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Optimization and Profitability of Hydro Power combined with Wind Power

by

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Abstract

Co-operation of wind and hydropower could have positive synergistic effects because of higher wind speeds in the winter and more water runoff during summer and also because water is saved while running the wind turbines instead of hydro power plants. In this study a location for wind turbines named Þröskuldar was chosen because of its reputation of being windy and also relatively close to power lines. The wind power is intended for co-operation with a proposed hydro power plant expansion of Mjólká in the West Fjords, so power can be stored as potential energy in water reservoirs. A model was built in Microsoft Excel to simulate and then optimize the operation of the power plants.

Wind data from 2012 was broken down into periods of the day, and seasons of the year and analyzed using the Weibull distribution to see the characteristics of the wind. Electricity consumption was taken into account to simulate the energy demand. The wind power was calculated for ENERCON E-44 wind turbines using its power curve. The hourly power was summed up to get the annual energy output and capacity factor. The wind energy was optimized to substitute the hydro power and to save the water in the reservoir for dealing with power failures and fluctuations in electricity use without exceeding the natural yearly water flow to the reservoir.

The wind energy calculations look promising and the results are similar in comparison to the data from the recently erected wind turbines by Búrfell. Two turbines with the hydro power could manage the fluctuations in energy demand. A 21 wind turbine wind farm with doubled hydro power could also fulfill the energy demand in the West Fjords and save power purchase from other power companies. The wind and hydro power options in this study are not feasible economically with the current costs and energy prices, but should be studied further as future options.

Úrdráttur

Samrekstur á vindafli og vatnsafli gætu haft jákvæð samlegðaráhrif vegna þess að vindhraði er meiri á veturna og vatnsrennsli er meira á sumrin og einnig vegna þess að hægt er að spara vatnið á meðan vindaflið er notað í stað vatnsaflsvirkjana. Í þessu verkefni voru Þröskuldar valdir sem vænlegur staður fyrir vindhverfla vegna þess hve vindasamt er þar og staðurinn liggur nálægt háspennulínu. Fyrirhuguð er samkeyrsla vindhverfla með stækkun vatnsaflsvikjunar í Mjólká í Arnarfirði á Vestfjörðum. Vatnsaflið sem sparast með því að láta vindhverfla keyra í stað vatnsaflsvirkjana geymist og verður að stöðuorku í uppistöðulónum. Líkan var sett saman í Microsoft Excel til að hámarka vinnsluna úr virkjunum.

Vindagögn frá árinu 2012 voru m.a. greind niður í tímabil dags og árstíðir og sett upp í Weibull dreifingu til að sjá eiginleika vindsins. Raforkunotkun ársins 2012 var tekin með í reikninginn til að líkja eftir orkuþörf. Vindaflið var reiknað út fyrir ENERCON E-44 vindhverfil fyrir hverja klukkustund með því að nota orkulínurit sem framleiðandinn gefur út. Þetta var lagt saman og þannig fékkst út ársorkuframleiðsla og orkugeta vindhverfilsins á þessum stað reiknuð út frá því. Vindorkuframleiðslan var hámörkuð til að ganga sem mest í stað vatnsafls og geyma þar með vatnið í lónum sem hægt væri að nota ef háspennulínan til Vestfjarða bilar eða til hafa vald á sveiflum í raforkunotkun án þess að nota meira vatnsmagn en náttúrulegt rennsli til uppistöðulónanna er árlega.

Vindorkuútreikningarnir gefa vænlegar niðurstöður og ekki verri en í samanburði við gögn frá vindhverflum Landsvirkjunar á Hafinu við Búrfell. Tveir vindhverflar með vatnsafli gætu hjálpað til við að mæta sveiflum í raforkunotkun. Vindmyllugarður með 21 vindhverfli og tvöfalt meira vatnsafl en gert var ráð fyrir í byrjun gæti uppfyllt orkluþörf Vestfjarða og sparað orkukaup frá öðrum raforkuframleiðendum. Enginn þeirra virkjanavalkosta sem fjallað er um í þessari rannsókn eru hagkvæmir miðað við núverandi kostnað og raforkuverð en ættu að rannsakast frekar sem framtíðarmöguleikar.

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1 Introduction

Wind energy is becoming an interesting option in Iceland with its progressing technology and declining cost and the fact that Iceland is very windy.

In Iceland electricity generation is 70% from hydro power and about 30% from geothermal. Only a small fraction is generated with fossil fuel or about 0,02% [1]. Hydro and geothermal resources have been utilized in large scale and the majority of the electricity goes to heavy industry [2]. If the electricity prices are compared to other European countries they are lowest in Iceland [3].

The West Fjords of Iceland are quite remote and far from the national grid. A 132kV line passes over high heaths and mountains to the West Fjords. This line is vulnerable to harsh weathers and if it fails, the West Fjords will experience power shortage. Orkubú Vestfjarða (OV) the West Fjords power company produced 43% of the electricity in the year of 2012. The rest they had to buy from other producers [4].

Hydropower is the safest option considering supply security and the generation can be easily adjusted. Hydroelectric power plants can be dispatched (i.e., generating unit that can be started and stopped when needed.), they turned on more quickly compared to other types of power plants which makes them very useful in emergency and peak up load situations.

Geothermal energy production is stable and offers the potential of multiple utilization. It can however take a long time, hours or days to shut down or ramp up power in geothermal power plants. The West Fjords are not a high temperature area but it does have some low heat areas. Electricity generation from geothermal resources is therefore not considered feasible there. The low temperature geothermal heat can however be used for district heating that would save the electric energy.

The features of wind energy are certainly different compared to hydro and geothermal energy. Wind energy is intermittent because the wind is fluctuating, however wind is an interesting option where there is a possibility to take advantage of the flexibility of hydro energy to level out the fluctuations that comes with wind power production and save water in the reservoirs as potential energy for high demand periods. There is even a possibility for using the extra energy for pumping up to reservoir when the energy demand is low and wind is strong. During the winter wind is usually stronger and there is little snow melting and therefore little water accumulating into hydroelectric reservoirs, so it is clear that combining wind and hydro power has positive synergistic effect.

1.1. Hydro Power Expansion on Gláma

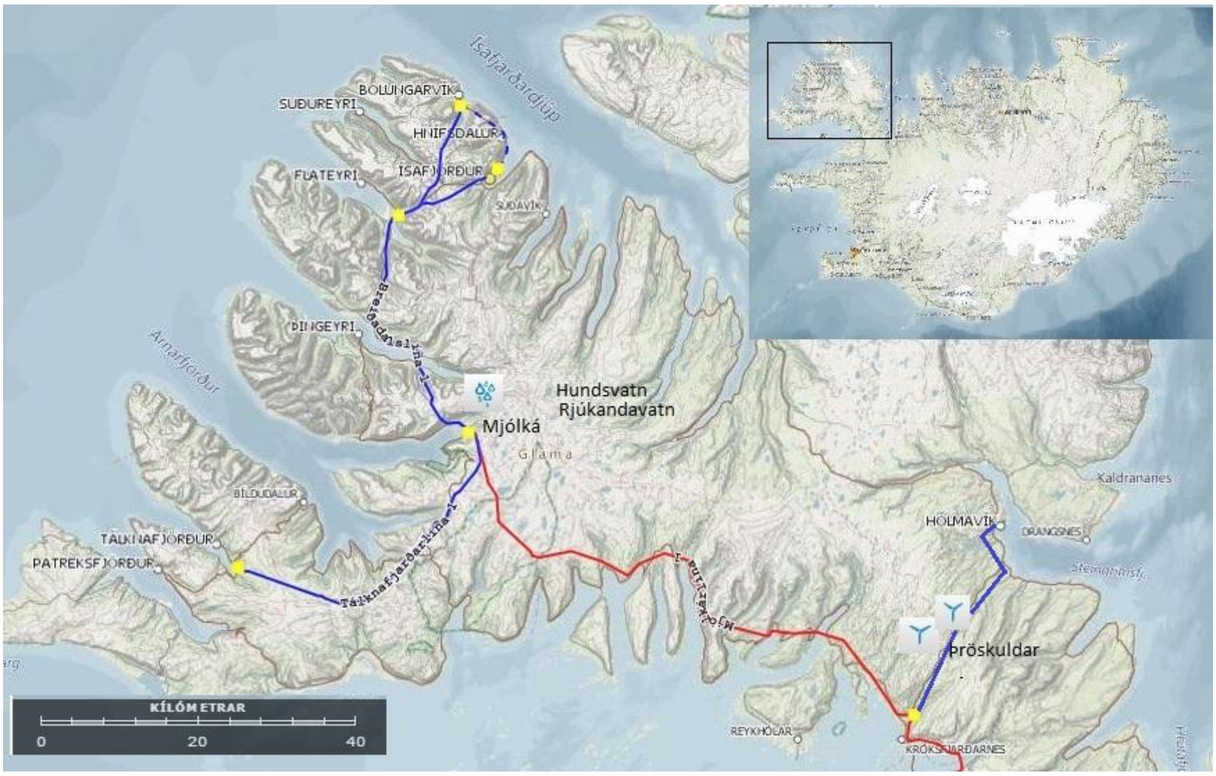

Figure 1 West fjords With the subjects places. Þröskuldar wind power site, Hundsvatn and Rjúkandavatns reservoirs, Gláma highland and Mjólká hydropower station. The red line indicates the 133kV powerline. The blue lines are lines with 66 kV and 33kV voltage. Yellow dots indicate substations [5].

Hydropower stations in the West Fjords are few and small compared to hydropower stations in other parts of Iceland. The biggest is Mjólká which is currently 10,6 MW (Mega Watts). OV has considered expanding the electricity production of Mjólká in a couple of ways. One is to harness water from another water catchment area on the other side of the mountain Gláma. The precipitation in the highlands of Gláma accumulates into lakes and rivers that run down into valleys and fjords all around the highland. The water from Gláma runs in different directions and cannot be used for electricity production in Mjólká power plant unless the water way is altered towards it. Verkís Engineers consulting company is assessing the possibility for OV to drill a tunnel with a Tunneling Boring Machine (TBM), through Gláma from Hundsvatn and Rjúkandavatn in the catchment area of Skötufjörður to the other side of Gláma in to the reservoir of Mjólká in Arnarfjörður named Borgarhvilftarvatn. The two lakes Hundsvatn and Borgarhvilftarvatn contain 20,6 Gigaliters (Gl) of water together [6].

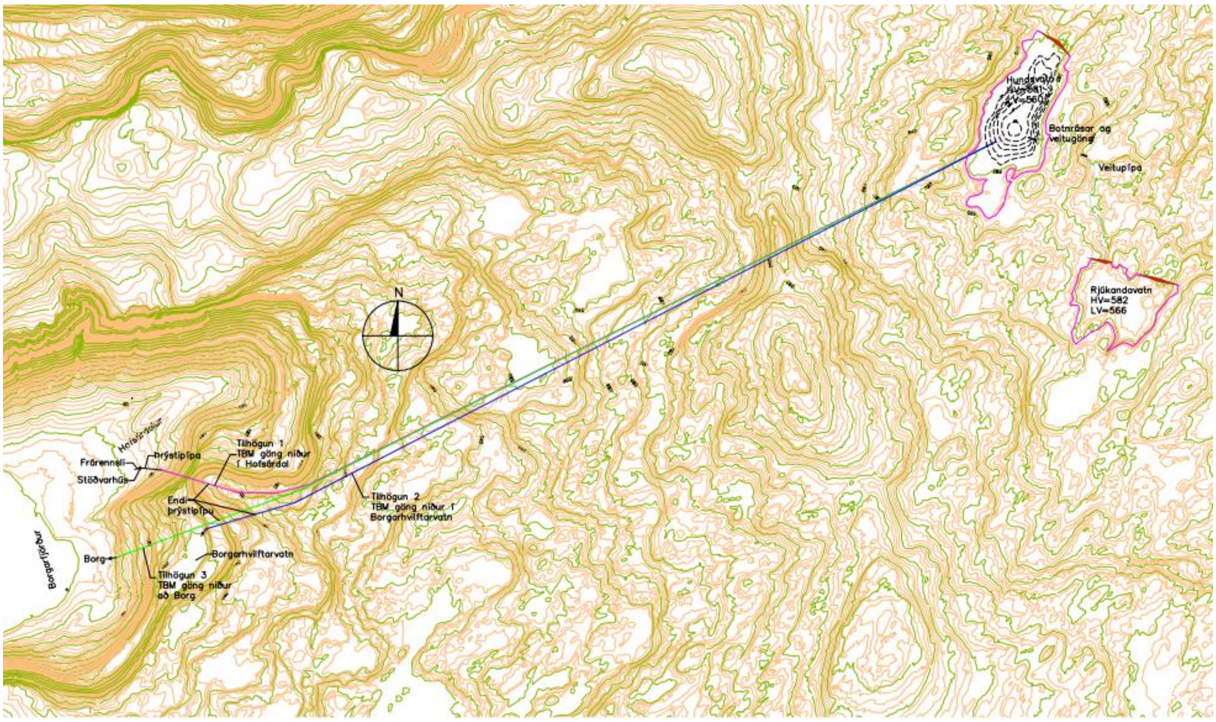

Figure 2 Possible ways to harness water on Gláma [6].

The path of the tunnel is shown on figure 2 and 3. The blue line on figure 2 indicates the path of the tunnel from Hundsvatn to Borgarhvilftarvatn in Arnarfjörður which is the reservoir for Mjólká power station. The height difference from Hundsvatn to Borgarhvilftarvatn is 361 meters, as shown on figure 3. The extra water that comes from Hundsvatn will be used for a new turbine by Borgarhvilftarvatn (Mjólká VI) and further expansion of the old Mjólká power station with new turbines and renewal of older turbines (Mjólká I). By doing so it is possible to expand the power generation from 10,6 up to 20 MW total [6].

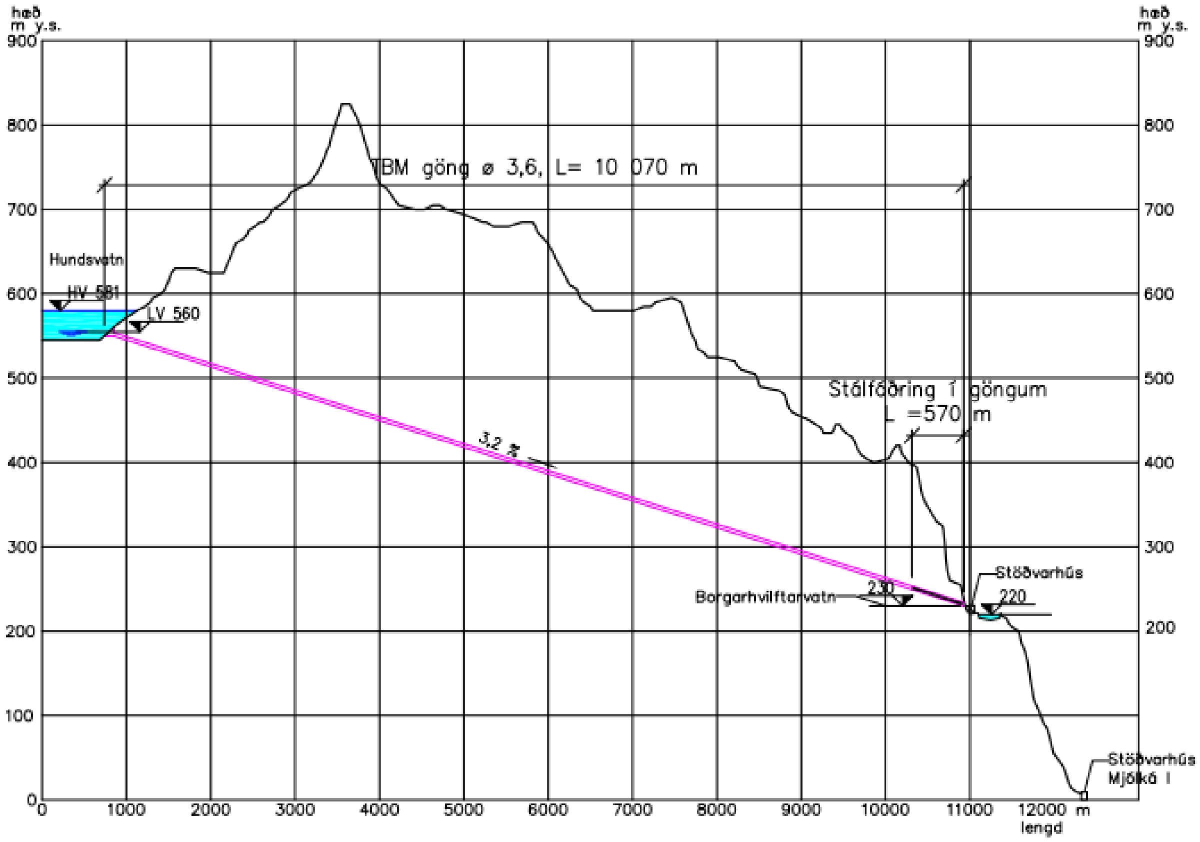

Figure 3 The TBM tunnel from Hundsvatn to Borgarhvilftarvatn [6].

1.2. Wind Power on Þröskuldar

A recently built road was named Þröskuldar and it passes a heath from Króksfjarðarnes to Hólmavík as seen on figure 1.

The Icelandic metrological office collects data of wind speed in a weather station located along the road passing the heath in approximately 370 meters above sea level. The wind seems to be strong and stable there. Also this site is close to the 33kV power lines passing the heath to Hólmavík as you seen in figure 1, so connecting wind turbines to the grid would be trivial and could be done with low connection cost. Because of that OV are interested on putting up wind turbines there. There are many windy places that could be good for wind power. On none of these places it is as easy to connect to the grid as Þröskuldar because of distance from power lines or the lines passing those places have too high voltage to be feasible to connect to.

From the wind data it is possible to estimate the capacity factor of a turbine on that site, the ideal number of wind generators and how much power will be possible to generate with these combinations of wind and hydro power.

1.3. Landsvirkjun's Wind Power Experiments.

Landsvirkjun has erected two wind turbines north of Búrfell Hydro power station on the south of Iceland. The wind turbines are at 270 meters elevation on an open plain close to the edge of the highland, called Hafið, which is known for being windy. The wind turbines are manufactured by the German company ENERCON. Landsvirkjun chose the model ENERCON E-44. This type of wind turbines have no gearbox and produce electricity with fewer turns, that reduces stress on moving parts and has lower maintenance cost and longer durability than wind turbines with gearboxes. They also have de-icing equipment which would be good for the Icelandic humid and cold conditions [7].

Wind turbines of this size have never been set up in Iceland before and it is the first time the feasibility of generating electricity with wind power is explored in Iceland. The new wind turbines have been running since December 2012 [8] and Landsvirkjun claims that the results with them are very good [9].

1.4. Aim and Objective

This thesis project is about an expansion of hydropower generation on the Gláma highland in the West Fjords of Iceland. Along with the hydro power expansion the idea is to put up wind turbines that substitutes the hydro power generation to save water into the hydropower reservoirs during high wind periods.

When the hydro power generation has increased temporarily, and even more than the catchment areas natural water runoff can provide, wind power can be used to compensate for the hydro power and the water loss can then be regained.

The aim of this study is to find the energy production in GWh/year and how much water can be saved with the use of wind turbines on a grid of hydro power stations. The objective is to build a model of the Mjólká hydro power station and wind power station on Þröskuldar to simulate the power generation and water consumption. The generation must be in compliance with the variable requirements of electricity at any time.

With the modeling it will be possible to see how much water will accumulate in the reservoirs while running the wind generators. Also it will be possible to optimize the power generation, considering the energy need in different times of the year and accumulation of water in the reservoir. The aim is to have the reservoir full in the fall before the energy need is the greatest during the winter. The stabilizing of fluctuations will result in better supply security and less purchase from the national grid.

There are many questions that need to be answered before deciding on the use of wind power in a specific location. In this study the wind data for the proposed site of wind turbines will be studied with the statistic methods that are commonly used.

The research question is: Is the expansion of Mjólká I, and the new Mjólká VI with wind turbine cooperation economically and technically feasible?

The underlying questions are how much water can be accumulated while the wind turbines are running, and: Is the wind turbine technology ready for the Icelandic market with the low electricity prices? Then it is possible to explore how much can be saved in external power purchase after the new wind farm and hydropower plant expansions have been built?

1.5. Motivation

Wind energy is the fastest growing renewable energy source in the world. The cost of wind energy is declining and the features of wind power are different from hydro and geothermal power. Geothermal energy production is stable and offers the potential of multiple utilization. Wind power is, however, an interesting third option where there is the possibility to take advantage of the flexibility of hydro power and level out the fluctuations that come by using with wind energy production. Landsvirkjuns success with their wind turbine project gives good prospect for further wind power development in Iceland.

Transmission losses and power failures have been frequent in the winters in the West Fjords of Iceland. These problems are mainly because of icing on the transmission lines and strong winds. New transmission to the West Fjords will cost approximately 10 billion Icelandic kroners (~82 million US Dollars) [10], but the new proposed power plants will cost about the same amount or even less [6]. It seems that strengthening the transmission lines to West Fjords is very costly, so it's logical to build new local power plants that could cost less. Also new local power plants will improve energy security because of less energy will have to be transmitted through the transmission lines to West Fjords that could fail anytime when bad weather conditions occur.

1.6. Outline of the Thesis

This project is focusing on the wind as a new power resource in Iceland so it gets more coverage than hydropower in this thesis.

In chapter 2 the background and history of wind power and the state of the technology is described shortly. Literature is reviewed; both recent publications on wind power as well as classical definitions and methods of wind and wind power measurements are also listed.

In chapter 3 the methods used in this study are described as well as the data. The first part describes the data for wind and hydro power. The second part describes the energy calculation model and the statistical methods for the modeling. The parts thereafter describe profitability assessment and some limitations to the study are also discussed.

In chapter 4 the results of the study are presented. The characteristics of the wind on Þröskuldar is described. The power output and feasibility for each scenario is listed.

In chapter 5 the work of this study is concluded. The chapter discusses the meaning of the results and highlights the most interesting findings. Moreover, a short summary of the contribution of the study is given and some future research suggested.

2. Background and Literature Review

2.1. Wind Energy History

Wind energy has been used a long time back in history to the golden times of Persians and Greeks up to around 3000 BC [11].

The wind turbines arrived in Europe in the 10th century A.D. and were used for various tasks such as pumping water, grinding corn, sawing wood and powering tools [12].

The golden age of wind mills began around 1100 in Western Europe and dominated until 1850. The Steam engine and later gasoline and electric motors ended this era [13].

The first wind turbine for electricity production was built in 1888 by Charles W. Brush [14]. The first wind turbines were first at small scale. Cheaper alternatives gave little progress to utilization of wind power until the oil crisis in 1973. The oil crisis started a widespread interest in wind turbines. Especially in the U.S. That time the aim of utilizing wind had shifted to generating electrical energy, not mechanical energy [12].

The concern about global warming, due to increased amount of CO_2 in the atmosphere, increased the installations of new wind turbines after 1990. Danish engineers then improved the wind turbine for electricity generation. They are considered the forerunners in modern wind turbine technology [11].

Denmark started the first commercially offshore wind farm in 1991 [13]. Installed capacity of wind energy over five folded in the 1990's and larger wind generators came to reality in that decade [12]. Since then wind turbines have been growing in capacity and size and the biggest wind generator today is 8 MW [15].

Wind used to be an expensive option compared to fossil fuel driven electric generation. Government support helped with further development of the wind turbine[13]. Government support has made research possible and wind turbine technology has made considerable progress. Therefore wind energy is becoming more and more efficient, economical and a viable option in electric energy generation.

In Iceland wind turbines had not been used for electricity generation in large scale until Landsvirkjun started in 2012. Small turbines have however been used on farms and by summerhouses. In Grímsey the electricity is currently from diesel generators. Wind turbine operation has been considered there a few times. In 2003 it was considered to put up a Vestas E47 (660kW) which is their smallest commercially mass produced wind turbine. That wind turbine never came although it was considered that it would have a high capacity factor [16].

2.2. Green Certificates and incentive policies

Green certificates are an approach to accelerate the switch to renewable energy. The green certificates confirms that electricity is produced from renewable energy sources like solar, geothermal, wave and tidal energy, hydroelectric power, biomass, biofuel, landfill gas, sewage treatment plants and wind, but not fossil fuels [17] [18]. European countries are using an approach of trading fixed quotas combined with green certificates. The government introduces fixed quotas regarding the amount of renewable energy per year electric system have to sell per year through their network. At the same time the electricity producers receive certificates for the amount of energy they sell into the grid. The electricity buyer has to buy those certificates as proof that they have fulfilled their obligations of buying renewable energy [19] [11].

These certificates are sold on a separated market independent from a specific electricity transmission system so Iceland can participate on the market with its green energy and have established laws about it [20]. That could give power companies some extra income [19].

Support from government with incentive policies, has been essential for the wind power industry [21]. Some countries that had not taken part in first innovation of wind power technology have used strategies in fostering joint ventures with manufacturing companies and established domestic developments in wind power [21]. The fixed feed in tariffs, government support to research etc. can drive further wind turbine development.

2.3. World Capacity

At the end of year 2012 installed wind capacity was 282.275 Megawatts, that can provide 580 Terawatt hours per year which is over 3% of the global electricity demand as seen in figure 4 [22].

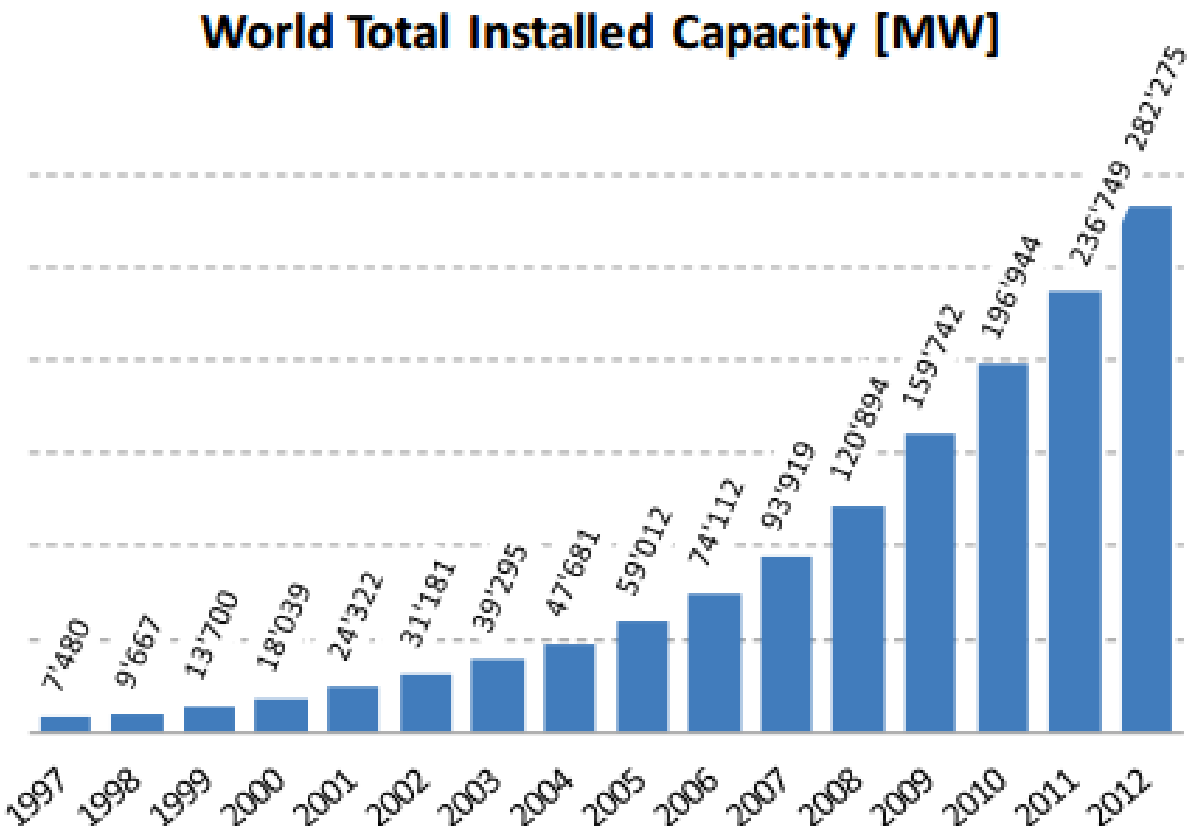

Figure 4 Total installed wind power capacity 1997-2012 According to World Wind energy Association [22]

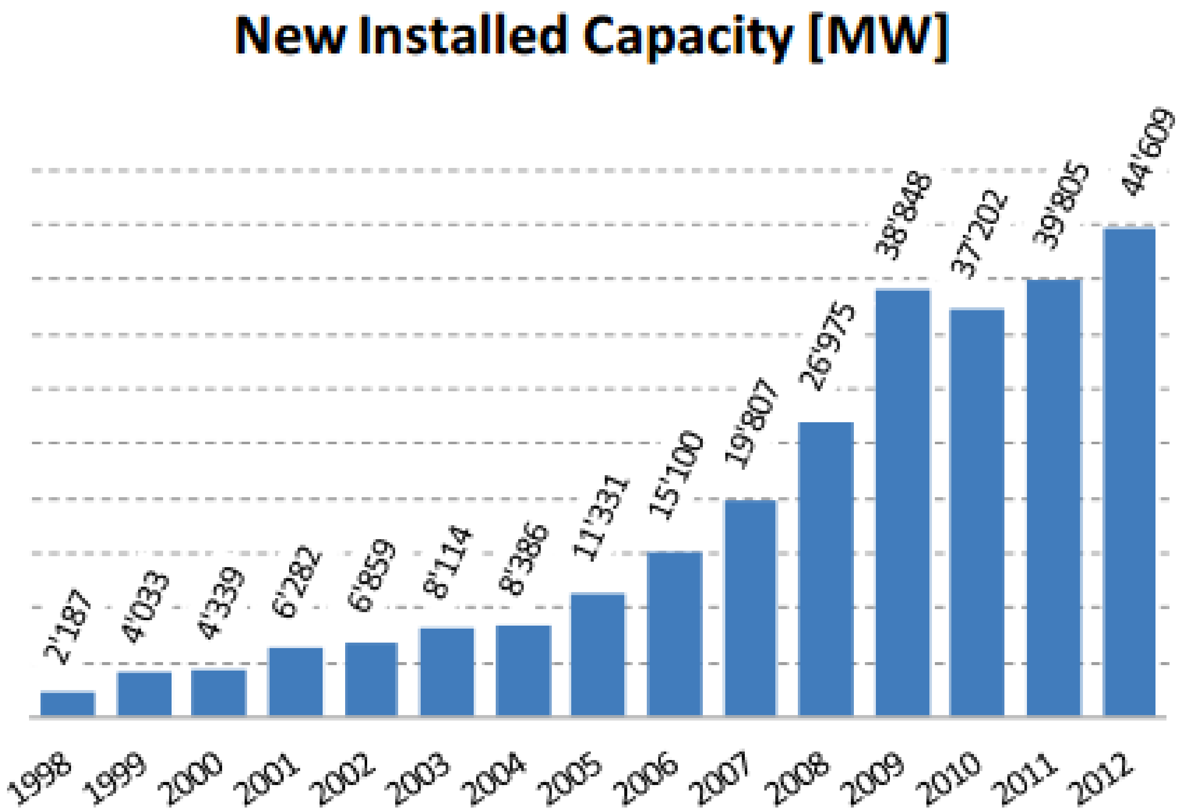

Figure 5 New installed wind power capacity 1998-2012 According to World Wind energy Association [22]

EIA's Annual Energy outlook for 2013 projects that wind energy generation in the world will almost triple before 2040 [23].

The World Wind Energy Association projects that installed capacity of wind will double from 2012 to 2016 and triple in 2020. WWEA also predicts wind power will be as much as installed hydro power capacity in the next eight years [22].

2.4. Wind Measurements

Wind measurements for the purpose of power utilization have not been conducted until recently in Iceland. Landsvirkjun has commissioned a wind map of Iceland that is still their industrial secret and access was not granted to it for this study.

The Icelandic metrological office (Veðurstofa Íslands) is participating with the Scandinavian countries in the IceWind project that is about wind engineering in cold climates. In this project a wind atlas will be created for Iceland. In that context the Icelandic metrological office has published on their website maps of wind speed and wind power density at 50 and 100 meters height [24]. On these maps it shows that there are many places in the West Fjords that have much wind speed. These maps are not accurate and it would be better to make measurements in a smaller scale.

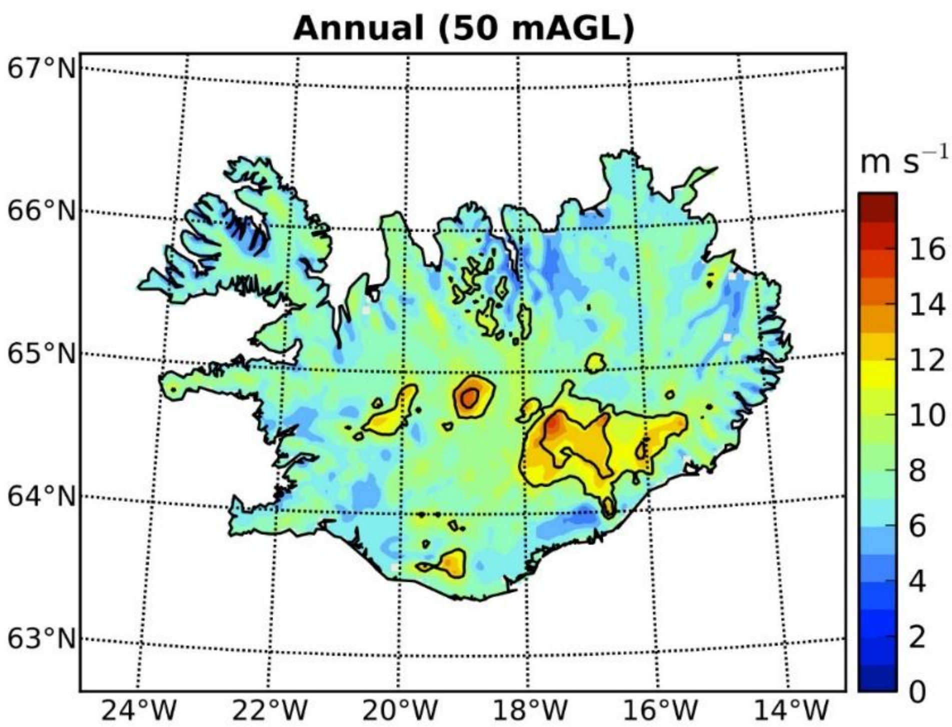

Figure 6 Annual Average Wind speed at 50m height above ground level [24]

The map on figure 6 shows the annual average wind speed seems to be 8-10 m/s in the Þröskuldar area. The proposed site for wind turbines is in a valley. The valley may have a channel effect as it lies in the direction South-West to North-East.

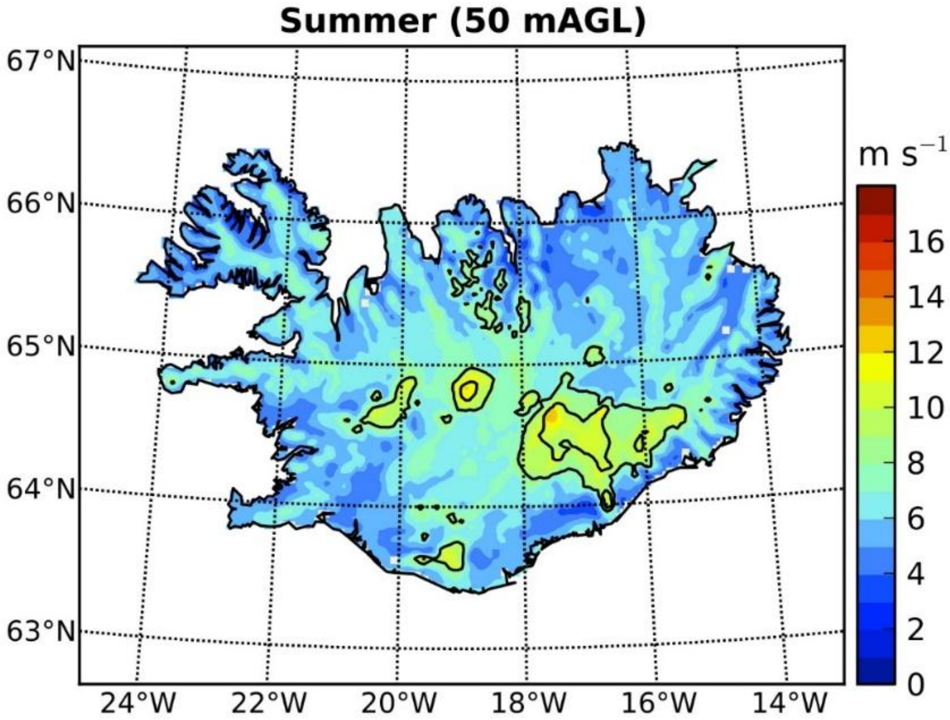

Figure 7 Summer Average Wind speed at 50m height above ground level [24]

In June, July, and August the average wind speed appears to be 8-9 m/s in the area. In the afternoon a sea breeze develops over land near coasts caused by temperature and pressure difference. The cold air forms higher pressure that moves inland to lower pressure warm air [25].

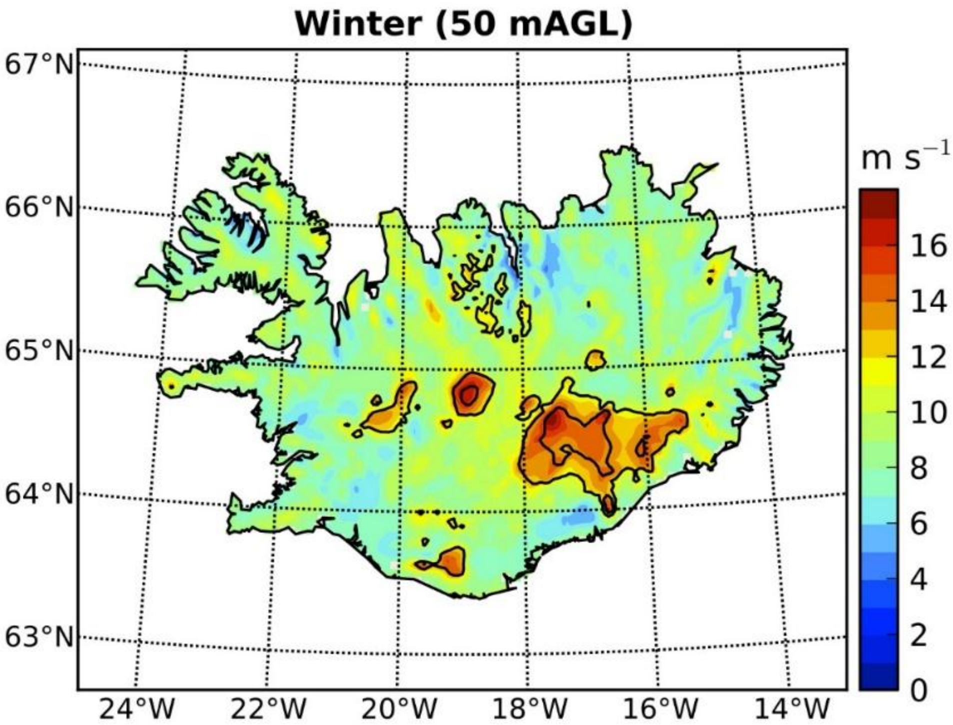

Figure 8 Winter Average Wind speed at 50m height above ground level [24]

Winter is windy with estimated 10-11 m/s average wind speed. That has as mentioned before, a positive synergistic effect in the integration with hydro power that mainly uses the water in the winter months that accumulates the most in to the reservoir during summer.

2.5. Cost of Energy

Levelized cost of energy is the sum of annual levelized costs of an energy system divided by the production in a year[12]. LCOE is described in a formula as

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{2.1.}$$

Where I_t is the investment cost, M_t is the maintenance cost, F_t is the fuel cost, $E_t$is the electricity production, r is the discount rate and n is the lifetime of the system. This can be used to compare costs of different types of energy sources.

It is difficult to make a general cost estimation of electricity production because costs can vary significantly between countries where conditions are different. Figure 9 shows average costs in different regions and it is significantly higher than Landsvirkjun has. This big difference may be because Landsvirkjun has managed to build up hydro power plants at low cost by making long-term contracts, selling steady energy in large amounts to aluminum

Smelters in Iceland[8]. Landsvirkjun sells about 74% of their energy to aluminum smelters [8] and 73% of total energy in Iceland goes to the aluminum industry.

Cost of wind power can also be different by region. Main reasons are different availability of the wind resource, different taxes etc. There are many organizations that calculate and estimate wind power cost.

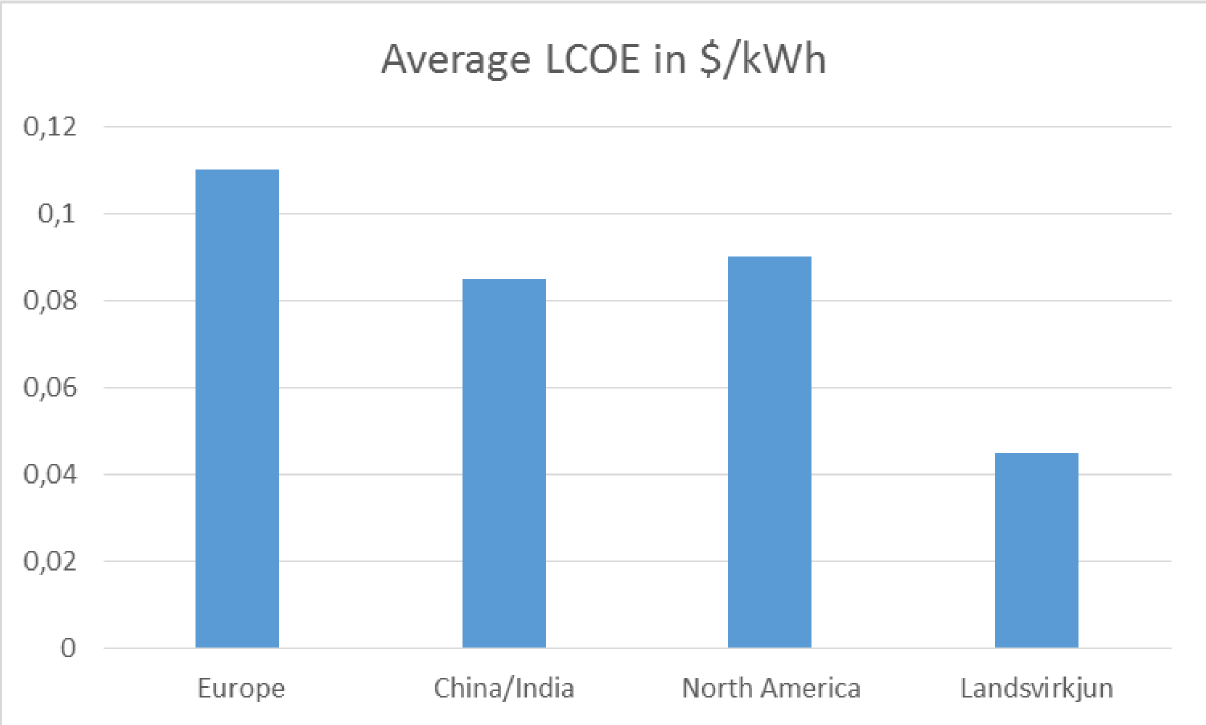

Figure 9 Average LCOE in diffrent regions

International Renewable Energy Agency (IRENA) makes an annual report on Renewable Power Generation Costs. The cost of onshore wind farms in 2011 was $0,06/kWh up to $0,14/kWh. The best sites in North America could deliver as low as $0,04/kWh [26].

Still the price of electric energy is very high in some places for instance in some of the Greek islands the price of maintenance and operation of conventional electric generation is around $1/kWh [27], which is vastly higher than the low prices in Iceland. The Icelandic nation can consider themselves fortunate with their low cost of electricity and still from renewable resources that leads to one of the best electricity prices in the world.

Landsvirkjun is currently operating wind turbines for research purposes, in Icelandic conditions. The goal of the research is to identify the real cost per MW, analyze the uptime and efficiency ratio and identify the environmental and social impact. The aim is also to research the possibilities of increased water retention in reservoirs. According to

Landsvirkjuns experience with their two wind turbines the cost of utilization of wind power is $45/MWh [28]. The long experience with geothermal and hydro power has made the electricity cost very low in Iceland. Geothermal power costs $38/MWh and hydro costs $34/MWh according to a presentation from Landsvirkjun [28].

Blanco (2009) states that the cost of an onshore wind farm is from 4,5€cent/kWh to 8.7€cent/kWh (or around $60 - $120/MWh). The main influencing factors are the running hours and the level of capital cost. This is much higher than the wholesale price of electricity in Iceland so it is clear that the wind power cost has to be lower or electricity prices in Iceland have to be higher for wind power to be feasible.

Increased commodity prices in the past years, the levelized cost of wind power going down and the fact that it has become closer to hydro power has made wind more feasible. It is still clear that it will not compete with the low cost of hydro power in Iceland in the near future especially since Iceland is not on the European market with a submerged cable.

Table 1 Levelized cost of electricity by source and regional variations of costs of plants entering service in 2018 [23]

	Range for total system levelized costs (2011 $/megawatthour) for plants entering service in 2018		
Plant type	**Minimum**	**Average**	**Maximum**
Dispatchable Technologies			
Conventional Coal	89.5	100.1	118.3
Advanced Coal	112.6	123.0	137.9
Advanced Coal with CCS	123.9	135.5	152.7
Natural Gas-fired			
Conventional Combined Cycle	62.5	67.1	78.2
Advanced Combined Cycle	60.0	65.6	76.1
Advanced CC with CCS	87.4	93.4	107.5
Conventional Combustion Turbine	104.0	130.3	149.8
Advanced Combustion Turbine	90.3	104.6	119.0
Advanced Nuclear	104.4	108.4	115.3
Geothermal	81.4	89.6	100.3
Biomass	98.0	111.0	130.8
Non-Dispatchable Technologies			
Wind	73.5	86.6	99.8
Wind - Offshore	183.0	221.5	294.7
Solar PV[1]	112.5	144.3	224.4
Solar Thermal	190.2	261.5	417.6
Hydro[2]	58.4	90.3	149.2

As seen in table 1 the average LCOE of onshore wind is $86,6/MWh. LCOE of hydro is $90,3/MWh and LCOE of geothermal is $89,6/MWh. The levelized cost of onshore wind turbines is lower than for hydropower and similar to geothermal according to the EIA annual energy outlook [23].

The levelized cost in the EIA calculations are far from Iceland's cost of energy. That is because of Iceland's special conditions. Low cost of land and the fact that hydropower is an experienced technology in Iceland and other factors make the cost low. Furthermore capacity factor of hydro power which is around 90%, is likely to be better than for new power plant technologies entering Iceland e.g. wind and tidal power. Wind energy is becoming an interesting option because the technology has progressed and cost of wind energy is declining.

2.6. Environmental Impact of Wind Power

Wind energy is a new energy source in Iceland so the environmental impact of it must be considered. Hydro power is however known in Iceland so environmental impact of it is not considered in this thesis.

Wind energy has many benefits. Wind energy is considered renewable energy. The source is completely natural because the sun makes the heat difference between hot and cold places that creates pressure difference that makes the wind blow. Wind turbines don't make any pollution from substances like carbon dioxide or pollutants that cause acid rain, smog, radioactivity or contamination in the soil or sea or water courses. The impact is more of social one.

The use of wind turbines is not possible when wind is too much or too little and then it has to be substituted by other energy sources like diesel or coal power plants to provide backup then the environmental benefit is little. But that is not the case in Iceland because the backup can be provided by hydro or geothermal power.

It is essential to select the location of the wind turbines carefully. The magnitude of the wind is the biggest factor, the location is also essential because of aesthetic effects. The visual pollution is mainly that the wind turbines are large, they are considered ugly and stand out in the environment.

They make a lot of noise when the blades turn and split the wind. The large rotating blades have much kinetic energy that is dangerous to birdlife and can also cause risk if failure occurs.

Wind turbines make little energy compared to their footprint in the nature so to produce enough many wind turbines are required in so called "wind farms" that take up a lot of space.

Sustainability isn't so simple because there are other things to think of like how the wind turbines are made. The parts of the wind turbines are recyclable; mainly steel and fiber glass. The turbine motor uses earth elements that are required for permanent magnets.

The building of a wind turbine includes welding, transport of large parts of it to the site of utilization pollutes the environment. Roads are necessary to get to the construction site and also power lines are necessary. The wind turbines need maintenance and upgrading when new improved technology comes that can cause some disruptions and pollute [30].

It is necessary to think of the changes of the future use of the land before the wind turbines are put up. With electric production many wind turbines are put up on one location. The turbines don't take more than about 2-3% of the land they are on. The rest of the land is not good for urban homes or commercial use because of noise impact. There for it is better for agriculture like corn fields or grazing lands for live stocks [31].

2.6.1. Wind turbine noise

The wind turbine isn't as noisy as many other machinery as seen in the table below. The noise can however be annoying if people are near them. Modern wind turbines are much quieter than older ones. There are two kinds of noise that come from wind turbines: The swishing sound is called aerodynamic noise that comes from the turbine blades when they split the wind and the mechanical noise from gearbox and the generator [32].

Table 2 Noise level of different activities

Source/activity	**Noise level in dB(acoustically weighted)**
Threshold of pain	140
Jet aircraft at 250m	105
Pneumatic drill at 7m	95
Truck at 48km/h at 100m	65
Busy general office	60
Car at 64km/h	55
Wind farm at 350m	35-45
Quiet bedroom	20
Rural night time background	20-40
Threshold of hearing	0
(Source: Department of the environment, 1993)	

The noise is mainly annoying because there is nothing that covers the noise since the windmill must stand in open space accessible to the wind. Wind turbines must withstand noise regulations of each country or the ones the IEA (International Energy Agency) sets.

2.6.2. Electromagnetic interference

Electromagnetic interference is a problem when there is something in the way of radio, television or other transmission waves on the way to the receiver. If the tower or blades contain metals they reflect the waves and interfere with the original signals and makes the waves distorted when they arrive to the receiver. This mainly depends on the materials the wind turbines are made of. Many of the blades are made of metal or glass fiber reinforced plastic that contains metal components and subsequently they reflect very much. On the other hand wooden blades absorb the waves. The shape of the tower and the blades matters also. If the shape is flat they reflect more than rounded shapes [32].

2.6.3. Visual impact

The biggest controversy of wind turbines is probably their visual impact. The moving blades draw attention in the landscape. It is essential to make the wind turbines as little prominent as possible. Their design, color, size, number of turbines and location is factors that have to be considered [32]. If the wind turbines are put somewhere they will not be seen like offshore the visual impact will be less. Offshore wind is although more costly to utilize as seen in table 1.

2.6.4. Public attitude

When people get to know more about wind energy and the arguments for and against wind power, they side more with wind power utilization [33]. Surveys made in the UK, Denmark and Netherlands show that the majority of those who live in the presence of wind farms and get their electricity from them are in favor of this clean energy [33][34]. They were more attractive of an option after the wind turbines became present in their area when they really got to see what an operating wind farm was like [33].

2.6.5. Birds

The fatality of birds flying into rotor blades is very low compared to other causes of bird fatality. On the chart below the mortality is shown in thousands of birds [35]. These numbers vary by conditions on each place. In Iceland it would probably be different because of different species and natural conditions. It is necessary to derive more accurate estimates at each local, or national conditions [36].

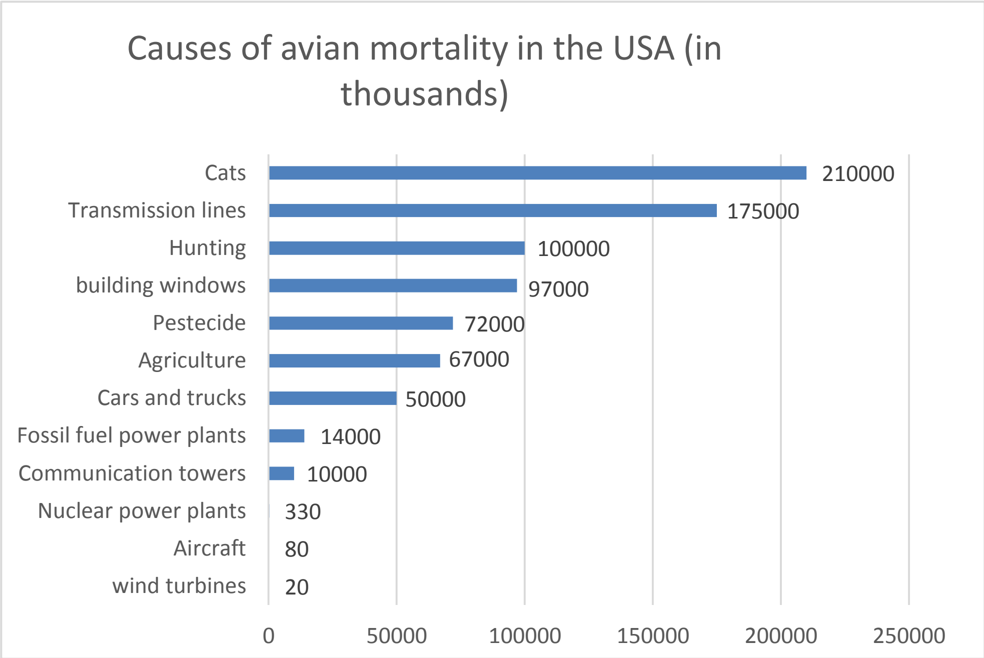

Figure 10 Causes of avian mortality in USA (in thousands)

3. Methods

This chapter covers the methods, describes the data used, and discusses the limitations of this study.

3.1. Wind Energy Calculations

The financiers set rules for the wind power projects require that proper wind measurements with a metrological mast must take place before the project gets funded. The met mast must reach the height of the proposed wind turbines hub height.

3.1.1. Projection of wind to higher altitudes

Where wind is measured near the ground it must be projected to higher altitudes by a widely used formula:

$$\frac{V(z)}{V(z_R)} = \left(\frac{z}{z_R}\right)^a \qquad (3.1)$$

In this formula the $V(z)$ is the wind speed at height z, $V(z_R)$ is the measured speed and a is the power law exponent which depends on the surface of the terrain and air stability [12].

The power law exponent characterizes the rate at which wind speed changes with height above the ground.

Earlier studies on the power law formula state the typical value of a = 1/7. Further studies has been done in Icelandic conditions. An unpublished research by Guðrún Nína Petersen which contains data from weather balloons released at Keflavík airport concludes that a is close to 1/7. K. Helgason states that in a research G.N. Petersen made for Landsvirkjun concluded that the value of a is closer to 0,12 in Búrfell area where Landsvirkjuns wind turbines are [37] [38].

3.1.2. Wind power estimations

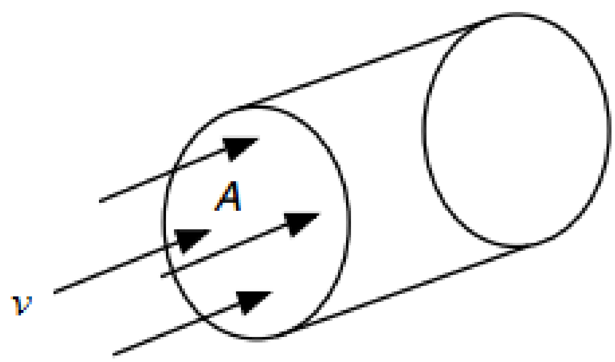

Figure 11 Flow of air through a disk. v: Wind velocity. A: Swept area

Thinking of a stream tube the total wind could only be captured if the wind speed reduces to zero. That is not realistic. The so called Betz limit that is 16/27 = 59% of the theoretical wind power. So the Betz limit is the maximum achievable extraction of wind power by an ideal wind turbine [12]. This is taken in account in the power curves and the power coefficients calculations.

To estimate the power of a wind through an area A, (as shown in figure 11) the continuity equation from fluid mechanics can be used where the mass flow of air dm/dt is a function of air of air density ρ and air velocity v shown as:

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \rho A v \qquad (3.2)$$

The power of flow can be calculated by putting in the kinetic energy per unit time and is then is given by:

$$P = \frac{1\mathrm{d}m}{2\mathrm{d}t} v^2 = \frac{1}{2}\rho A v^3 \qquad (3.3)$$

To calculate the power P of a wind turbine the following equation is used where C_p is the power coefficient:

$$P = 0{,}5\, \rho\, C_p\, v^3\, A \tag{3.4}$$

The capacity factor is a measure of the efficiency of a wind turbine in each location. It is the ratio of the energy actually produced divided by the maximum energy the turbine can produce.

$$CF = \frac{E_{year}}{E_R} \tag{3.5}$$

E_{year} is the actual energy produced annually and E_R is the maximum energy that the specific turbine can produce per year.

3.1.3. Power curves

The power that is available from a wind turbine can be shown by a machine power curve that comes with each wind power electric generator. These curves are unique for each turbine, based on tests on the machines [12]. These tests are made by accredited institutions that document the evidence of these measurements on respective power curve certificates [39].

Power curves have four defined speeds [39]:

1. The startup speed is the wind speed needed for beginning turning the blades
2. The cut in speed is usually around 4 m/s. That is the wind speed needed for beginning producing electricity.
3. Nominal speed is the maximal power output of the turbine, even though it can endure more wind speed.
4. Cut out speed (usually 25 m/s) is the wind maximum speed that the wind turbine switches off to prevent damage because of excess wind forces.

Figure 12 shows a power curve for ENERCON E-44 wind turbine used in this study [40]. This power curve is shown and explained in chapter 3.2.1.

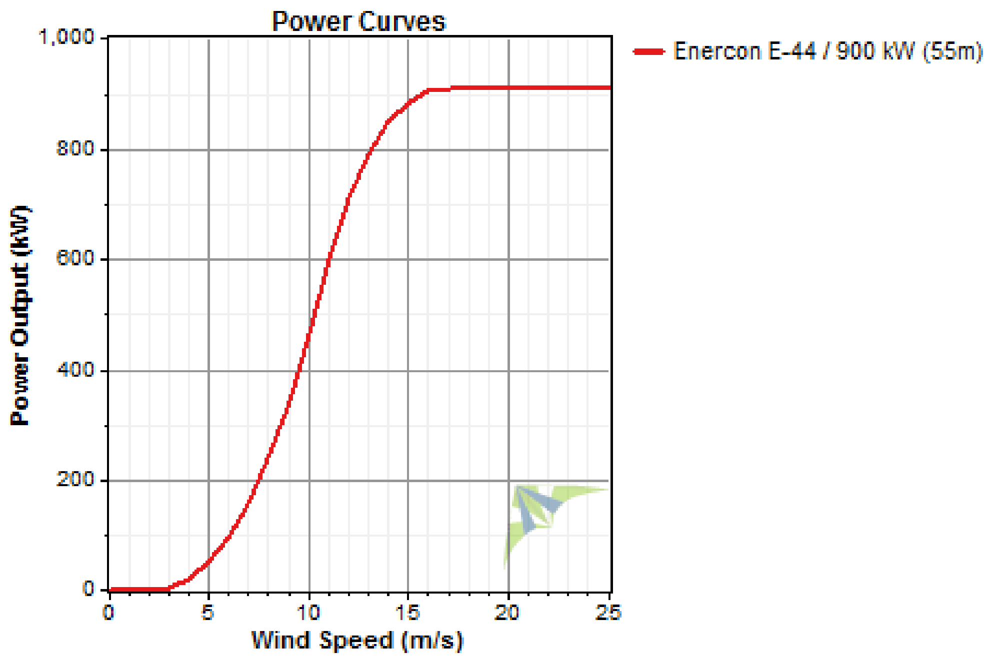

Figure 12 ENERCON E-44 power curve [39]

ENERCON E-44 can be equipped with a patented storm control feature that allows operation above wind speed of 25 m/s up to 34 m/s. The storm control makes the power reduce gradually from 28 – 34 m/s but not stop abruptly [41].

The exact power curve for operation above 25 m/s is not given in the wind turbines specifications brochures. That may be because of different conditions like gusts and average wind speed. The settings of storm control can be altered to different conditions [41].

Activated storm control linearly reduces the rotational speed of the turbine at 28,5 to 34 m/s. This reduces the active power production. Then it shuts down at 34 m/s rated at 10 minutes average [41].

If the wind turbine has a cup anemometer, storm control is deactivated automatically in temperature below 3°C [41]. For this study this temperature happens in only about 1,4% of the time also given the criteria that wind is more than 25 m/s.

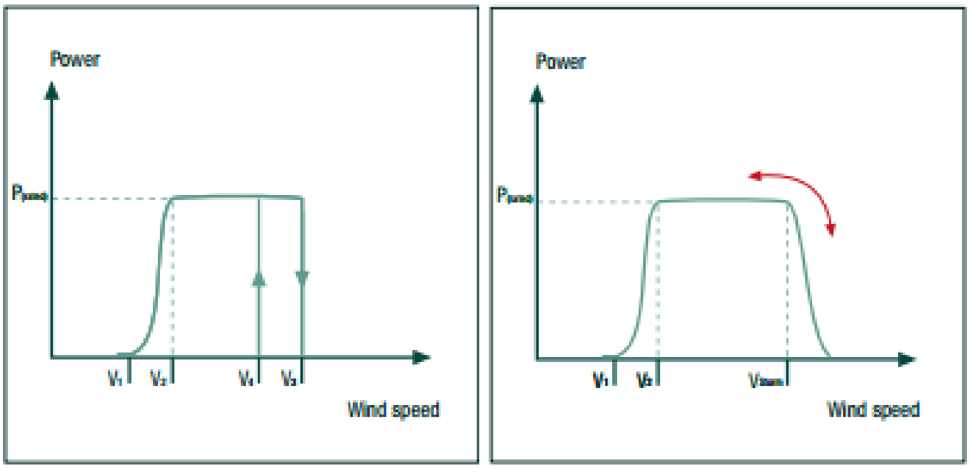

Figure 13 Power curve of a wind turbine without and with ENERCON storm control [41]

3.1.4. Weibull distribution

Wind is different by location. It is necessary to analyze the frequency of the different wind speeds before erecting a wind turbine in a proposed location to see if it fits the wind turbines features. Weibull distribution is good way to characterize the variations in wind speed [12]. Wind speed can be statistically modelled by using Weibull distribution, which is a commonly used function to correct the measured wind data that holds the frequency of different wind speeds to the Weibull curve. Weibull distribution is calculated by this function of v:

$$f_w(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \tag{3.6}$$

Where $f_w(v)$ is the probability of wind speed v, c (m/s) is the scale parameter and k (dimensionless) is the shape parameter [42][43]. Larger scale parameter means more spread out distribution. The k values closer to 1 means that distribution is relatively flat that means highly variable winds and higher k values means more peaked distribution that indicates regular and steadier winds [42].

3.2. Data

To get the most accurate results the aim was to get the most recent and neighboring sources as possible.

3.2.1. Hydro power data

Hydro power cost has been estimated for this project [6] by Verkís Engineers consulting company. All figures for cost estimation, flow in and out of the reservoir, the size of turbines, pipes and reservoir etc. are taken from this report.

Verkís has calculated the cost of building a power plant with the tunnel drilling from the catchment area on the other side of Gláma. Building cost of the hydro power plant with all its utilities is taken from the Verkís report without interest which is calculated in the profitability model. According to the Verkís report: Operation and Maintenance cost (O&M) is 0,8% of the building cost of the hydro power plant.

The hydro power turbine in Mjólká VI is 6,81 MW and uses 2,2 liters per second when running on full potential.

The average wholesale price of electricity in Iceland is $33/MWh according to Landsvirkjun's 2012 annual report.

The price of electricity that is used in this study is taken from the the Verkís report. The price without transmission cost and tax is showed in table 3.

Table 3 Estimated electricity price according to Verkís report.

Winter	0,0333	USD/kWh
May and September	0,0250	USD/kWh
Summer	0,0167	USD/kWh
Power charge	0,0558	MUSD/MW/a

Hydrology of the area was taken from a report made by the National Energy Authority (Orkustofnun) [44]. From that report the average run to the catchment area of Hundsvatn and Rjúkandavatn combined from the year 1997 – 2001 is 1,9 m^3/s. It is stated that this might be overrated or underrated because of insufficient measurements in the river below in the summer of 2001. There is more runoff during the summer months than the winter from December to March the main water usage period. The Verkís report says that the winter flow is only 51% of the yearly average flow which is 1,9 m^3/s. Therefore in the model the winter flow (December - March) is kept 0,969 m^3/s and summer (June-July) flow is 3,762 m^3/s. in the fall and spring (April-May and August-November) it is 1,9 m^3/s. That gives an average 1,9 m^3/s. This is done for simplicity reasons and because the actual hourly flow data was not accessible but the flow diagram in figure 14 was taken into consideration. This method does not affect the energy calculations because the reservoir is so big that it will not empty anyway and it fills up during the summer and stays full until 1. October. Then the reservoir empties during winter and the most melting and runoff is during the summer, so the summer is the time when that water could overflow and go wasted.

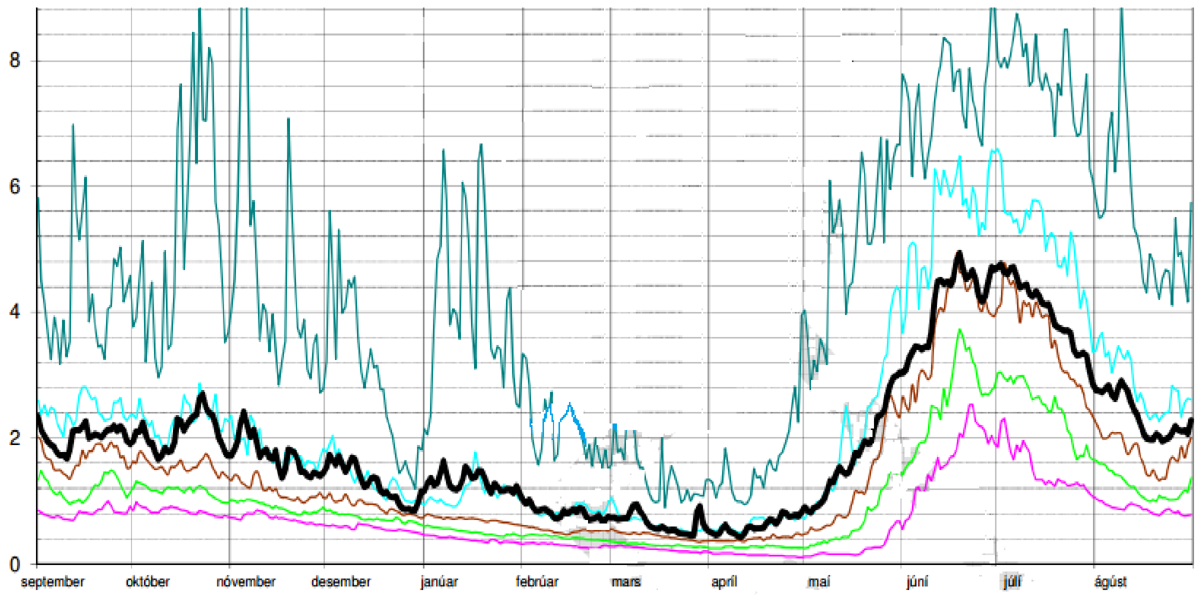

Figure 14 The black line shows the average flow in Hundsvatn and Rjúkandavatn in m^3/s from 1. September to 31. August. The other lines are not related to this thesis[6].

Energy is difficult to store except as potential energy in hydro power reservoirs. Fluctuations in energy use are diurnal that vary from day to night and also there are seasonal fluctuations where energy demand is lower during the summer and higher during winter. It is essential to know these fluctuations as other regular changes in electricity consumption, for predicting, planning, and operating a power system. To make the model more realistic, energy consumption data was used to take in the fluctuations. Since this data of energy consumption was confidential the data was changed to ratios or parameters that didn't show the actual megawatts generated.

3.2.2. Wind power data

Wind data was taken from the weather station owned by the Icelandic Road Administration (Vegagerð Ríkisins). This data contains hourly mean wind in 6 meters above ground. The data contained a few gaps where the wind speed measurement had dropped out for a few hours. That could be because of minor breakdowns or freezing. Those gaps were filled with data from Reykhólar which has similar wind as seen in figure 15.

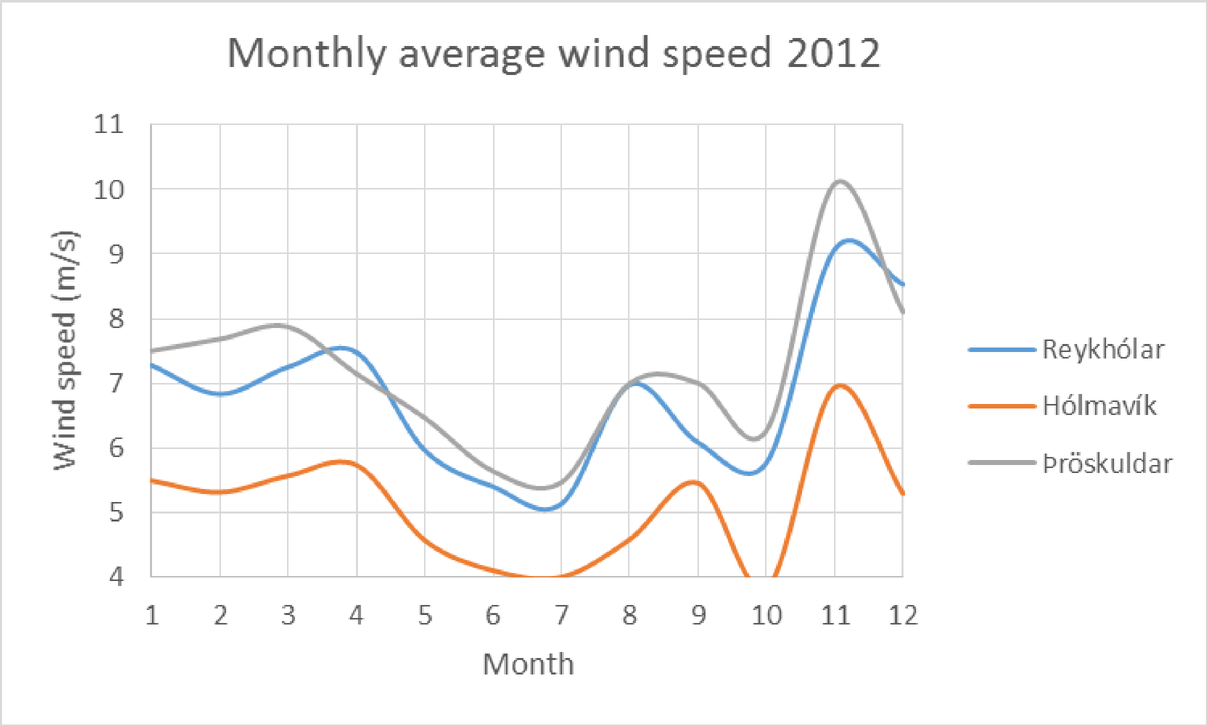

Figure 15 Monthly average wind speeds at weather stations close to Þröskuldar.

Figure 15 shows the wind speeds in Hólmavík and Reykhólar compared to Þröskular. Reykhólar is known as a windy place and has wind speeds very similar to Þröskuldar.

The best way to estimate the wind power would be to build a mast that goes up to 55 meter height and take the measurements there to get more accurate wind. Since the measurements were taken at 6 meters height above ground it had to be calculated to the 55 meter hub height of the wind turbine with formula 3.1 using $\alpha = 0{,}11$. The α value is chosen this low because this location is in a high altitude which usually is covered with snow in the winter. As said in chapter 2.6.1. the α at Búrfell was estimated to be 0,12.

In chapter 4.6 where Þröskuldar is compared with Búrfell, wind data was taken from the weather station at Búrfell but not at the location of the wind turbines at Hafið. The wind measurement mast at Hafið (Búrfell) has been removed and therefore the measurements are taken from the nearest weather station.

The power curve given for ENERCON E-44 was used to obtain the energy with the given wind data. The wind was incorporated with the corresponding energy in the power curve. An application called Windographer was also used for comparison. Windographer calculates the properties of the wind. The results show wind distributions from this program.

There are several reports that project the cost of wind power. The aim was to get as real figures as possible from as close and recent experience as possible. Wind power cost figures are taken from Landsvirkjun and from the proposed wind farm in the Faroe Islands which will contain 13 ENERCON E-44 wind turbines [45][46]. The cost figures from Landsvirkjun are higher than the cost figures from the Faroe Islands. That could be because they have more experience with wind generators and more trained staff, which could also mean that they are further down the learning curve. Landsvirkjun had to start with training staff, make wind measurements etc. which has already mostly been done in the Faroe Islands because of their earlier wind utilization.

In this study's profitability analysis the first two wind turbines will cost as much as they did at Landsvirkjun ($4 million for two wind turbines). Their recent experience is used because it gives a realistic idea of starting wind power operations. These numbers include the cost of foundations, roads, infrastructure and connection to the grid. Also they include training of personell.

The next wind turbines after the first two will have the same cost in the profitability assessment as they will have cost in the Faroe Islands' next wind farm ($1,3million each) [46].

The cost of operation and maintenance (O&M) is highly variable between countries from $10/MWh in the United States to $38/MWh in Austria. This depends mostly on the size of the market, how new and sophisticated the technology of the turbine is and the capacity factor [47]. The O&M cost of wind energy in Norway is from $20/MWh to $37/MWh [47]. In this profitability assessment the average of Norway's O&M cost $29/MWh is chosen because of similarity with Iceland.

3.3. Model

3.3.1. Wind power station description

This part describes a proposed wind power station, the circumstances of the location and the capacity factor of the wind power station.

Figure 16 ENERCON E-44 [39]

The wind turbines are from the German company ENERCON and of the model E-44. They are 900kW and their hub height is 55m. These wind turbines are gearless. That means less moving parts and fewer treads which means less maintenance [39].

The turbines have a controllable pitch system on the blades that can control the speed of the rotation. They are also equipped with an emergency power supply that makes them safe if power is absent. It goes then to the neutral position and brakes down in high wind storms. It has also a rotor brake and rotor lock to cut out of operation during high wind periods[39].

Cut out speed with storm control is 28 – 34 m/s, it does however depend on the storm control system settings of the turbine [41]. Without storm control on, the cut out speed is 25 m/s. The storm control feature explained in chapter 2.6.3 is not taken into account in the energy calculations but that could add a few more percent to the yearly electricity generation.

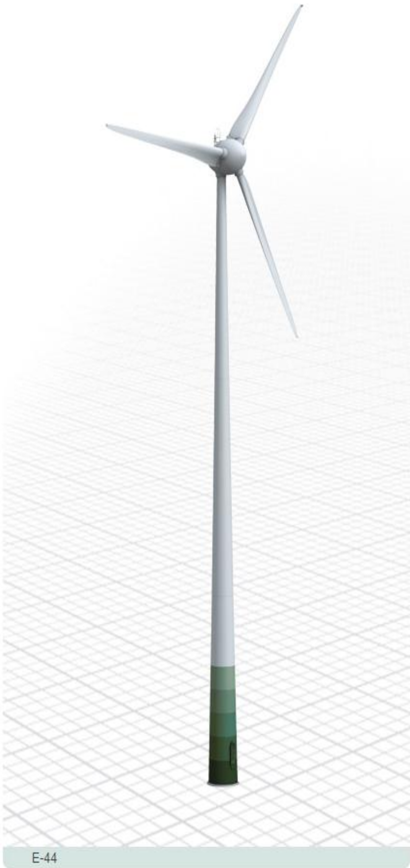

Figure 17 ENERCON E-44

As stated before the given power curves are based on tests the wind turbine manufacturer makes before it goes on the market. They show how much power the wind turbine can generate at a certain wind speed and they show the cut in and cut out speed of the turbine. The standards with power curves are that measurements of external interferences, like turbulence interference, are not taken into consideration [39].

In this study the power curve given by ENECON (table 4, figure 18) was used. This power curve depends on standard air density that is 1,225 kg/m^3. This air density is likely to be too high for Þröskuldar because it is in 370 meters height above sea level. Lower air density gives lower wind energy. Accurate measurements on air density at Þröskuldar may have to be done to get a better power estimation. Turbulence and gusty wind could slow down the rotation of the turbine but turbulence was neglected because the time frame of this study did not allow that although it is theoretically possible to study the turbulence, air density, and make more accurate wind measurements. The gain of these studies would be little because there are some other uncertainties in the wind data.

Table 4 The power curve and power coefficient for ENERCON E-44 [41]

Wind (m/s)	Power P (kW)	Power-coefficient Cp (-)
1	0.0	0.00
2	0.0	0.00
3	4.0	0.16
4	20.0	0.34
5	50.0	0.43
6	96.0	0.48
7	156.0	0.49
8	238.0	0.50
9	340.0	0.50
10	466.0	0.50
11	600.0	0.48
12	710.0	0.44
13	790.0	0.39
14	850.0	0.33
15	880.0	0.28
16	905.0	0.24
17	910.0	0.20
18	910.0	0.17
19	910.0	0.14
20	910.0	0.12
21	910.0	0.11
22	910.0	0.09
23	910.0	0.08
24	910.0	0.07
25	910.0	0.06

$\rho = 1.225 kg/m^3$

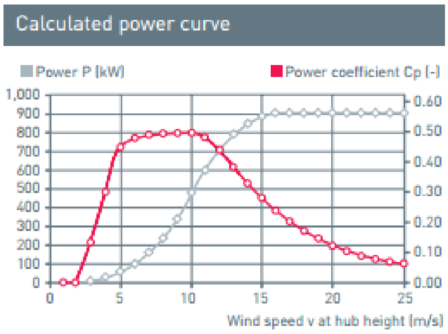

Figure 18 The power curve and power coefficient for ENERCON E-44 [41]

3.3.2. Hydro power expansion description

The proposed hydro power expansions are described in the Verkís report [6] about harnessing the lakes Hundsvatn and Rjúkandavatn upon Skötufjörður catchment area to Mjólká power station (see figure 1-3).

As described in chapter 1.1 the most feasible way is to drill a tunnel to the reservoir Borgarhvilftarvatn and install a 6,8 MW turbine there (Mjólká VI) that uses the 361 meter drop through the tunnel from the Hundsvatn / Rjúkandavatn reservoir. With this increased water that flows down from Borgarhvilftarvatn down to Mjólká I turbine in the old Mjólká power station, it is possible to install a new and bigger turbine alongside the old one. The new turbine will be 3,1 MW and with the renewal of pipes to the power station it will increase the efficiency of the old turbine in Mjólká I by 1,2 MW. The increase in the old power station will then be 4,3 MW. There is also a possibility to at least double the flow and adding another turbine at Borgarhvilftarvatn because of the large diameter of the tunnel. Then it will have the capacity of 13,6 MW. That will be called Mjólká VI-B. The increased flow can also be used in the old Mjólká I by renewal of pipes and turbines and make the increase go up to 6,3 MW. That will be called Mjólká I-B

3.3.3. Scenarios

The model of the energy output is calculated for the following scenarios:

- **Scenario A**:

Mjólká VI with water flow of 2,2 m^3/s and 6,81 MW.

Mjólká I will increase by 4,3 MW and 2 ENERCON E-44 wind turbines with 1,82 MW output.

Total 12,93 MW in power.

- **Scenario B**:

Mjólká VI-B with possible double flow 4,4 m^3/s and two hydro turbines 13,62 MW.

Mjólká I-B (6,3 MW)

21 ENERCON E-44 wind turbines (19,11 MW). Total 39,03 MW power.

- **Scenario C**: Only hydro power (as described in Verkís report).

Mjólká VI with water flow of 2,2 m^3/s and 6,81 MW output

Mjólká I will increase by 4,3 MW.

Total 10,13 MW

There are several other ways to put up scenarios but these are considered to be realistic setups. The first scenario is considered as a setup for testing purposes and the second scenario is an idea of a future wind farm.

3.3.4. Model description

A model was built of the proposed wind and hydro power plants to simulate the power generation from the wind and hydro power expansions. The power plant expansion of old Mjólká I and new power plants (Mjólká VI and Wind turbines) was only taken into account in this model.

With the model it was possible to quantify the water that accumulates into the reservoirs while running the wind turbines. After that it was possible to see how much power and energy could be generated. This model was done with Microsoft Excel.

In the model it was assumed that there is 100% availability of the wind turbines and the hydro station. There will be no downtime due to maintenance or malfunction. The regular maintenance was assumed to be addressed in the summer when winds are slow and electricity demand is lowest. Besides, the repairs normally do not last for many days so downtime was neglected in the calculations.

The model holds the wind data for Þröskuldar and the power curve for ENERCON E-44 wind turbine. Also the energy consumption data from year 2012 was used to take the oscillations in energy demand into account.

	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1			Number of wind turbines	Installed Wind el Capacity (kW)	Mjólká 6 Installed Hydro el capacity (kW)	Mjólká 1 Expansion	Hours of hydro generation	Average Water use (m3/s)	Reservoir size (Gl)	Accumulated over flow (m3)	Accumulated over flow (Gigaliters)	Average Spillwater if reservoir full (m3/s)	Possible extra GWh and W	Status of reservoir 30, sept.
2		100%	2	1820	6810	4300	7490	1,881	20,6	595009	0,60	0,02	0,47	20,60
3		Capacity factor:		39%	86%	86%	105%						58,97	
4	Time	Vind data (m/s)	Calculated to 55m height	Wind Power Generation (kW)	Mjólká VI Hydro generation (kW)	Mjólká I expansion Hydro genration (kW)	Generation factor	Water used in Mjólká 6 (m3/s)	Flow in Hundsv. Rjúkandav (m3/s)	In-out Water saved (m^3/s)	In-out Water saved (m^3/h)	Hundsv. + Rjúkandav. reservoir (Gl)	Overflow Skötufjörður(Gl/h)	Overflow Skötufjörður (m3/h)
14	1.1.2012 09:00	7,6	10	932	5839	3687	0,993	1,9	0,969	-0,92	-3301,90	17,20	0,00000	0,0
15	1.1.2012 10:00	7,7	10	932	5994	3784	1,020	1,9	0,969	-0,97	-3482,02	17,19	0,00000	0,0
16	1.1.2012 11:00	8,2	10	932	6173	3898	1,050	2,0	0,969	-1,03	-3690,82	17,19	0,00000	0,0
17	1.1.2012 12:00	6,5	8	476	6692	4225	1,056	2,2	0,969	-1,19	-4293,82	17,19	0,00000	0,0
18	1.1.2012 13:00	6,0	8	476	6810	4300	1,077	2,2	0,969	-1,23	-4431,60	17,18	0,00000	0,0
19	1.1.2012 14:00	6,7	9	680	6622	4181	1,080	2,1	0,969	-1,17	-4212,67	17,18	0,00000	0,0
20	1.1.2012 15:00	6,7	9	680	6703	4232	1,093	2,2	0,969	-1,20	-4307,15	17,17	0,00000	0,0
21	1.1.2012 16:00	6,5	8	476	6810	4300	1,125	2,2	0,969	-1,23	-4431,60	17,17	0,00000	0,0
22	1.1.2012 17:00	6,3	8	476	6810	4300	1,163	2,2	0,969	-1,23	-4431,60	17,16	0,00000	0,0
23	1.1.2012 18:00	6,6	8	476	6810	4300	1,176	2,2	0,969	-1,23	-4431,60	17,16	0,00000	0,0
24	1.1.2012 19:00	6,1	8	476	6810	4300	1,164	2,2	0,969	-1,23	-4431,60	17,16	0,00000	0,0

Figure 19 Screenshot of the model.

The first lines show some explanations and assumptions for the calculations. Also it shows the water use and status of the reservoir and more for tuning energy production in the model.

The wind data for each hour is in column D in line 5 to 8787. Energy calculation is in the following columns F, G and H and the same lines as the hourly wind.

The first columns holds the chronology and the hourly time period (dd.m.yyyy.hh.mm). The next column D holds the wind data. In column E wind data is projected to 55 meters height and rounded to an integer to match the power curve.

In column F he wind was incorporated with the corresponding energy in the power curve. The wind data at each hour from column E was incorporated with the corresponding power (Watts) in the power curve table using the VLOOKUP function in Excel and the outcome is the amount of Watts for every hour of the year. Those watts summed up is the total energy generation for the power plant or the GigaWatt-hours for the year (GWh/yr).

The given ENERCON E-44 power coefficiency (column S) is also used in calculating power using formula 2.5 which should give the same result as above (column T and U).

With wind turbines taken into account the hydro power in Mjólká VI (column G) was reduced versus wind power generation for each hour. The hydro power was also multiplied with the factor of electricity demand for each hour (column I).

The water use of the power station was estimated by the water that is running through the turbine. The turbine use was tuned with a multiplication factor (cell I3) so it would not exceed the natural 1,9 m^3/s water-flow to the reservoir (cell J2) and reservoir at 1. October was supposed to be full with 20,6 Gl (cell P2).

Column J holds the hourly water flow to the Mjólká VI hydro power generator.

Column K holds the simulated flow to the Hundsvatn and Rjúkandavatn reservoir.

Next columns calculate the overflow and water level status in the reservoir at each hour. The aim was to minimize spill water or overflow, have a full reservoir in the fall (1. October) and let the water in the reservoir suffice until next spring.

In the last columns (Q and R) the electricity generations from Mjólká I, Mjólká VI and the wind turbines are summed up.

Below in the last lines the energy is summed up

In Scenario A the number of wind turbines are chosen so that the average flow does not exceed the inflow to the reservoir, 1,9 m^3/s.

Scenario B makes it possible to meet the fluctuations in energy demand and peaks even more with several more wind turbines. The number of turbines is optimized in both scenarios to get the best use of water as possible and meet the variable energy demand.

3.4. Profitability

A profitability model for the new hydro and wind power plants, was made in Excel. This analysis was made for wind generators and hydropower plants expansion, using cost and income figures. The cost and income figures for the hydro power plant are taken from the report made by Verkís. The cost of the hydro power expansion is not linear, because the tunnel will have more flow capacity than the 2,2 m^3/s that is planned with the first turbine. Also the increase in cost of power station, generator, electric equipment and possibly a stronger grid connection varies. The connection of the first wind turbine costs more than the next after because the transmitter has already been installed there with the first wind turbine.

For wind power the cost figures from Landsvirkjun's recently built wind generators were used. Profitability assessment was done for the above described A and B scenarios using the energy output for each scenario:

3.5. Limitations of the study

The wind can be intermitting from day to day but yearly fluctuations are usually very little [48]. Therefore a single year was used for this study to project the wind power generation.

The water flow measurements of Gláma highland and into Rjúkandavatn and Hundsvatn lake are from 2001 [44]. They had some limitations like measurements were lacking and contour lines were not correct on older maps. There is a need for more recent and better measurements to make the energy calculations more accurate. Also hourly flow data was not available so a simulation had to be done like mentioned before in the model description.

The ENERCON E-44 was chosen for this study because they have been put up and used both in the in the harsh weather conditions of the Faroe Islands and in Iceland with good results so far. The cost figures are present and good experience of utilizing this wind turbine is stated. It may be that another type of wind turbine is optimal in this location, but since the choosing of wind turbine model is not the aim of this study this type of wind turbine was used for simplicity reasons.

4. Results

The main results and the research question will be answered here.

4.1. Wind

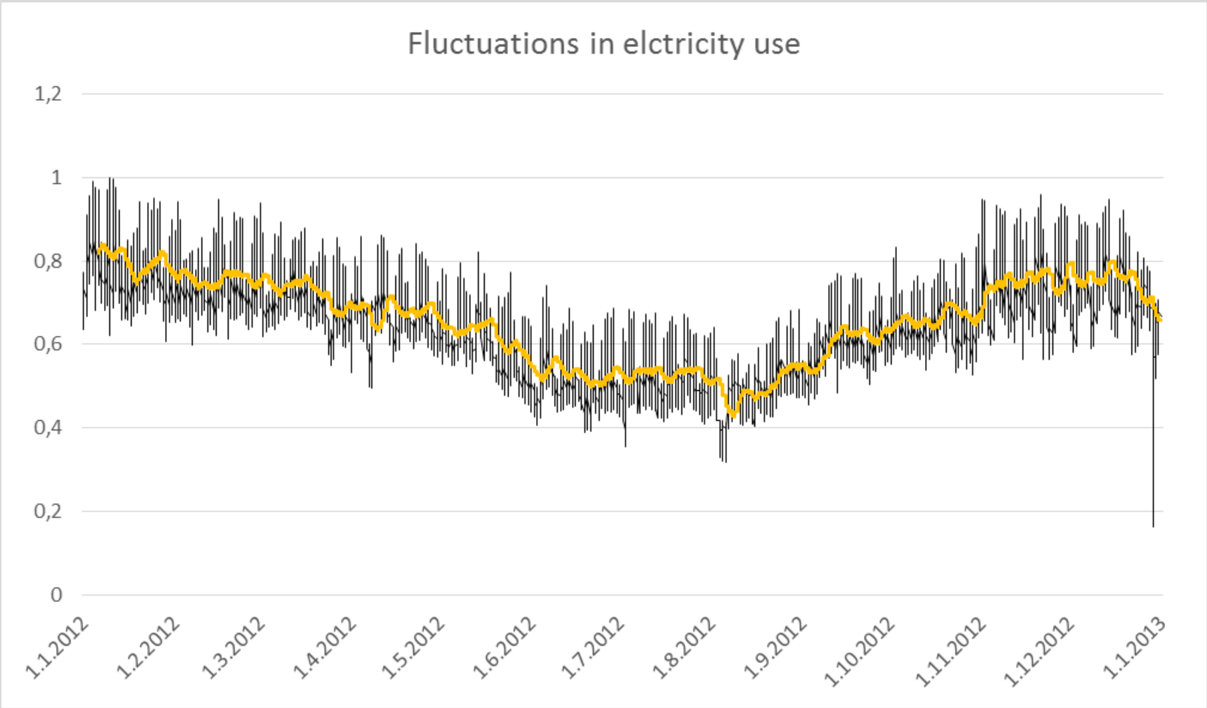

Figure 20 Electricity use in year 2012 displayed as proportions of maximum use.

Figure 20 shows the fluctuations in electricity use in the West Fjords. There are diurnal fluctuations and seasonal variations. More use during day and winter. In figure 21 and 22 the wind speed is shown. Higher wind speeds during winter and lower in June and July. Looking at the seasonal fluctuations in figures 20 and 22 those two figures match up mostly.

Where the line goes down in the end of the year in figure 20 is because the powerlines broke in a bad weather at the 29th of December. The wind is still very intermitting between days. If the monthly average is shown (figure 22) the difference between seasons becomes clearer.

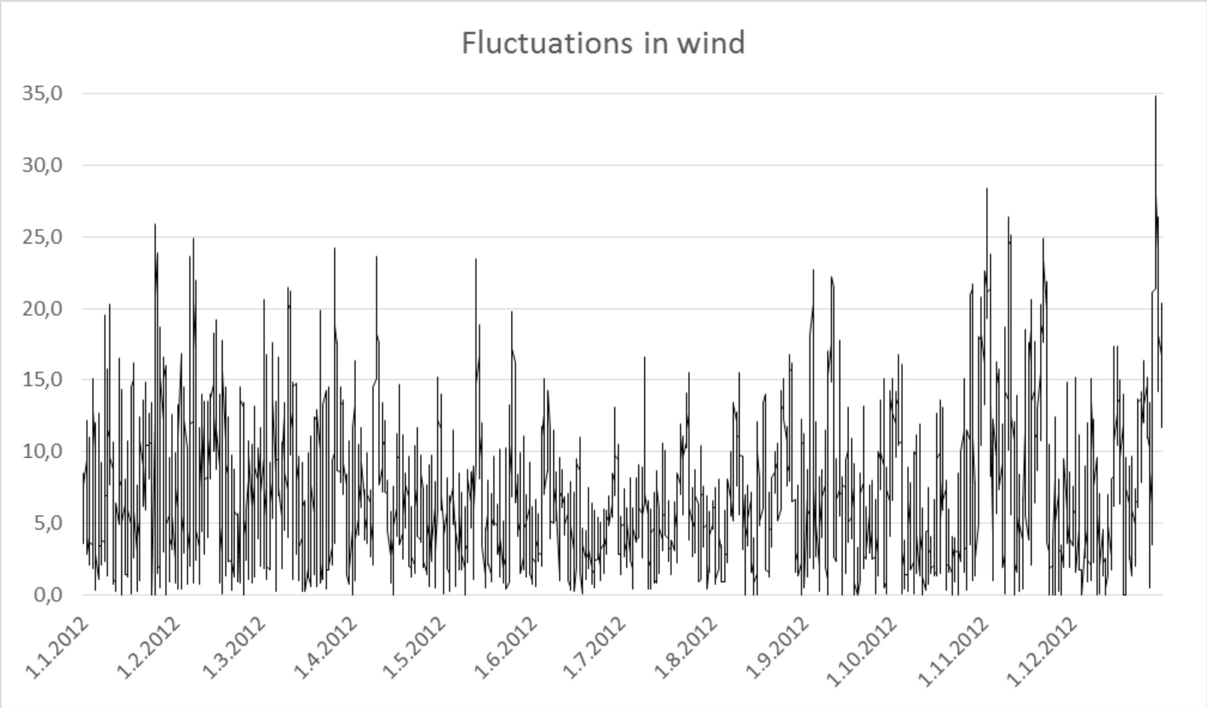

Figure 21 Wind data showing fluctuations in wind speed (m/s) on vertical axis by time on horizontal axis

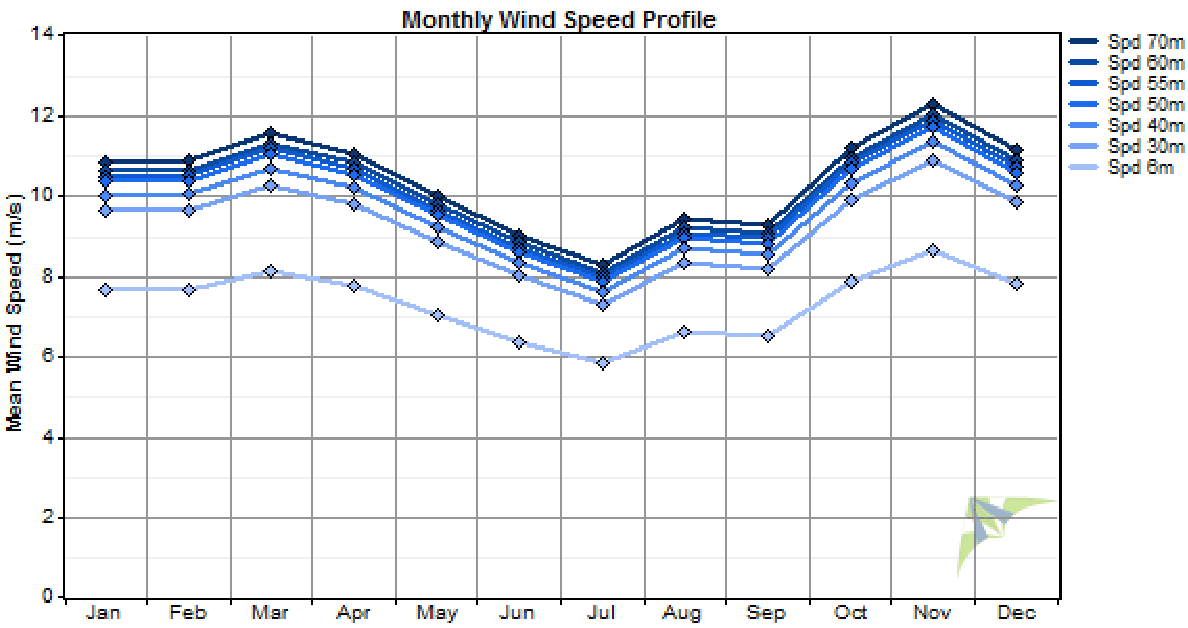

Figure 22 monthly average wind speed at diffrent heights in 2012

As seen in figure 22 it is clear that average wind is more in the winter than the summer. That fits decently to the electricity consumption in figure 20.

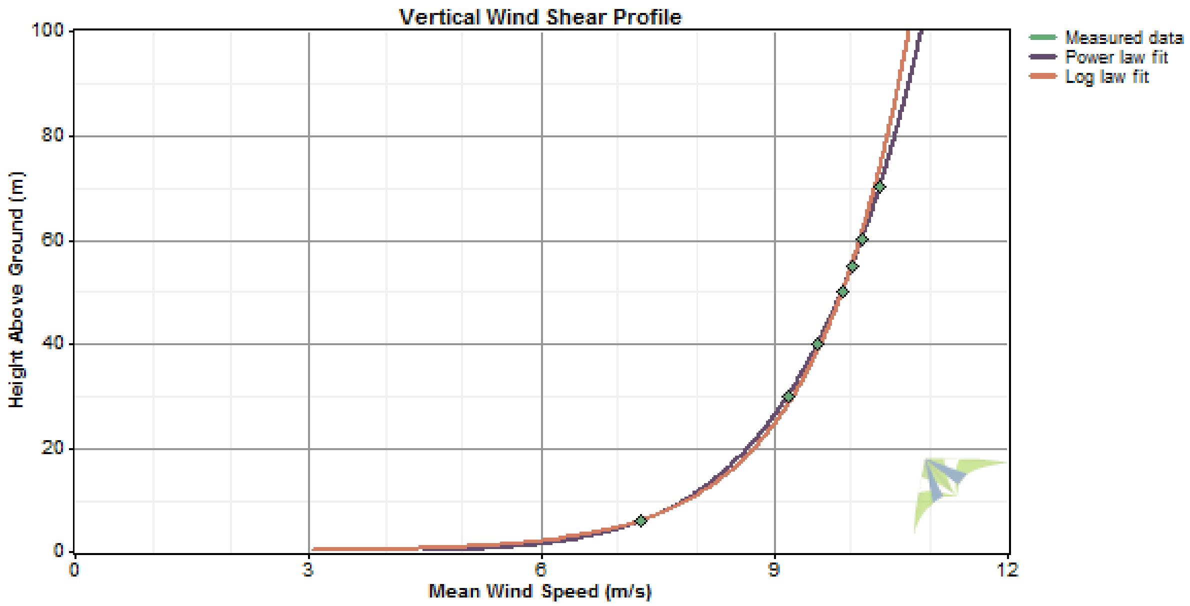

Figure 23 The green dots are evaluated wind speeds calculated up to diffrent heights.

This curve in figure 23 is a possible power curve based evaluation that is calculated with formula 2.2. Proper measurements in those heights are necessary to confirm that this is real.

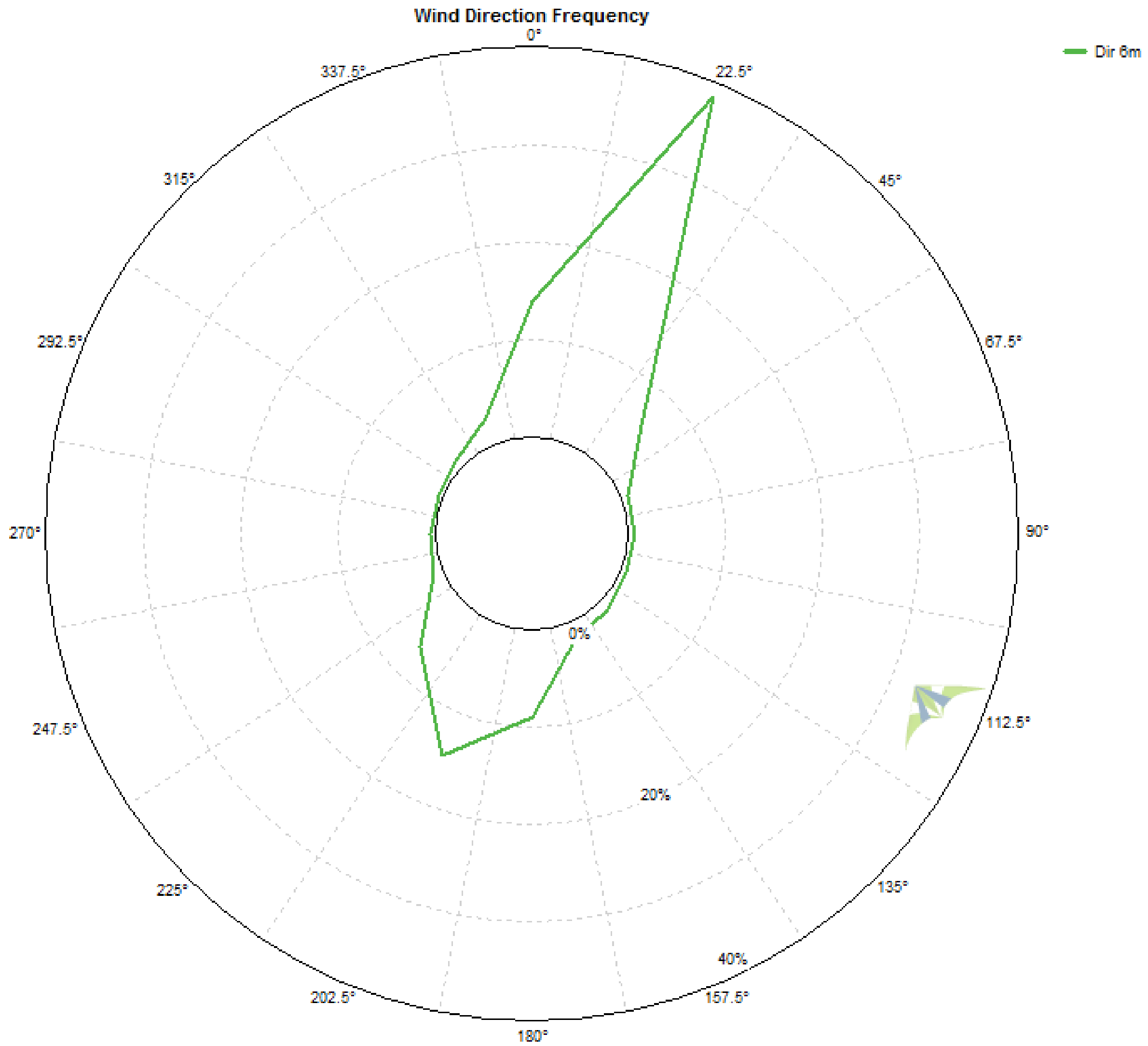

Figure 24 The wind rose 2012 for Þröskuldar

The wind rose in figure 24 shows clearly that the prevailing winds are North-East and South-West. That is the same direction as the direction of the surrounding mountains. This indicates that the surrounding mountains have a channeling effect on the wind and they cut out the other directions.

The following figures (25-36) show the diurnal profile of wind speed on the y-axis (m/s) and hour on the x-axis for each month of the year 2012. They show that wind goes faster during the winter than in the summer (May-September) when wind is usually below 10 m/s. Wind is also usually faster in the afternoon. In the winter months wind is steadier and faster.

From April to September the sea breeze usually takes place in the afternoon. Sunshine during the day makes a pressure difference between sea and land that gives steady wind into the land in the afternoon.

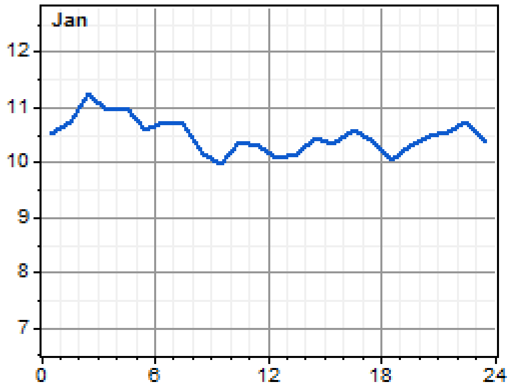

Figure 25 mean diurnal fluctuation for January

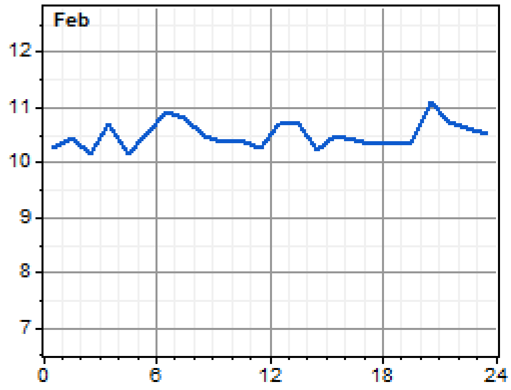

Figure 26 mean diurnal fluctuation for February

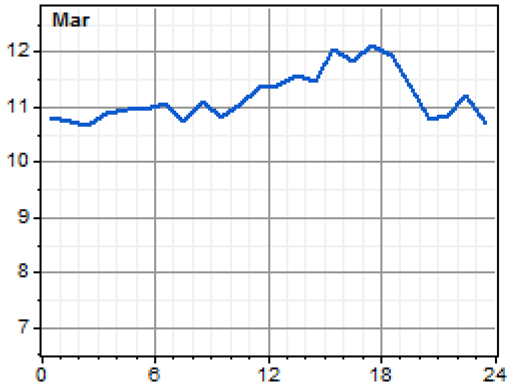

Figure 27 mean diurnal fluctuation for March

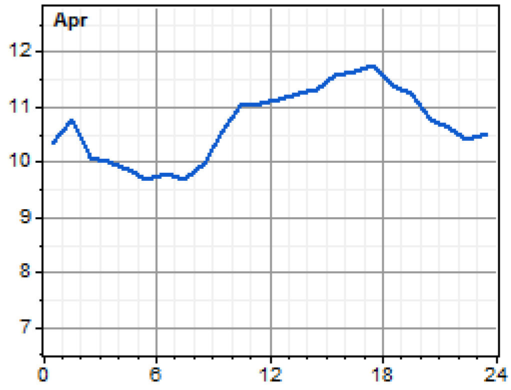

Figure 28 mean diurnal fluctuation forApril

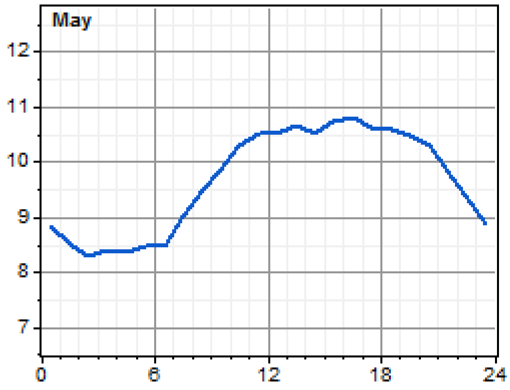

Figure 29 mean diurnal fluctuation for May

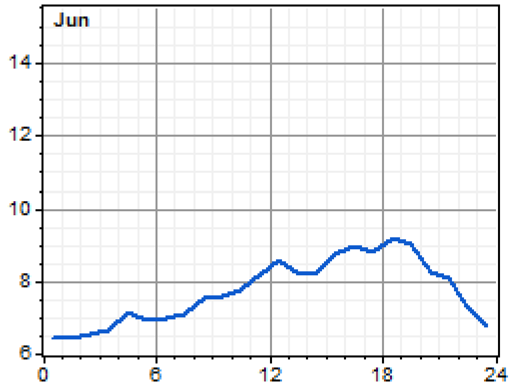

Figure 30 mean diurnal fluctuation for June

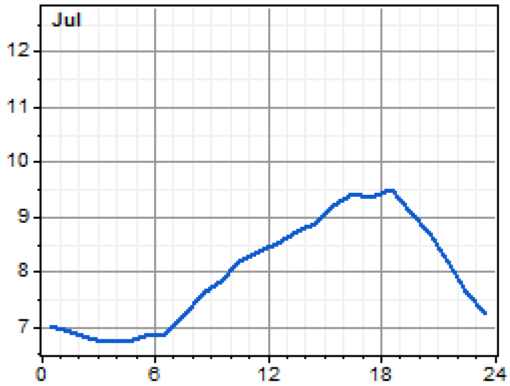

Figure 31 mean diurnal fluctuation for July

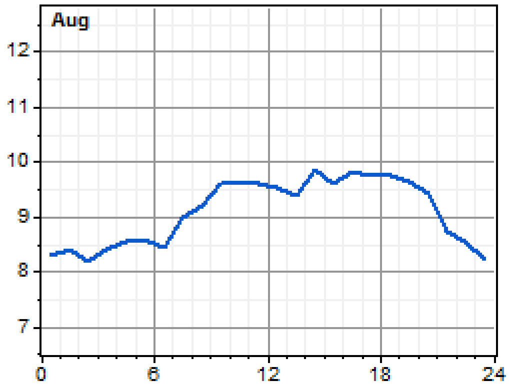

Figure 32 mean diurnal fluctuation for August

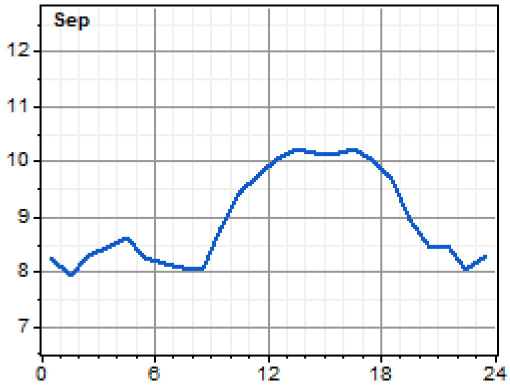

Figure 33 mean diurnal fluctuation for September

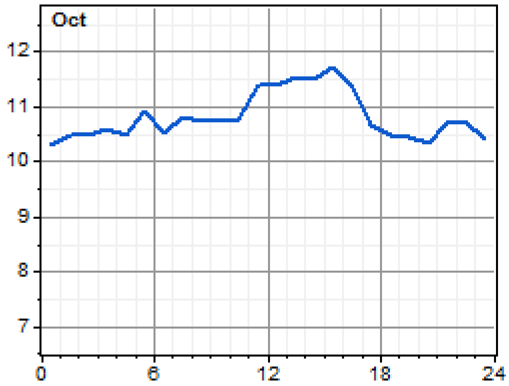

Figure 34 mean diurnal fluctuation for October

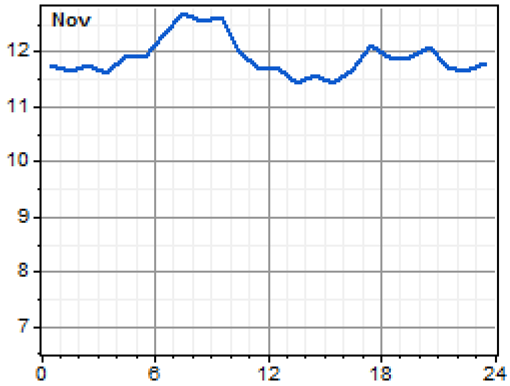

Figure 35 mean diurnal fluctuation for November

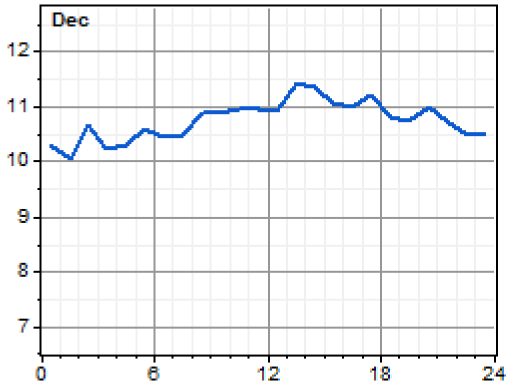

Figure 36 mean diurnal fluctuation for December

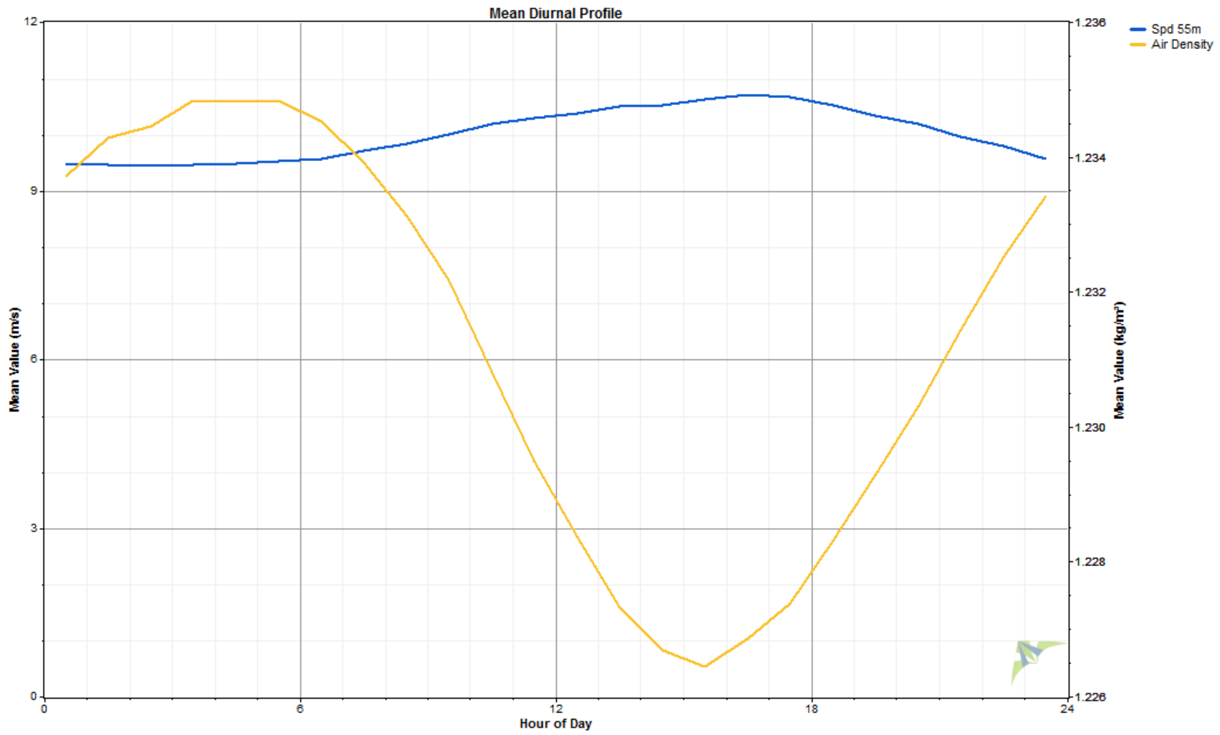

Figure 37 Daily fluctuation of wind speed (blue line) and air density (yellow line)for all months in 2012.

The above figure 37 shows that air density falls down and wind speed increases, in the rising temperature of the day. Air density affects the power density of the wind according to formulas 2.3 – 2.5 page 17.

Table 5 Average estimated wind speed at 55 meters height. Overall average: 9,16 m/s

Hours	Dec - Mar	Apr - May	Jun - Aug	Sept - Nov
02-04	10,2	7,3	6,8	10,2
05-07	10,0	7,8	7,0	9,8
08-10	9,5	8,9	7,8	10,0
11-13	9,5	9,7	8,1	9,9
14-16	9,7	9,8	8,5	10,3
17-19	10,3	9,5	8,5	9,9
20-22	10,3	8,7	7,9	9,3
23-01	10,1	7,7	7,0	9,9

The table above shows average wind speed in different seasons and different time of the day. This is the estimated wind in 55 meters altitude. The wind is stronger in the winter especially in December through March and it also appears that the wind is slower in the spring and summer mornings but more in the winter night.

Table 6 Frequency of wind speed below 4 m/s at 55 meters height.

Hours	Dec - Mar	Apr - May	Jun - Aug	Sept - Nov
02-04	16%	36%	34%	25%
05-07	15%	27%	27%	28%
08-10	18%	21%	19%	25%
11-13	19%	13%	14%	21%
14-16	19%	10%	7%	19%
17-19	19%	7%	7%	21%
20-22	24%	13%	16%	27%
23-01	19%	26%	29%	27%
Average	18,8%	19,1%	19,2%	24,2%

The overall yearly average is 20%. The wind measurements show that although wind is stronger during the winter it appears to drop a lot below 4 m/s during the winter months. This happens usually when the land is cold with weak pressure gradient. These low wind periods are essential to predict for the wind and hydro co-operation. In figure 38, the December month is taken for instance to show that there are some longer periods even half or whole days of wind calmer than 4 m/s.

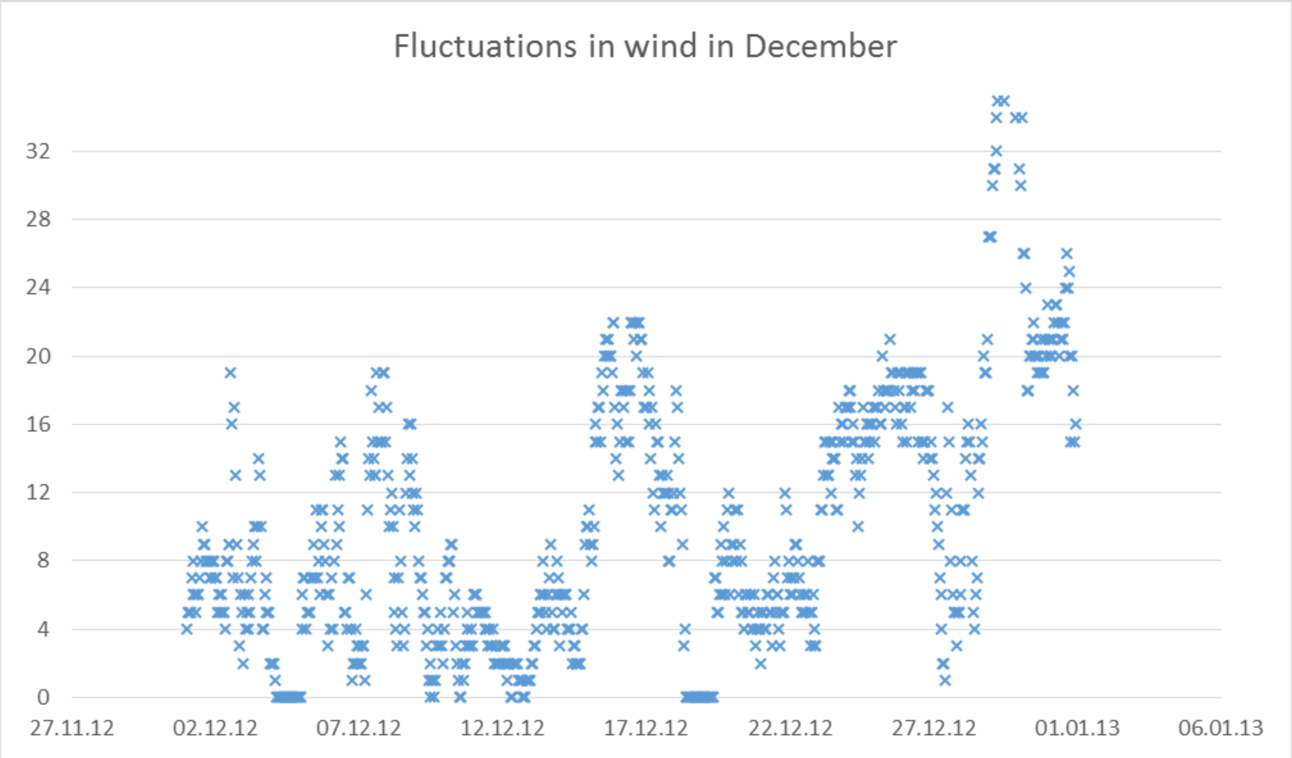

Figure 38 Cases of wind speeds in December 2012

Table 7 Frequency of wind speed above 25 m/s at 55 meters height.

Hours	Dec - Mar	Apr - May	Jun - Aug	Sept - Nov
02-04	2,7%	0,0%	0,0%	3,7%
05-07	1,1%	1,1%	0,0%	3,7%
08-10	1,1%	0,0%	0,0%	4,4%
11-13	1,6%	0,0%	0,0%	2,9%
14-16	0,3%	0,0%	0,0%	3,7%
17-19	2,5%	0,0%	0,0%	2,6%
20-22	2,7%	0,0%	0,0%	2,6%
23-01	3,3%	0,0%	0,0%	5,9%
Average	1,9%	0,1%	0,0%	3,7%

Table 7 shows the frequency of stronger winds above 25 m/s. They are more frequent during the winter especially from September to November. This also shows that bad weather is more frequent in the nights. It almost never happens in the summer. The winter is windier especially during the night. The overall yearly average is 1,4%.

4.2. Weibull Distributions

Figures 39-43, the following tables 8-12, show histograms of the wind distribution and analysis for December to March, from April to May, from June to August, from September to November and last the whole data period, respectively. The histograms show the frequency of each wind speed in percent. These tables and histograms were made in a PC program called Windographer that is used to analyze wind data [40].

Table 8 Wind speed distribution analysis December - March

Algorithm	Weibull k	Weibull c (m/s)	Mean (m/s)	Proportion Above 10.163 m/s	Power Density (W/m2)	R Squared
WAsP	1.803	11.706	10.409	0.461	1,475.0	0.93684
Actual data	(2,924 time steps)		10.163	0.461	1,475.0	

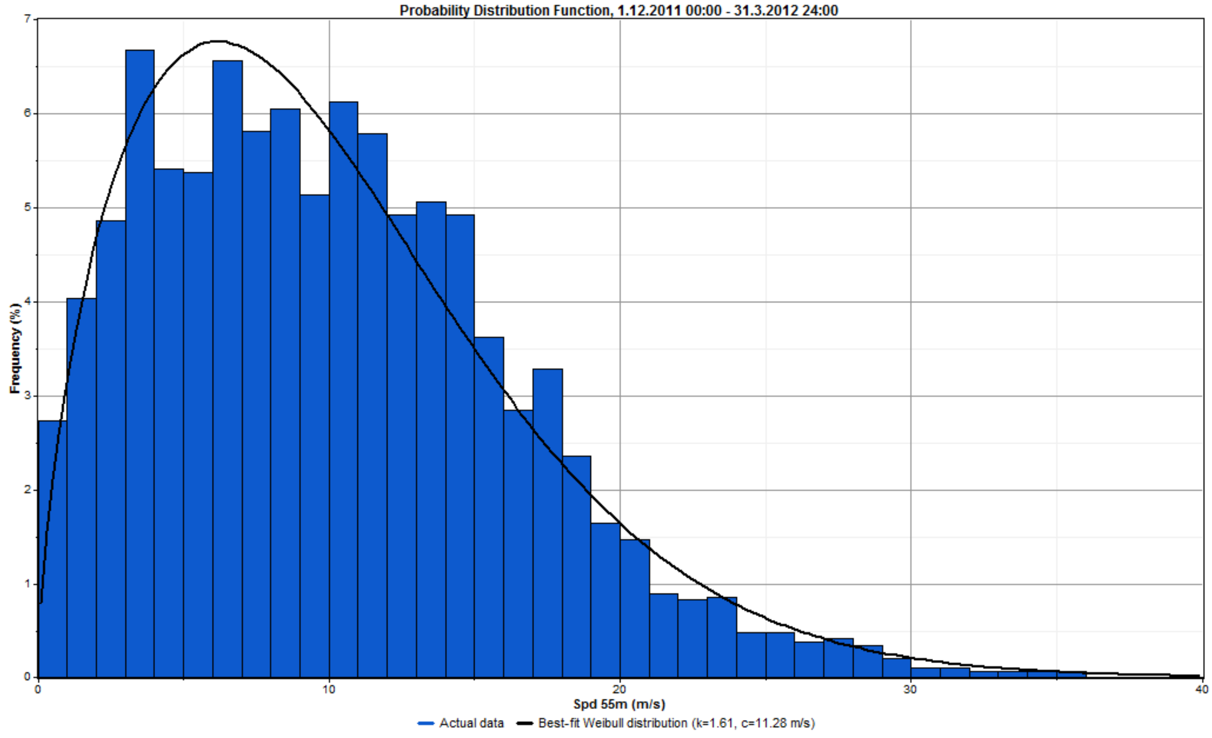

Figure 39 Weibull distribution December – March

This figure shows that the highest frequency of wind is between 4 m/s and 15 m/s. The black line shows the Weibull fit according to WAsP calculation methods. WAsP is a PC program that analyses wind resources, it is developed and distributed by the Department of Wind Energy at the Technical University of Denmark [49]. The k factor of 1,8 tells that the peak is high up which means steady wind and distribution to higher wind speeds is shorter. It is favorable to have high k value at least over 1,2 but not too high because then the wind is less distributed to higher wind speeds (as said in chapter 2.6.4). The R Squared value shows how well the data fits to Weibull. December to March has a 93,7% Weibull fit.

Table 9 Wind speed distribution analysis April - May

Algorithm	Weibull k	Weibull c (m/s)	Mean (m/s)	Proportion Above 9.326 m/s	Power Density (W/m2)	R Squared
WAsP	1.572	10.271	9.224	0.423	1,221.4	0.84054
Actual data	(1,464 time steps)		9.326	0.423	1,221.4	

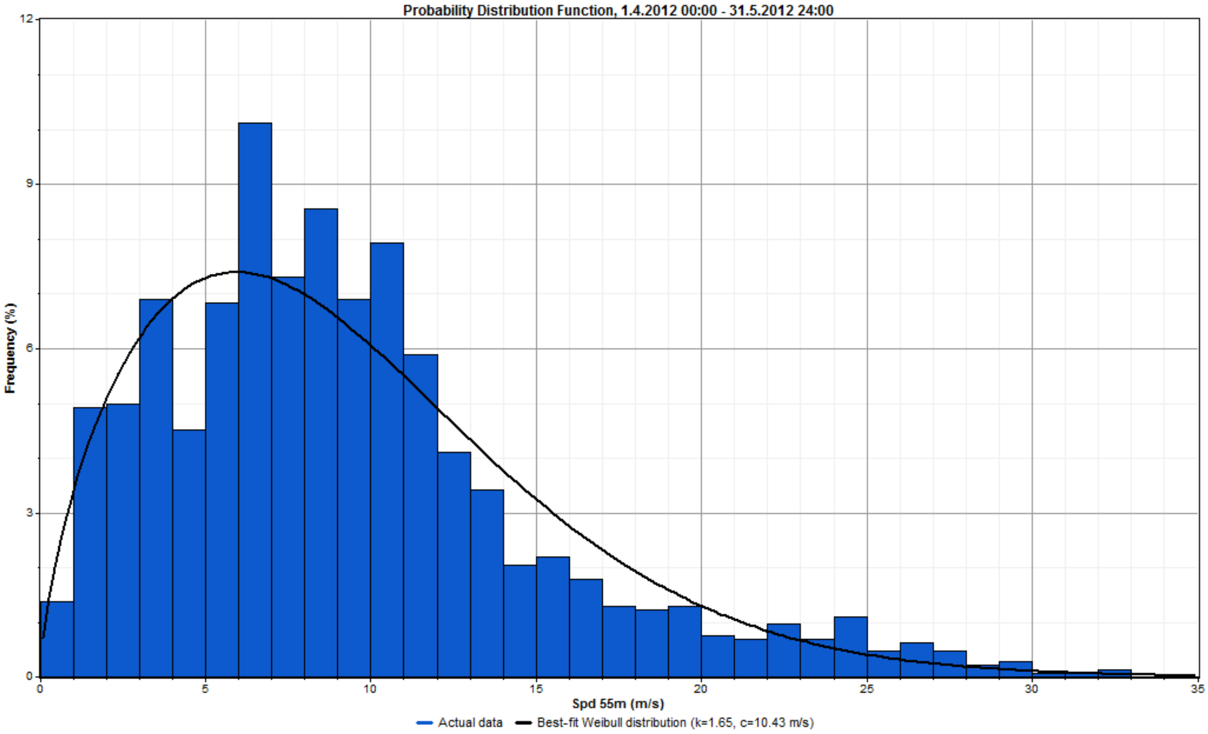

Figure 40 Weibull distribution April – May

The spring months are calmer than winter although the wind speeds are well distributed up to 32 m/s. This period is badly Weibull fitted. This may be because there is little data behind the histogram.

Table 10 Wind speed distribution analysis June – August (from Windographer)

Algorithm	Weibull k	Weibull c (m/s)	Mean (m/s)	Proportion Above 8.281 m/s	Power Density (W/m2)	R Squared
WAsP	1.814	9.134	8.119	0.433	695.2	0.92888
Actual data	(2,208 time steps)		8.281	0.433	695.2	

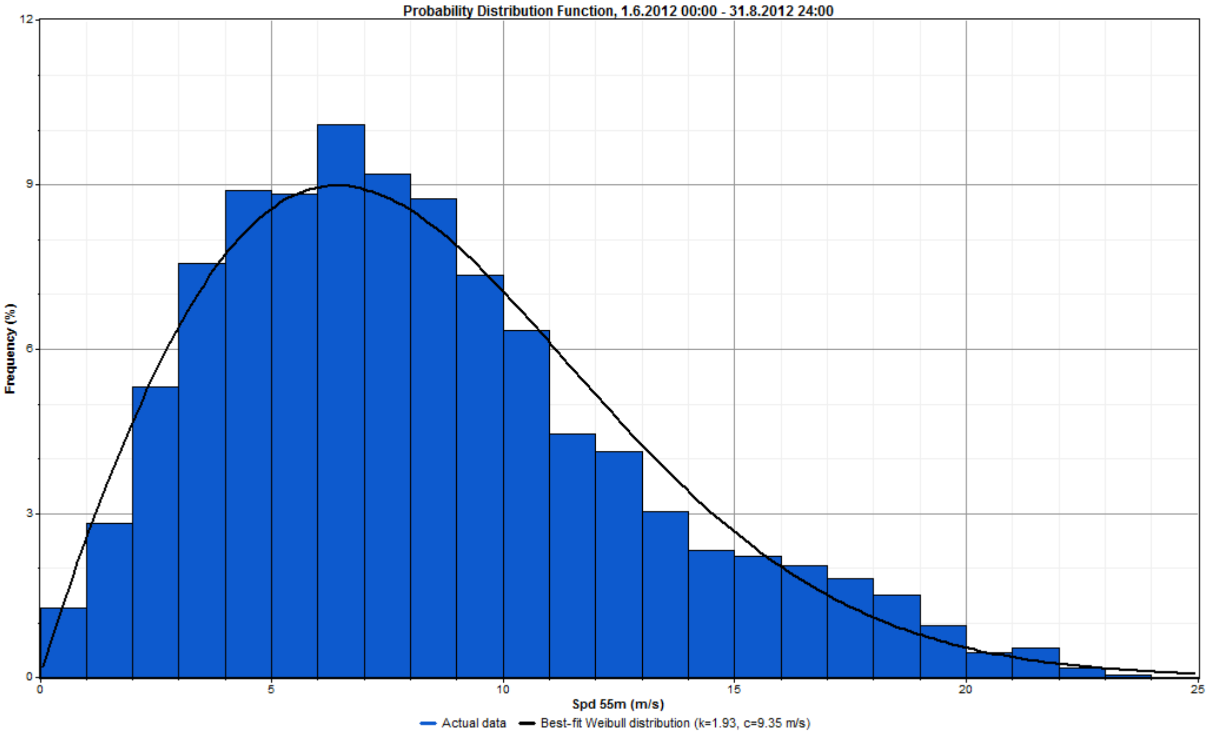

Figure 41 Weibull distribution June – August

June to August are overall a lot calmer and the highest wind is 24 m/s. The Weibull fit is about 93% which is fairly good.

Table 11 Wind speed distribution analysis September - November

Algorithm	Weibull k	Weibull c (m/s)	Mean (m/s)	Proportion Above 10.660 m/s	Power Density (W/m2)	R Squared
WAsP	1.410	11.719	10.669	0.417	2,223.7	0.93112
Actual data	(2,183 time steps)		10.660	0.417	2,223.7	

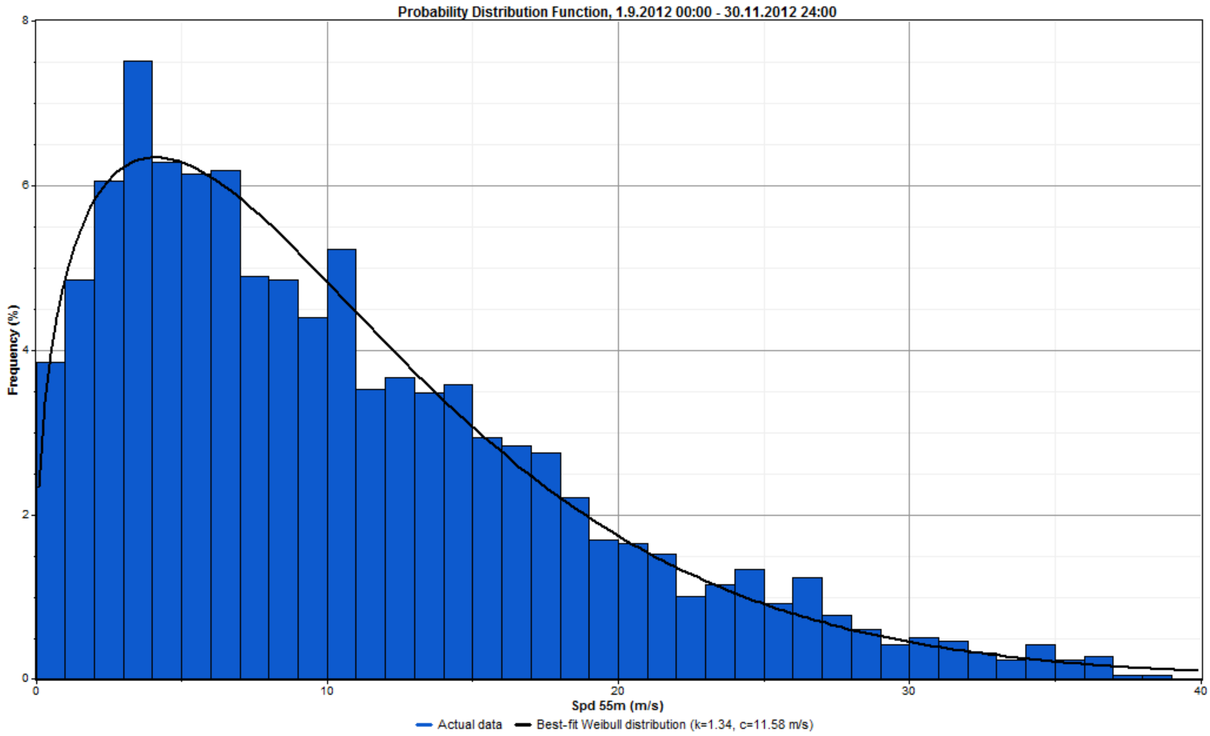

Figure 42 Wind distribution September – November

Winds below 4 m/s are frequent and in the beginning of the winter stronger winds from 25 up to 39 m/s are becoming more frequent.

Table 12 Wind speed distribution analysis for 26.11.2009 – 6.9.2013

Algorithm	Weibull k	Weibull c (m/s)	Mean (m/s)	Proportion Above 9.851 m/s	Power Density (W/m2)	R Squared
WAsP	1.512	10.916	9.845	0.425	1,569.7	0.98971
Actual data	(8,783 time steps)		9.851	0.425	1,569.7	

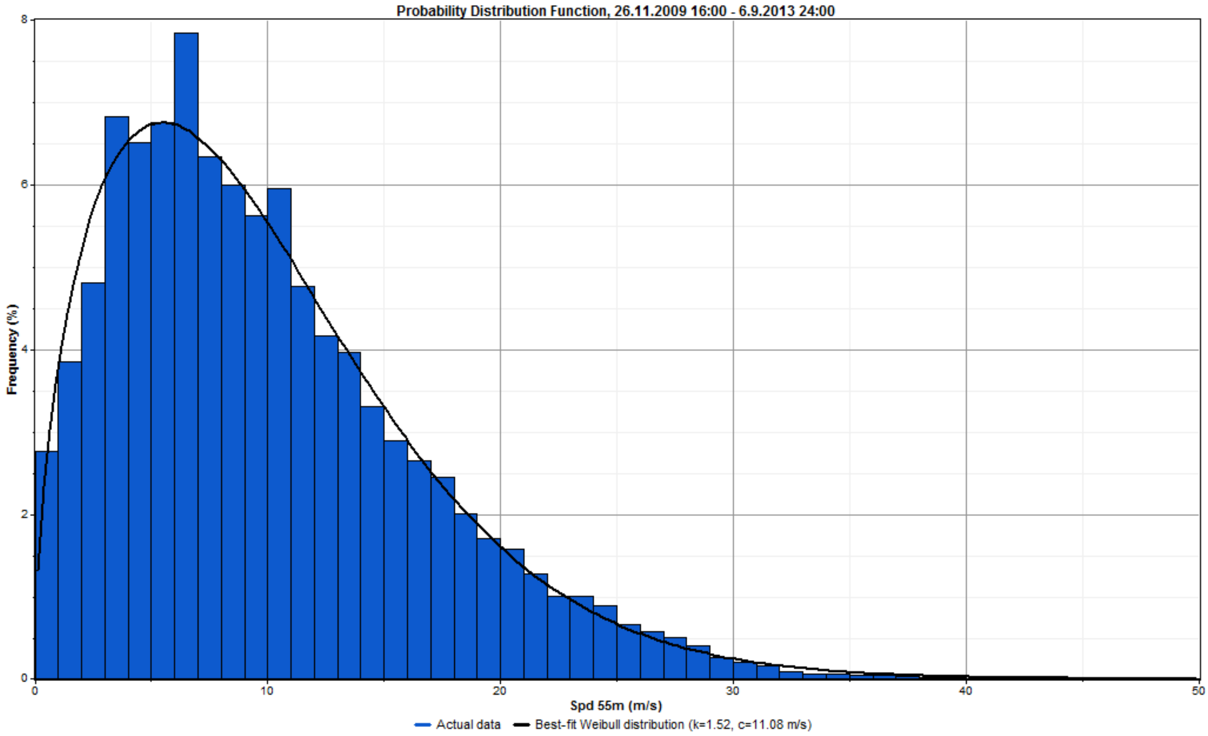

Figure 43 Wind speed distribution from 26.11.2009 to 6.9.2012. Black line shows the Weibull distribution line

The Weibull distribution is well fitted to the data. The R Squared value is 99% which shows that there is a longer period of data behind the histogram. The error gets bigger the shorter timeframe of data that is used. Therefore to get as accurate an estimation as possible it might be best to get as many time steps as possible and therewith get as accurate data as possible. The Weibull error is usually around 3% or even lower [50] so that is one of the uncertainties.

This wind distribution diagram in figure 43 would be considered well distributed and well suited for wind power usage. The Weibull k is the shape factor that is close to optimal for wind power. The wind is well distributed to higher wind speeds. Energy output

4.3. Energy output

Tables 13-15 show the results for scenario A, B and C described in chapter 3.2.3.

Table 13 Estimated Yearly Energy output of scenario A: 2,2 m^3/s flow through Mjólká VI and Mjólká I along with two ENECON E-44 wind turbines. Using wind data from year 2012

Scenario A	Installled power (MW)	Winter (GWh)	May / Sept. (GWh)	Summer (GWh)	Annual generation (GWh/yr)	Capacity factor
Wind power 2xENERCON E-44	1,82	3,99	0,93	1,26	6,18	39%
Hydro power Mjólká I	4,30	20,23	5,23	6,83	32,30	86%
Hydro power Mjólká VI	6,82	32,04	8,29	10,82	51,15	86%
Combined	12,94	56,25	14,45	18,91	89,63	

The scenario A setup in table 13 allows the Mjólká VI turbine to manage the fluctuations that come with the variable wind energy and the fluctuations in electricity demand. The two wind turbines save 7,2 Gl of water per year. That gives about 5,7 GWh/yr extra to manage fluctuations. The electricity generated in the model goes from 2,63 MW up to the maximum installed capacity of 12,9 MW. With this setup the hydro power is used about 7000 hours over the year as expected before in the report from Verkís [6].

Table 14 Estimated Yearly Energy output of scenario B: doubled flow 4,4 m^3/s with two 6810 kW turbines at Mjólká VI, and bigger expansion in Mjólká I of 6,3 MW and a wind farm with a 21 wind turbines. Using wind data from year 2012

Scenario B	Installled power (MW)	Winter (GWh)	May / Sept. (GWh)	Summer (GWh)	Annual generation (GWh/yr)	Capacity factor
Wind power 21xENERCON E-44	19,11	41,85	9,81	13,23	64,90	39%
Hydro power Mjólká I-B	6,30	14,46	3,97	5,38	23,82	43%
Hydro power Mjólká VI-B	13,60	31,27	8,59	11,63	51,49	43%
Combined	39,01	87,58	22,37	30,24	140,21	

21 ENERCON E-44 wind turbines have the capacity to substitute for Mjólká I-B and VI-B which on the contrary meets the fluctuating wind energy production. This setup fulfills about all the 140 GWh that OV has to buy from external producers [4] and makes the company independent with electric power.

The system fluctuates from 4 MW up to 22 MW in the model, because it follows the electricity demand fluctuations given from OV. It could manage up to the maximum capacity of 39 MW in case of failures in other power stations.

The 21 wind turbines save almost 60 Gl of water per year. That is almost all the water flowing (60Gl) to the reservoir in a year. That gives about 50 GWh/yr extra to manage fluctuations.

The wind power is used as much as possible when there is wind. Mjólká I is used as normally for about 7000 hours during the year, although it has to be limited to the small size of its reservoir. Mjólká VI is limited to the 1,9 m^3/s average flow so it is only used about 3500 hours. This setup has the capacity to serve as temporary backup power, as long as there is enough water in the reservoir.

With so many wind turbines there is a good chance to save the water in the hydro power plant and use it later when needed.

Table 15 Estimated Yearly Energy output of scenario C: Mjólká VI and Mjólká I without wind turbines

	Installled power (MW)	Winter	May / September	Summer	Annual generation (GWh/yr)	Capacity factor
Hydro power Mjólká I	4,30	20,59	5,16	6,62	32,38	86%
Hydro power Mjólká VI	6,81	32,61	8,17	10,49	51,28	86%
Combined	11,11	53	13	17	83,66	

In the hydro only setup of the model (table 15) the fluctuations go from 2,44 MW up to maximum capacity 1,11 MW. The scenario with this little capacity has less ability of meeting fluctuations in electricity demand and giving backup power.

4.4. Profitability

Here below are the profitability assessments results for the scenarios A, B and C described in chapter 3.2.3.

Table 16 Costs and income

		Scenario		
		A	B	C
Wind Turbines	MUSD	4,0	27,4	0,0
Hydro power plant	MUSD	70,7	78,2	70,7
Total Cost	**MUSD**	**74,7**	**105,6**	**70,7**
Energy production	GWh/a	89,6	140,2	83,7
Annual income	MUSD	3,6	5,8	2,8
Initial cost per energy unit	USD/(kWh/a)	0,83	0,75	0,85
Wind O&M Cost $29/MWh	MUSD	0,18	1,88	0,00
Hydro O&M Cost 0,8% of initial cost	MUSD	0,57	0,63	0,57
Annual income - cost	MUSD	2,86	3,28	2,24
Repayment time without intrest	years	26	32	32

To see if the project is profitable we need to calculate the Net Present Value (NPV) of the cash flow and get a positive NPV result. Internal Rate of return (IRR) gives the lowest interest rate that can give a positive NPV. IRR is also called the effective interest rate. The results of these calculations are shown in table 17.

Table 17 NPV and IRR of the three scenarios A, B, and C given that the interest rate is 5%

	A	B	C
NPV	-26	-49	-32
IRR	2%	1%	1%

To make the scenarios work (give a positive NPV) the price has to rise or cost has to be lower as shown in table 18.

Table 18 The ratio that price must go up by or the cost must go down for the projects to be feasible

	A	B	C
Price	142%	150%	166%
Cost	66%	53%	55%

The power plants in scenario B that are considered in this study would serve well as backup power instead of the 10,8MW of diesel stations that are being built when this is written. They cost 12,5 MUSD. If that amount was put into these hydro and wind power plants for rural area helping reasons things would look different for them economically. In Landsvirkjuns last fall meeting, it was stated that the price offered to new large heavy industries is $43/MWh. It is likely that this will be the price in all the new heavy industry contracts in Iceland. As said in chapter 3.1.1 the current price is $33/MWh so this is a 33% increase in electricity price.

Table 19 Scenario D with diesel backup power stations cost subtracted fom the scenario B cost and 33% higher energy price compared to Scenario B.

		Scenario	
		B	D
Wind Turbines	MUSD	27,4	27,4
Hydro power plant	MUSD	78,2	78,2
Diesel power station	MUSD	0,0	-12,5
Total Cost	**MUSD**	**105,6**	**93,1**
Energy production	GWh/a	140,2	140,2
Annual income	MUSD	5,8	7,7
Initial cost per energy unit	USD/(kWh/a)	0,75	0,66
Wind O&M Cost $29/MWh	MUSD	1,9	1,9
Hydro O&M Cost 0,8% of initial cost	MUSD	0,6	0,6
Annual income - cost	MUSD	3,3	5,2
Repayment time without intrest	years	32	18

The scenario D with the diesel power stations subtracted and energy price of $43/MWh is almost feasible as seen in table 26.

Table 20 NPV and IRR of snenario B compared to scenario D.

	B	D
NPV	-49	-4
IRR	1%	5%

For scenario D having a positive NPV either the price would have to be only 3% higher or cost only 4% lower.

4.5. Pessimistic and very pessimistic

The energy output above may be rather optimistic because it includes that the wind turbines will have 100% availability, the data may be unreal, there are oscillations in the wind that cannot be met with hydro power, the wind turbulence has not been studied to know how it affects the production and other things could go wrong in the co-operation. Below tables show energy output of 90% and 75% wind strength of the power plant setup of scenario A and B showed in chapter 3.2.3.

Table 21 Estimated Yearly Energy output of scenario A. 90% Pessimistic with wind.

Scenario A	Installled power (MW)	Winter (GWh)	May / Sept. (GWh)	Summer (GWh)	Annual generation (GWh/yr)	Capacity factor
Wind power 2xENERCON E-44	1,82	3,61	0,81	1,03	5,45	34%
Hydro power Mjólká I	4,30	19,83	5,07	6,62	31,53	83%
Hydro power Mjólká VI	6,82	31,41	8,04	10,48	49,93	83%
Combined	12,94	54,85	13,92	18,13	86,91	

Table 22 Estimated Yearly Energy output of scenario B. 90% Pessimistic with wind

Scenario B	Installled power (MW)	Winter (GWh)	May / Sept. (GWh)	Summer (GWh)	Annual generation (GWh/yr)	Capacity factor
Wind power 21xENERCON E-44	19,11	37,92	8,46	10,82	57,22	34%
Hydro power Mjólká I	6,30	13,53	3,76	5,13	22,42	41%
Hydro power Mjólká VI	13,60	29,26	8,12	11,09	48,48	41%
Combined	39,01	81	20	27	128,11	

The 90% wind scenario comes down on the total energy output so a few more wind turbines might be needed to keep up the 140 GWh/yr production.

Table 23 Estimated Yearly Energy output of scenario A. 75% Pessimistic with wind.

Scenario A	Installled power (MW)	Winter (GWh)	May / Sept. (GWh)	Summer (GWh)	Annual generation (GWh/yr)	Capacity factor
Wind power 2xENERCON E-44	1,82	2,86	0,60	0,69	4,15	26%
Hydro power Mjólká I	4,30	20,32	5,24	6,85	32,41	86%
Hydro power Mjólká VI	6,82	32,19	8,29	10,85	51,34	86%
Combined	12,94	55,37	14,12	18,39	87,90	

Table 24 Estimated Yearly Energy output of scenario B. 75% Pessimistic with wind

Scenario B	Installled power (MW)	Winter (GWh)	May / Sept. (GWh)	Summer (GWh)	Annual generation (GWh/yr)	Capacity factor
Wind power 21xENERCON E-44	19,11	30,03	6,25	7,25	43,53	26%
Hydro power Mjólká I	6,30	13,67	3,79	5,18	22,63	41%
Hydro power Mjólká VI	13,60	29,55	8,19	11,19	48,93	41%
Combined	39,01	73	18	24	115,10	

To keep up the same energy production there is need for more wind turbines. For instance in the 75% wind scenario in table 22, there is a need for 13 more wind turbines to keep up the 140 GWh/yr. These pessimistic scenarios would then be costlier and less feasible.

4.6. Búrfell vs. Þröskuldar

Table 25 Calculated output for Landsvirkjuns wind turbines at Búrfell using wind measurements from 2012

Búrfell	Installled power (kW)	Annual generation (GWh/yr)	Capacity factor
Wind power 2xENERCON E-44	1820	5,02	31%

Using the same energy calculation methods used for the wind turbines on Þröskuldar, the estimated energy output for Búrfell appears to be 5,0 GWh/year compared to 6,1 GWh/year on Þröskuldar. This means a higher Capacity factor for Þröskuldar which has a capacity factor of 39% and at Búrfell it is 31%. Landsvirkjun expected in their calculations prior to the installation of the wind turbines, that the yearly generation would be 5,4 GWh [51]. It is likely that these expectations will come true.

Looking at wind speed distribution histogram it is obvious that the nature of wind is a little different in the two places. The distribution and frequency of wind in higher speeds is more at Þröskuldar but frequency of medium wind speed is more at Búrfell which has a more peaked histogram. The wind is more distributed at Þröskuldar. The Weibull error is assumed to be similar for the two locations.

Table 26 Comparision on k, c, and U-bar (average wind)

Þröskuldar		Búrfell	
k (shape factor)	1,51	k (shapee factor)	1,79
U_bar	9,16	U_bar	8,40
c (skale factor)	10,16	c (skale factor)	9,44

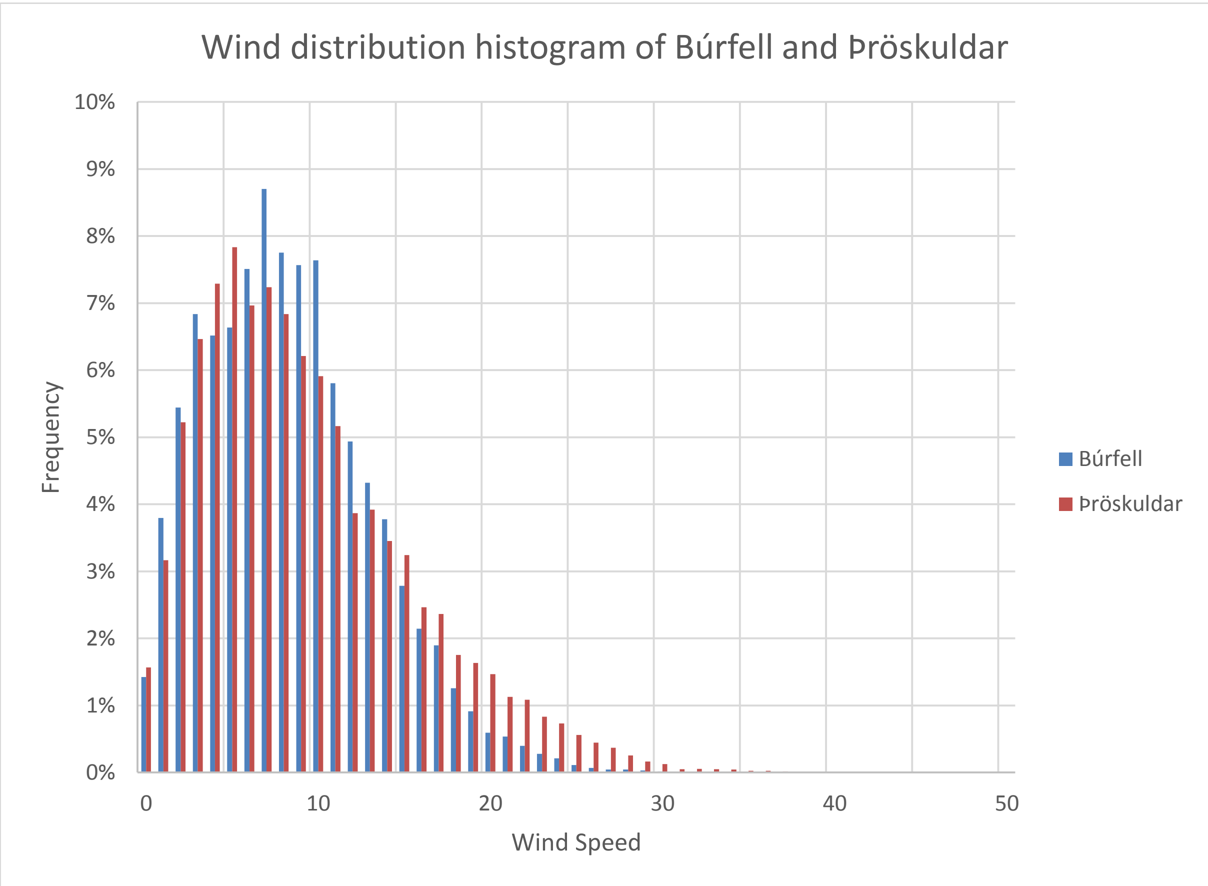

Figure 44 Distribution of wind speeds at Búrfell in blue and Þröskuldar in red.

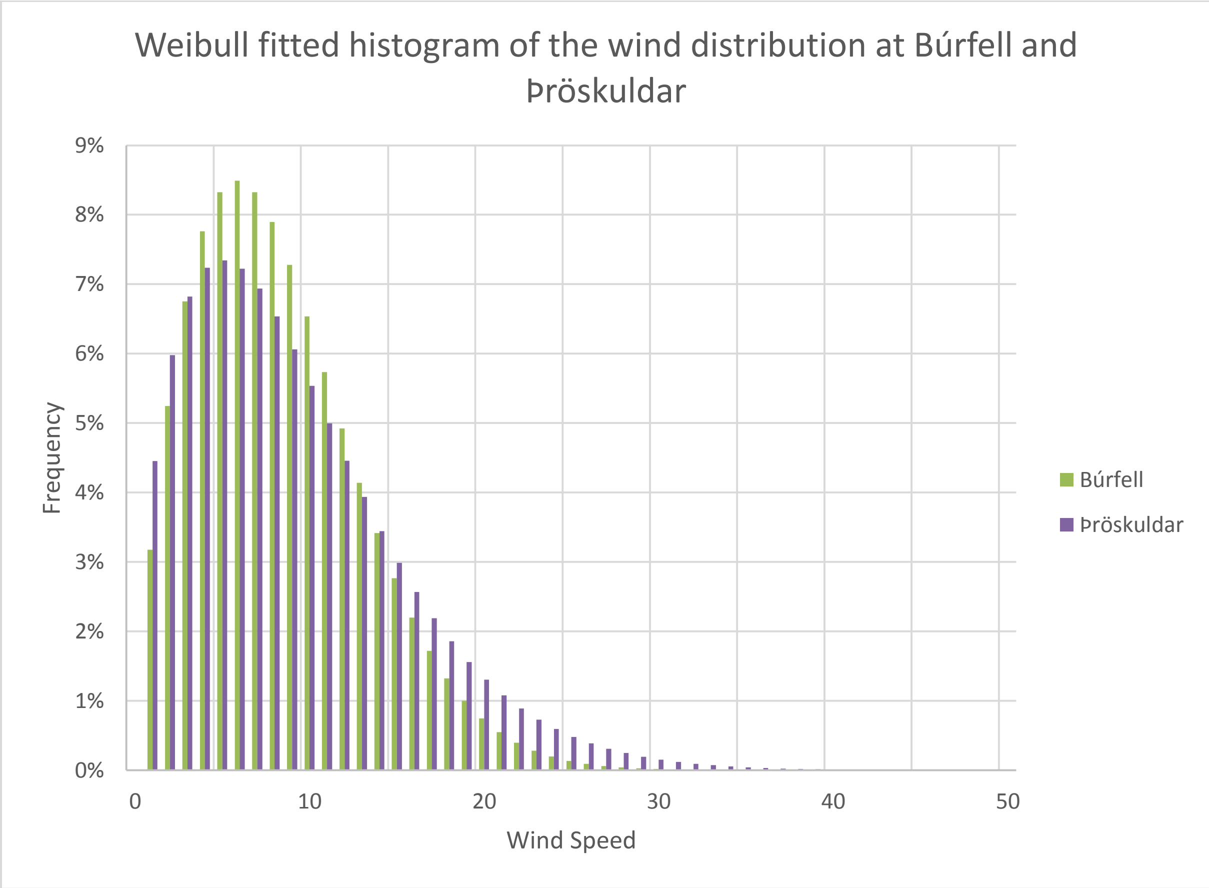

Figure 45 Wind distributions fitted into weibull for Búrfell in green and Þröskuldar in violet.

Using the ttest function in Excel the Weibull curve is estimated and it turns out that the fit is 97% in Þröskuldar and 99% at Búrfell.

5. Conclusions

Main outcomes will be interpreted here along with what could be done better. Also this chapter contains a summary of contribution.

5.1. Discussion

Hydro power plants with reservoirs is an ideal source of energy to go with wind power because it is dispatchable with the intermittent wind power.

Wind power along with hydro power will have a long-term positive effect on the energy production in the West Fjords and increase the ability to deal with fluctuations and power failures in the region.

Energy security is increased with wind turbines in the system and there is less need for buying from others through the long lines to the West Fjords, or backup from fossil fuel power sources. The backup will be in the energy stored in the reservoirs. Other types of backup with fossil fuels should be the last resort because of CO_2 emissions that comes with it.

There are uncertainties in the outcome from wind energy calculations which are shown in tables 13 and 14 page 46, because of the fluctuations, uncertainty with turbulence, gusts, insufficient measurements and the Weibull fit used.

Further analysis concludes that short time data like data in figure 39 and 40 (page 47-48) do not give good enough Weibull fit, so that gives a reason to doubt that one year is enough for wind power estimation.

There might also be problems with icing on blades in the winter because the location of wind turbines is in high altitude (370 m).

The channel effect is clear on the South-West to North-East wind directions that are the prevailing wind directions on Þröskuldar.

Wind above 25 m/s is 1,4% of the time but never happens in the summer time as shown in table 7 page 40. In the winter and fall it happens frequently, but in the fall there is still water flowing into reservoirs. The comparison in figures 44 and 45 show that wind speed has more variance up to more than 30 m/s on Þröskuldar. The lower k value of 1,51 for Þröskuldar supports that fact.

The wind is hard to predict in details so it is difficult to predict how power production from a combined wind and hydro power stations could operate in real life. The goals should be when this power mix is operated:

1. Wind turbines should at all times be used as much as possible instead of hydro to store the water.
2. In low wind seasons as the summer when water is plenty because the snow is melting, the hydro power can be used more.
3. If there was a submerged cable to Europe the sea breeze comes in the summer afternoon that could come in as cheap electricity that could be sold for the peak price period in European electricity market in the afternoon.

The energy output the two Landsvirkjun wind turbines at Búrfell is expected to be 5,4 GWh/year for their location and that seems to be realistic. The two locations Búrfell and Þröskuldar have a slightly different wind distribution and average wind as seen on figure 44 on page 56.

The profitability assessment for all the scenarios have a negative result. That is mainly because of high cost of TBM tunnel for the hydro power and the cost wind power is too high for the Icelandic market compared to hydro power and geothermal power in Iceland, but in the near future it is expected that the cost of hydro power will rise with fewer and more expensive resources, and wind energy technology will continue to progress. Therefore the cost per MW of wind power is expected to go down as it has done the last decades.

Hydro and geothermal power has a lot lower cost per MWh. The wind is not expected to be used much in the near future in Iceland. Although it should be used for testing and research purposes and especially in special conditions where no other renewable sources are available. An ideal place would be a windy place where there is no hydro or geothermal power available like on islands like Grímsey where oil is used for heating and electricity [52]. Oil should be the last choice in a country that uses 99,08% renewable energy for electricity and district heating [53].

The Mjólká VI hydro power plant does not appear to be feasible but if another more feasible hydro power option is taken, then wind with hydro power should be considered to store energy and increase energy security. The utilization of wind energy in connection with other power plants could, decrease the risk of electricity shortages in poor water years.

Green certificates described in chapter 2.2 could help bring in higher income for the wind power. Hydro and geothermal power is also green energy that gets green certificates so that does not help the propagation of wind turbines more than other energy sources in Iceland.

Hydro and geothermal power resources will eventually come to exhaustion in the future. According to the master plan for hydro and geothermal resources Iceland the available options have been narrowed down putting many of them into protection or pending class [54]. Wind power would then be the next choice.

5.2. Summary of contribution

The aim of this study was to calculate the energy production and how much water could be saved with the use of wind turbines on a grid of hydro power stations. A model was made in Excel of the Mjólká hydro power station and wind power station on Þröskuldar to simulate the power generation and water consumption.

Wind data was analyzed statistically for the location of Þröskuldar. Those wind measurements were broken into seasons of the year and it was checked if they could fit the consumption and work together with the hydro power and the seasonal water flow into respective reservoirs.

Two ENERCON E-44 wind energy converters on Þröskuldar can generate 6,1 GWh/year and save 7,1 Gl of water for later use when needed.

To be energy independent, OV could double the flow capacity to Mjólká VI with another hydro turbine and put up a wind farm with 21 wind turbines like described in scenario B. This setup can manage large fluctuations and is estimated to generate 140 GWh/year and the wind power can substitute for 61 GWh/year and saves about 57 Gl in the reservoir.

A pessimistic scenario is also put up for 90% wind in table 14 page 46. Then more wind turbines would be needed to keep up the 140 GWh/year need to be energy independent in the region. A more pessimistic scenario with 75% wind needs a lot more wind turbines (table 18 page 48).

These proposed power plants are not considered feasible economically unless the price for electricity goes up or the cost of wind turbines goes down. If prices go up and cost is lowered like stated in the end of chapter 5.1 this could be realistic. The tunnel drilled with the hydro power plant is too costly for this small amount of water flow. Other alternatives than Mjólká VI in hydro power should be considered.

5.3. Future research

As described in chapter 2.2 government incentives for development of wind energy in Iceland could help with research on extracting this vast resource. These incentives could be tax reduction, research funding, feed in tariffs and other supportive policies. This is essential to build up a wind power industry in Iceland's special conditions.

The wind appears to be very steady but there are many uncertainties that need further research. The fluctuations are not known well enough. A study is needed on turbulence factor, what is the loss due to turbulence, and how much that affects the generation. In order to examine the turbulence wind data is needed with more time resolution like 1 sec interval wind data to see the fluctuations in the wind. That would take too much time for this study and the difference was concluded to be negligible along with other uncertainties like variable wind and precipitation.

The surrounding landscape has a big effect on how the wind blows. There might be gusts and turbulence that cause uncertainty in the wind. It is necessary to raise masts with weather measurement equipment to reduce this uncertainty by measuring at the height of the proposed project.

Pumped hydro was not included in this thesis but should be considered because it might be useful to use wind driven pumps to pump water back up to the reservoir during low demand seasons and sell the stored energy when demand is high [55]. Pumped hydro should be considered in a wind and hydropower system.

More substantial water runoff research should be made for the Gláma highland because this is an important future energy source for the West Fjords.

The calculations of this study could be taken further with better data and more information through more research in the future. Also the calculations from this study could be implemented to other locations and other hydro power plants to see the feasibility of different possibilities.

The wind with hydro resources in Iceland are big and possibly a connection to other markets with higher energy prices could make them very feasible economically. With a cable it would be possible to sell the excess available energy that comes from wind power and cannot be used for some reason locally. This extra energy might be some extra fluctuations in wind, like the sea breeze in the summer time or extra wind that cannot be put into the co-operation instead of hydro power for some reasons.

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