Possible impacts of climate change on the wind energy potential in Búrfell

Birta Kristín Helgadóttir

Faculty of Civil and Environmental Engineering
University of Iceland
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Birta Kristín Helgadóttir

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

Advisors
Dr. Sigurður Magnús Garðarsson
Dr. Halldór Björnsson
Dr. Guðrún Nína Petersen

Faculty Representative
Einar Sveinbjörnsson

Faculty of Civil and Environmental Engineering
School of Engineering and Natural Sciences
University of Iceland
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Faculty of Civil and Environmental Engineering
School of Engineering and Natural Sciences
University of Iceland
Hjarðarhaga 6
107, Reykjavik
Iceland

Telephone: 525 4700

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Abstract

Climate change is expected to cause significant changes in meteorological conditions, such as wind intensity, air temperature, precipitation, and humidity resulting in changed weather conditions and more extreme weather patterns. The main topic of this study was to examine the possible change in climate and its impact on the wind resource in Iceland with main focus on the Búrfell region in the southern Iceland. The study was done in collaboration with the Icelandic Meteorological Office and Landsvirkjun. The study was based on data from a meteorological mast at Búrfell, measuring wind speeds in 10 m height above ground level. Forecasts and historical hind casts for the Búrfell area from a regional climate model, based on simulations from a global climate model were obtained and used to project the possible change in wind speeds, Weibull parameters, and energy density in the area during the 21st century. The results presented in this study showed an increase in extreme winds and a decrease in average wind speeds for the Búrfell area. The energy densities for the projected scenarios were calculated for three time periods, i.e. the whole data set (2050 – 2100), the first part (2050 – 2066) and the latter part (2086 – 2100). The calculated energy densities were 10 – 23% lower compared to the historical data, depending on the time period. Based on these findings, climate change will affect the wind energy potential at Búrfell. However, since the energy densities from the projected scenarios were still within the boundaries that define the highest wind class the area is still considered a viable option for wind power utilization.
Útdráttur

# Table of Contents

List of Figures .................................................................................................................. xi
List of Tables ...................................................................................................................... xiv
Abbreviations .................................................................................................................... xvi
Acknowledgements ......................................................................................................... xvii

## 1 Introduction ................................................................................................................. 1
  1.1 General introduction ................................................................................................. 1
  1.2 Thesis objectives ...................................................................................................... 2
  1.3 The wind resource .................................................................................................. 3
    1.3.1 The atmosphere .................................................................................................. 3
    1.3.2 The wind climate ............................................................................................... 4
  1.4 Climate change and weather .................................................................................... 5
  1.5 Wind power ............................................................................................................. 7
    1.5.1 History of wind power .................................................................................... 7
    1.5.2 Wind power in Iceland .................................................................................... 10
    1.5.3 Wind power production at Hafný ................................................................. 12
  1.6 Literature review of potential climate change impacts on wind power ............. 14

## 2 Methods ....................................................................................................................... 19
  2.1 Theory ..................................................................................................................... 19
    2.1.1 Wind speed characteristics ............................................................................. 19
    2.1.2 Wind power extraction ................................................................................... 21
    2.1.3 Wind data analysis .......................................................................................... 22
    2.1.4 Weibull distribution analysis ......................................................................... 23
    2.1.5 Energy density ................................................................................................. 24
    2.1.6 Wind speed extrapolation ............................................................................. 25
    2.1.7 Climate models ............................................................................................... 26
  2.2 Data .......................................................................................................................... 27
    2.2.1 Data gathering ................................................................................................. 27
    2.2.2 Data analysis .................................................................................................... 28

## 3 Modeling and results .................................................................................................. 29
  3.1 Wind speed distributions ......................................................................................... 29
  3.2 Weibull distribution analysis .................................................................................. 33
    3.2.1 Weibull distribution plots .............................................................................. 34
    3.2.2 Scale and shape parameters ........................................................................... 35
  3.3 Energy density ......................................................................................................... 37
  3.4 Adjustments of the wind speed ............................................................................. 38
  3.5 Discussion ................................................................................................................ 45
  3.6 Limitations ................................................................................................................ 47
  3.7 Future research ....................................................................................................... 47
4 Conclusions ...........................................................................................................49

5 Bibliography .........................................................................................................51

Appendix A Tables ....................................................................................................57

Appendix B R Code ..................................................................................................61
List of Figures

Figure 1-1 Location of Búrfell, in the southwest part of Iceland. The meteorological mast is located northeast of the red mark and the experimental wind turbines to the north. (From: NLSI, 2014) ................................................................. 1

Figure 1-2 The layers of Earth’s atmosphere in relation to average profile of air temperature above the surface of the earth (From: Ahrens, 2009). .......................... 3

Figure 1-3 The complete diagram summarizing atmospheric circulation. (From: Earthguide, 2013). ............................................................................................................. 5

Figure 1-4 Hero’s windmill toy. (From: Musgrow, 2010). .......................................................... 7

Figure 1-5 Global cumulative installed wind capacity (MW) 1996 - 2013. (From: GWEC, 2014).......................................................................................................................... 10

Figure 1-6 Looking south at wind turbine 1, at Hafn̄ with Búrfell in the background. (From: Landsvirkjun, 2014) ................................................................................................................. 11

Figure 1-7 Wind energy production (MW/h) in the first year of production from wind turbine 1 (columns) and the monthly mean wind speed (line, m/s). (From: Arnardóttir, M.( personal communication, January 2014)) ........................................ 12

Figure 1-8 Wind energy production (MW/h) in the first year of production from wind turbine 2. (columns) and the monthly mean wind speed (line, m/s). (From: Arnardóttir, M.( personal communication, January 2014)). ......................... 13

Figure 1-9 Topographic map of Iceland, with locations of the sites that were specially analyzed by Nawri et al. (2013). From Nawri et al. (2013). ....................... 17

Figure 2-1 Time and space scales of atmospheric motion (From: Manwell et al., 2002) ................................................................................................................................................. 20

Figure 2-2 Theoretical maximum power coefficient as a function of tip speed ratio for an ideal horizontal axis wind turbine, with and without wake rotation (From: Manwell, 2002). ........................................................................................................ 22

Figure 2-3 An example of Weibull probability function for various shape factors, $k$ and an average velocity of 6 m/s (From: Manwell et al., 2002) ......................... 24

Figure 2-4 The regional climate model nesting approach. (From: Giorgi, 2008) ............. 26

Figure 2-5 The 10 m met mast at Búrfell (From: Landsvirkjun, 2013). ............................ 27

Figure 3-1 A boxplot of daily average wind speed distribution (m/s) for all data sets. See Table 2-1 for clarification of the names of the data sets. The dotted

vii
tail above each box represents the distribution of higher wind speeds, i.e. the extremes. The boxplot summarizes the average wind speeds and shows the correlation between the models. ................................................................. 29

Figure 3-2 Observed annual average wind speed distribution (m/s) at Búrfell from 1993 – 2013. The distribution is relatively even for this 20 year period. ....... 30

Figure 3-3 Annual average wind speed (m/s) for historical runs with ECEARTH and CERFACS from 1970 – 2005. The distribution is relatively even for this 35 year period. ................................................................. 31

Figure 3-4 Annual average wind speed (m/s) from CERFACS model for RCP45 and RCP85 from 2050 – 2100. The distribution shows an overall decrease in average wind speeds for this 50 year period. ................................................................. 32

Figure 3-5 Annual average wind speed (m/s) from ECEARTH model for emission scenarios from 2050 – 2100. The distribution shows an overall decrease in average wind speeds for this 50 year period. ................................................................. 33

Figure 3-6 Empirical Cumulative Distribution Function (blue curve) and Weibull Cumulative Distribution Function (black curve) for BUR and all model simulations. From left to right and downwards, the figures represent Weibull distribution: BUR, CERH, ECH, CER45, CER85, EC45 and finally EC85. ........................................................................................................ 34

Figure 3-7 Scale factors for BUR and all model simulations. The scale factor A (m/s) will decrease based on projected scenarios CER45, CER85, EC45 and EC85. ........................................................................................................ 35

Figure 3-8 Shape factors for BUR and all model simulations. The shape factor k will increase according to EC45 and EC85 but decrease according to CER45 and CER85. ........................................................................................................ 36

Figure 3-9 Energy Density for each model in W/m² with adjusted confidence intervals at 10 m AGL for the latter part of the 21st century (2050 – 2100). ........................................................................................................ 38

Figure 3-10 A comparison of adjusted wind speed distributions after shifting the model results so that the historic runs have the same average as the measured data, and performing height extrapolation of the wind speeds (m/s) from 10 m AGL to 50 m AGL for ECEARTH and CERFACS model. ....... 39

Figure 3-11 Scale parameters for adjusted wind speed distributions after height extrapolation of the wind speeds (m/s) from 10 m AGL to 50 m AGL for all data sets. ........................................................................................................ 40

Figure 3-12 Shape parameters for adjusted wind speed distributions after height extrapolation of the wind speeds (m/s) from 10 m AGL to 50 m AGL for all data sets. ........................................................................................................ 41
Figure 3-13 Energy density calculated based on adjusted wind speeds, i.e. extrapolated up to 50 m (above) and 100 m (below) AGL for the latter part of the 21st century (2050 – 2100). .................................................................42

Figure 3-14 Energy density calculated based on adjusted wind speeds, i.e. extrapolated up to 50 m (above) and 100 m (below) AGL for the years 2050 – 2065. ...........................................................................................................43

Figure 3-15 Energy density calculated based on adjusted wind speeds, i.e. extrapolated up to 50 m (above) and 100 m (above) AGL for the latter part of the 21st century (2086 – 2100). .................................................................44

Figure 3-16 Results from calculations of change in energy density at 50 m AGL for all model simulations for the whole time series (2050 - 2100), the first part (2050 - 2066) and for the latter part (2086 - 2100).................................45
List of Tables

Table 2-1 The models from the CORDEX runs used in this study are presented below. The models are described briefly, i.e. what the RCM’s and the GCM’s are, which scenario do they describe, which time period do they cover and how are they abbreviated in the following sections of this thesis. The last row in the table briefly describes the observed data from Búrfell. ................................................................. 28

Table 3-1 Comparison of BUR and ECH energy densities at 55 m AGL to the energy densities from Nawri et.al. The energy densities are in W/m² .......................... 46

Table A-1 Wind speed distribution from meteorological mast at Búrfell and from RCM.................................................................................................................. 57

Table A-2 Scale factors for the models and for Búrfell, historical data as well as upper (97,5%) and lower (2,5%) confidence intervals. ......................... 57

Table A-3 Shape factors for the models and for Búrfell, historical data as well as upper (97,5%) and lower (2,5%) confidence intervals. ......................... 57

Table A-4 Calculated energy density (W/m²) for each model simulation based on the Weibull factors, as well as confidence intervals at 10 m AGL. The CERFACS and ECEARTH RCP runs are calculated for the whole time period (2050 – 2100). ................................................................. 58

Table A-5 Calculated energy density (W/m²) for each model simulation based on the Weibull factors with adjusted confidence intervals at 10 m AGL. The CERFACS and ECEARTH RCP runs are calculated for the whole time period (2050 – 2100). ................................................................. 58

Table A-6 Calculated scale factors with maximum and minimum values for each simulation after speed and height correction at at 50 m AGL. The CERFACS and ECEARTH RCP runs are calculated for 2050 – 2066. ........... 58

Table A-7 Calculated shape factors with maximum and minimum values for each simulation after speed and height correction at 50 m AGL. The CERFACS and ECEARTH RCP runs are calculated for 2050 – 2066. ........... 58

Table A-8 Calculated energy density (W/m²) for each model simulation based on the Weibull factors with confidence intervals for corrected height at 50 m AGL. The CERFACS and ECEARTH RCP runs are calculated for 2050 – 2066. ................................................................. 59

Table A-9 Calculated energy density (W/m²) for each model simulation based on the Weibull factors with confidence intervals for corrected height at 100 m
AGL. The CERFACS and ECEARTH RCP runs are calculated for 2050 – 2066.

Table A-10 Calculated energy density (W/m²) for each model simulation based on the Weibull factors with confidence intervals for corrected height at 50 m AGL. The CERFACS and ECEARTH RCP runs are calculated for 2086-2100.

Table A-11 Calculated energy density (W/m²) for each model simulation based on the Weibull factors with confidence intervals for corrected height at 100 m AGL. The CERFACS and ECEARTH RCP runs are calculated for 2086-2100.

Table A-12 Calculated energy density (W/m²) for each model simulation based on the Weibull factors with confidence intervals for corrected height at 50 m AGL. The CERFACS and ECEARTH RCP runs are calculated for the whole period (2050 – 2100).

Table A-13 Calculated energy density (W/m²) for each model simulation based on the Weibull factors with confidence intervals for corrected height at 100 m AGL. The CERFACS and ECEARTH RCP runs are calculated for the whole period (2050 – 2100).

Table A-14 Calculated change in energy density at 50 m AGL for all model simulations for the whole time series (2050 - 2100), the first part (2050 - 2066) and for the latter part (2086 - 2100).
Abbreviations

RCM  Regional climate model
GCM  Global Climate Model
EWEA European wind energy association
GWEC Global wind energy council
UNFCCC United Nation Framework Convention on Climate Change
IPCC Intergovernmental Panel on Climate Change
WWEA World Wind Energy Association
IMO Icelandic Meteorological Office
CORDEX Coordinated Regional Climate Downscaling Experiment
SMHI Swedish Meteorological and Hydrological Institute
CMIP5 Coupled model intercomparison project 5
RCA4 Rossby Centre Atmospheric model 4
AGL Above ground level
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1 Introduction

1.1 General introduction

Iceland is a country with an ample amount of renewable energy resources. Development of hydropower for electricity production began early in the 20th century with a small power plant in Hafnarfjörður in 1904. The first geothermal power station for same purposes began operations in 1969, located in the northeast part of Iceland. Up to the present day, hydropower and geothermal power have been the two main pillars of electricity generation for the country and Icelanders can proudly say that about 85% of total primary energy consumption and 100% of generated electricity comes from renewable energy sources (Askja Energy, 2014).

Wind energy has not been utilized much in Iceland for electricity production purposes. In the 19th century, wind energy was in some places used for grinding corn, pumping water and various other purposes. In the 20th century, when use of electricity was brought to Iceland, small wind power stations were common at farms and in the last few decades such power stations have been used to produce electricity for summerhouses and smaller equipment, such as weather stations (Iceland Meteorology Office, 2012).

Due to Iceland’s geographical location it seems ideal for wind exploitation. In recent years, interest in wind power use has grown in Iceland and in December 2012 the Icelandic national power company Landsvirkjun installed two experimental wind turbines in the southern part of Iceland, called Hafið. So far, the turbines have been more efficient than expected and the possibility of further exploitation in the area is currently under research. This type of renewable energy source has low environmental impacts and can also be used in combination with hydropower because of the different characteristics in each source. Winds tend to be stronger in the wintertime, when the riverflow is lowest. Hence the wind resource can be used as a counterbalance to hydro power, and allow for more efficient regulation of water in the reservoirs. The main purpose of Landsvirkjun’s project is to obtain experience in the Icelandic climate and perhaps to add the third pillar to the Icelandic power system.

![Figure 1-1 Location of Búrfell, in the southwest part of Iceland. The meteorological mast is located northeast of the red mark and the experimental wind turbines to the north. (From: NLSI, 2014)]
The wind possesses kinetic energy that can be converted to mechanical energy which can then be used for electricity production. Compared to conventional energy produced by installations such as oil, coal and natural gas, it contributes no greenhouse gas emissions or other harmful types of emissions when operating. The installation and demolition of a wind turbine is relatively simple compared to e.g. hydropower and the environmental effects of a wind farm are almost non-existent. Empowering and promoting the use of renewable energy sources of this kind is important in adapting to climate change. The challenges of mitigating climate change mainly involve reducing and hopefully eventually eliminating the use of fossil-fuels and switching to renewable sources of energy, and the wind energy may contribute to this in a large way.

Expansion within the wind energy industry over the last years is thought to play a major role in reducing climate change impacts in the near future, according to recent research (Pryor & Barthelmie, 2010). Adapting to climate change and implementing various mitigation measures are extremely important for the future but regardless of future emission reductions, due to past emissions climate change is estimated to continue. If emissions are not reduced quickly enough, the rate of climate change may increase and escalate in the near future. Many renewable energy sources depend on the prevailing climate and, it seems sensible to consider the impacts of predicted climate change on such sources. When it comes to climate change and global warming Iceland is in a fragile position. It is vulnerable to global warming simply because of its geographic location. With all its glaciers and volcanoes, it will be significantly affected by melting ice and weather changes (Jónsdottir, 2012).

In the past, the Icelandic Meteorology Office has participated in Nordic projects (CE and CES) regarding research on possible climate change impact on the wind as a source of energy. Based on this research the wind resource is not believed to change significantly, however extreme weathers and winds are thought to show some alterations. Such alterations could have significant effects on harvesting the wind energy and energy production and it is therefore worth exploring the possible changes in the wind climate of Iceland (Fenger et al, 2007; Þorsteinsson & Bjornsson, 2012).

**1.2 Thesis objectives**

The objective of this study was to examine and understand the possible sensitivity of wind power to climate change in Búrfell. In this study the wind speed distributions and energy densities were evaluated and future scenarios were presented. Both wind speeds from regional climate model simulations, and measured data from the meteorological mast at Búrfell were used. The results from the regional climate model, were obtained by downscaling two different global climate models, and examining a historic (control) run of both models. For these model runs two different climate change scenarios for future greenhouse gas emissions were examined. The data analysis was divided in three main parts. First the wind speed distributions were examined from all model simulations and compared to the observed data from Búrfell. The Weibull distribution was then applied to the models to calculate the shape and scale parameters to examine the possible change in the wind. Lastly the energy density was calculated based on the previously computed parameters.
1.3 The wind resource

1.3.1 The atmosphere

The atmosphere is the gas envelope that surrounds planet Earth. It’s vertical structure can be broken into four different layers: the troposphere, stratosphere, mesosphere, and thermosphere which are shown in Figure 1-2. The boundaries between the layers are known as the tropopause, stratopause, and mesopause. The troposphere is the lowest layer of the atmosphere, located closest to the earth’s surface and stretches up to an average altitude of 11 km. The thickness of the layer can go up to 16 km in the tropics but may go down to 6 km close to the poles. In the lowest part of the troposphere is a layer that is generally referred to as a boundary layer, but due to the interaction with the surface, the atmosphere in this layer behaves somewhat differently than the rest of the troposphere (Ahrens, 2009). The thickness of this layer varies but it is generally around 1 – 2 km deep. Due to the interaction with the surface of the earth, the boundary layer is far more turbulent than the rest of troposphere above it (the free troposphere). In it physical quantities, such as moisture and heat, and also particulate matter and chemicals (including pollutants) are rapidly dispersed. The boundary layer responds to changes in the surface radiative balance, and surface heating may result in vertical air motion (Stull, 1998). With regards to wind energy, this layer is the relevant one, and further discussion of the influence of climate change on the wind resource, will therefore focus on this layer.

Figure 1-2 The layers of Earth’s atmosphere in relation to average profile of air temperature above the surface of the earth (From: Ahrens, 2009).
1.3.2 The wind climate

The primary driver of atmospheric motion is the unequal heating of the earth's surface. In the tropics solar heating is intense, less so in the polar regions. The general circulation of the atmosphere is in response to this, with warmer air from the tropics moving poleward and colder air from higher latitudes moving equatorward (Ahrens, 2009).

This exchange of warm and cold air is complicated by the fact that due to the earth's rotation air parcels originating in the tropics have a different angular momentum than air parcels at higher latitudes. Mathematical analysis of motion on a rotating sphere shows that this effect leads to a force that deflects horizontal motion to the right in the northern hemisphere, to the left in the southern hemisphere. This is usually referred to as the Coriolis effect, in honor of Gaspard-Gustave Coriolis, who first worked out the mathematics behind the effect. So, in the case of a non-rotating earth one can envision the heat exchange as a thermally direct circulation cell, one in each hemisphere, with warm air rising close to the equator, moving poleward aloft and descending at higher latitudes. At the surface the colder air from high latitude would move equatorward, thus completing the circuit. However, since the earth rotates the Coriolis effect deflects and breaks the thermally direct cell into two thermally direct cells, and one intermediate cell, and the transforms the wind patterns into alternating bands of easterly and westerly winds.

The wind belts and the jet streams circling the planet are thus controlled by three circulation cells: the Hadley cell, the Ferrel cell, and the Polar cell. The Hadley cell, is named after the English meteorologist George Hadley who first gave a satisfactory description of it. In the tropics intense ground level heating leads to ascending motion in the atmosphere and air rises up to the tropopause level. From there the air aloft moves polewards about 30 degrees latitude where it descends. The bottom branch of the Hadley cell has air moving equatorward, but it is deflected by the Coriolis force, resulting in easterly winds, normally called the trade winds (Ahrens, 2009).

Like the Hadley cell, the Polar cell is also a thermally direct cell. It is most easily described as cold air descending over the poles, and moving equatorwards at low levels (also deflected by the Coriolis force into the polar easterlies) with compensating polewards flow of air aloft. The Polar cell also extends about 30° latitude, with ascending motion occurring close to the 60th parallel where the cold Arctic air meets warmer mid-latitude air at the polar front.

Between the Hadley cell and Polar cell, the "Ferrel cell" controls the circulation. In it, the low level air flow is poleward, but is deflected by the Coriolis force resulting in a wind band of predominant westerlies. The Ferrel cell connects the descending branch of the Hadley cell with the air moving polewards at low levels. When this air meets with the low level cold air from the polar cell at the polar front the warmer air rises above the colder air, but the density contrast fuels mid-latitude storm systems. This circulation cell was first described by William Ferrel who was an American meteorologist that made important contribution to scientific understanding of airflow around cyclones. Indeed, the Ferrel cell is characterised by weather systems that move poleward, often along mid-latitude storm tracks and doing so contribute to the transport of heat to the higher latitudes.

Figure 1-3 shows a diagram summarizing atmospheric circulation. It can also be seen that the Hadley cell extends from the equator to about 30 degrees, the Ferrel cell extends from
approximately 30 to 60 degrees and the Polar cell extends from 60 to 90 degrees N and S latitude. The figure also shows

![Diagram of atmospheric circulation](image)

*Figure 1-3 The complete diagram summarizing atmospheric circulation. (From: Earthguide, 2013)*

the main air currents, the trade winds and the westerlies. The figure also shows near the equator a region called the Inter-tropical Convergence Zone (ITCZ) where the Hadley cells of the southern and northern hemispheres meet. This zone moves every season away from the equator due to changes in subtropical high-pressure in opposite hemispheres.

The above is description is primarily a description of the global circulation of the atmosphere. In addition other drivers affect the circulation, such as land-ocean contrasts, surface characteristics (topography and type of surface), and in mid-latitudes storm systems tend to be the daily weather maker.

### 1.4 Climate change and weather

Changes in weather patterns

The Earth’s climate is changing in ways that affect weather and oceans, snow, ice, ecosystems, and society. The release of carbon dioxide from the burning of fossil fuels for energy is one of the main contributors to increasing greenhouse gas concentrations in the atmosphere (Hartman et.al, 2013). This increase is reported to be causing irreversible changes to the earth’s climate, giving rise to temperature increases and other consequent alterations in weather patterns.
Weather can be considered as the total range of atmospheric conditions at any specific time or place. The climate is a sum total of the weather experienced at a place over some period of time. Because the average conditions of the weather elements change from year to year, the climate can only be defined in terms of a longer period of time, and 30 years is a common interval. When the atmospheric conditions such as air temperature, density, humidity etc. change it affects the weather and thus the climate (Petersen, Mortensen, Landberg, Jörg, & Frank, 1997).

With increasing greenhouse gas concentrations, more and more of the earth's heat radiation to space is trapped in the atmosphere resulting in a warming of the atmosphere. This has affected the atmospheric circulation and weather-related phenomena in many ways. It is likely that some features of the global circulation described above have moved poleward, involving a widening of the tropical belt, a poleward shift of storm tracks and jet streams and further the northern polar vortex may have contracted (Hartman et al., 2013). Furthermore, there is evidence that extreme events have changed, with heat waves becoming more common and more intense and an increase in precipitation (Hartman et al., 2013).

Climate change

Climate change may be defined as major changes in temperature, precipitation, or wind patterns, among other effects, that occur over several decades or longer (EPA, 2013).

Climate change and global warming are one of the most critical issues in today's society. Climate change stemming from human activity is one of the greatest challenges to mankind in the 21st century. It is a global issue, and measures designed to reduce it cannot be successful unless the nations of the world act together in a coordinated and harmonious manner (IPCC, 2012).

Various measures have been taken around the world, both minor and major, to reduce the GHG emissions, fight global warming and the possible effects of climate change. The Intergovernmental Panel on Climate Change (IPCC), founded in 1988 is the leading international body for assessing global climate change. It’s role is "...to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation. IPCC reports should be neutral with respect to policy, although they may need to deal objectively with scientific, technical and socio-economic factors relevant to the application of particular policies". The IPCC published its first assessment report in 1990 and following this the United Nations Framework Convention on Climate Change (UNFCCC) was signed in at the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, June, 1992 (IPCC, 2014). The countries of the world have joined forces under the UNFCCC and work within its boundaries in order to coordinate measures for mitigation and adaptation to climate change. Iceland is a part of this framework and operates as such in relation to those matters (The Ministry for the Environment in Iceland, 2006).

In 1997 the Kyoto Protocol to the framework convention was adopted. It binds industrialized nations and the European community to follow emission reduction targets but developing countries were not required to reduce emissions. The targets for the first
commitment period are a 5% emission reduction on average based on the 1990 levels. The Protocol’s first commitment period started in 2008 and ended in 2012. The second commitment period targets are to reduce greenhouse gas emissions by 20% below the 1990 levels (Gruet, R., 2011). This period began on 1 January 2013 and will end in 2020. The UNFCCC and the Kyoto Protocol represent the international response to the evidence, gathered and confirmed by the IPCC, that climate change is occurring, and that it is mainly a result of human activities. (UNFCCC, 2014). In relation to wind power, climate change is thought to have some impacts on the resource in the future. The potential impacts on wind power, in particular, have been studied in recent years mainly with simulation experiments to explore past and present climate as well as various emission scenarios of climate change. In this study, two emission scenarios were examined for evaluating the future vulnerability of wind power at Búrfell.

1.5 Wind power

1.5.1 History of wind power

The wind has been used since the beginning of time and wind turbines have existed in the world in some form for at least three thousand years (Burton et al., 2001). According to writings of Hero of Alexandria from the beginning of the first century, wind was utilized in some way. Illustrations of a windmill providing an organ with air exist and are thought to be from that time. Figure 1-4 from Musgrow’s review (2010) on the first windmills, shows the illustration of how this organ might have looked.

![Figure 1-4 Hero's windmill toy. (From: Musgrow, 2010).](image)

However there has been a debate about whether such a device actually existed and if the drawings were original. Nevertheless there is still evidence that shows that windmills, both mechanically driven and gearing, were most likely first used to water wheels, for grinding grain in mills at that time and some of these types of machine are still in existence in parts of Northern Europe. Evidence of the first windmills, Persian windmills, have been found in
a region in eastern Iran and are thought to be from the tenth century. A detailed description of these windmills dates back to the thirteenth century. Unlike the traditional English windmills these had a vertical axis and were only suitable to use where the winds blew from one prevailing direction. Historically, wind power was used for almost any type of mechanical work from pumping water from the ground, direct consumption and farming irrigation to sawing wood and powering tools. The use of windmills spread rapidly and so-called post mills were introduced. The mills are what people generally imagine when they hear the word “windmill”. They have four sails made from wood and a canvas is spread over the wood framework of each sail. These mills differed from the previous Persian mills mainly due to the fact that they rotated around the horizontal axis, making them more efficient since they were moving in a direction that was at the right angles to the wind. Additionally the Persian windmills were driven by the aerodynamic drag whereas the post mills were more like wind turbines today, which are driven by the aerodynamic lift. An important difference between horizontal axis windmills and vertical axis, drag driven windmills is therefore their efficiency to convert energy into a useful power. The horizontal axis windmills were almost five times more powerful than the Persian windmill. The post windmill is thought to be the result of a very long and creative process of developing windmills in the twelfth century (Musgrow, 2010).

The use of the wind resource continued to develop over time and the initial use of electricity generation from wind power is from the end of the 19th century. A professor from Glasgow, James Blyth, was the first one to build a windmill to generate electricity in 1887. Blyth was an expert in electric matters and very enthusiastic in developing the windmill further. Charles Brush was another pioneer who in 1888 built a large windmill to illuminate his mansion in Cleveland. However, even though those creative innovators found ways to generate wind power for their households neither of them had developed a system which was good enough to use on a large-scale (Musgrow, 2010). The growth and development in wind power generation continued and from the 1930s onwards there were examples of wind turbines for production of electricity being developed in the former USSR, the UK, Denmark, France and Germany but, due to the relatively low price and high availability of fossil fuels, serious interest was not shown until the 1970s (Burton et al., 2001).

During the oil crisis of the seventies, a rising oil price drove governments to invest in research in wind power as an alternative to fossil fuel based power generation. A raft of developments led to the initial trials of wind power for grid connected electricity generation. A number of designs were considered but have converged on a Danish design of a three-bladed horizontal axis machine - although vertical axis turbines made a short appearance in the U.S.A. The Californian state government initiated some of the most favorable financial support mechanisms for wind power development (Manwell et al., 2002) which, in its technological infancy, was much more expensive than conventional power. Thus, it was the first part of the world to use wind power on a relatively large scale in the late 1970s and early 1980s, although with quite small – in today’s terms – 100kW machines (Burton et al., 2001). The Reagan administration terminated the incentives in the early 1980s however, as the oil price stabilized, and the race for wind power generation faded (Manwell et al., 2002).

During the 1990s with mounting concern about climate change and other energy security issues, wind became more attractive to nations keen to establish an indigenous, independent and clean energy source. Denmark is now considered to be the country at the
forefront of wind technology development. It is home to both premier research facilities and a large proportion of the turbine manufacturing industry, and generates approximately 28% of its electricity from wind power. By the end of 2008, the country with the largest installed wind power capacity was the USA with over 25 GW; Germany was a close second with almost 24 GW and the UK was ranked 8th with 3.2 GW (Danish Wind Industry Association, 2013).

In 2011, renewable energy supplied 19% of global energy consumption and the cumulative installed wind capacity in the world was 238 GW. In 2012 the global wind power market grew by roughly 18% compared to that with more than 45 GW of new wind power installed (GWEC, 2013). By the end of 2013 global installed wind power capacity was up to a total of 318 GW with 35 GW of new installations of which 14 GW were added in the first six months of the year. This increase is a little less than in the first half of 2011 and 2012 when 18.4 GW and 16.5 GW were added. The annual growth rate in wind capacity decreased a little between years but wind power is still expected to expand to 1000 GW before 2020 (Fried, 2014).

The utilization of wind energy has been the fastest growing energy technology in the world for the past decade. The biggest wind power producers in the world by country in 2013 were Germany, China, India and the UK. The traditional wind countries are however China, USA, Germany, Spain and India and they represent together over 70% of the global wind capacity. China has currently the largest wind market size of any country and by last June, China had around 67.7 GW of wind capacity from its installations. Out of the EU countries, Germany is the biggest one and Spain, the UK and Italy follow. Europe is still the continent with the most installed capacity which by the end of 2013 was 121,474 MW and is expected to continue growing (Pineda et al, 2014).

In 2013, the UK became one of the major wind energy producers in the world. This enormous expansion mainly involved offshore wind farms. There were only four countries in total which installed more than 1 GW in the first half of 2013, i.e. China, the UK, India and Germany. In 2012, only three countries had a market volume of more than 1 GW so even though the total expansion in 2013 was a little less than in the previous years there was still a huge increase within the industry. In the first half of 2013 the overall wind turbine efficiency of five countries improved from 2012, i.e. China, Germany, the UK, Canada, Denmark. Other five countries, Spain, India, Italy, France, and the USA, experienced some drawbacks whereas the US market came to a virtual standstill, with only 1.6 MW of new capacity installed, only 1% of installed capacity in 2012.

The Global Wind Energy Council (GWEC) is the international trade association for the wind power industry and represents the entire wind energy sector. Figure 1-5 shows the GWEC summary of the total annual installations of wind capacity since 1996.
The total installed capacity by the end of 2013 reached 318 GW as is shown in Figure 1-5 which is enough to provide almost 4% of the global electricity demand. Even though there was a decrease in installed capacity in 2013 it can be expected that wind markets worldwide will set a new record in 2014 (Gsänger, 2013; Fried, 2014). According to Stefan Gsänger, secretary general at WWEA, wind energy can cover the entire demand for energy around the world. Furthermore, he claims that excess wind energy can be used for heating and transportation purposes. Every country can harvest wind energy and in some regions wind energy is the cheapest option for electricity generation. This has been established in Brazil, e.g. where wind power was found to be cheaper than every other energy option – including hydroelectricity and gas (Nielsen, 2011; Climate Change TV, 2013).

To summarize, wind is rapidly becoming a major source of electricity around the world. It varies by regions, with Europe being the leader in installed capacity per capita, but with constant technical development and cost reductions wind power is becoming one of the cheapest options for new electricity in number of areas and will most likely keep on growing for the next years.

### 1.5.2 Wind power in Iceland

While many countries in Western Europe, are focusing on wind power to increase their share of renewable energy, Iceland has not yet constructed a single operating wind farm. The reason is simple: Icelandic energy firms have always had the privilege of being able to harness abundant low-cost geothermal- and hydropower options. Most of these power options are operated by the Icelandic power company, Landsvirkjun, the biggest power supplier. In January 2012, Landsvirkjun started operating two 900 kWh wind turbines. The wind turbines are from the German wind power company Enercon and are of the model E-44 (Landsvirkjun, 2014). They are located in the southern part of Iceland and are a part of a research and development project which the company is conducting on the use of wind power in Iceland. With the construction and installation of these two turbines Iceland became the 100th country to utilize wind energy on the national grid. When considering such a big project there are many factors that have to be accounted for. Landsvirkjun had been monitoring various factors in the area, i.e. wind speeds, possible icing, snow drift, ash and soil erosion, wildlife, environment and society, to name a few. Operation and maintenance cost was studied along with availability percentage of the turbines in the Icelandic nature and possible joint operation with hydropower system, transport and electricity (Landsvirkjun, 2014). In June 2012 Landsvirkjun applied for a license to operate
two wind turbines. In October 2012 the Icelandic power company Landsvirkjun started constructions for installing two wind turbines close to Búrfell Hydropower station in a region called Hafið. The constructions were finished in December and the turbines have been up and running since January 2013. The wind turbines have 900 kW each capacity with 1.8 MW of total installed power. They are estimated to generate up to 5.4 GWh/year. The hub height is 55 meters and the spades are 22 meters long resulting in 77 meters at the highest point. The turbines were produced by the German energy company Enercon, which specializes in manufacturing direct-drive wind turbines where the generator produces electricity with fewer turns resulting in reduced energy loss and noise, increased engine life, reduced mechanical stress, etc. When wind speed is between 15 – 28 m/s, the turbines reach full capacity but below 3 m/s and above 34 m/s the generation stops. The turbines are located in an area with relatively stable wind speeds. They are connected to an underground electric cable which lies to Búrfell Hydropower station and the cables are underground in order to minimize environmental effects. The wind turbines were located close to the hydropower station mainly due to favourable wind climate and access to the grid. The area has good wind energy potential due to relatively high average wind speeds. The area has shown the potential of offering a capacity factor close to 50% which is exceptionally high for an on-shore wind farm and the access to the transmission grid is good so it was easy to connect the turbines to the electricity distribution system. This location for wind power technology development is therefore thought to be feasible in many ways.

The German energy company, Enercon, conducted the installation of the turbines and after the constructions were finished and necessary monitoring and testing was completed the project was handed over to Landsvirkjun (Landsvirkjun, 2014).

Figure 1-6 Looking south at wind turbine 1, at Hafið with Búrfell in the background. (From: Landsvirkjun, 2014)
Wind power utilization is still at an early stage in Iceland. There are many areas that have been monitored for some time and show great potential for setting up wind turbines. With this research and development project Landsvirkjun aims to provide operational experience with wind turbines onshore and in the Icelandic climate. A few Icelandic institutions and companies including the Icelandic Meteorological Office and Landsvirkjun, have in recent years participated in the Nordic wind energy project ICEWIND. The objectives of ICEWIND are to support European targets for the amount of renewable power integration into the power systems in 2020, with the inevitable move towards offshore. The project outcomes are expected to be relevant for other cold climate areas of the world. One of the products of the project is an Icelandic wind atlas (Nawri et al. 2014). The project is supported by the Nordic Top-level Research Initiative and the Nordic wind energy industry and will hopefully offer opportunities to increase renewable electricity generation in Iceland (Thorsteinsson & Bjornsson, 2011).

1.5.3 Wind power production at Hafið

The two wind turbines started operating at Hafið in January 2013 and have showed remarkable results during their first year. Before operation they were estimated to produce on average 5.4 GWh in one year. The most recent data show a total production of 6 GWh and a capacity factor of almost 40%.

The following figures show the production distribution each month for the first year of the turbines operating. In Figure 1-7, for wind turbine 1, the maximum production months were January and December. January shows a combination of numbers from 2013 and 2014 because production in 2013 began on January 21st. Therefore, in order to get a complete year, the values from January 2013 (21st – 31st) and January 2014 (1st-20th) were combined. The same goes for Figure 1-8 illustrating the production and wind speeds for turbine 2.

![Figure 1-7 Wind energy production (MWh) in the first year of production from wind turbine 1 (columns) and the monthly mean wind speed (line, m/s). (From: Arnardóttir, M. (personal communication, January 2014))](image-url)
Figure 1-8 shows a similar pattern, which is expected as the turbines are located close to each other. The location of turbine 1 is shown in Figure 1-6 and turbine 2 is located approximately where the photo is taken, just 500 meters NW of turbine 1. The production in May and July (2013) was significantly lower in wind turbine 2 but due to the fact that it was out of operation most part of May and for some time in July as well.

![Wind energy production (MW/h) in the first year of production from wind turbine 2. (columns) and the monthly mean wind speed (line, m/s). (From: Arnardóttir, M. (personal communication, January 2014)).](image)

The figures show good possibilities for further utilization, but in order know the full potential of the area, it is important to examine all externalities, including possible climate change effects on the source.
1.6 Literature review of potential climate change impacts on wind power

Renewable energy sources are thought to play a huge role in climate change mitigation in the future. Climate change might possibly affect wind energy since the wind energy is a function of the cube of wind speed as well as e.g. the density of air. A slight change in the wind climate can therefore affect the wind as an energy resource. The possible impacts of climate change on wind energy have been investigated to some extent, mainly focusing on the measured near-surface wind speeds and recent articles have reported possible declines in wind speeds leading some to doubt the prospects within the wind industry (Pryor & Barthelmie, 2010).

Climate change concerns and its possible effects on the future have been a major incentive in utilizing renewable energy sources further and developing the technology within that field. Global use of renewable energy has grown rapidly and in 2012 wind energy continued to grow significantly (Fried, 2014). Climate change is however thought to have some impact on the resources. Recent studies show that the increase in global average surface temperatures may reduce the availability of wind energy for electricity production in some areas. Average surface temperatures are thought to possibly affect the atmospheric circulation and therefore the global wind patterns, i.e. the trade winds and the westerlies, at least during the extreme events (Earthguide, 2013).

Wind as a source renewable energy is governed ultimately by the climate which, as mentioned in the previous section, is projected by climate scientists to undergo significant change in the coming century. In the wind climate (Section 1.3.2.), it was noted that the atmospheric circulation is driven by difference in solar heating. From the definition of renewable energy, it is understood that most of the renewable resources are governed by the sun. Consequently, it is likely that in a changing climate, renewable energy resources are going to be vulnerable to that change.

A number of studies have been done on whether hydro power production may possibly be reduced due to the predicted changes in climate. Hydro power might possibly be more affected than wind power due to glaciers melting and changes in precipitation patterns. According to Harrison et al. (2003) climate change will most likely have negative effects on river flows, making hydro power projects susceptible to climate change. Hydro power is an important factor in the Icelandic energy mix. It is relatively stable and the energy is generally reliable throughout the year. This reliability can however vary between years due to lack of precipitation which affects the storage in the reservoirs and therefore hydropower is said to fluctuate between years. According to the Nordic projects (CE and CES) the mass balance of glaciers in Iceland is changing rapidly due to the climate changes. Approximately 11% of the country is covered with glaciers or ice and roughly 20% of the total precipitation is stored there. In these Nordic projects, climate model simulations were used to project the possible impacts of climate change on glaciers and ice sheets. The results showed e.g. that most glaciers and ice caps will disappear in the next 100 – 200 years which will affect the runoff water from glacier rivers to hydro power plants significantly. The potential energy in the total river flows to the power system of Landsvirkjun will increase significantly by 2050 (Fenger et al, 2007; Þorsteinsson & Bjornsson, 2012). The possibility of using hydro power with wind power has also been discussed. Wind power fluctuates daily but is relatively stable from year to year but with
seasonal variations. Wind power can be used throughout the year and reduced the need for water regulation. Combining these two renewable energy sources to create a balance in the system might be a good addition to the energy mix in Iceland.

With recent growth in wind power generation, studies of climate change impact on the resource are increasing. Most climate change studies related to effects on wind energy use climate models, both regional (RCM) and global (GCM), for empirical and dynamical downscaling of future wind speeds and changes in wind power density and power production. Regional climate models have been developed to get better climate projections at higher resolutions from coupled atmosphere-ocean general circulation models (AOGCM). A study of the impact of climate change on wind energy resource over the USA based on RCM simulations was conducted by Pryor et al. (2011). The historical trends in wind speeds were analysed and probabilistic projections for the future were made using regional climate model simulations based on input data from three global climate models and one observational dataset. The future simulations that were conducted assumed high CO₂ emission scenarios. The results showed good correlations of the average annual energy density from the four data sets (three simulated and one observed) during the historical period (1979-2000). There were however some discrepancies in the regional and global climate model simulations. The comparisons therefore emphasized the importance of using several models for simulations like these when assessing the wind resource and possible climate change. From the simulations for the future scenario (2041-2062) for all four models, there seemed to be a slight increase in the magnitude of the wind resource due to climate change, over the continental US (Pryor et.al, 2011).

A group of scientists analysed the possible changes in intense and extreme wind speeds over northern Europe by examining near-surface wind speeds under different climate scenarios. This study was based on dynamical downscaling of ECHAM4/OPYC3 AOGCM. The results showed possible higher wind speeds during 2071 – 2100 relative to 1961-1990 for these model simulations but for the RCM simulation with different boundary conditions (HadAM3H) the results were little to no change. This emphasizes the degree of the uncertainty in the projected changes in the wind resource from different model simulations (Pryor et.al, 2005a, b).

In a similar study for northern Europe, based on dynamical downscaling of ECHAM5 using HIRHAM5 and RCA3, extreme wind speeds, wind gusts, directional distribution and energy density were studied because of relevance to the wind energy industry as well as structural engineering projects susceptible to extreme winds. The main results of this study were that extreme wind speeds with long return periods are not likely to increase. Intense winds are also not likely to occur more frequently throughout the course of the 21st century according to the data from this study (Pryor et.al, 2012).

Pryor & Barthelmie (2010) wrote a review on climate change effects on wind energy where they addressed the main factors possibly affecting the wind climate, the wind resource, energy density and the design, operation and maintenance of wind turbines. Pryor & Barthelmie’s review was based on a number of studies, including their own, in which many of them were analyzes based on GCMs and RCMs, with either statistical or dynamical downscaling. According to the paper, by the end of the 21st century, there might be a slight decrease in the wind energy density in southeast Europe during wintertime but an increase in the northern region. The same goes for the annual mean wind speeds. For the
USA, the decline in wind speeds is expected to be less than 5% within the 21st century, based on empirical downscaling using two GCMs.

In Pryor & Barthelmie (2010) some features which global warming might impact were discussed, i.e. icing, extreme wind speeds, sea ice, permafrost, air density, temperature, land use and corrosion to name a few. Climate change can have, and in some cases already has had, significant impacts on these features resulting in changes in design, operation and maintenance for wind farms. For example, increased air temperature results in a decrease in air density which then causes a decrease in the energy density. An increase in extreme wind speeds and wind gusts, especially in ten-minute sustained extreme wind speeds, 3-s average gusts and extreme wind directional changes can be critical when designing wind turbines and needs to be accounted for. Some of these factors, such as increased air temperature, icing and sea ice can have positive effects on the development, i.e. with higher air temperatures there is the possibility of less icing. Therefore, some areas that might have been excluded due to icing can become feasible. The same goes for sea ice retreat, opening unused spaces for further exploitation. The main conclusion from this review is that GCMs and RCMs cannot completely imitate the current and future wind climates but from the research up to the present date it doesn’t seem like the wind speeds and energy density will change much in most parts of Europe and some parts of North America in the 21st century.

The IMO participated in the Nordic Project on Climate and Energy systems (CES) in 2007 – 2011. The main emphasis was on assessing the impacts of climate change on hydropower, wind energy and energy from biomass. Approximately 100 scientists and 30 institutions participated in the project from the Nordic countries and the Baltic region. Regional climate models (among other tools) were used to calculate possible development of air temperature, precipitation and wind speeds in an area covering the Nordic and the Baltic countries. The impact of climate change on average wind speeds had been reported earlier (Pryor & Barthelme, 2010) and therefore the main emphasis was on extreme wind speed occurrences. The overall results show a slight increase in extreme wind speeds (Thorsteinsson & Bjornsson, 2011).

In 2013 the IMO published a report on the Wind energy potential in Iceland as apart of the ICEWIND project. This report was based on simulations from the Weather Research and Forecast (WRF) model to estimate the potential wind energy for 14 different sites in Iceland (see Figure 1-9). This analysis was compared the WRF model simulations and the Norwegian Reanalysis at 10 km spatial resolution (NORA10) with measured data from weather stations. The main result from this study was the wind atlas for Iceland which provides an overview across the coutry of the wind statistics relevant to wind energy assessment. Additionally, wind climates for 14 test sites in Iceland were analysed. The analyzes showed good potential for wind energy generation in Iceland (Nawri et.al, 2014).
Based on the previously reviewed literature the global climate will most likely change storm characteristics and therefore also the current wind resource and thus how the wind industry will operate. However, the changes in annual energy densities are not estimated to be significant during the 21st century and thus the wind energy industry will most likely continue to contribute to electricity generation throughout this century (Pryor et al., 2011) and with further research and technological development hopefully for a longer period of time.
2 Methods

Wind speed data were obtained for the analysis, calculations and modelling, from a 10 meter meteorological mast located in the Búrfell area. The dataset is from 1994 – 2013 and includes hourly values for 10 minute average wind speed as well as 3 second wind gusts for the period. The wind speed distribution were analysed by fitting it to Weibull distribution and associated Weibull parameters obtained. Data sets from several climate models were also analysed in the same way in order to be able to predict the possible future distribution. When the Weibull parameters had been calculated for all data sets the results were compared and analysed. Based on the model projections and the correlation with the actual data from Búrfell an indication for future behaviour was established.

Based on these data the estimated wind energy densities were calculated and the energy potential of the area assessed. The results were compared to the current energy production of the experimental wind turbines in the area. This method gave an estimate of how global warming and climate change might impact the wind energy potential in the area in the future. As an addition to the study it was suggested to look into the possible effects on some other factors that need to be considered when building a windfarm. Factors that are important to consider when designing a windfarm include energy density, icing, air temperature, air density, corrosion, blade erosion due to airborne particles, wind shear across blades, turbulence intensity, occurrence of extreme wind speeds and directional change.

Energy potential and wind speed distribution were the main topics of this study. As mentioned in the literature review, climate change is thought to affect extreme weather patterns in the future and cause an increase in those events. This was discussed briefly in the results section here. Other factors mentioned above in relation to windfarm design were not examined.

2.1 Theory

In this section the theoretical part of the calculations and modeling is discussed with main emphasis on the characteristics of wind speeds and distribution, the potential power that can be extracted from the wind, the analysis of the Weibull parameters and finally the climate models that were used for data gathering.

2.1.1 Wind speed characteristics

Atmospheric motion varies in both time and space. Although the motion is continous it is often helpful to divide it up with regards to the size and time frame of atmospheric phenomena. Figure 2-1 summarizes the variability of atmospheric motion in relation to time and space as applied to wind energy. Space variations depend on large scale atmospheric flow as well as regional and local orography and surface characteristics.
Since wind power is directly related to the wind speed cubed it is imperative to be aware of any site-specific wind characteristics. Even small errors in estimation of wind speed can have large effects on the energy yield, but also lead to poor choices for turbine and site. An average wind speed is not sufficient. The main characteristics related to wind turbine design include average wind speeds, wind speed distributions on an annual basis as well as diurnal and seasonal changes, fluctuations, prevailing wind direction and wind shear.

Wind can vary on a seasonal basis, and as explained earlier winds in Iceland are stronger during winter than summer. Long-term fluctuations in wind speed occur over longer time scales, i.e. greater than one year. Such fluctuations affect wind turbine production in the long run. The ability to estimate the inter-annual variability at a given site is almost as important as estimating the long-term mean wind at a site. To determine the long-term distribution of wind speeds, meteorologists generally use 30 years of wind speed data in order to get as accurate estimations of weather or climate variations as possible. Nevertheless, with the technology today, shorter data records can be useful.

Winds do also vary on very short timescales. Such fluctuations generally include turbulence and gusts and refer to variations over time intervals of ten minutes or less. Ten-minute averages are typically determined using a sampling rate of about 1 second. It is generally accepted that variations in wind speed that have periods from less than a second to ten minutes and a stochastic character represent turbulence. These turbulent fluctuations need to be quantified when assessing wind energy potential since turbine design generally includes maximum load and fatigue prediction, control system and power quality. Turbulence can be thought of as random wind speed fluctuations imposed on the mean wind speed. These fluctuations occur in all three directions: longitudinal (in the direction of the wind), lateral (perpendicular to the average wind), and vertical and can affect the design process (Manwell et al., 2002).
2.1.2 Wind power extraction

Wind turbine power production depends on the interaction between the rotor and the wind. A typical horizontal axis wind turbine uses airfoils to transform the power in the wind by converting kinetic energy moving towards the blades into mechanical energy. Generally the power in the wind can be found by considering the kinetic energy. The kinetic energy of mass in motion is

\[ E = \frac{1}{2} mv^2 \quad (2.1) \]

where \( m \) is the mass flow rate and \( v \) is the velocity of the moving mass. Power is then expressed as

\[ P = \frac{1}{2} mv^2 = \frac{1}{2} \rho Av^3 \quad (2.2) \]

where \( \rho \) is the air density, \( A \) is the swept area of the turbine blades and \( v \) is the cubed wind speed of the incoming air. It is noted that the wind power density is proportional to the density of the air. For standard conditions (sea level 15°C) the density of air is 1.225 kg/m\(^3\). At higher altitude (such as the study site in this thesis) the density is lower, and in this study we assume that the density to be 1.1 kg/m\(^3\). The power from the wind is proportional to the area swept by the rotor.

As mentioned previously the wind power density is proportional to the cube of the wind velocity. For deriving the power coefficient the power can be expressed in the following way,

\[ P = Fv = 2\rho Av^3 a(1-a) \quad (2.3) \]

where \( a \) is an axial flow induction factor in the turbine (see Manwell et.al, 2002) and \( v \) is the cubed wind speed of the incoming air. The power coefficient, \( C_p \), can now be defined as the ratio of power extracted by turbine to the power available in the air,

\[ C_p = \frac{2\rho Av^3 a(1-a)}{\frac{1}{2} \rho Av^3} = 4a(1-a)^2 \quad (2.4) \]

The maximum value of \( C_p \) occurs when \( \frac{dC_p}{da} = 0 \) which gives \( a = \frac{1}{3} \). This results in a power coefficient, \( C_p = 0.593 \).

This value is known as the Betz limit and indicates that the maximum value of energy extracted from the wind can only be 59% of the initial kinetic energy. This limit is most commonly used in relation to the maximum efficiency for horizontal axis wind turbines. In practice, a maximum of about 45% of the available wind power is harvested by the best modern horizontal axis wind turbines (Manwell, 2002).
In Figure 2-2 the Betz limit of the ideal turbine is demonstrated with the power coefficient on the y-axis and the tip speed ration on the x-axis. The tip speed ratio is the ratio between the rotational speed of the tip of a blade and the actual velocity of the wind and is related to the efficiency of a turbine. The results show that, as the tip speed ratio increases, the closer the power coefficient can get to the theoretical maximum value. These equations can be used to look at the operation of an ideal wind turbine, assuming wake rotation. Wake rotation losses occur when wind turbines rotate at lower velocities, resulting in a lower power coefficient. Losses due to these wake effects are less in high speed wind turbines with higher tip speed ratios and therefore lower torque.

As seen in Equation (2.2) the relationship between the power available in the wind and the initial wind speed when hitting the blades of a turbine is cubic. That indicates that a minor change in the velocity can greatly impact the power output from a turbine. For this reason it is important to study the changes in wind, both short term and long term in order to utilize the wind in the most efficient way possible (Manwell, 2002).

2.1.3 Wind data analysis

Wind data analysis can be done in a number of ways. Wind data generally include average horizontal wind speeds over specific time intervals, variations in the horizontal wind speed over the sampling intervals (standard deviation, turbulence intensity, maxima), average horizontal wind direction, variations in the horizontal wind direction over the sampling intervals (standard deviation), speed and direction distributions, duration of the wind speed within a given wind speed range, gust parameters estimation, analysis and autocorrelation, power spectral density, length and time scales, and spatial and time correlations with nearby measurements, steady and fluctuating wind components (u, v and w) and finally diurnal, seasonal, annual, inter-annual and directional variations of any of the before mentioned parameters.

The most important parameter to have when assessing the potential of a prospective wind turbine site is the average wind speed distribution. The extreme wind speed distribution is
also important since it includes the highest wind speed expected over a specific period of time. Extreme wind speeds are of particular concern in the design process, since turbines are generally designed to withstand defined extreme events, such as the fifty year occurrences or other similar infrequent conditions. Extreme winds are normally described in terms of likely recurrence period, i.e. how long the periods are expected to be between events. Particularly, a value of an extreme wind speed is the value of the highest wind speed, averaged over some appropriate time interval, with an annual probability of occurrence of 1/N years.

The wind speed distribution is one of the main wind characteristics. It is of great importance not only for structural and environmental design and analysis, but also for the assessment of the wind energy potential and the performance of wind energy conversion system as well. Over the last two decades many studies have been devoted to development of adequate statistical models to describe wind speed frequency distribution with probability density functions.

The Weibull, Rayleigh and Lognormal probability density functions are commonly used for fitting the measured wind speed probability distribution. The Rayleigh distribution uses one parameter: the mean wind speed. The Weibull distribution is based on two parameters and, thus, can better represent a wider variety of wind regimes. Both the Rayleigh and Weibull distributions are called ‘skew’ distributions in that they are defined only for values greater than 0 (Manwell et al., 2002).

The wind speed probability density distributions and their functional forms represent the major aspects in wind related literature. Their use includes a wide range of applications, including identifying the parameters of the distribution functions and analyzing the wind speed data as well as wind energy economics (Buhairi, 2006).

In this thesis, the Weibull density function was used to analyze the data and describe the wind speed frequency distribution.

**2.1.4 Weibull distribution analysis**

A Weibull distribution is a function commonly used for fitting wind speed frequency distributions. It is widely used in statistical analysis on wind data to represent the wind speed probability density function.

As covered in previous section, wind energy density $E$ is proportional to air density ($\rho$) and wind speed ($v$) at the specific height in question. By assuming that time series of wind speeds conform to a two parameter Weibull distribution as is common in most high-wind speed environments (Manwell et al., 2002) the power can be expressed as

$$P(U) = 1 - \exp \left[ -\left( \frac{v}{A} \right)^k \right]$$

where $A$ (m/s) and $k$ (nondimensional) are the Weibull scale and shape parameter, respectively. The size of the shape parameter describes the influence of the topography on wind speeds and ranges between 1.2 (mountains) to 4.0 (monsoon regions). The scaling factor $A$ is roughly 125% of the average annual wind speed. Generally, the wind speed
distribution is measured first, and then the size of the parameters is estimated and then used for further calculations.

Examples of Weibull probability density functions, for various values of $k$, are given in Figure 2-3. The peak of the curve gets sharper as the value of the shape parameter increases, indicating that there is less wind speed variation.

![Figure 2-3 An example of Weibull probability function for various shape factors, $k$ and an average velocity of 6 m/s (From: Manwell et al., 2002)](image_url)

In this study, the shape and scale parameters were estimated with the built-in Weibull distribution function in the statistical programme R (R Core Team, 2013).

### 2.1.5 Energy density

When the Weibull parameters have been calculated from the wind data in a specific area the energy density, $E$, in W/m$^2$ can be determined with the following equation, (Nawri et.al, 2013),

$$ E = \frac{1}{2} \rho A^k \Gamma \left(1 + \frac{1}{k}\right) \quad (2.6) $$

Where $\rho$ represents air density, $\Gamma$ is the standard Gamma function and $A$ and $k$ are the scale and shape parameters. Generally, a higher $k$ value will result in a higher modal value of wind speed but lower frequencies of winds at high speeds. Higher $A$ values tend to produce more spread distributions that have larger ranges of wind speeds. The combined effects of various $A$ and $k$ parameters will result in permutations of the typical Weibull shape in terms of skewness and spread. The Weibull distribution is reported to be representative of the hourly wind speed distribution at most wind sites (Petersen, 1997) but a Weibull distribution fitted to daily wind speeds is potentially different in terms of the shape parameter as time-period averaging will reduce the variance in the data.
The Gamma function is defined as

\[ \Gamma = \int_0^\infty e^{-x}x^{t-1} \, dx \quad (2.7) \]

where the Gamma is a function of the shape parameter, \( k \), i.e. \( x = (1 + 1/k) \).

For the mean energy density, a 95% confidence interval is generally calculated. Confidence intervals are indication of the calculations accuracy as well as a measure of how stable the calculated value is. The confidence interval is calculated from the sample mean \( (E_{\text{mean}}) \) and the sample standard deviation \( (\sigma) \). First, the margin of error is calculated

\[ x \cdot \frac{\sigma}{\sqrt{n}} \quad (2.8) \]

where \( x \) is the confidence coefficient, here 1.96 for 95% confidence interval and \( n \) is the sample size. The confidence interval can be calculated (R Core Team, 2013) as

Upper limit \( E_{\text{mean}} + \text{margin of error} \) \quad (2.9)

Lower limit \( E_{\text{mean}} - \text{margin of error} \) \quad (2.10)

### 2.1.6 Wind speed extrapolation

Wind speeds vary depending on their elevation above ground. Two mathematical models or laws are generally used when modeling the vertical profile of wind speeds in flat terrain. The first one is the log law. The log law is based on a combination of theoretical and empirical research. The second one is the power law and was used in this study to extrapolate wind speeds higher up. It can be described as a simple model for the vertical wind speed profile and is represented with the following equation,

\[ \frac{U(z)}{U(z_r)} = \left( \frac{z}{z_r} \right)^\alpha \quad (2.11) \]

where \( U(z) \) is the wind speed at height \( z \), \( U(z_r) \) equals the wind speed at height \( z_r \) (note: \( z = 10 \) m in this study) and \( \alpha \) is a power law exponent, related to the surface friction. In practice it varies with parameters like time of day, season, surface roughness, temperature, etc. (Manwell, et al. 2002).

In Iceland, the value \( 1/7 \) (0.143) has been used for this exponent. According to Blöndal et.al (2011) this value gives approximately 25.8% increase in wind speeds extrapolated from 10 m up to 50 m AGL and 34.6% higher wind speed from 10 m to 80 m AGL. However Petersen & Björnsson (2012) found that for the Búrfell area the most optimal value is 0.12 for most parts of the year (a slightly lower during summer when the wind speed is also lower). With this value the increase in wind speed from 10 m AGL (above ground level) up to 50 m AGL (possible hub height) can be 21.3% and up to 100 m AGL it
can be 31.8%. For the modeling and analysis part in this study the power law exponent used will be 0.12.

### 2.1.7 Climate models

Climate change predictions depend on many external factors. Current and future emissions of greenhouse gases and other natural and man-made forcing elements determine partially the future behaviour of the climate system. Modelling and simulating the future of our climate can therefore be extremely complex and is based on various scenarios which then are used for climate model projections. With an ensemble method the results from multiple models and scenario simulations can be applied to map out the possible future and understand the uncertainties (IPCC, 2013).

Regional Climate Models (RCMs), are physical climate models which provide higher resolution on climate information than Global Climate Models (GCMs), but over a much smaller regional area (see Figure 2-4). The driving conditions for the RCM, i.e. surface boundary conditions, initial conditions, etc. are obtained from a GCM. The models work on similar physical principles as the RCMs, modelling the dynamic response of circulations and climate variables but within a small area to the large scale forcings from the GCM data. The advantage of using RCMs to downscale GCM data is that they are capable of producing physically consistent output at high enough resolution to be used in regional climate impacts studies. They are however quite complex and require large computational resources and time (Giorgi et al, 2001; Pryor et al, 2005b).

![Figure 2-4 The regional climate model nesting approach. (From: Giorgi, 2008)](image)

In recent years there have been research projects where several different RCMs where run in a coordinated fashion using data from selected GCMs. A current project of this type is the Coordinated Regional Climate Downscaling Experiment (CORDEX). The main goals of CORDEX were to create a framework for evaluating and comparing the range of dynamical and statistical approaches of regional climate downscaling used around the world, proposing the best ones when possible. Additionally CORDEX has contributed significantly to the WMO Global Framework for Climate Services by providing climate
predictions at the regional scale and through increasing science capacity in developing regions (Giorgi et.al, 2009)

2.2 Data

2.2.1 Data gathering

The measurements applied in this study were obtained from IMO. These are from the automatic weather station Búrfell located just northeast of Búrfell (64°07.010', 19°44.691'). Figure 2-5 shows the meteorological mast at Búrfell and the location is shown in Figure 1-1.

*Figure 2-5 The 10 m met mast at Búrfell (From: Landsvirkjun, 2013).*

The weather station is close to where the experimental wind turbines are at Hafið and its elevation is 249 m.a.s.l. The national power company, Landsvirkjun, is the owner of the station and it has been operating since 1993 (IMO, 2014).

The simulation data sets were obtained from the CORDEX project discussed earlier. In this study, the results from a specific RCM from the Swedish Meteorological Institute (SMHI) were used for running the simulations for the CORDEX data. This RCM is a new version of the Rossby Centre regional atmospheric model, called RCA4 (Kupiainen et.al, 2011). To run this model within CORDEX, two types of GCMs were used as boundary conditions and scaled down in a grid with 12 km large boxes covering the whole of Europe. These GCMs were the CNRM-CM5 (Voldoire et.al, 2011) from CERFACS climate modelling and the European ECEARTH (Hazeleger et.al, 2012). For these two combinations, i.e. the ECEARTH-RCA4 and CERFACS-RCA4 there were 3 different simulations performed.
The first one was for the historical period (1970-2005). The other two were for different emission scenarios, i.e. RCP4.5 for a likely scenario of CO₂ emissions and RCP8.5 for an extreme scenario of CO₂ emissions. These simulations should be able to demonstrate how RCA4-GCM coupled models react to global warming. The models used in this study have been presented in this section. Table 2-1 is a summary of the models, the time period they cover and how they will be discussed and abbreviated in the following sections.

Table 2-1 The models from the CORDEX runs used in this study are presented below. The models are described briefly, i.e. what the RCM’s and the GCM’s are, which scenario do they describe, which time period do they cover and how are they abbreviated in the following sections of this thesis. The last row in the table briefly describes the observed data from Búrfell.

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Time period</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCA4</td>
<td>Historical values from the CERFACS model</td>
<td>1970 – 2005</td>
<td>CERH</td>
</tr>
<tr>
<td></td>
<td>Emission scenario 45</td>
<td>2050 – 2100</td>
<td>CER45</td>
</tr>
<tr>
<td></td>
<td>Emission scenario 85</td>
<td>2050 – 2100</td>
<td>CER85</td>
</tr>
<tr>
<td>ECEARTH</td>
<td>Historical values from the ECEARTH model</td>
<td>1970 – 2005</td>
<td>ECH</td>
</tr>
<tr>
<td></td>
<td>Emission scenario 45</td>
<td>2050 – 2100</td>
<td>EC45</td>
</tr>
<tr>
<td></td>
<td>Emission scenario 85</td>
<td>2050 – 2100</td>
<td>EC85</td>
</tr>
<tr>
<td>Observed data</td>
<td>Búrfell data</td>
<td>1993 – 2013</td>
<td>BUR</td>
</tr>
</tbody>
</table>

2.2.2 Data analysis

For data analysis, the statistical programme R, through R Studio (R Core Team, 2013), was mainly used. As mentioned previously, the IMO provided all data. The data were imported into R Studio where the Weibull constants and energy densities were calculated. These climate data sets were retrieved from the Earth System Grid Federation (ESGF) server of the Danish Meteorology Office (DMO). The data loaded from there were model simulations for wind speeds, one value per day. The results were then interpolated to the location (same GPS points) of the meteorological mast at Búrfell. Therefore, the data from the models are time series with a daily resolution and the time stamp was always 12:00. It is important to note that the daily model values are daily averages of model fields, in contrasts with the observations from Búrfell, but those data were 10 min averages supplied for each hour of the day. The Búrfell data was therefore altered, i.e. the average daily value for each day was calculated based on the 10 min averages to ensure consistency between the data sets in further calculations. Table A – 1 in Appendix A shows the range of wind speeds for the last 30-40 years. The table also shows the projected wind speeds for the years 2050-2100.
3 Modeling and results

3.1 Wind speed distributions

The annual energy output which can be expected from a wind farm depends on the potential wind power output which varies by the wind speed and therefore the wind speed distributions for a proposed wind farm site needs to be known beforehand.

First, the wind speed distributions were assessed by comparing the daily average wind speeds from observations at Búrfell and all climate model simulations in a boxplot as shown in Figure 3-1. In each box the central mark represents the median. The edges of the boxes are the lower hinges which are defined as the 25th percentile and the upper hinges which are defined as the 75th percentile. The distribution extends to the upper whisker which represent the most extreme data points which are not considered outliers. An outlier is an observation that is numerically distant from the rest of the data and is plotted individually. The lower whisker runs from the lower hinge of the box to the extreme low observation. Figure 3-1 shows slightly lower wind speed in the CERH simulation than in BUR observations. The ECEARTH runs seem to have somewhat stronger winds and the ECH run, the historical simulation, is quite similar to the actual measured data from Búrfell. For both CERFACS and ECEARTH the wind speeds seem to decrease in the RCP runs, slightly more for the RCP85 emission scenario than in the RCP45. From this short and simple analysis the ECEARTH runs are probably the most comparable to the Búrfell data.

![Figure 3-1: A boxplot of daily average wind speed distribution (m/s) for all data sets. See Table 2-1 for clarification of the names of the data sets. The dotted tail above each box represents the distribution of higher wind speeds, i.e. the extremes. The boxplot summarizes the average wind speeds and shows the correlation between the models.](image)

For further analysis the timeseries were examined in order to check possible errors in the data and compare the wind speed distributions from observations at Búrfell to the historical runs and the projected scenarios. The mean annual wind speeds were plotted up instead of daily mean in order to avoid chaos in the figures. An overview of the average, maximum and minimum wind speeds from all model simulations and observations can be found in Table A-1 in Appendix A.
The following figures in this section (3.1) show the annual average wind speed distributions for the observed data at Búrfell as well as all climate model simulations. For the distribution at Búrfell (Figure 3-2) the annual averages ranged from 6.5 – 7.5 m/s and for the whole time period the average is 7.02 m/s. The distribution from 1993 to 2013 shows slight fluctuations and an overall decrease in the wind speeds over this 20 year time period.

![Figure 3-2 Observed annual average wind speed distribution (m/s) at Búrfell from 1993 – 2013. The distribution is relatively even for this 20 year period.](image)

The points represent the observed data and the solid curve is found using smooth loess method to demonstrate the smoothed conditional mean of the data set. The loess method builds a curve which describes the main part of the variations in the data. This method enables a simple interpretation of big and complex data sets. The shaded area shows the 95% confidence interval for the smooth loess curve (R Core Team, 2013).

A comparison of the historical runs from both GCM’s is shown in Figure 3-3. The points represent average wind speed for each year. The curve was plotted to get the overall trend in the data. The annual averages for CERH ranged from 6.7 – 7.1 m/s and the overall average wind speed for the CERH time series was 6.39 m/s. For the ECH the annual averages ranged from 6.3 – 6.5 m/s and the overall average wind speed was 6.47 m/s so the difference is not much. They grey area represents the confidence band based on the observed wind speeds. Comparing these distributions to the BUR observations, the ECH average was a bit closer to the average wind speed at Búrfell than the CERH. The difference is however not significant and therefore both data sets (CERH and ECH) are considered reliable in comparison to Búrfell and the future projections for now.
Figure 3-3 Annual average wind speed (m/s) for historical runs with ECEARTH and CERFACS from 1970 – 2005. The distribution is relatively even for this 35 year period.

The comparison of the two CO₂ emission scenarios for CERFACS, CER45 and CER85, is shown in Figure 3-4. These scenarios were presented in Table 2-1, where RCP45 is a likely scenario to happen and the RCP85 is the worst case scenario for the latter part of the 21st century (2050 – 2100). As in previous figures (Figure 3-3 and Figure 3-2) the dots represent average wind speed for each year. The curve was plotted to get the overall trend in the data. They grey area represents the confidence band based on the observed wind speeds. The annual average wind speeds for the time period for CER45 ranged from 5.9 – 7.0 m/s and the overall average was 6.3 m/s. For CER85 the range of annual average wind speeds was from 5.6 – 6.7 m/s and the overall average was 6.1 m/s. As the range of wind speeds for both scenarios indicates, the average values fluctuate somewhat throughout the time period. The overall trend is however a decrease for both scenarios. Comparing those scenarios to the BUR distribution results in an 11% decline in average annual wind speeds for CER45 and a 13% decline in average annual wind speeds for CER85.
A comparison of the two CO₂ emission scenarios for ECEARTH, EC45 and EC85, is shown in Figure 3-5. As mentioned before, these scenarios were presented in Table 2-1, where EC45 is a likely scenario to happen and the EC85 is the worst case scenario for the latter part of the 21st century (2050 – 2100). As in previous figures (Figure 3-2, Figure 3-3 and Figure 3-4) the dots represent average wind speed for each year. The curve was plotted to get the overall trend in the data. They grey area represents the confidence band based on the observed wind speeds. The annual average wind speeds for the time period for EC45 ranged from 6.2 – 7.1 m/s and the overall average was 6.7 m/s. For EC85 the range of annual average wind speeds was from 5.8 – 7.3 m/s and the overall average was 6.5 m/s. The distribution shows fluctuations of wind speeds throughout the whole time period but overall there will be a decrease in average wind speeds for the EC85 simulation during this 50 year period. For the EC45 simulation the average annual wind speeds fluctuate in the beginning showing an increase in wind speeds but are stable from mid-century and throughout the rest of the period. Comparing those scenarios to the BUR distribution results in an 5% decline in average annual wind speeds for EC45 and a 7% decline in average annual wind speeds for EC85.
Figure 3-5 Annual average wind speed (m/s) from ECEARTH model for emission scenarios from 2050 – 2100. The distribution shows an overall decrease in average wind speeds for this 50 year period.

The results from the analysis of the wind speed distributions within the simulations and the observations from Búrfell show a relatively stable trend in all distributions. A comparison of the historical model runs shows that the RCA4 generates more wind when using ECH data than when using the CERH data. For the emission scenarios the wind is generally higher for the EC45/CER45 than for the EC85/CER85. There are however some values in between during the beginning of the ECEARTH run (ca. 2050 – 2055) where the EC45 are lower than the EC85. The final conclusion from this analysis is that the average wind speeds is likely to decrease in the Búrfell area, but the extent of change depends on the actual future emission scenario. The correlation between the two historical runs (ECH and CERH) and the observed data from Búrfell is very good and strengthens the results presented in the following chapters.

Based on this analysis there might be some bias in the data which need to be corrected for before using the results. It can however be good to review the data before correcting to see how the corrections can affect the results in the end.

### 3.2 Weibull distribution analysis

According to Nawri et al. (2013) common values for the Weibull parameters are approximately 7 for the scale factor \((A)\) and 2 for the shape factor \((k)\). These values are initial values to use for the maximum likelihood estimation (MLE) for the Weibull parameters, \(A\) and \(k\). The calculations were done via the program R Studio with the MASS package (R Core Team, 2013) and the complete code is shown in Appendix B. Note that when using the MLE method to find the Weibull distribution, all zero-values have to be eliminated.
3.2.1 Weibull distribution plots

The results from the Weibull parameter calculations show that the climate model correlates with the observed data from Búrfell. Figure 3-6 shows the comparison between the empirical cumulative distribution function and the cumulative distribution function related to the Weibull parameters for BUR and simulations from all climate models. The multi-panel figure of the Weibull distribution for all climate models shows a good correlation between the theoretical model and the observed and projected wind speed distributions of daily average wind speed data. The cumulative frequency is also known as the probability plot and represents the sum of the frequencies from the lowest value up to the considered point, in this case from zero to one. The data departs from the distribution only at low winds, which is acceptable for wind energy calculations since low winds have less an

![Weibull distribution plots](image)

*Figure 3-6 Empirical Cumulative Distribution Function (blue curve) and Weibull Cumulative Distribution Function (black curve) for BUR and all model simulations. From left to right and downwards, the figures represent Weibull distribution: BUR, CERH, ECH, CER45, CER85, EC45 and finally EC85.*
impact on total energy density. The blue curve represents the empirical distribution and the black curve is the fitted Weibull distribution of the observed and simulated data.

### 3.2.2 Scale and shape parameters

The wind speed data sets from the model simulations and observations at Búrfell were analyzed using Weibull distributions in order to investigate the Weibull shape and scale parameters and to see whether there were any significant changes in these parameters. The data sets fitted quite well to the Weibull distribution except for the lowest wind speed values, as was presented in previous section. However, that is not important when it comes to energy density calculations and wind power production since wind turbines generally do not start operating until the wind speed reaches 2 – 3 m/s.

To examine the distribution further the shape and scale parameters, with 2.5% and 97.5 confidence intervals, from all data sets were compared. They are presented in Figure 3-7 and Figure 3-8. The scale parameters were in the range of 6.9 – 7.9. These values are within the range of the average annual wind speeds of the data sets discussed in Section 3.1 and consistent with the description of the scale parameter in Section 2.1.4, which are roughly 125% of the average annual wind speed. The ECEARTH and CERFACS model simulations differ in values but the trend in the scale parameter for both models is similar.

![Figure 3-7 Scale factors for BUR and all model simulations. The scale factor A (m/s) will decrease based on projected scenarios CER45, CER85, EC45 and EC85.](image)

The reason for the variations between the models is the slight difference in average annual wind speeds which was discussed in Section 3.1. Additionally, according to Petersen (1997), higher values of A tend to produce more spread distributions that have larger ranges of wind speeds. Figure 3-7 shows a decrease in the scale parameter for the projected scenarios which might indicate a less spread distributions of larger ranges of wind speeds since the values for the projected scenarios seem to move further and further away from
the observed and historical values. Accurate values of the scale parameters are presented in Table A-2 in Appendix A.

The shape parameters were calculated in a similar way and the results are presented in Figure 3-8. The shape parameter describes the nature of the wind, i.e. variability or stability of the resource. Characteristics of the shape parameter were briefly described in Section 2.1.5. Typically, a higher $k$ value will result in a higher frequent value of wind speed but lower frequencies of winds at high speeds. For most common wind conditions, the value of $k$ ranges between $1.5 - 3$. Smaller values of $k < 1.5$ correspond to highly variable wind or potential gusts, whereas $k = 2$ corresponds to moderate wind. A shape parameter with $k > 3$, indicates regular, steady wind. (Zaccheus & Komla, 2012). In this case the shape parameters were in the range of $2.1 - 2.4$ indicating a moderate to steady wind. Historical values for BUR, CERH and ECH were somewhat different. This difference is most likely due to the wind speed variations within each data set because even though the averages for the annual wind speeds were quite similar for all data sets (see Section 3.1 and Table A-1 in Appendix A) the frequency of high and low wind speeds varies between.

![Figure 3-8 Shape factors for BUR and all model simulations. The shape factor $k$ will increase according to EC45 and EC85 but decrease according to CER45 and CER85.](image)

Figure 3-8 shows an increase in the shape factors for the projected scenarios based on the ECEARTH model simulations. The ECH model value is slightly lower than the BUR value or approximately 5%. The CERH model value is almost 10% lower than the BUR value which indicates that the ECEARTH projected scenarios are more likely to represent the future change of the shape factor. The ECEARTH model simulation for both historical and projected scenario show almost a linear increase in the shape parameter. The CERFACS model simulation however gives a low shape parameter for the CERH, a slight increase for the CER45 scenario and then a decrease for the CER85 scenario. As previously stated these variations between models are due to difference in average wind speeds within the
data sets. To support this explanation, the maximum wind speeds of each data set show a similar pattern (see Table A-1 in Appendix A).

To summarize the results for the parameters presented in this section, there will be a decrease in the scale parameters at Búrfell according to the projections from ECEARTH and CERFACS models indicating lower average wind speeds in the future. The shape parameter will most likely increase based on the projections from ECEARTH model, indicating more stable winds in the area. In theory, average energy density, decreases with increasing \( k \). This will be discussed further in the following sections.

### 3.3 Energy density

In Section 2.1.4 the theory behind the Weibull distribution analysis was presented followed by theory and equations for calculating energy density based on the Weibull parameters. Equation (2.6) has 4 variables, the gamma function (a built-in function in R), the shape parameter \((k)\), the scale parameter \((A)\) and the air density \((\rho)\). According to Nawri et al. (2013) the standard air density for wind energy assessment is \( \rho = 1.225 \, \text{kg/m}^3 \) for dry air with air temperature of 15°C and atmospheric pressure of 1013.25 hPa. Icelandic climate differs from these conditions depending on the terrain elevation at the site under consideration. For the Búrfell area the air density can be assumed 10% lower than the standard air density. The air density in this study was assumed constant with the value \( \rho = 1.1 \, \text{kg/m}^3 \). This value affects the energy density calculations and varies from season to season. Assuming it to be a constant can therefore cause a skew in the results. The implications are addressed further in the discussion section. The energy density was calculated along with upper and lower confidence intervals (same as for the Weibull parameters) and the results are shown in Table A-4 in Appendix A.

Since the gamma function is a monotonically decreasing function, the highest energy density come from the largest scale factor and smallest shape factor. The estimation of the extreme values (confidence interval for upper and lower limits) is therefore wider than a standard 95% interval since it assumes that the worst extreme values of \( A \) and \( k \) happen simultaneously. This does not really affect the energy density calculations. However another approach to estimate the 95% interval was to assume the uncertainties (upper and lower limits) for \( A \) and \( k \) are normally distributed around the median value. This was done with calculations in R Studio, see Appendix B. The theory behind this was basic and was briefly explained in Section 2.1.5. The adjusted and corrected confidence intervals for upper and lower limit were calculated based on equations in Section 2.1.5 and are presented in Table A-5 and Figure 3-9. After the corrections for the confidence interval of the energy density the interval of confidence decrease slightly, giving a better estimation of the actual energy density value.

The energy density at 10 m AGL in Figure 3-9, for BUR and ECH is similar. The EC45 and EC85 values show a significant decrease in the energy density for the time period 2050 – 2100, compared to BUR and ECH. Although the results based on the CERFACS model are much lower than the ones based on the observed wind from Búrfell, the trend in the future scenarios is still the same, showing a decrease in energy density at 10 m AGL. This indicates that climate change might affect the wind energy potential within the Búrfell area to some extent.
The energy densities calculated in this section were all based on wind speeds at 10 m AGL. Wind turbine towers vary from 30 – 50 meters and up to 100 – 135 meters height. To get a more specific estimate for possible energy potential of the Bíurfell area, the wind speeds from all data sets were extrapolated up to 50 m and 100 m. The calculations will be presented and discussed in the following sections.

### 3.4 Adjustments of the wind speed

The main objective of this study was to see whether and how predicted climate change might impact the wind energy potential in Iceland. With two historical data sets (ECH and CERH) from a regional climate model and one observed from Bíurfell the possible change for two emission scenarios was estimated. Wind speeds in the historical models were corrected based on the average values in the measured wind, i.e. the difference between the measured and the modelled wind speed in the historic run was calculated and added to the model results. Calculation setup is shown in the R Studio code in Appendix B.

**Height extrapolation**

Additionally, since energy density values calculated from the models were all based on the observed/re-analyzed wind speeds at 10 m height and the wind turbine hubs are generally located higher above ground, corrections for the height were applied and the adjusted wind speed values were extrapolated up to 50 meters above ground level, based on Equation (2.6). For the adjusted wind speed distribution (from 10 m AGL to 50 m AGL) the historical runs from CERFACS and ECEARTH were compared to the Bíurfell distribution. The results for the ECEARTH and CERFACS model are shown in Figure 3-10. The figure shows a overall good correlation between the CERH and ECH wind speed distributions.
compared to BUR. However for the lowest daily averages, i.e. when wind is between 0 and 1.5 m/s the fit is not perfect. Such

![Comparison of adjusted wind speed distributions](image)

Figure 3-10 A comparison of adjusted wind speed distributions after shifting the model results so that the historic runs have the same average as the measured data, and performing height extrapolation of the wind speeds (m/s) from 10 m AGL to 50 m AGL for ECEARTH and CERFACS model.

low wind speeds are of no interest here and therefore not important. For further calculations they will be removed excluded (to get a better fit and energy density) since turbines do not generally produce energy when wind speeds are below 2-3 m/s.

**Scale and shape parameters**

For the adjusted wind speeds, all calculations previously presented in Sections 3.1, 3.2 and 3.3 were repeated for 50 m AGL, starting with estimating the Weibull parameters again.
The adjusted scale and shape parameters are shown in Figure 3-11 and Figure 3-12. The scale parameters were in the range of 9.2 – 9.7. In Section 2.1.6 the increase in scale parameters due to height extrapolation of wind speed was discussed. According to Petersen & Björnsson (2012) the increase for wind speeds extrapolated from 10 to 50 m AGL has been estimated to be 21.8% of the initial wind speeds. The scale parameters presented in Figure 3-11 are within this range and are consistent with the description of the scale parameters in Section 2.1.6., being roughly 125% of the average annual wind speed.

Figure 3-11 shows that the Weibull scale parameter increases with the height. The ECEARTH and CERFACS model simulations are far more similar at 50 m AGL. The scale parameter for CERH and ECH is close to being exactly the same as the BUR scale parameter. As for the projected scenarios, there will be an overall decrease in the scale parameters due to increased CO₂ emissions. Like before, this decrease indicates a less spread distributions of larger ranges of wind speeds since the values for the projected scenarios seem to move further and further away from the observed and historical values. Accurate values of the scale parameters are presented in Table A-6 in Appendix A.

![Figure 3-11 Scale parameters for adjusted wind speed distributions after height extrapolation of the wind speeds (m/s) from 10 m AGL to 50 m AGL for all data sets.](image)

The shape parameters for adjusted wind speed distributions after height extrapolation of the wind speeds (m/s) from 10 m AGL to 50 m AGL are presented in Figure 3-12. In this case the shape parameters were in the range of 2.2 – 2.4 which is almost the same as for wind speeds at 10 m AGL, only with a bigger confidence interval. The pattern was similar to the shape parameters for 10 m AGL but the distribution of the values was however completely different. The CERH shape parameter is much closer to the BUR parameter than the one from ECH. However the difference between ECH and BUR is only 4% so the difference is similar to what it was for shape parameter at 10 m AGL. The CER45 and CER85 show almost no change in the shape parameter, whereas the EC45 and EC85 project an almost linear increase in the shape parameter.
Figure 3-12 Shape parameters for adjusted wind speed distributions after height extrapolation of the wind speeds (m/s) from 10 m AGL to 50 m AGL for all data sets.

The ECEARTH model simulation for both historical and projected scenario show almost a linear increase in the shape parameter. The CERFACS model simulation however gives a low shape parameter for the CERH, a value similar to BUR from the CER45 scenario and then a slight decrease for the CER85 scenario. Accurate values of the scale parameters are presented in Table A-7 in Appendix A.

To summarize the results for the parameters presented here are similar to the ones in Section 3.2.2. The scale parameters generally increase with the height. Regardless, there will be a decrease in the scale parameters at Búrfell according to the projections from ECEARTH and CERFACS models indicating lower average wind speeds in the future. The shape parameter will most likely be the same based on the projections from the CERFACS model but it might increase based on the projections from ECEARTH model, indicating more stable winds in the area.

Energy density

The energy density at 50 m AGL was calculated based on the adjusted wind speeds and scale and shape parameters. Additional calculations for energy densities at 100 m AGL were performed, simply to compare the magnitude of the energy output from different heights. The results are presented in Figure 3-13.

The pattern is relatively similar to the energy density calculated for 10 m AGL. The ECEARTH and CERFACS model simulations look more alike but there is still an overall decrease in energy density for the projected scenarios. The maximum decrease in energy density is for the EC85. This indicates that climate change might affect the wind energy potential within the Búrfell area to some extent. It is obvious from Figure 3-13 that the energy density increase with height. However, the change in elevation from 50 to 100 m does not affect projected scenarios from the ECEARTH and CERFACS model simulations.
The data sets for the projected scenarios were divided into two 15-year subsets. One period stretches over the first fifteen years (2050 – 2065) and the other period covers the end of the 21st century (2086 – 2100). The first fifteen years are presented in Figure 3-14. The results for this time period show a decrease in the energy density for the projected scenarios at 50 m and 100 m AGL. The change is however not as big as it was for the whole time period (Figure 3-13), indicating that the climate change might have more impact during the latter part of the 21st century.
Figure 3-14 Energy density calculated based on adjusted wind speeds, i.e. extrapolated up to 50 m (above) and 100 m (below) AGL for the years 2050 – 2065.

The results for the latter time period (2086 – 2100) are presented in Figure 3-15. As for the previously presented time periods the pattern in the energy density is similar. The ECH and CERH are similar to BUR and there is a total decrease for both climate model simulations. The overall decrease in energy density during the latter period is however more than for the other time periods, confirming that the decrease in the energy density for the projected scenarios at 50 m and 100 m AGL will be more during the latter part of the century. This means that climate change impact will increase throughout the century.
resulting in a decrease in energy density of approximately 10 – 23% (based on values of energy density from tables 10 and 11 in Appendix A). This will be discussed in the following section and the numerical comparison will be presented graphically.
3.5 Discussion

The key findings of this study were that the wind speed distributions in the Búrfell region will most likely change during the 21st century. Based on the values in Table A-1 for the CO₂ emission scenarios and historical runs for CERFACS and ECEARTH models there will be a decrease in average wind speeds but the maximum wind speeds might increase somewhat. These changes are not significant but still indicate that extreme events might increase even though the overall wind speed averages decrease.

The calculations for wind speeds at 50 m AGL, for the years 2050 – 2065 showed an overall decrease in energy density. The ECH was generally a bit more like the BUR than the CERH. The values from the EC45 and EC85 were therefore more likely to represent possible future projections. The EC45 (a likely CO₂ emission scenario) showed a 10% decrease in the energy density. For EC85 (maximum CO₂ emission scenario) the decrease in energy density was 15% (see Table A-8 for calculated values). For comparison, the energy densities for wind speeds at 100 m AGL for the same time period were calculated and showed the same decrease ratio. These calculations were also performed for other time periods, i.e. the latter part of the century (2086 – 2100) at 50 and 100 m AGL and for the whole time period at 50 and 100 m AGL. The results from the energy density calculations for all time periods are shown in Figure 3-16 where the values are presented as a ratio of the BUR value. The values are presented in Table A-14.

Figure 3-16 Results from calculations of change in energy density at 50 m AGL for all model simulations for the whole time series (2050 - 2100), the first part (2050 - 2066) and for the latter part (2086 - 2100)
For the latter part of the century at 50 m AGL the model showed a 16% decrease in energy density for the EC45 scenario. For the EC85 scenario there was a 23% decrease in energy density. This indicates that the wind energy potential might be less by the end of the 21st century. Finally the same calculations were performed for the whole period (2050 – 2100). At 50 m AGL the model showed a 13% decrease in energy density for the EC45 scenario and for the EC85 scenario there was a 20% projected decrease. For energy densities at 100 m AGL for all time periods the results showed the same decrease ratio.

The expected energy production in the Búrfell area has already been investigated to some extent. In Nawri et al. (2013) the average energy density for winter, annual and summer at 55 m AGL for the Búrfell area were presented. For comparison, the wind speeds for BUR and ECH were extrapolated up to 55 m AGL resulting in the energy densities presented in Table 3-1. These values are compared to the energy densities from Nawri et.al in the same table.

Table 3-1 Comparison of BUR and ECH energy densities at 55 m AGL to the energy densities from Nawri et.al. The energy densities are in W/m²

<table>
<thead>
<tr>
<th>Energy density</th>
<th>Data from Nawri et.al (2013)</th>
<th>Data derived from results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter</td>
<td>Annual</td>
</tr>
<tr>
<td>2010</td>
<td></td>
<td>1230</td>
</tr>
</tbody>
</table>

There is a large difference between the annual energy density from Nawri et.al and the ones from this study. The main reason for this significant difference is most likely that the values used in this study are based on daily averaged winds whereas the input data in Nawri et al. (2013) are based on hourly wind measurements. A simple comparison of the energy density calculated from the hourly values observed at Búrfell, 55 m AGL to the energy density from the daily averages at 55 m AGL showed a 37% higher energy density for the hourly values than for the daily averages or 812 W/m² (see last lines in R code, Appendix B). This value is not too far from the average annual energy density in Nawri et.al (2013) and is definitely above the average power density in summer. This implies that the main reason for the difference in the values from this study compared to the values from Nawri et.al (2013) is the averaging process of the wind speed data.

The purpose of this comparison was to see whether the energy densities obtained from the climate model simulations were comparable to other studies done in the area. It should be emphasised that this difference does not take away from the main results obtained here, that the wind energy density might decrease somewhat by the end of this century.

Other reasons for this difference might be the fact that the energy densities in this study are calculated on an annual basis whereas the wind conditions in Iceland are generally characterized by a strong seasonal cycle, with average wintertime power densities typically between 2 and 5 times higher than in summer. Considering the seasonal changes and repeating the analysis by dividing the calculations into two periods per year (winter/summer), the results would most likely show similar energy densities as in Nawri et al. (2013).
In addition to the previous comparison with Nawri et al. (2013), the wind energy potential of the region has been studied from observations and by applying the wind energy model WaSP (Petersen & Björnsson, 2012). The results from this study were similar to the one described in this thesis with an average energy density ranging from 600 to 975 W/m². The results presented in this study are therefore in accordance with what has already been done.

Lastly in order to determine the feasibility of wind energy production at Búrfell based on the results from this study, the annual averages of wind power density and available power were compared with the wind resources of other countries. The highest wind power class in Western Europe, not including Iceland, stretches over the western and northern coast of Ireland, the whole of Scotland, and the northwestern tip of Denmark. The annual average wind power density for this class at 50 m AGL is everything over 250 W/ m² for sheltered terrain, over 700 W/m² along the open coast and over 1800 W/m² on top of hills and ridges. Based on the results from this study, it is clear that Búrfell is well within the range of that wind power class (Nawri, et al., 2013).

3.6 Limitations

The results presented in previous sections show a definite change in the wind resource at Búrfell. There are however some weaknesses in the data analysis that need to be addressed.

The final results were based on two different GCMs (CERFACS and ECEARTH) with one RCM (RCA4). Climate models use various approaches to try to simulate the climate. No model is perfect and therefore the scientific approach to climate change is to use a number of models and run them for different scenarios and compare differences in the climate each model simulates not the climate themselves.

Although the models can replicate the climate to some extent they cannot, due to e.g. the horizontal resolution, resolve all factors important for weather, e.g. surface roughness variations and changes with time.

Finally, it is worth noting that the air density was assumed as a constant (1.1 kg/m³) when calculating the energy density with the Weibull parameters. That is not the case in general because air density changes some 10% between seasons. If air density of 1.2 kg/m³ would have been used, the energy density would have been somewhat higher and closer to the compared values from Nawri et al. (2013). In addition to that the value of the α, used when extrapolating the wind speed up to 50 and 100 m AGL, was assumed constant (0.12). It can however range from 0.8 (summer) to 0.13 (winter). These assumptions might have skewed the results slightly.

3.7 Future research

Other factors that can possibly affect wind power extraction and should also be analyzed in relation to climate change and wind energy potential are air temperature, air density and the occurrence of extreme wind speeds. For further research in the Búrfell area it would be interesting to analyze extreme wind speed occurrences, i.e. wind speeds which exceed e.g. 25 m/s and 28 m/s. These are the cut-off wind speeds for the biggest wind turbine manufacturers (Vestas and Enercon), i.e. this is when the turbines stop generating electricity from the wind. This is however not the case if you have the Storm control
device on your wind turbine which gradually slows down the turbine when wind speeds range from 28 m/s to 34 m/s. This allows for more production capacity but it is expensive. It is therefore important when checking the feasibility of building a windpark, to examine the occurrence of extreme winds especially within this range of speeds.

Other factors to analyze in relation to reduced wind speeds and energy density are air temperature and air density. The air density is an important parameter for estimating the site specific energy density. The air density varies with atmospheric pressure and air temperature with increasing altitude.
4 Conclusions

Iceland lies in the North Atlantic and high wind speeds are common, particularly during the winter time. The wind resource has been studied considerably in Iceland and results have shown that there are good prospects for wind energy utilization.

The main objective of this thesis was to see whether climate change could possibly affect the resource. Regional and global climate models were used to project the changes in wind speed distribution and energy density throughout the 21st century. The results showed a 3-4% reduction in average wind speeds at 10 m AGL. For wind speeds at higher elevation there was a similar change. However there was significant increase in the maximum wind speeds for all projected scenarios which again indicates that with global warming and climate change, extreme wind occurrences might increase.

The results presented in this study showed a decrease in average wind speeds for the Búrfell area. The energy densities for the projected scenarios were calculated for three time periods during the 21st century, the whole data set (2050 – 2100), the first part (2050 – 2066) and the latter part (2086 – 2100). The calculated energy densities were 10 – 23% lower compared to the historical data, depending on the time period and CO2 emission scenarios. Based on these findings, climate change will affect the wind energy potential at Búrfell. The main conclusion from this study is therefore that the energy density in the Búrfell area will decrease throughout this century due to climate change impacts on the wind resource. According to the results, the latter part of the 21st century will suffer the biggest changes in average wind speeds and the energy density. Additional impacts of the climate change might be a growth in vegetation and forests due to a warmer climate. With such change, the surface roughness might increase and that is a factor known to affect wind power in a negative way. Nevertheless, since the energy densities from the projected scenarios were still within the boundaries that define the highest wind class in Europe, the area is still considered a viable option for wind power utilization.
5 Bibliography


The Ministry for the Environment in Iceland. (2006). *Iceland's fourth national communication on climate change (under the UNFCCC) and Iceland's report on demonstrable progress (under the Kyoto protocol)*. Reykjavik: The Ministry for the Environment in Iceland.


Appendix A  Tables

Table A-1 Wind speed distribution from meteorological mast at Búrfell and from RCM

<table>
<thead>
<tr>
<th>Data sets</th>
<th>Average wind speed</th>
<th>Maximum wind speed</th>
<th>Minimum wind speed</th>
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</thead>
<tbody>
<tr>
<td>BUR</td>
<td>7.00 m/s</td>
<td>35.8 m/s</td>
<td>0 m/s</td>
</tr>
<tr>
<td>CERH</td>
<td>6.40 m/s</td>
<td>22.99 m/s</td>
<td>0.89 m/s</td>
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<tr>
<td>CER45</td>
<td>6.30 m/s</td>
<td>25.23 m/s</td>
<td>0.59 m/s</td>
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<tr>
<td>CER85</td>
<td>6.11 m/s</td>
<td>23.09 m/s</td>
<td>0.75 m/s</td>
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<tr>
<td>ECH</td>
<td>6.89 m/s</td>
<td>23.14 m/s</td>
<td>0.82 m/s</td>
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<td>EC45</td>
<td>6.66 m/s</td>
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<td>EC85</td>
<td>6.47 m/s</td>
<td>25.79 m/s</td>
<td>0.78 m/s</td>
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</table>

Table A-2 Scale factors for the models and for Búrfell, historical data as well as upper (97.5%) and lower (2.5%) confidence intervals.

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</thead>
<tbody>
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<td>7.372756</td>
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Table A-3 Shape factors for the models and for Búrfell, historical data as well as upper (97.5%) and lower (2.5%) confidence intervals.

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<th>Hi</th>
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<tr>
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<td>2.298608</td>
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Table A-4 Calculated energy density (W/m²) for each model simulation based on the Weibull factors, as well as confidence intervals at 10 m AGL. The CERFACS and ECEARTH RCP runs are calculated for the whole time period (2050 – 2100).

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<th>Elo</th>
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<tr>
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Table A-5 Calculated energy density (W/m²) for each model simulation based on the Weibull factors with adjusted confidence intervals at 10 m AGL. The CERFACS and ECEARTH RCP runs are calculated for the whole time period (2050 – 2100).

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<th>Elo</th>
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<tbody>
<tr>
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<td>247.53</td>
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Table A-6 Calculated scale factors with maximum and minimum values for each simulation after speed and height correction at 50 m AGL. The CERFACS and ECEARTH RCP runs are calculated for 2050 – 2066.

<table>
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<tr>
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Table A-7 Calculated shape factors with maximum and minimum values for each simulation after speed and height correction at 50 m AGL. The CERFACS and ECEARTH RCP runs are calculated for 2050 – 2066.

<table>
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Table A-8 Calculated energy density (W/m²) for each model simulation based on the Weibull factors with confidence intervals for corrected height at 50 m AGL. The CERFACS and ECEARTH RCP runs are calculated for 2050–2066.

<table>
<thead>
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<th>Elo</th>
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</thead>
<tbody>
<tr>
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Table A-9 Calculated energy density (W/m²) for each model simulation based on the Weibull factors with confidence intervals for corrected height at 100 m AGL. The CERFACS and ECEARTH RCP runs are calculated for 2050–2066.

<table>
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<tr>
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</table>

Table A-10 Calculated energy density (W/m²) for each model simulation based on the Weibull factors with confidence intervals for corrected height at 50 m AGL. The CERFACS and ECEARTH RCP runs are calculated for 2086-2100.

<table>
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<th>Model</th>
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<tr>
<td>BUR</td>
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</tr>
<tr>
<td>CER45</td>
<td>519.00</td>
<td>546.75</td>
<td>492.92</td>
</tr>
<tr>
<td>CER85</td>
<td>479.84</td>
<td>506.28</td>
<td>455.03</td>
</tr>
<tr>
<td>ECH</td>
<td>588.39</td>
<td>609.34</td>
<td>568.30</td>
</tr>
<tr>
<td>EC45</td>
<td>496.95</td>
<td>523.14</td>
<td>472.34</td>
</tr>
<tr>
<td>EC85</td>
<td>455.05</td>
<td>479.65</td>
<td>431.97</td>
</tr>
</tbody>
</table>

Table A-11 Calculated energy density (W/m²) for each model simulation based on the Weibull factors with confidence intervals for corrected height at 100 m AGL. The CERFACS and ECEARTH RCP runs are calculated for 2086-2100.

<table>
<thead>
<tr>
<th>Model</th>
<th>E</th>
<th>Ehi</th>
<th>Elo</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUR</td>
<td>734.49</td>
<td>767.53</td>
<td>703.15</td>
</tr>
<tr>
<td>CERH</td>
<td>734.59</td>
<td>759.54</td>
<td>710.61</td>
</tr>
<tr>
<td>CER45</td>
<td>666.10</td>
<td>701.71</td>
<td>632.63</td>
</tr>
<tr>
<td>CER85</td>
<td>615.84</td>
<td>649.78</td>
<td>584.00</td>
</tr>
<tr>
<td>ECH</td>
<td>754.91</td>
<td>781.81</td>
<td>729.12</td>
</tr>
<tr>
<td>EC45</td>
<td>637.69</td>
<td>671.30</td>
<td>606.09</td>
</tr>
<tr>
<td>EC85</td>
<td>583.93</td>
<td>615.52</td>
<td>554.27</td>
</tr>
</tbody>
</table>
Table A-12 Calculated energy density (W/m$^2$) for each model simulation based on the Weibull factors with confidence intervals for corrected height at 50 m AGL. The CERFACS and ECEARTH RCP runs are calculated for the whole period (2050 – 2100)

<table>
<thead>
<tr>
<th>Model</th>
<th>$E$</th>
<th>$E_{hi}$</th>
<th>$E_{lo}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUR</td>
<td>572.49</td>
<td>598.21</td>
<td>548.09</td>
</tr>
<tr>
<td>CERH</td>
<td>572.37</td>
<td>591.81</td>
<td>553.69</td>
</tr>
<tr>
<td>CER45</td>
<td>544.83</td>
<td>560.27</td>
<td>529.89</td>
</tr>
<tr>
<td>CER85</td>
<td>505.42</td>
<td>519.92</td>
<td>491.40</td>
</tr>
<tr>
<td>ECH</td>
<td>588.39</td>
<td>609.34</td>
<td>568.30</td>
</tr>
<tr>
<td>EC45</td>
<td>516.02</td>
<td>530.79</td>
<td>501.76</td>
</tr>
<tr>
<td>EC85</td>
<td>470.94</td>
<td>484.28</td>
<td>458.05</td>
</tr>
</tbody>
</table>

Table A-13 Calculated energy density (W/m$^2$) for each model simulation based on the Weibull factors with confidence intervals for corrected height at 100 m AGL. The CERFACS and ECEARTH RCP runs are calculated for the whole period (2050 – 2100)

<table>
<thead>
<tr>
<th>Model</th>
<th>$E$</th>
<th>$E_{hi}$</th>
<th>$E_{lo}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUR</td>
<td>734.49</td>
<td>767.53</td>
<td>703.15</td>
</tr>
<tr>
<td>CERH</td>
<td>734.59</td>
<td>759.54</td>
<td>710.61</td>
</tr>
<tr>
<td>CER45</td>
<td>699.22</td>
<td>719.04</td>
<td>680.05</td>
</tr>
<tr>
<td>CER85</td>
<td>648.67</td>
<td>667.28</td>
<td>630.67</td>
</tr>
<tr>
<td>ECH</td>
<td>754.91</td>
<td>781.81</td>
<td>729.12</td>
</tr>
<tr>
<td>EC45</td>
<td>661.93</td>
<td>680.89</td>
<td>643.59</td>
</tr>
<tr>
<td>EC85</td>
<td>604.16</td>
<td>621.28</td>
<td>587.60</td>
</tr>
</tbody>
</table>

Table A-14 Calculated change in energy density at 50 m AGL for all model simulations for the whole time series (2050 - 2100), the first part (2050 - 2066) and for the latter part (2086 - 2100)

<table>
<thead>
<tr>
<th>Model</th>
<th>2050 - 2100</th>
<th>2050 - 2066</th>
<th>2086 - 2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUR</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CERH</td>
<td>0.9997904</td>
<td>0.9997904</td>
<td>0.999790389</td>
</tr>
<tr>
<td>CER45</td>
<td>0.9516847</td>
<td>0.9839997</td>
<td>0.906566054</td>
</tr>
<tr>
<td>CER85</td>
<td>0.8828451</td>
<td>0.9429684</td>
<td>0.838163112</td>
</tr>
<tr>
<td>ECH</td>
<td>1.0277734</td>
<td>1.0277734</td>
<td>1.027773411</td>
</tr>
<tr>
<td>EC45</td>
<td>0.9013607</td>
<td>0.9317543</td>
<td>0.868050097</td>
</tr>
<tr>
<td>EC85</td>
<td>0.822617</td>
<td>0.8811682</td>
<td>0.794861046</td>
</tr>
</tbody>
</table>
Appendix B  R Code

# Data import
# BURFELL
tempin = read.table("Burfell_maelingar2.txt", header=FALSE, skip=1)
tax = as.Date(paste(as.character(tempin$V1), as.character(tempin$V2)))
lim = paste(as.character(tempin$V1), as.character(tempin$V2))
tax2 = strptime(lim, format="%Y-%m-%d %H:%M:%S")
Burvind = data.frame(timi=tax2, dags=tax, numdag=as.numeric(tax), vindur=tempin$V3)
Burvind = Burvind[complete.cases(Burvind),]  # henda út línum með NA

# CORDEX
CERFACSHist = read.table("CERFACS_RCA4_historical.txt")
CERFACS45 = read.table("CERFACS_RCA4_rcp45.txt")
CERFACS85 = read.table("CERFACS_RCA4_rcp85.txt")
EC_EARTHHist = read.table("EC_EARTH_RCA4_historical.txt")
EC_EARTH45 = read.table("EC_EARTH_RCA4_rcp45.txt")
EC_EARTH85 = read.table("EC_EARTH_RCA4_rcp85.txt")

dagvind = tapply(Burvind$vindur, Burvind$numdag, mean)

# calculate daily averages
dagvind = tapply(Burvind$vindur, Burvind$numdag, mean)
# compare distribution of daily averages and hourly averages
require(ggplot2)
bb <- as.data.frame(qqplot(dagvind, Burvind$vindur, plot.it=FALSE))
ggplot(bb) + geom_point(aes(x=x, y=y)) +
  geom_abline() +
  theme_minimal() +
  scale_x_continuous("Daily average for wind speeds (m/s)") +
  scale_y_continuous("Hourly values for wind speeds (m/s)")

# Create a list with all data, choose short names so the fit to the
boxplot
AllirDagvindar = list(BUR = dagvind, CERH = CERFACSHist$V3, CER45 =
  CERFACS45$V3, CER85 = CERFACS85$V3, ECH = EC_EARTHHist$V3,
  EC45 = EC_EARTH45$V3, EC85 = EC_EARTH85$V3)

library(RColorBrewer)
boxplot(AllirDagvindar, ylab = "Wind speed (m/s)",
  col=(colorRampPalette(brewer.pal(8,"Greys"))(8)))
boxplot(AllirDagvindar, ylab = "Wind speed",
  ylim = c(0,15),
  col=(colorRampPalette(brewer.pal(9,"Oranges"))(8)),
  theme_bw(base_size = '12', base_family = 'Times'),
  theme_classic())

# lets take a look at the time series
library(ggplot2)
library(reshape2)
ReiknaAr <- function(Likangogn) {require(lubridate)
  Ar = year(as.Date(as.character(Likangogn$V1)))
  Arsmedaltal = tapply(Likangogn$V3, Ar, mean)
data.frame(Ar = unique(Ar), Medal = Arsmedaltal)}

TS_CERH = ReiknaAr(CERFACSHist)
TS_CER45 = ReiknaAr(CERFACS45)
TS_CER85 = ReiknaAr(CERFACS85)
TS_ECH = ReiknaAr(EC_EARTHHist)
TS_EC45 = ReiknaAr(EC_EARTH45)
TS_EC85 = ReiknaAr(EC_EARTH85)
ArBur = year(unique(Burvind$dags))
TS_Dag = data.frame(Ar = unique(ArBur), Medal = tapply(dagvind,ArBur,
  mean))

# create a ggplot for the BUR time series
g = ggplot(TS_Dag, aes(Ar, Medal))
summary(g)
BU = g + geom_point(color='grey8', size = 3) +
   smooth(fill='grey88', col='grey8',)
   labs(x = 'Year', y = 'Average wind speed (m/s)') +
   theme_bw(base_size = '12', base_family = 'Times') +
   theme_minimal()
print(BU)
# geom_smooth: method="auto" and size of largest group is <1000, so
# using loess. Use 'method = x' to change the smoothing method.
# plot CERH and Búrfell on same axis for comparison
comboDagCERH = cbind(TS_Dag[TS_Dag$Ar %in% TS_CERH$Ar, ],
                      TS_CERH[TS_CERH$Ar %in% TS_Dag$Ar, ])[, c(1, 2, 4)]
names(comboDagCERH) <- c("Ar", "BUR", "CERH")
ComboMelt = melt(comboDagCERH, id.vars = c("Ar"))
names(ComboMelt) <- c("Ar", "Origin", "Meðalvindur")
comboDAGCERH = qplot(Ar, Meðalvindur, data = ComboMelt, group = Origin,
                      color = Origin) +
                      labs("Year") +
                      ylab("Annual average wind speed (m/s)")
+ggtitle("Comparison of annual average wind speed at BUR and in INT")
DAGCERH = comboDAGCERH + geom_point() +
          theme_bw(base_size = '12', base_family = 'Times') +
          theme_minimal() + geom_smooth(fill='grey88')
print(DAGCERH)
# plot CERH and Búrfell on same axis for comparison
comboDagECH = cbind(TS_Dag[TS_Dag$Ar %in% TS_ECH$Ar, ],
                     TS_ECH[TS_ECH$Ar %in% TS_Dag$Ar, ])[, c(1, 2, 4)]
names(comboDagECH) <- c("Ar", "BUR", "ECH")
ComboMelt = melt(comboDagECH, id.vars = c("Ar"))
names(ComboMelt) <- c("Ar", "Origin", "Meðalvindur")
comboDAGECH = qplot(Ar, Meðalvindur, data = ComboMelt, group = Origin,
                     color = Origin) +
                     labs("Year") +
                     ylab("Annual average wind speed (m/s)")
+ggtitle("Comparison of annual average wind speed at BUR and in INT")
DAGECH = comboDAGECH + geom_point() +
         theme_bw(base_size = '12', base_family = 'Times') +
         theme_minimal() + geom_smooth(fill='grey88')
print(DAGECH)
# plot Historic/CTRL runs together for comparison
Historic = cbind(TS_ECH, TS_CERH[, 2])
names(Historic) <- c("Ar", "ECH", "CERH")
CNTRL = melt(Historic, id.vars = c("Ar"))
names(CNTRL) <- c("Ar", "Origin", "Medalvindur")
compHIST = qplot(Ar, Medalvindur, data = CNTRL, group = Origin, color = Origin) +
            labs("Year") +
            ylab("Average wind speed (m/s)")
+ggtitle("Annual average wind speed for Control runs with ECH and CERH")
HIST = compHIST + geom_point() +
       theme_bw(base_size = '12', base_family = 'Times') +
       theme_minimal() + geom_smooth(fill='grey88')
print(HIST)
# plot emission scenarios: CERFACS RCP4.5 and RCP8.5
ScenCER = cbind(TS_CER45, TS_CER85[, 2])
names(ScenCER) <- c("Ar", "CER45", "CER85")
CERSCEN = melt(ScenCER, id.vars = c("Ar"))
names(CERSCEN) <- c("Ar", "Scenario", "Medalvindur")
compC4585 = qplot(Ar, Medalvindur, data = CERSCEN, group = Scenario,
                  color = Scenario) +
                  labs("Year") +
                  ylab("Average wind speed (m/s)")
C4585 = compC4585 + geom_point() +
        theme_bw(base_size = '12', base_family = 'Times') +
        theme_minimal() + geom_smooth(fill='grey88')
print(C4585)
# plot emission scenarios: ECEARTH RCP4.5 and RCP8.5
ScenEC = cbind(TS_EC45, TS_EC85[, 2])
names(ScenEC) <- c("Ar", "EC45", "EC85")
```r
ECSCEN = melt(ScenEC, id.vars = c("Ar"))
names(ECSCEN) <- c("Ar", "Scenario", "Medalvindur")
compEC4585 = ggplot(Ar, Medalvindur, data = ECSCEN, group = Scenario, 
color = Scenario) + xlab("Year") + ylab("Average wind speed (m/s)"")
EC4585 = compEC4585 + geom_point()+ theme_bw(base_size = '12', 
base_family = 'Times') + theme_classic() + theme_minimal() + 
geom_smooth(fill='grey88')
print(EC4585)
summary(with(TS_Dag, glm(Medal ~ Ar)))
summary(with(TS_CERH, glm(Medal ~ Ar)))
summary(with(TS_ECH, glm(Medal ~ Ar)))
summary(with(TS_EC45, glm(Medal ~ Ar)))
summary(with(TS_EC85, glm(Medal ~ Ar)))
summary(with(TS_CER45, glm(Medal ~ Ar)))
summary(with(TS_CER85, glm(Medal ~ Ar)))
#Now for the Weibull analysis
library(MASS)
library(fitdistrplus)
library(ggplot2)
fitWeib <- function(datain) {require(MASS)
iuse = (datain > 0) # omit data if wind is below 0 m/s
datain = datain[iuse]
lout = fitdistr(datain, densfun = dweibull, start = list(scale  = 7, 
shape = 2))
ldag = fitWeib(dagvind)
lCERH = fitWeib(CERFACSHist$V3)
lCER45 = fitWeib(CERFACS45$V3)
lCER85 = fitWeib(CERFACS85$V3)
lECHist = fitWeib(ECEARTHHist$V3)
lEC45 = fitWeib(ECEARTH45$V3)
lEC85 = fitWeib(ECEARTH85$V3)
#weibull for BUR
x = seq(0, 25) #distribution for values up to 25 m/s
weibDAG =qplot(x, pweibull(x, scale = ldag$estimate["scale"], shape = 
ldag$estimate["shape"]),geom='line', type = "l", 
unique(ldag), ecdf(ldag)(unique(ldag))*length(ldag))
weibDAGB = weibDAG + 
theme_bw(base_size = '12', base_family = 'Times') + 
theme_minimal()+ 
scale_x_continuous("Wind (m/s)") + 
scale_y_continuous(limits=c(0,1),"Cumulative frequency")+ 
geom_line()+ 
geom_smooth(stat='smooth',method='loess', level=0)
print(weibDAGB)
# weibull for CERH
x = seq(0, 25)
luse = lCERH
Dat = CERFACSHist$V3
weibCERH=qplot(x, pweibull(x, scale = luse$estimate["scale"], shape = 
luse$estimate["shape"]), geom='line', type = "l", 
unique(luse), ecdf(luse)(unique(luse))*length(luse))
weibCERHI = weibCERH + 
theme_bw(base_size = '12', base_family = 'Times') + 
theme_minimal()+ 
scale_x_continuous("Wind (m/s)") + 
scale_y_continuous(limits=c(0,1),"Cumulative frequency")+ 
geom_line()+ 
geom_smooth(stat='smooth',method='loess', level=0)
print(weibCERHI)
```
#weibull for CER45
x = seq(0, 25)
luse = lCER45
Dat = CERFACS45$V3
weibCER45 = qplot(x, pweibull(x, scale = luse$estimate["scale"], shape = luse$estimate["shape"]),
type = "l", geom='line', type = "l", unique(luse),
ecdf(luse)(unique(luse))*length(luse))
weibCER45s = weibCER45 +
  theme_bw(base_size = '12', base_family = 'Times') +
  theme_minimal() +
  scale_x_continuous("Wind (m/s)") +
  scale_y_continuous(limits=c(0,1),"Cumulative frequency")+
  geom_line()+
  geom_smooth(stat='smooth',method='loess', level=0)
print(weibCER45s)
#weibull for CER85
x = seq(0, 25)
luse = lCER85
Dat = CERFACS85$V3
weibCER85 = qplot(x, pweibull(x, scale = luse$estimate["scale"], shape = luse$estimate["shape"]), type = "l", geom='line', type = "l", unique(luse),
ecdf(luse)(unique(luse))*length(luse))
weibCER85s = weibCER85 +
  theme_bw(base_size = '12', base_family = 'Times') +
  theme_minimal() +
  scale_x_continuous("Wind (m/s)") +
  scale_y_continuous(limits=c(0,1),"Cumulative frequency")+
  geom_line()+
  geom_smooth(stat='smooth',method='loess', level=0)
print(weibCER85s)
#weibull for ECH
x = seq(0, 25)
luse = lECHist
Dat = ECEARTHHist$V3
weibECH = qplot(x, pweibull(x, scale = luse$estimate["scale"], shape = luse$estimate["shape"]), type = "l", geom='line',
type = "l", unique(luse), ecdf(luse)(unique(luse))*length(luse))
weibECHI = weibECH +
  theme_bw(base_size = '12', base_family = 'Times') +
  theme_minimal() +
  scale_x_continuous("Wind (m/s)") +
  scale_y_continuous(limits=c(0,1),"Cumulative frequency")+
  geom_line()+
  geom_smooth(stat='smooth',method='loess', level=0)
print(weibECHI)
#weibull for EC45
x = seq(0, 25)
luse = lEC45
Dat = ECEARTH45$V3
weibEC45 = qplot(x, pweibull(x, scale = luse$estimate["scale"], shape = luse$estimate["shape"]), type = "l", geom='line',
type = "l", unique(luse), ecdf(luse)(unique(luse))*length(luse))
weibEC45s = weibEC45 +
  theme_bw(base_size = '12', base_family = 'Times') +
  theme_minimal() +
  scale_x_continuous("Wind (m/s)") +
  scale_y_continuous(limits=c(0,1),"Cumulative frequency")+
  geom_line()+
  geom_smooth(stat='smooth',method='loess', level=0)
print(weibEC45s)
#weibull for EC85
x = seq(0, 25)
luse = 1EC85
Dat = ECEARTH85$V3
weibEC85 = qplot(x, pweibull(x, scale = luse$estimate["scale"], shape = luse$estimate["shape"]), type = "l", geom='line', type = "l", unique(luse), ecdf(luse)(unique(luse)) * length(luse))
weibEC85s = weibEC85 +
  theme_bw(base_size = '12', base_family = 'Times') +
  theme_minimal() +
  scale_x_continuous("Wind (m/s)") +
  scale_y_continuous(limits = c(0, 1), "Cumulative frequency") +
  geom_line() +
  geom_smooth(stat = 'smooth', method = 'loess', level = 0)
print(weibEC85s)
#multipanel for weibull plots
library(ggplot2)
library(gridExtra)
grid.arrange(weibDAGB, weibCERHI, weibCER45s, weibCER85s, weibECHI, weibEC45s, weibEC85s, ncol = 2, heights = 3, widths = 3)
#next: see whether Weibull changes and how these changes affect the energy density
#first we take a look at the scale factor
require("ggplot2")
# create dfscale:
sc = c(ldag$estimate["scale"], confint(ldag)[1, ])
df = data.frame(t(sc), model = "BUR")
sc = c(lCERH$estimate["scale"], confint(lCERH)[1, ])
df = rbind(df, data.frame(t(sc), model = "CERH"))
sc = c(lCER45$estimate["scale"], confint(lCER45)[1, ])
df = rbind(df, data.frame(t(sc), model = "CER45"))
sc = c(lCER85$estimate["scale"], confint(lCER85)[1, ])
df = rbind(df, data.frame(t(sc), model = "CER85"))
sc = c(lECHist$estimate["scale"], confint(lECHist)[1, ])
sc = c(lEC45$estimate["scale"], confint(lEC45)[1, ])
sc = c(lEC85$estimate["scale"], confint(lEC85)[1, ])
sc = c(lEC85$estimate["scale"], confint(lEC85)[1, ])
sc = c(lEC85$estimate["scale"], confint(lEC85)[1, ])
sc = c(lEC85$estimate["scale"], confint(lEC85)[1, ])
sc = c(lEC85$estimate["scale"], confint(lEC85)[1, ])
names(df) <- c("scale", "low", "hi", "model")
dfscale = df
print(dfscale)
#plot the scale parameters for all models
print(ggplot(dfscale, aes(model, scale)) +
  geom_bar(stat = 'identity', position = 'dodge') +
  labs(x = 'Model', y = 'Scale (A)') +
  theme_bw(base_size = '12', base_family = 'Times') +
  theme_classic() +
  theme_minimal())
#Now for the shape factpr
# create dfshape:
sc = c(ldag$estimate["shape"], confint(ldag)[2, ])
df = data.frame(t(sc), model = "BUR")
sc = c(lCERH$estimate["shape"], confint(lCERH)[2, ])
df = rbind(df, data.frame(t(sc), model = "CERH"))
sc = c(lCER45$estimate["shape"], confint(lCER45)[2, ])
df = rbind(df, data.frame(t(sc), model = "CER45"))
sc = c(lCER85$estimate["shape"], confint(lCER85)[2, ])
df = rbind(df, data.frame(t(sc), model = "CER85"))
sc = c(lECHist$estimate["shape"], confint(lECHist)[2, ])
sc = c(lEC45$estimate["shape"], confint(lEC45)[2, ])
sc = c(lEC85$estimate["shape"], confint(lEC85)[2, ])
sc = c(lEC85$estimate["shape"], confint(lEC85)[2, ])
sc = c(lEC85$estimate["shape"], confint(lEC85)[2, ])
sc = c(lEC85$estimate["shape"], confint(lEC85)[2, ])
names(df) <- c("shape", "low", "hi", "model")
dfshape = df
print(dfshape)
sc = c(lCER85$estimate["shape"], confint(lCER85)[2,])
df = rbind(df, data.frame(t(sc), model = "CER85"))
sc = c(lECHist$estimate["shape"], confint(lECHist)[2,])
df = rbind(df, data.frame(t(sc), model = "ECH"))
sc = c(lEC45$estimate["shape"], confint(lEC45)[2,])
df = rbind(df, data.frame(t(sc), model = "EC45"))
sc = c(lEC85$estimate["shape"], confint(lEC85)[2,])
df = rbind(df, data.frame(t(sc), model = "EC85"))

names(df) <- c("shape", "low", "hi", "model")
dfshape = df
print(dfshape)

# plot shape parameter for all models
h = ggplot(dfshape, aes(model, shape))
summary(g)
b = h + geom_point(color='steelblue', size = 3) + geom_errorbar(aes(x = model, y = shape, ymin = low, ymax = hi), width = 0.25, colour = 'steelblue') + labs(x = 'Model', y = 'Shape (k)') + theme_bw(base_size = '12', base_family = 'Times') + theme_classic() + theme_minimal()
print (b)

# now we can calculate energy density
rho = 1.1
ED = cbind(dfscale, dfshape)[, 1:7]

names(ED) <- c("scale", "scale_low", "scale_hi", "model", "shape", "shape_lo", "shape_hi")

ED$E = 1/2 * rho * (EDscale)^3 * gamma(1 + (3/EDshape))
ED$Ehi = 1/2 * rho * (EDscale_hi)^3 * gamma(1 + (3/EDshape_hi))
ED$Elo = 1/2 * rho * (EDscale_lo)^3 * gamma(1 + (3/EDshape_lo))

EnergyDensity = ED[, c(4, 8:10)]
print.data.frame(EnergyDensity, digits = 5)

# plot the energy density for WSD at 10 m AGL without corrected confidence interval
g = ggplot(EnergyDensity, aes(model, E))
summary(g)
p = g + geom_point(color='steelblue', size = 3) + geom_errorbar(aes(x = model, y = E, ymin = Elo, ymax = Ehi), width = 0.25, colour = 'steelblue') + xlab('Model') + ylab(expression(paste('E'~W/m^{2}))) + theme_bw(base_size = '12', base_family = 'Times') + theme_classic() + theme_minimal()
print(p)

# confidence interval corrected for the energy density
rho = 1.1
ED2 = EnergyDensity
ED2[, 3:4] = NA
for (i in c(1:length(ED2$model))) {
  # since the error bars are normally distributed the distance from center  # (mean value)  # to the boundary should be 1.96 standard deviations. The rnorm is used to  # calculate
  scaleDist = rnorm(10000, mean = dfscale$scale[i], (dfscale$scale[i] - dfscale$low[i])/1.96)
  shapeDist = rnorm(10000, mean = dfshape$shape[i], (dfshape$shape[i] - dfshape$low[i])/1.96)
  EDdist = 1/2 * rho * (scaleDist^3) * gamma(1 + 3/shapeDist)
  hilo = quantile(EDdist, c(0.975, 0.025))
  ED2[i, 3] = hilo[1]
  ED2[i, 4] = hilo[2]
}
EnergyDensity = ED[, c(4, 8:10)]
print.data.frame(ED2, digits = 5)
# plot the energy density for WSD at 10 m AGL with corrected confidence interval

g = ggplot(ED2, aes(model, E))
summary(g)
p = g + geom_point(color='steelblue', size = 3) + geom_errorbar(aes(x = model, ymin = Elo, ymax = Ehi), width = 0.25, colour = 'steelblue') + xlab('Model') + ylab(expression(paste('E'~W/m^{2}))) + theme_bw(base_size = '12', base_family = 'Times') + theme_classic() + theme_minimal()
print (p)

# the following codes are inserted below in order to calculate for specific periods
# they should be inserted after V3 in the projected scenarios, i.e. ec45/85 and cer45/85
# [year(ECEARTH45$V1)>2086]  
# [year(ECEARTH85$V1)>2086]  
# [year(CERFACS45$V1)>2086]  
# [year(CERFACS45$V1)<2066]  
# [year(ECEARTH85$V1)<2066]  
# [year(CERFACS85$V1)<2066]  

# extrapolation factor from 10 m to 50 or 100 m
windcorr = (50/10)^0.12 # vindjafnan V_z=V_R(z/z_R)^alpha

correction for the wind speeds
DiffEC = mean(dagvind) - mean(ECEARTHHist$V3)
DiffCER = mean(dagvind) - mean(CERFACSHist$V3)

NewBur = dagvind*windcorr
NewEChist = (ECEARTHHist$V3 + DiffEC)*windcorr
NewEC45 = (ECEARTH45$V3 + DiffEC)[year(ECEARTH45$V1)<2066]*windcorr
NewEC85 = (ECEARTH85$V3 + DiffEC)[year(ECEARTH85$V1)<2066]*windcorr
NewCERhist = (CERFACSHist$V3 + DiffCER)*windcorr
NewCER45 = (CERFACS45$V3 + DiffCER)[year(CERFACS45$V1)<2066]*windcorr
NewCER85 = (CERFACS85$V3 + DiffCER)[year(CERFACS85$V1)<2066]*windcorr

#lets see how the distribution for the historical/CTRL runs fit to the measured data
newfitBURCERH <- as.data.frame(qqplot(NewBur, NewCERhist, plot.it=FALSE))
ggplot(newfitBURCERH) + geom_point(aes(x=x, y=y)) + geom_abline() + theme_minimal() + scale_x_continuous("BUR wind speeds (m/s)") + scale_y_continuous("CERH wind speeds (m/s)"")

newfitBURECH <- as.data.frame(qqplot(NewBur, NewEChist, plot.it=FALSE))
ggplot(newfitBURECH) + geom_point(aes(x=x, y=y)) + geom_abline() + theme_minimal() + scale_x_continuous("BUR wind speeds (m/s)") + scale_y_continuous("ECH wind speeds (m/s)"")

#repeat Weibull calculations
fitWeib <- function(datain) { require(MASS)
iuse = (datain > 1.5) # omit data if wind is below 1.5 m/s
datain = datain[iuse]
lout = fitdistr(datain, densfun = dweibull, start = list(scale= 7, shape = 2))
}
lNewBur = fitWeib(NewBur)
lNewECHist = fitWeib(NewEChist)
lNewEC45 = fitWeib(NewEC45)
lNewEC85 = fitWeib(NewEC85)
lNewCERHist = fitWeib(NewCERhist)
lNewCER45 = fitWeib(NewCER45)
lNewCER85 = fitWeib(lNewCER85)
# create data frames for the corrected scale and shape parameters
# create dfscale:
scale = c(lNewBur$estimate["scale"], confint(lNewBur)[1,])
df = data.frame(t(scale), model = "BUR")
scale = c(lNewCERHist$estimate["scale"], confint(lNewCERHist)[1,])
df = rbind(df, data.frame(t(scale), model = "CERH"))
scale = c(lNewCER45$estimate["scale"], confint(lNewCER45)[1,])
df = rbind(df, data.frame(t(scale), model = "CER45"))
scale = c(lNewCER85$estimate["scale"], confint(lNewCER85)[1,])
df = rbind(df, data.frame(t(scale), model = "CER85"))
scale = c(lNewECHist$estimate["scale"], confint(lNewECHist)[1,])
df = rbind(df, data.frame(t(scale), model = "ECH"))
scale = c(lNewEC45$estimate["scale"], confint(lNewEC45)[1,])
df = rbind(df, data.frame(t(scale), model = "EC45"))
scale = c(lNewEC85$estimate["scale"], confint(lNewEC85)[1,])
df = rbind(df, data.frame(t(scale), model = "EC85"))
names(df) <- c("scale", "low", "hi", "model")
dfscaleNew = df
print(dfscaleNew)
# new scale parameter
g = ggplot(dfscaleNew, aes(model, scale))
summary(g)
p = g + geom_point(color='steelblue', size = 3) + geom_errorbar(aes(x = model, y = scale, ymin = low, ymax = hi), width = 0.25, colour = 'steelblue') + labs(x = 'Model', y = 'Scale (A)') + theme_bw(base_size = '12', base_family = 'Times') + theme_classic() + theme_minimal()
print (p)
# create dfshape:
scale = c(lNewBur$estimate["shape"], confint(lNewBur)[2,])
df = data.frame(t(scale), model = "BUR")
scale = c(lNewCERHist$estimate["shape"], confint(lNewCERHist)[2,])
df = rbind(df, data.frame(t(scale), model = "CERH"))
scale = c(lNewCER45$estimate["shape"], confint(lNewCER45)[2,])
df = rbind(df, data.frame(t(scale), model = "CER45"))
scale = c(lNewCER85$estimate["shape"], confint(lNewCER85)[2,])
df = rbind(df, data.frame(t(scale), model = "CER85"))
scale = c(lNewECHist$estimate["shape"], confint(lNewECHist)[2,])
df = rbind(df, data.frame(t(scale), model = "ECH"))
scale = c(lNewEC45$estimate["shape"], confint(lNewEC45)[2,])
df = rbind(df, data.frame(t(scale), model = "EC45"))
scale = c(lNewEC85$estimate["shape"], confint(lNewEC85)[2,])
df = rbind(df, data.frame(t(scale), model = "EC85"))
names(df) <- c("shape", "low", "hi", "model")
dfshapeNew = df
print(dfshapeNew)
# new shape parameter
g = ggplot(dfshapeNew, aes(model, shape))
summary(g)
p = g + geom_point(color='steelblue', size = 3) + geom_errorbar(aes(x = model, y = shape, ymin = low, ymax = hi), width = 0.25, colour = 'steelblue') + labs(x = 'Model', y = 'Shape (k)') + theme_bw(base_size = '12', base_family = 'Times') + theme_classic() + theme_minimal()
print (p)
# finally the new energy density
rho = 1.1
EDNew = cbind(dfscaleNew, dfshapeNew)[, 1:7]
names(EDNew) <- c("scale", "scale_low", "scale_hi", "model", "shape", "shape_lo", "shape_hi")
\[ EDNew E = \frac{1}{2} \rho (EDNew scale)^3 \gamma(1 + \frac{3}{EDNew shape}) \]
\[ EDNew Ehi = \frac{1}{2} \rho (EDNew scale_hi)^3 \gamma(1 + \frac{3}{EDNew shape_lo}) \]
\[ EDNew Elo = \frac{1}{2} \rho (EDNew scale_lo)^3 \gamma(1 + \frac{3}{EDNew shape_hi}) \]

\[ \text{EnergyDensityNew} = \text{EDNew}[c(4, 8:10)] \]

\begin{verbatim}
# new energy density
print.data.frame(EnergyDensityNew, digits = 5)
g = ggplot(EnergyDensityNew, aes(model, E))
summary(g)
p = g + geom_point(color='steelblue', size = 3) + geom_errorbar(aes(x = model, ymin = Elo, ymax = Ehi), width = 0.25, colour = 'steelblue') +
xlab('Model') + ylab(expression(paste('E'~W/m^{2}))) + theme_bw(base_size = '12', base_family = 'Times') + theme_classic() + theme_minimal()
print(p)
\end{verbatim}

# calculation for comparison of hourly and daily values in results
# first we calculate the energy density for hourly values
test = fitWeib(Burvind$vindur*windcorr)
EDtest = \frac{1}{2}1.1*(test$estimate[1]^3)*gamma(1+3/test$estimate[2])
# then we calculate the energy density for the daily values
test2 = fitWeib(dagvind*windcorr)
EDtest2 = \frac{1}{2}1.1*(test2$estimate[1]^3)*gamma(1+3/test2$estimate[2])
# difference is therefore
EDdiff = EDtest/EDtest2
# this represents the percentage
print(EDdiff-1)