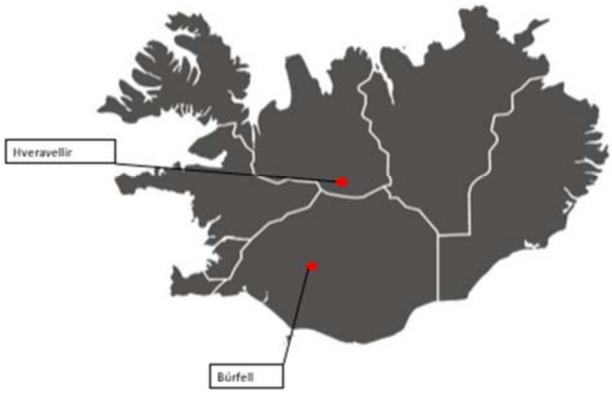


Figure 31. Map showing the location of Hveravellir and Búrfell.

5.3.1 Production at Hveravellir and Búrfell

Figure 32 presents the production profile for Hveravellir and Búrfell. For 30% of the time series the production level detected for those locations is 90-100% of rated power. If turbines are placed at both locations the production level most often detected is 40-60% of rated power. This production level is detected for 30% of the time series and indicates that the cumulative production is 2,8 - 4,2MWh/h.

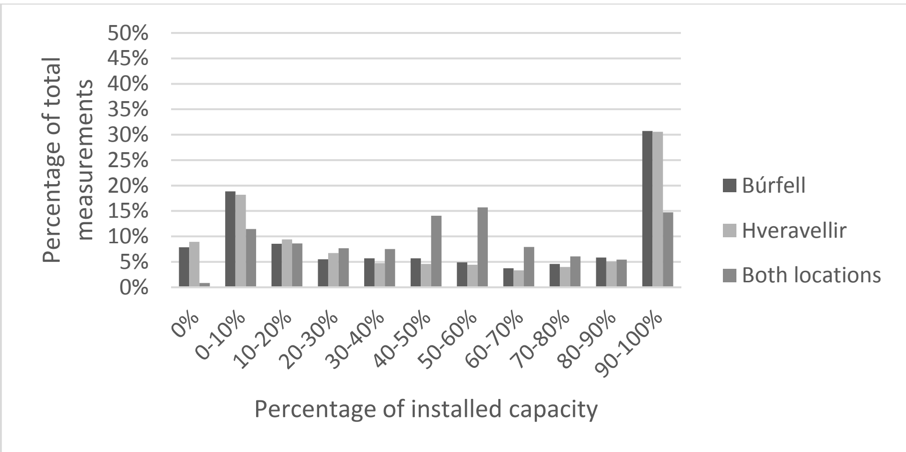


Figure 32. The percentage of occurrences of each capacity level over the measurement time for Hveravellir and Búrfell.

Turbines located at Hveravellir and Búrfell complement each other for 15% of the time as can be seen in Figure 33. For 84% of the time there is some production at both locations. The occurrences of no production decreases from 7% to 1% compared to the Base Case.

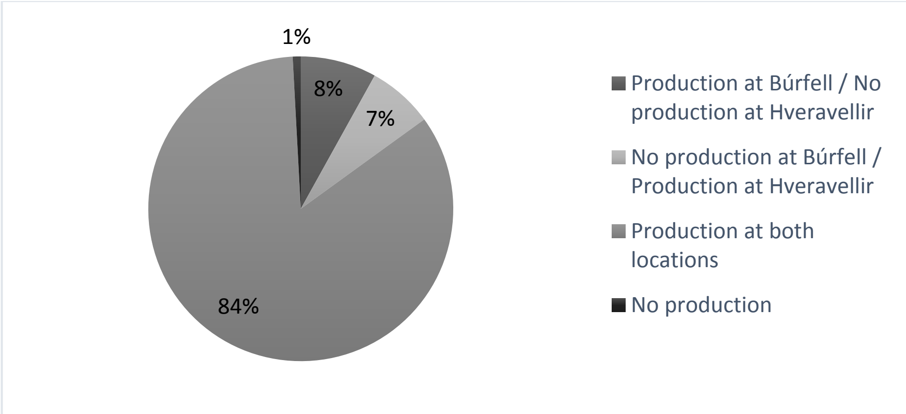


Figure 33. Comparison of the production at Búrfell and Hveravellir.

As Figure 34 presents there is full production at one of the locations while the other produces less for 25% of the time considered. For 71% of the time there is less than full production and for 4% of the time there is full production at both locations. Which is a decrease in full production compared to the Base Case. However, by placing one turbine at Hveravellir and one at Búrfell the production exceeds the rated power of one turbine for 53% of the time and this is an increase compared to the Base Case.

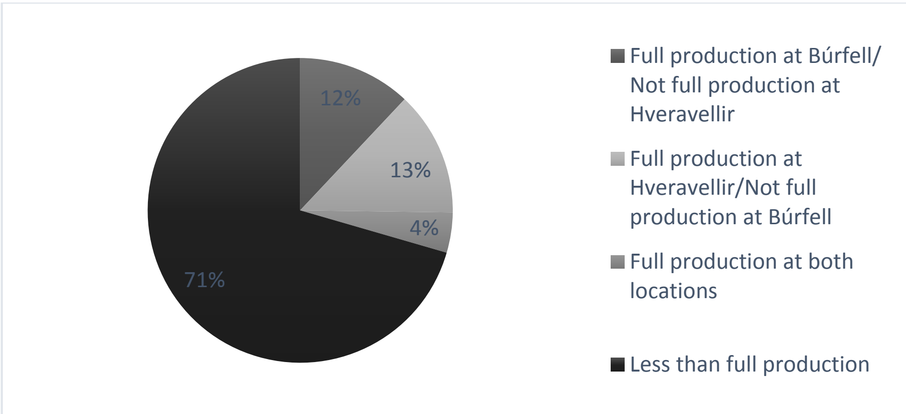


Figure 34. Comparison of how often full production levels are reached at Búrfell and Hveravellir.

There are higher production levels detected at Hveravellir than Búrfell for 47% of the time considered. The total average increase in production by placing a turbine at Hveravellir is 1,14MWh/h.

5.3.2 Production profile for Hveravellir and Búrfell

Monthly production profiles for 2012-2015 are presented in Figure 35. The seasonal variations are clearly presented and the interaction between locations are similar for the years considered. The monthly correlation coefficient is 0,53 which is rather high. This can be seen, for some months in Figure 35, as production at both locations increases simultaneously. The red curve presents the aggregated production profile if one turbine is placed at each location. Due to the similarities of the profiles the aggregated profile does not even out the production profile at Búrfell significantly. For the monthly profile of 2015 it can be seen that the higher production at Hveravellir projects the production profile at Búrfell upwards resulting in higher production for most of the months.

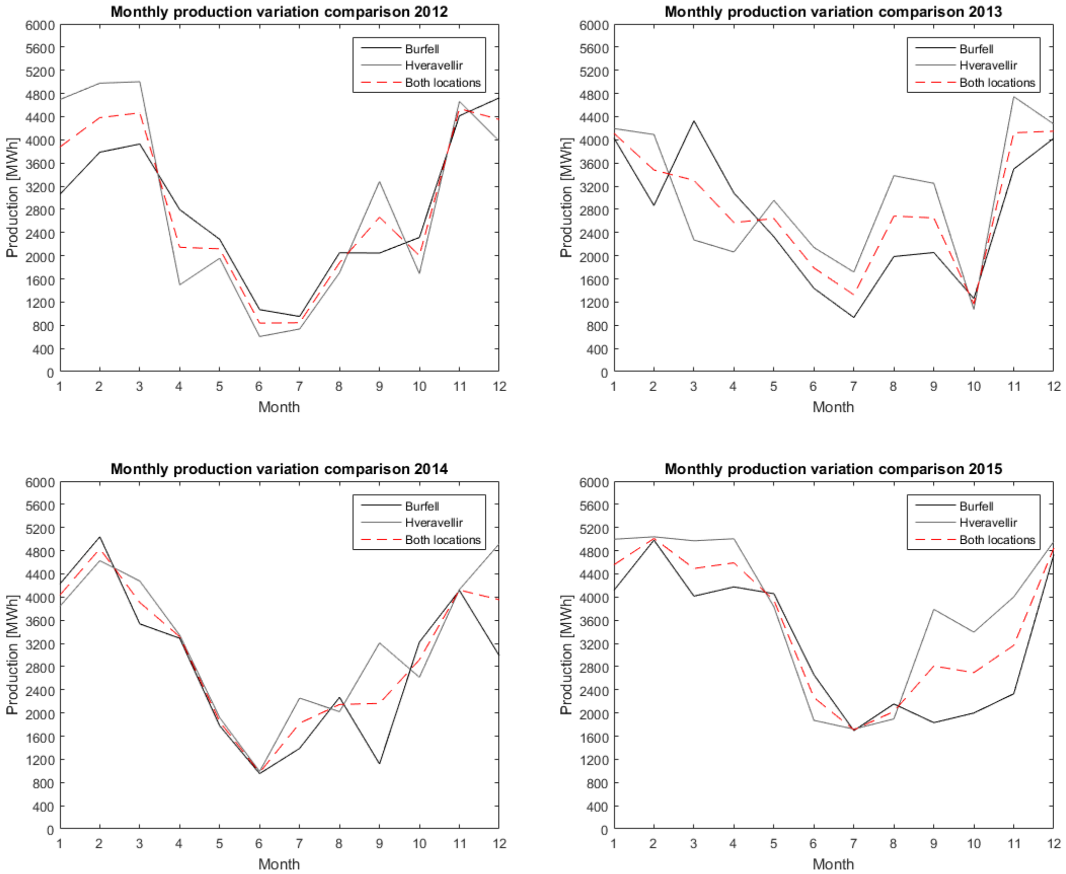
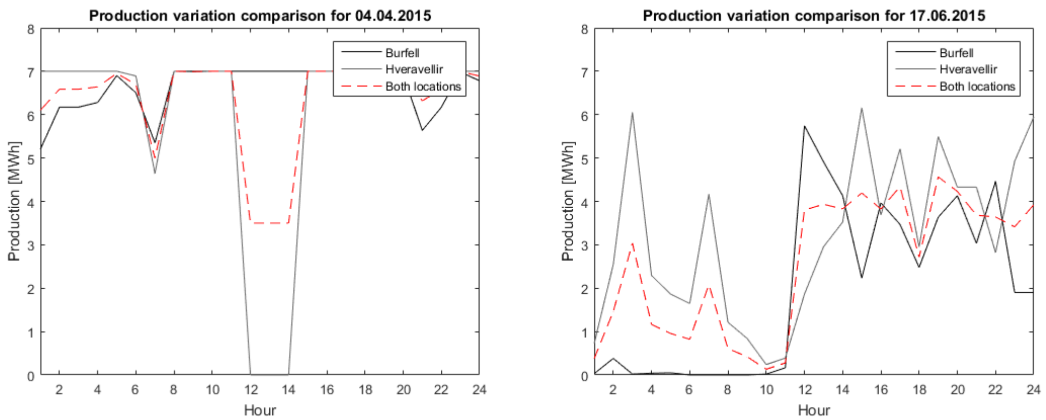


Figure 35. Comparison of monthly production levels at Hveravellir and Búrfell for 2012-2015.

In Figure 36 the hourly variations are presented for one day per season in the year 2015. For 17.06.2015 it can be seen how the production at Hveravellir helps even out the production at Búrfell for the afternoon hours. For other hours the fluctuations do not decrease significantly by placing one turbine at Hveravellir.



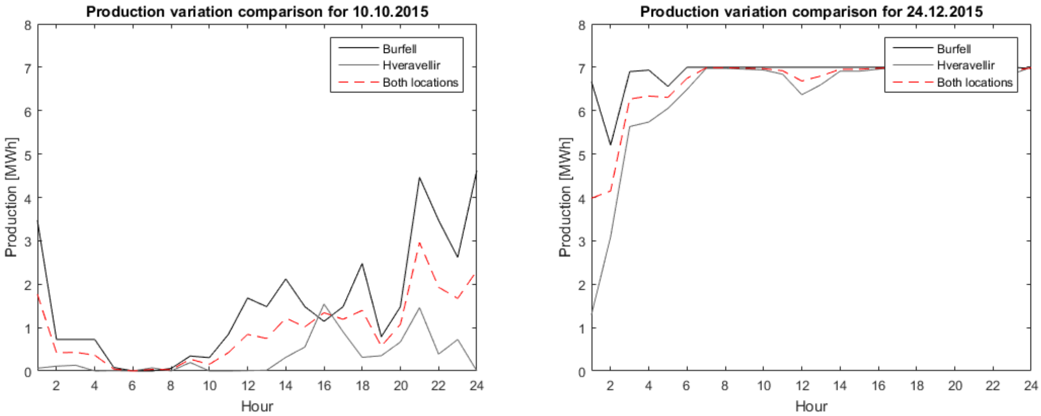


Figure 36. Intraday production comparison for Hveravellir and Búrfell.

5.4 Case D

The locations of Höfn í Hornafirði and Búrfell are presented in Figure 37. The wind speeds correlation between Höfn í Hornafirði and Búrfell is negative for hourly, daily, monthly, weekly, seasonal, winter and autumn comparison. The most negative correlation, -0,38, is detected for monthly and autumn comparison. The highest correlation, 0,73, occurs during summer. The correlation of production is negative for all time steps considered except yearly, winter, spring and summer. The most negative production correlation, -0,50, is detected for the seasonal comparison.

Possible production at these two locations as well as the interaction between them are considered in sub-sections 5.4.1 and 5.4.2.

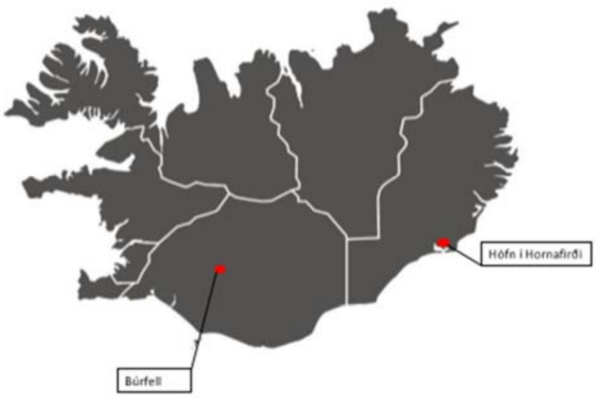


Figure 37. Map showing the location of Höfn í Hornafirði and Búrfell.

5.4.1 Production at Höfn í Hornafirði and Búrfell

Figure 38 shows the percentages of observed production levels if a turbine is placed at Höfn í Hornafirði, Búrfell or both locations. As can be seen the highest occurring production level for Höfn í Hornafirði and Búrfell is 90-100% of rated power. This production level occurs for 32% of the time for Höfn í Hornafirði and 31% of the time for Búrfell. If turbines are placed at both locations the production profile is more even, however, the total power output of the turbines is most often 40-60% of the installed capacity. This indicates that for 35% of the time the cumulative production is 2,8 - 4,2MWh/h.

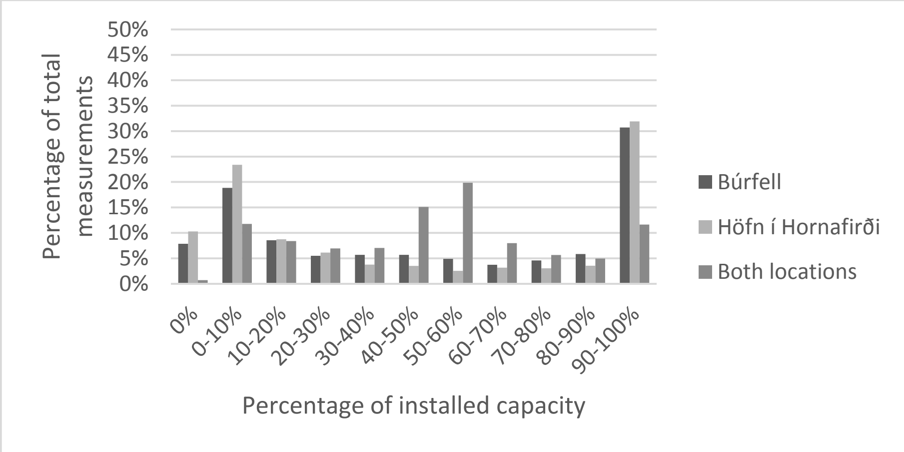


Figure 38. The percentage of occurrences of each capacity level over the measurement time for Höfn í Hornafirði and Búrfell.

In order to understand the interaction of the locations it is examined how often there is production at one location while there is no production at the other location. As can be seen in Figure 39, Búrfell and Höfn í Hornafirði complement each other for 16% of the time series. For 1% of the time series there is no production at the two locations and for 83% there is some production at both locations. Therefore, the number of hours of production increases compared to the Base Case.

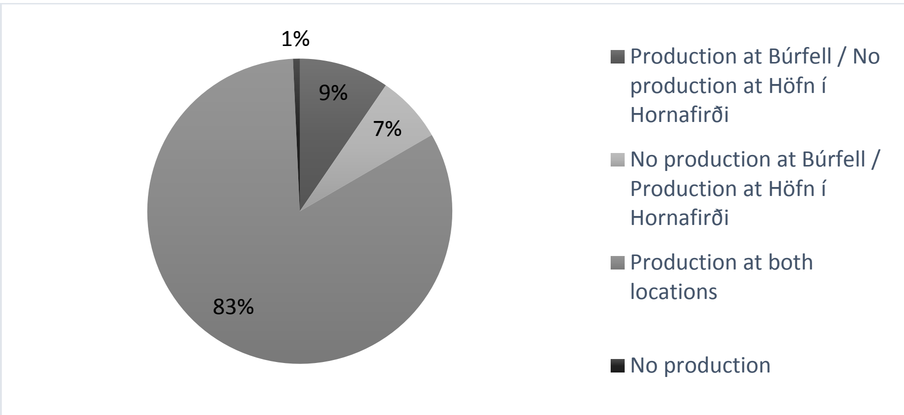


Figure 39. Comparison of the production at Búrfell and Höfn í Hornafirði.

The occurrences of full production at both locations are shown in Figure 40. There it can be seen that for 30% of the time series there is full production at one of the considered locations. For 3% of the time series there is full production at both locations simultaneously and for 67% of the time series there is less than full production detected. For 33% of the time there is some full production. The cumulative production at Höfn í Hornafirði and Búrfell exceeds the rated power of one turbine for 53% of the time considered. This is an increase of 4% compared to the Base Case.

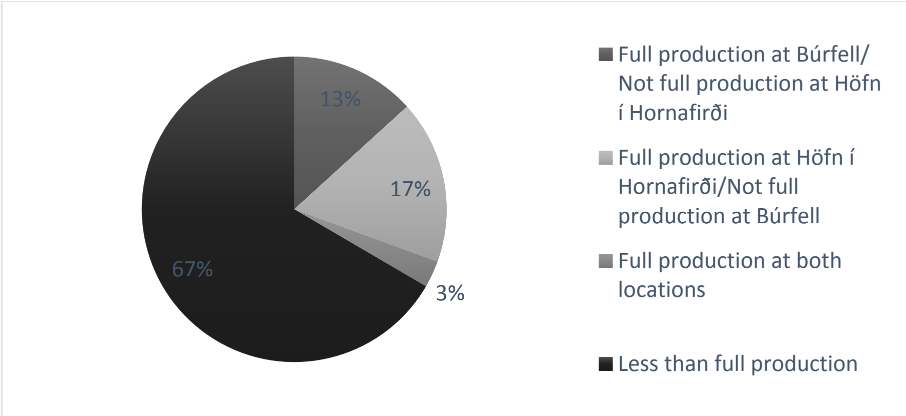
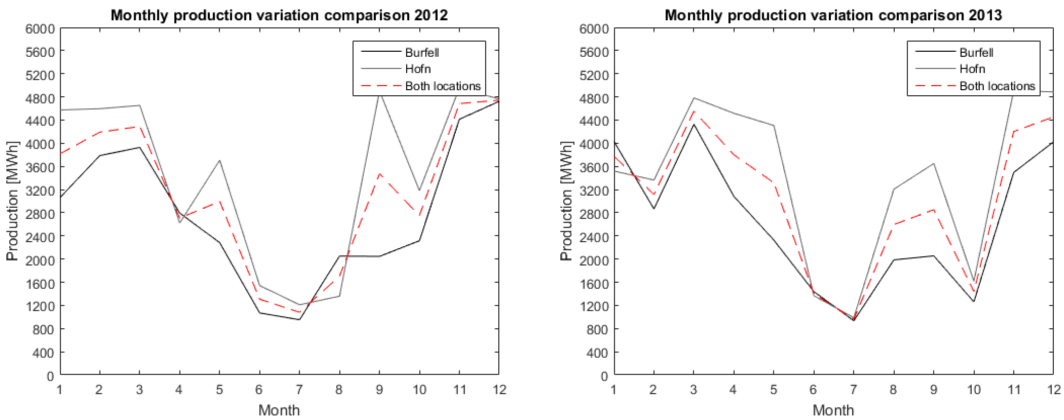


Figure 40. Comparison of how often full production levels are reached at Búrfell and Höfn í Hornafirði.

A turbine located at Höfn í Hornafirði has higher production level than a turbine located at Búrfell for 46% of the time considered. The average total increase in production is 1,19MWh/h.

5.4.2 Production profile for Höfn í Hornafirði and Búrfell

The monthly production profiles presented in Figure 41 show the interaction between the two locations. The production at Höfn í Hornafirði compensates for the production at Búrfell for many months of the year. The production profile variation between years is greater for the production at Höfn í Hornafirði than for Búrfell. The red curve presents the aggregated production profile for the two locations. It can be seen that the production at Höfn í Hornafirði projects the production profile at Búrfell upwards. The aggregated production profile is highly variable and fluctuating between months.



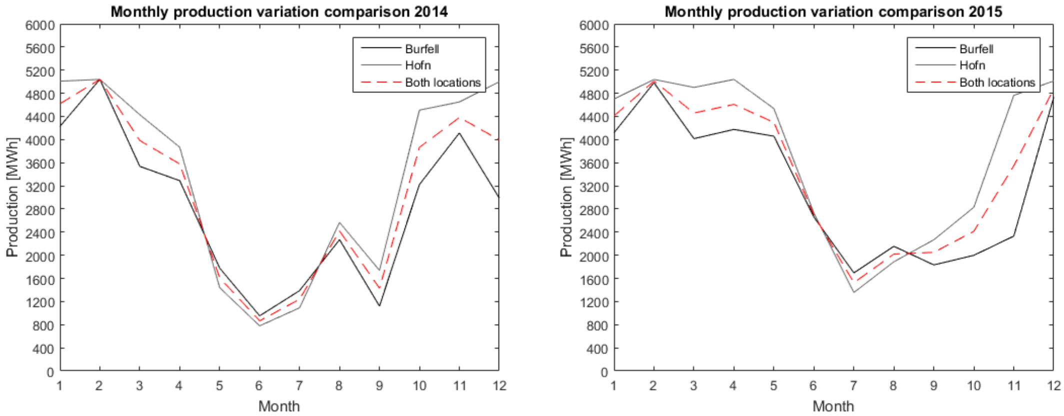


Figure 41. Comparison of monthly production levels at Höfn í Hornafirði and Búrfell for 2012-2015.

The hourly fluctuations are presented in Figure 42. One day for every season in 2015 is considered for the comparison. The production profile at Höfn í Hornafirði is highly fluctuating. For some hours during 17.06.2015 the production at Höfn í Hornafirði decreases the fluctuations in the production at Búrfell. However, during 24.12.2015 the production at Höfn í Hornafirði increases the fluctuations in the profile. These fluctuations might decrease if a high wind ride through turbine is considered.

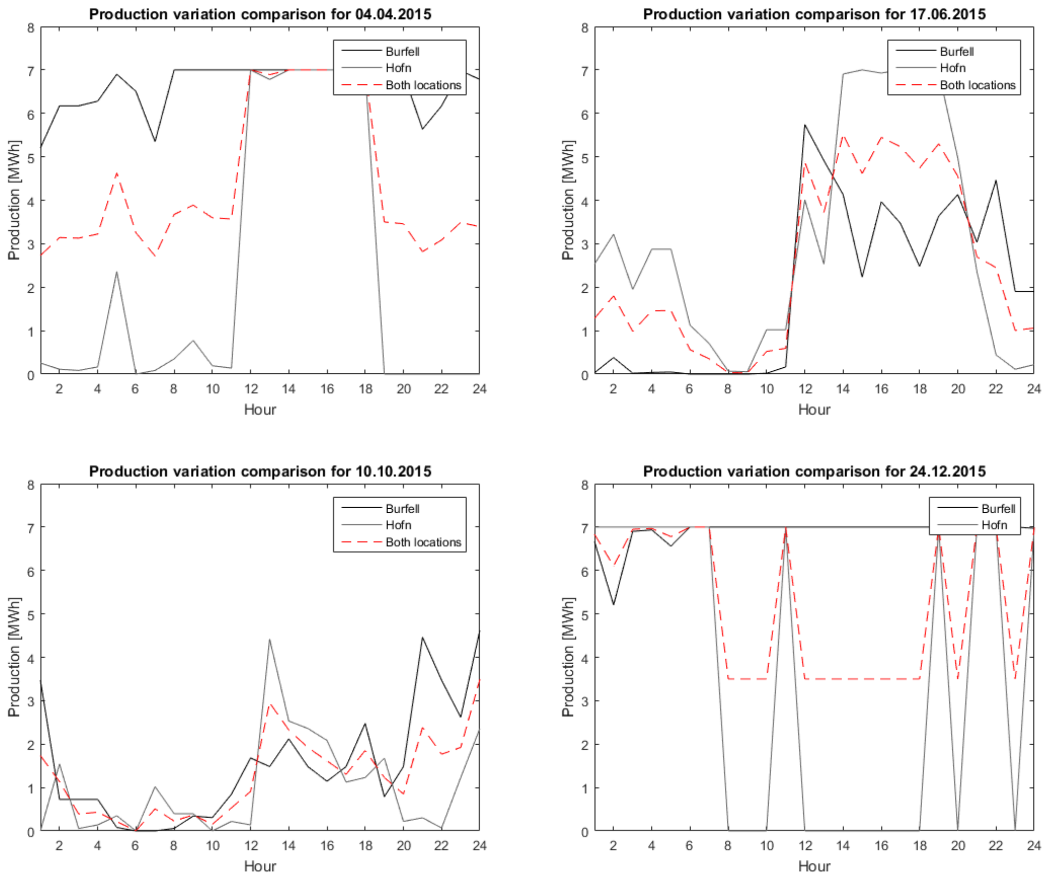


Figure 42. Intraday production comparison for Höfn í Hornafirði and Búrfell.

5.5 Case E

The locations of Steingrímsfjarðarheiði and Búrfell are presented in Figure 43. Negative correlation, -0,35, of wind speed is detected for winter comparison. For other time steps the correlation of wind speed is positive or close to neutral. Correlation of power production is negative for winter comparison. The highest correlation is detected for the summer comparison. Despite the rather neutral and positive correlations of wind speeds and production, the interaction of these locations are of interest due to estimated annual production and capacity factor.

Possible production at these two locations as well as the interaction between them are considered in sub-sections 5.5.1 and 5.5.2

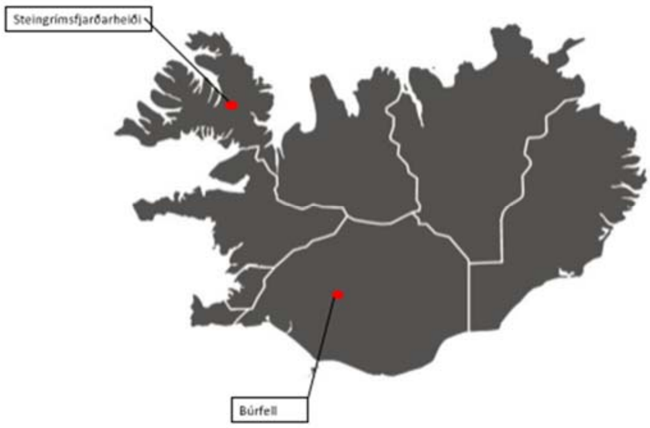


Figure 43. Map showing the location of Steingrímsfjarðarheiði and Búrfell.

5.5.1 Production at Steingrímsfjarðarheiði and Búrfell

Figure 44 presents the production profile at Búrfell and Steingrímsfjarðarheiði as well as the combined production profile. The production profile of these two locations is similar. As can be seen the production level most often detected for Steingrímsfjarðarheiði and Búrfell is 90-100%. For the combined production the production level is more even but 40-60% of installed capacity is the level with highest occurrence. Therefore, for 33% of the time the cumulative production is 2,8 - 4,2MWh/h.

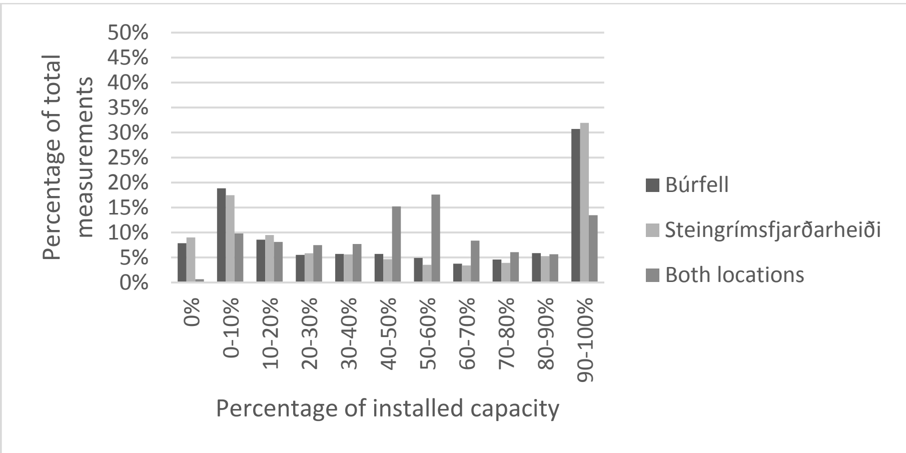


Figure 44. The percentage of occurrences of each capacity level over the measurement time for Steingrímsfjarðarheiði and Búrfell.

As shown in Figure 45, the two locations complement each other for 15% of the time considered. There is production at both locations for 84% of the time considered. The level of no production decreases by 7% compared to the Base Case.

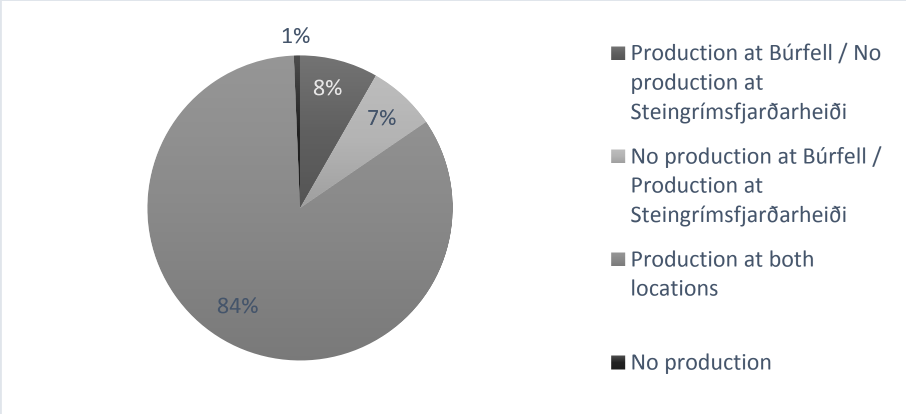


Figure 45. Comparison of the production at Búrfell and Steingrímsfjarðarheiði.

In Figure 46 the occurrences of full production are presented. For 25% of the time there is full production at one or both of the locations considered. Less than full production levels are detected for 75% of the time. Full production levels are more often detected at Búrfell than at Steingrímsfjarðarheiði. The cumulative production at Búrfell and Steingrímsfjarðarheiði exceeds the rated power of one turbine for 54% of the time. This is an increase of 5% compared to the Base Case.

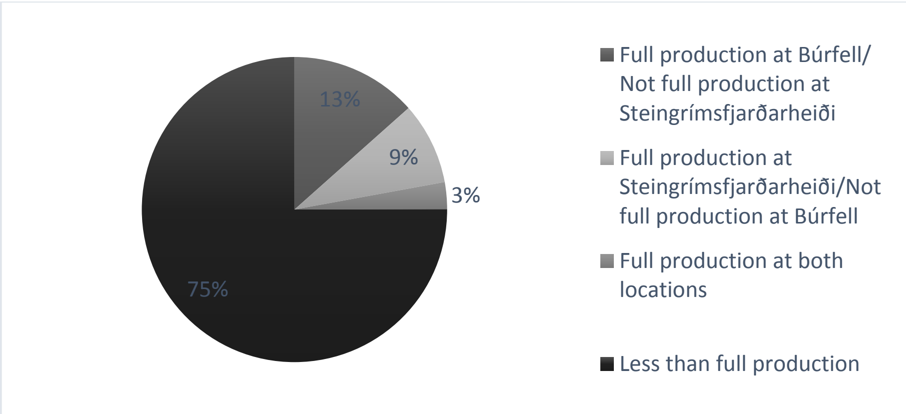


Figure 46. Comparison of how often full production levels are reached at Búrfell and Steingrímsfjarðarheiði.

A turbine located at Steingrímsfjarðarheiði has higher production than a turbine located at Búrfell for 49% of the time considered. The total average increase in power production is 1,23MWh/h.

5.5.2 Production profile for Steingrímsfjarðarheiði and Búrfell

The monthly production variations are shown in Figure 47. The seasonal variations at both locations are clearly visible. The production profiles change between years but some trends can be detected. The production at Steingrímsfjarðarheiði exceeds the production at Búrfell for some months. The red curve represents the aggregated production profile for the two locations. Since the production profiles are similar the aggregated production does not significantly even out Búrfell’s production profile.

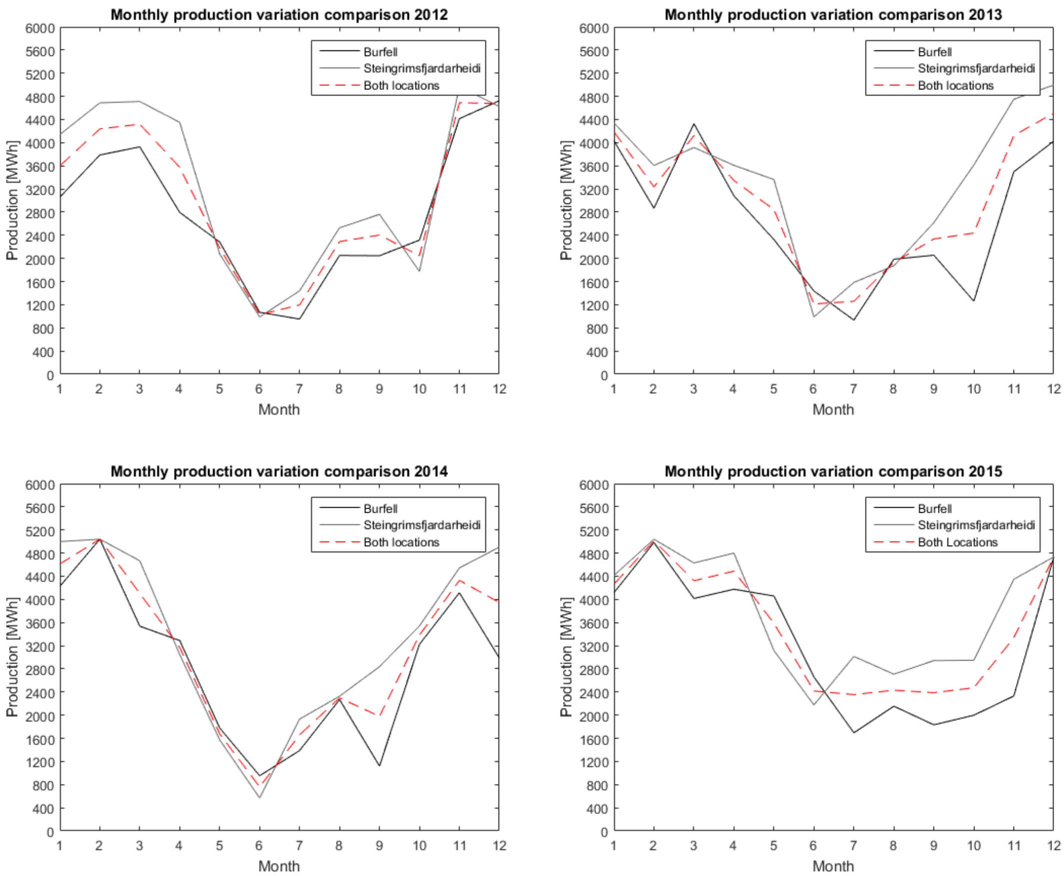
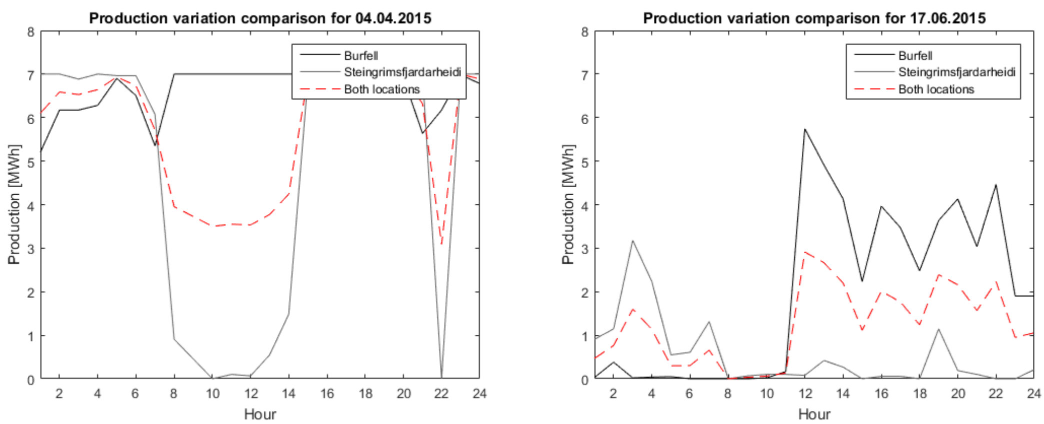


Figure 47. Comparison of monthly production levels at Steingrímsfjarðarheiði and Búrfell for 2012-2015.

The hourly production profiles for Búrfell and Steingrímsfjarðarheiði are presented in Figure 48. The aggregated production profile, for both locations, is represented by a red curve. As can be seen for the production profile of 17.06.2015 the aggregated profile is smoother than if there is only production at Búrfell. However, lower production levels are reached.



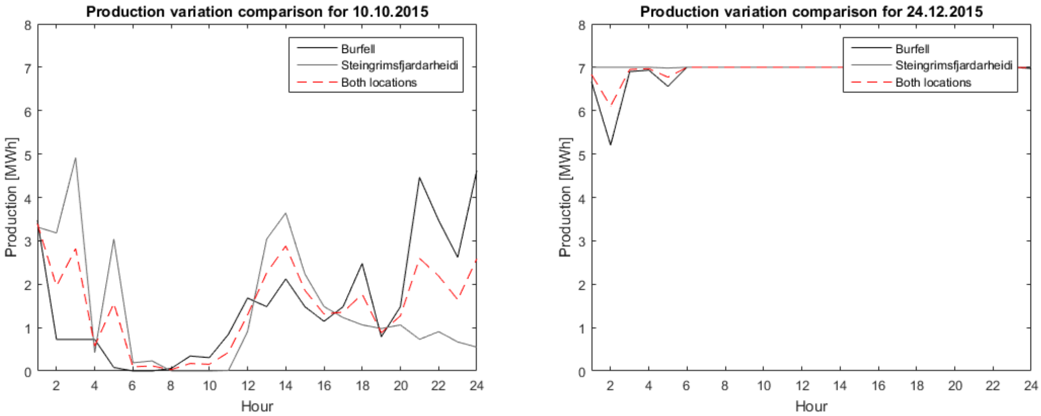


Figure 48. Intraday production comparison for Steingrímsfjarðarheiði and Búrfell

6 Summary and discussion

In this chapter the results of the research are summarized, the energy system needed to reap the benefits of synergetic effects of wind turbines is discussed and a sensitivity analysis for the roughness length is presented.

6.1 Discussion of the main results

As the results presented in Chapter 4 indicate there are many areas in Iceland that have feasible circumstances for wind power production. The capacity factor at the locations considered feasible is very high compared to the global average.

For this research the negative correlation of wind behavior between locations is of special interest. The negative correlation indicates that there is a negative relationship of wind behavior at the considered locations. As presented in Chapter 4, Section 4.2, the wind speeds at Höfn í Hornafirði and Grímsstaðir most often result in negative correlation to the wind speeds measured at Búrfell for the considered time steps.

The many time steps considered make it difficult to draw a conclusion of which location complements Búrfell in the best way. The interactions of locations with Búrfell differ between time steps. The correlation for smaller time steps of hours and days is close to neutral and this indicates no clear relationship of behavior of the wind at the considered locations. For the case of neutral correlation of wind it is difficult to use the synergetic effects of turbines in order to even out the production profile. Due to the different behavior of the wind it is difficult to predict how to operate the turbines in the optimal way to save regulating power.

The production level at Búrfell is rather high and there are few opportunities for improvements. For 8% of the time series considered there is no production detected at Búrfell and there is full production for 16% of the time series considered. Considering this, it is clear that finding a place to complement Búrfell without decreasing the total production level is difficult. Since complementing Búrfell with another location with lower production level will lead to a decrease in annual production and capacity factor compared to investing in more turbines at the Búrfell area. From economical and energy system point of view it is important to maximize the production at the two locations while there is not a lot of wind power in the system. However, this thesis shows that the time of no production can be minimized at the cost of slightly lower production level. This results in a more stable grid and decreased need for regulating power during certain time steps. Therefore, it is important to find a compromise between maximizing the total production level and minimizing the time of no production.

Negative correlation for wind speeds at Grímsstaðir and Búrfell is observed for many time steps. However, when evaluating this result it can be seen that the wind speed at Búrfell is most often higher than the speed at Grímstaðir. Therefore, when the production decreases at Búrfell the production at Grímsstaðir does not increase enough to compensate for the decrease at Búrfell. The capacity factor for the combined production at Grímsstaðir and Búrfell is lower than if both turbines are located at the Búrfell area. Considering the results presented in Chapter 5, Section 5.1 where time series of Case A are evaluated it can be seen that for Case A the production exceeds the production of one turbine for as many hours as for the Base Case. The turbine at Grímsstaðir produces more than the turbine at Búrfell for 41% of the time. This means that there are higher production levels at Búrfell for 59% of the time considered. By evaluating those results, it can be seen that the production level at Grímsstaðir is too low to complement the production at Búrfell. Therefore, Grímsstaðir is not considered the best location for a turbine to complement the production at Búrfell.

Holtavörðuheiði has a negative correlation of production to Búrfell for winter comparison. The correlation of wind speed to Búrfell is close to neutral for all of the time steps considered. Therefore, it is difficult to predict in which way production at Holtavörðuheiði might complement the production at Búrfell. The annual production and capacity factor for the combined production at Holtavörðuheiði and Búrfell is estimated to be high. There is a 4% increase of production level exceeding rated power of one turbine compared to the Base Case. There is a higher level of production at Holtavörðuheiði for 47% of the time compared to Búrfell. Considering the production levels at the two locations it can be seen that Holtavörðuheiði complements the production at Búrfell at the monthly level, especially for the late summer and autumn months. For a smaller time scale the fluctuations in production at Holtavörðuheiði are extreme and it is difficult to see how and if it complements the production at Búrfell. Case B results in slightly higher capacity factor than the Base Case. However, Holtavörðuheiði is located at a high altitude and that might induce problems with icing on the turbines. This as well as relatively high average wind speed should be kept in mind for further analysis for this location.

Hveravellir results in a negative correlation to Búrfell for the winter comparison. This behavior is of most interest since hydro power is limited during winter when waters are frozen. The correlation is rather neutral and it is difficult to estimate if the production at Hveravellir complements the production at Búrfell. The combined production exceeds the production of one turbine more often than for the Base Case. However, there are higher production levels at Hveravellir than Búrfell for 47% of the time considered. The capacity factor of Case C is the same as for the Base Case. The comparison of production levels seem to indicate that during winter the production at Hveravellir complements the production at Búrfell and by doing so increases the opportunity of saving hydro power. However, the geographical location of Hveravellir is a problem when it comes to implementing wind power production. Hveravellir is located in the Icelandic highlands, far away from grid connection. Even though considering the possible expansion of the national grid this location might become more feasible, it is highly unlikely that a power plant will be built in this recommended conservation area.

Höfn í Hornafirði has a negative correlation to Búrfell for many time steps considered. Under close examination, the production levels at Höfn í Hornafirði compensate for low production levels at Búrfell for many of the time steps considered. The capacity factor for Case D is the same as for the Base Case. However, the annual production is slightly lower. The cumulative power production for Case D exceeds the production of one turbine for 53% of the time which is an increase of 4% compared to the Base Case. A turbine located at Höfn í Hornafirði has higher production levels than a turbine located at Búrfell for 46% of the time. There was no negative correlation detected for the winter comparison but the higher production level at Höfn í Hornafirði compensated for lower average monthly production at Búrfell for the years considered in Chapter 5, Section 5.4.2. As mentioned above this is of special interest in order to save hydro power. For the smaller timescales it is difficult to predict if the production profiles at Höfn í Hornafirði and Búrfell interact in a good way. However, the negative correlation detected for the smaller time steps indicate good interaction between the two locations. Höfn í Hornafirði is close to a grid connection. It is relatively far away from other power plants such as hydro and geothermal, therefore, there is a need for local power production. For this analysis the roughness length at Höfn í Hornafirði is high and the feasibility of the location is sensitive to a change in the roughness length. This is considered further in Section 6.3.

The wind speed and production profile of Steingrímsfjarðarheiði has negative correlation to the wind speed and production profile at Búrfell for the winter comparison. For the winter comparison the production level at Steingrímsfjarðarheiði is overall higher than for Búrfell. The capacity factor of the cumulative production at Steingrímsfjarðarheiði and Búrfell is 51% which is higher than for the Base Case. The cumulative production at Steingrímsfjarðarheiði and Búrfell exceeds the rated power of one turbine for 54% of the time which is 5% more than for the Base Case. The production at Steingrímsfjarðarheiði exceeds the production at Búrfell for 49% of the time. Considering the monthly production profile it can be seen that during the winter and autumn months the production at Steingrímsfjarðarheiði complements the production at Búrfell without decreasing the total production. For the summer season the cumulative production is similar to the production of the Base Case. Considering the smaller time steps presented in Chapter 5, Section 5.5.2, it is problematic to see that the production at Steingrímsfjarðarheiði helps even out the production at Búrfell. The high altitude location of Steingrímsfjarðarheiði might induce problems with icing. Additionally, the high average wind speeds exceeding 10m/s can increase the wear on the turbine. This should be kept in mind before further analyzing this location for power production.

For the cases considered in Chapter 5, Cases B - E have feasible interactions with Búrfell for the winter months. The production profile at these locations is higher than at Búrfell for the winter months. Therefore, there is an opportunity to save regulating power by implementing turbines at one of the considered locations.

Considering the feasible locations examined in Chapter 5, Steingrímsfjarðarheiði, Hveravellir and Holtavörðuheiði are located at high altitudes and the effects of icing on the turbines are not considered. Additionally, the production levels at these locations are overall higher than the production levels at Búrfell. Therefore, it is not certain if it is the correlation between areas which complements the production at Búrfell or the higher production level. The average wind speeds at hub height are higher than 10m/s for all the locations which is rather high and might shorten the lifetime of the turbine. The roughness length at these locations are most likely not overestimated as it is equal to the average roughness length of 3cm. Therefore, the wind speeds at hub height are most likely not overestimated but rather underestimated.

It is commonly accepted that by placing wind turbines at different geographical areas it is possible to smoothen out the production profile for wind power (Olauson, Bergström, & Bergkvist, 2015). Figure 49 shows how the monthly production profile of 2015 looks if one turbine is placed at each of the locations considered for Cases B - E compared to placing as many turbines at Búrfell. The monthly production level is overall higher than if all the turbines are placed at Búrfell. The production level is more stable for the first four months of the year and there are smaller variations between months. For both cases the production decreases severely during the spring months and for the combined case it stays stable during summer. During the autumn season the production increases again. The production level of the spread out production is higher than if all turbines are located at Búrfell. This indicates that if turbines are located at different areas less regulating power is needed. On smaller timescales it is very difficult to predict the interactions between locations since the correlation is close to neutral on the hourly scale for most of the turbines. Therefore, it is not clear how they interact on this small scale and there is an opportunity for further research.

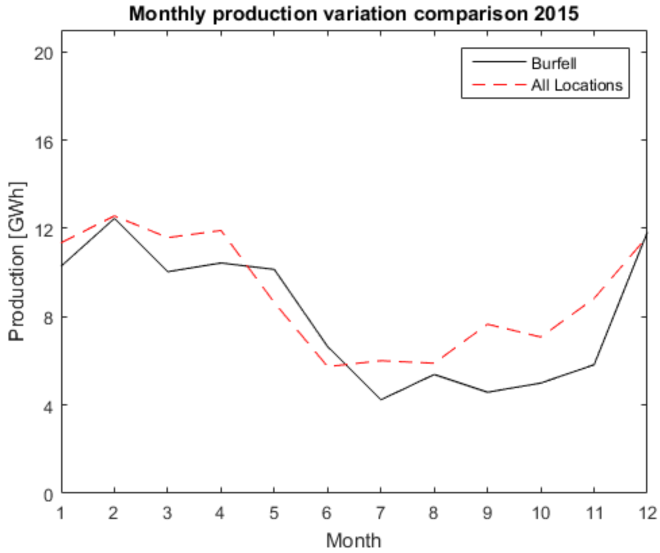


Figure 49. Aggregated monthly production level for Cases B – E in Chapter 5 compared to production at Búrfell.

The main result from this research is that on monthly basis there are several locations with high production levels resulting in negative correlation to Búrfell. Therefore, power production at those locations can even out the production level at Búrfell without significantly decreasing the total production.

6.2 Implementing wind power production to a hydro dominated system

The hydro dominated power system of Iceland creates an exciting ground for wind power integration. To reap the benefits of synergetic effects of geographical spreading of wind turbines the hydro dominated power system is of great importance. This research has shown that in Iceland there are some locations with feasible wind circumstances to complement the planned generation at Búrfell. The negative correlations indicate good interaction and decreased variability of production when it is spread over larger area. For the smaller time steps it is difficult to analyze the effects while the monthly production profiles even out the fluctuations and complement the production at Búrfell. The smoother production profiles detected for cases B - E for the winter months indicates that hydro power can be saved during these months. Since there is a low level of water inflow to reservoirs during winter due to frozen waters this can help increase the efficient use of the reservoirs during other months of the year. That is, less water has to be saved during the summer season for winter utilization.

The seasonal fluctuations in the production profiles for the cases considered in Chapter 5 are clear. As introduced in Chapter 1, Section 1.2 there is a large inflow to hydro reservoirs during spring and summer while the frozen waters are melting. During this time it can be detected in the production profiles in Chapter 5 how the power generation by wind decreases. This further emphasizes the advantages of integrating wind power production in a highly hydro dominated system.

For smaller time scales of hours and minutes it is not clear from this research how efficiently the production at the considered locations complement the production at Búrfell. To control the production and stabilize the grid, a highly sophisticated control system is needed. It has to respond quickly to changes in power production from the wind turbines and increase the production from the hydro plants. Hydro power plants with reservoirs have the possibility to ramp up in few minutes. The reservoirs act as energy storage and can help stabilize the power production from the wind turbines (Eurelectric, 2015).

For the Icelandic power system the planned implementation of wind power is a small share of the total power production. Currently there is no need to consider the situation of too high production levels resulting in a need for load curtailment.

6.3 Sensitivity analysis of roughness length

As mentioned in Chapter 3, Section 3.3 the roughness length of the terrain is highly important when evaluating possible power production at a location. The roughness length is evaluated for all locations using the CORINE factor and validated using visual observation in Google Earth Pro©. Decrease in the roughness length affects the possible power production. Therefore, it is important to estimate the change of power production with respect to change of roughness length. The effects on the average speed and the production are evaluated for a decrease of roughness length by 5%, 50% and if the roughness length is estimated 3cm for all locations.

The effects on the speed and production differ with the original roughness length and average speed at anemometer height. For locations with the same original roughness length and different average speed at anemometer height the locations with lower average speed are more affected by a decrease in roughness length. For locations with different roughness lengths the effect on the speed is more for locations with higher roughness length. Therefore, it is estimated that the locations with high roughness length and low average speed are affected the most when roughness length is changed. Production and speed at Patreksfjörður are highly vulnerable to a change in roughness length and the feasibility of the location decreases rapidly with decreased roughness length. The average wind speed at anemometer height at Patreksfjörður is below 5,1m/s which is considered the speed needed to economically utilize wind power (NREL). A 5% decrease in roughness length results in 0,7% change in production and 50% decrease results in 8% decrease in production as well as 3% decrease in capacity factor. If the roughness length is decreased to the Icelandic average of 3cm, the production decreases by 24%. This shows that decreasing the roughness length highly affects the production potential at Patreksfjörður.

Höfn í Hornafirði is one of the most feasible locations to implement wind power production to complement the planned production at Búrfell. The anemometer at Höfn í Hornafirði is located within the town and therefore the CORINE factor detected results in high roughness length of 50cm. This is significantly higher than the average estimated value of 3cm for Iceland. Therefore, the production error at this location is estimated with respect to the roughness length of the terrain. It is evaluated how much the speed and production changes with a decrease of 5%, 50% and a decrease to 3cm of the roughness length. The change in speed is biggest for the change to 3cm where the average speed decreases by approximately 19% and the production by 16%. The production decreases slightly less since the decrease in average speed indicates that the probability of extreme wind speeds decreases. If the case of Höfn í Hornafirði and Búrfell is considered, it is observed that by changing the roughness length at Höfn í Hornafirði the production decreases by approximately 0,2%, 3% and 8% for 5%, 50% and a decrease to 3cm respectively. This indicates that in the worst case scenario the cumulative annual production decreases by approximately 8%. The change in annual production for a change in roughness length is presented in Figure 50.

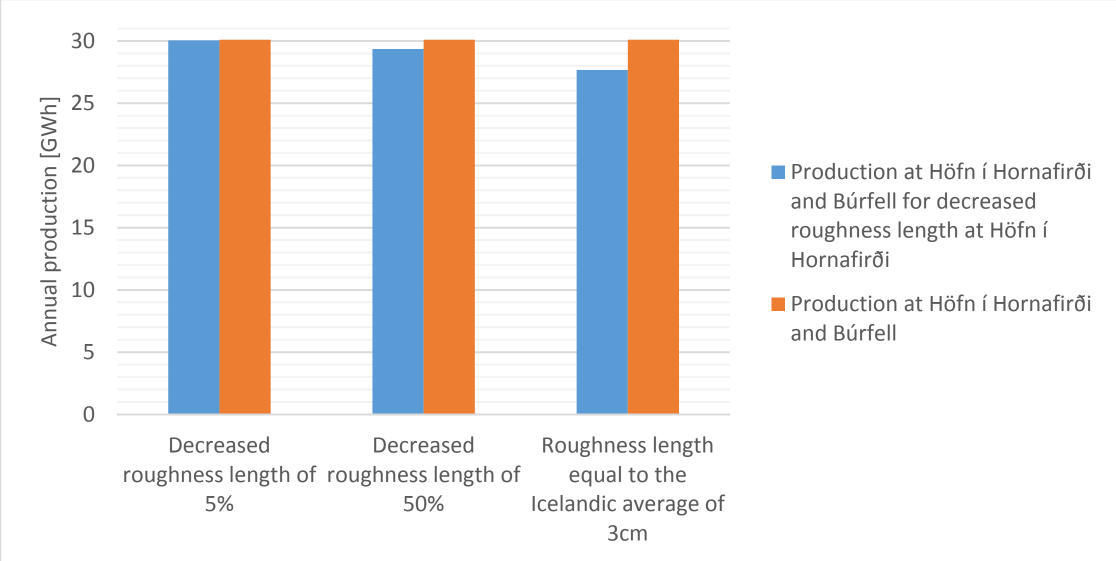


Figure 50. Change in annual cumulative production at Höfn í Hornafirði and Búrfell with a decrease in roughness length at Höfn í Hornafirði.

The biggest decrease of cumulative production if the roughness length at Höfn í Hornafirði is wrongly estimated is therefore roughly 8% and the decrease in capacity factor is 4%. This results in a lower capacity factor for the combination of Höfn í Hornafirði and Búrfell than if two turbines are placed at Búrfell. By analyzing the monthly production levels for roughness length of 3cm at Höfn í Hornafirði it is observed that the production levels at Höfn í Hornafirði complement the production at Búrfell for fewer months of the year. This emphasizes the importance of estimating the roughness length correctly. It is therefore suggested that further measurements of wind speeds at locations outside of Höfn í Hornafirði should be collected and analyzed as well as the roughness length of the terrain validated.

7 Conclusions and recommendations for further research

Höfn í Hornafirði is the only location that results in both negative correlations and high enough production level to complement the production at Búrfell. It is located close to the sea at a flat and open area. The location is close to grid connection and there is a lack of local power production in this area. The interaction of the production at Höfn í Hornafirði and Búrfell is promising. Therefore, it is of special interest to further examine the feasibility of wind power production at this location. The estimated roughness length at Höfn í Hornafirði is 50cm. This is relatively high and contributes to the high average wind speed at hub height exceeding 10m/s. However, the sensitivity analysis shows that the estimated average wind speeds and production levels at Höfn í Hornafirði are highly vulnerable to a change in the roughness length. Therefore, it is uncertain, despite the negative correlation to wind data at Búrfell, if the production level is high enough to compensate for lower production at Búrfell. Further research should be conducted both in order to validate the feasibility of wind power production and to better understand the interaction with the production at Búrfell.

This research has numerous limitations and there are possibilities to improve the accuracy of the results. The wind direction is not taken into consideration in this research despite being an important parameter for site analysis for wind power production. The turbulence of the wind profile highly affects the possible production at a location as well as the lifetime of the turbine, these effects are not considered in this research. For this research the power curve for the ENERCON E101 E2 3,5MW turbine is considered. If other turbine models are considered the results might change. The calculation of correlation of wind data from different sites to the data at Búrfell has to be complemented by the production potential at the locations in order to get a valid result. As for the case of Grímsstaðir, negative correlation is detected but the production levels calculated are too low to properly complement the production at Búrfell. The results from the sensitivity analysis of the roughness length stresses the fact that it is necessary to measure the wind speed in more details as well as validate the roughness length where it might be feasible to implement wind power production. No economic analysis is conducted and therefore it is not clear at this stage if it makes economic sense to implement wind power production at the sites proposed. Implementing wind power production at two different areas is expected to have a higher capital cost than if the turbines are all located in the same area.

Considering the aforementioned limitations the following suggestions are put forward for further research:

- Economic analysis of the locations suggested in Chapter 5.
- Considering other turbine models in order to maximize the efficiency at the feasible location.
- Detailed measurements of wind speeds, wind direction and turbulence at the most economically feasible location.
- The effects on the national grid if wind power production is implemented at different locations and the possibility to minimize effects of bottlenecks in the grid.
- Examine how much hydro power can be saved by locating turbines at different geographical areas compared to just one.

Despite the limitations of this research it is clear that placing turbines at different geographical areas results in a smoother production profile and decreased variability of production. Resulting in an opportunity to reduce the need of regulating power. This research has showed that the correlation of wind data between locations is not a good enough parameter to estimate the interaction of production at different locations. The production level must be considered in order to validate the feasible interactions of the locations.

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Appendices

Appendix 1

Table 10. Names and information about the weather stations used in this thesis.

Number	Name of station	Altitude above sea level [m]	Height of measurement device [m]	Roughness length of the terrain [m]	First measure-ment	Final measure-ment	Number of measure-ments
3471	*Akureyri*	31	10,06	0,600	1.1.2006 00:00	1.1.2016 00:00	87530
6420	*Árnes*	90	10,06	0,030	1.1.2006 00:00	1.1.2016 00:00	87649
6430	*Búrfell*	249	10,03	0,030	1.1.2006 00:00	1.1.2016 00:00	87170
3317	*Blönduós*	8	10,03	0,03	1.1.2006 01:00	1.1.2016 00:00	87645
2738	*Bolungarvík*	27	10,04	0,500	1.1.2006 00:00	1.1.2016 00:00	87475
4271	*Egilstaðir*	23,5	10,04	0,005	1.1.2006 00:00	1.1.2016 00:00	87634
4323	*Grímsstaðir*	390	NaN	0,030	20.9.2012 20:00	1.1.2016 00:00	28734
5544	*Höfn Í Hornafirði*	5	10,53	0,500	27.4.2007 13:00	1.1.2016 00:00	75149
3696	*Húsavík*	28,2	10,38	0,030	1.1.2006 00:00	1.1.2016 00:00	87640
6935	*Hveravellir*	641	11,62	0,030	1.1.2006 00:00	1.1.2016 00:00	86671
1779	*Hvanneyri*	12,4	10,43	0,050	1.1.2006 00:00	1.1.2016 00:00	87241
5933	*Kárahnjúkar*	639	10,06	0,030	1.1.2006 00:00	1.1.2016 00:00	87622
6272	*Kirkjubæjarklaustur*	22	10,04	0,030	1.1.2006 00:00	1.1.2016 00:00	87300
2319	*Patreksfjörður*	43	10,05	0,500	1.1.2006 00:00	1.1.2016 00:00	87266
4828	*Raufarhöfn*	4	9,95	0,300	1.1.2006 00:00	1.1.2016 00:00	87049
1475	*Reykjavík*	52	10,07	0,500	1.1.2006 00:00	1.1.2016 00:00	87548

Number	Name of station	Altitude above sea level [m]	Height of measurement device [m]	Roughness length of the terrain [m]	First measure-ment	Final measure-ment	Number of measure-ments
6975	*Sandbúðir*	820	10,03	0,005	1.1.2006 00:00	1.1.2016 00:00	85802
6017	*Stórhöfði*	118	10,32	0,030	1.1.2006 00:00	1.1.2016 00:00	87648
2050	*Stykkishólmur*	12,4	10,00	0,300	1.1.2006 00:00	1.1.2016 00:00	87555
32097	*Holtavörðuheiði*	370	NaN	0,03	1.1.2006 00:00	1.1.2016 00:00	87113
35315	*Kvísker*	30	7,57	0,03	1.1.2006 00:00	1.1.2016 00:00	87249
32474	*Steingrímsfjarðarheiði*	440	NaN	0,03	1.1.2006 00:00	1.1.2016 00:00	86067

Appendix 2

Table 11. Wind speed and corresponding power output for ENERCON E-101 E2 3500kW turbine

Wind speed $\left[\frac{m}{s}\right]$	**Power** $[kW]$
1,0	0,0
2,0	3,0
3,0	37,0
4,0	116,0
5,0	253,0
6,0	469,0
7,0	775,0
8,0	1175,0
9,0	1680,0
10,0	2280,0
11,0	2810,0
12,0	3200,0
13,0	3400,0
14,0	3465,0

Wind speed $\left[\frac{m}{s}\right]$	Power $[kW]$
15,0	3500,0
16,0	3500,0
17,0	3500,0
18,0	3500,0
19,0	3500,0
20,0	3500,0
21,0	3500,0
22,0	3500,0
23,0	3500,0
24,0	3500,0
25,0	3500,0

Appendix 3

Table 12. Correlation between locations for hourly, daily, weekly, monthly and yearly production. Yellow cells represents the most neutral correlation, red cells the most positive and green cells the most negative for all time steps.

		Hourly production	Daily production	Weekly production	Monthly production	Yearly production
Grímstaðir	***Búrfell***	0,00	0,00	-0,08	-0,21	-0,85
Höfn Í Hornafirði	***Búrfell***	-0,03	-0,08	-0,18	-0,44	0,29
Hveravellir	***Búrfell***	0,12	0,22	0,35	0,64	0,68
Kárahnjúkar	***Búrfell***	0,09	0,18	0,29	0,66	0,57
Raufarhöfn	***Búrfell***	0,09	0,17	0,34	0,69	0,37
Stykkishólmur	***Búrfell***	0,09	0,17	0,29	0,66	0,85
Holtavörðuheiði	***Búrfell***	0,04	0,11	0,29	0,54	0,70
Kvísker	***Búrfell***	0,13	0,23	0,50	0,83	0,78
Steingrímsfjarðarheiði	***Búrfell***	0,02	0,06	0,20	0,44	0,76
Patreksfjörður	***Búrfell***	0,10	0,17	0,35	0,72	0,70

Table 13. Correlation between locations for seasonal, winter, spring, summer and autumn production. Yellow cells represents the most neutral correlation, red cells the most positive and green cells the most negative production for all time steps.

		Seasonal production	Winter production	Spring production	Summer production	Autumn production
Grímstaðir	***Búrfell***	-0,48	-0,96	-0,83	0,68	0,92
Höfn Í Hornafirði	***Búrfell***	-0,50	0,23	0,06	0,69	-0,24
Hveravellir	***Búrfell***	0,76	-0,03	0,79	0,75	0,43
Kárahnjúkar	***Búrfell***	0,77	0,14	0,69	0,15	0,18
Raufarhöfn	***Búrfell***	0,76	0,23	0,67	0,69	0,47
Stykkishólmur	***Búrfell***	0,85	0,06	0,75	0,89	0,76
Holtavörðuheiði	***Búrfell***	0,71	-0,06	0,43	0,78	0,49
Kvísker	***Búrfell***	0,90	0,56	0,67	0,93	0,91
Steingrímsfjarðarheiði	***Búrfell***	0,61	-0,28	0,65	0,94	0,80
Patreksfjörður	***Búrfell***	0,87	0,66	0,47	0,96	0,89