Technical University of Denmark DTU

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Wind Energy in Greenland: current and future applications

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1 Introduction

1.1 Why is Wind Energy interesting in Greenland?

Greenland is a vast peninsula covered with ice by more than 80% of its extension. It presents harsh climatic conditions which make it difficult for living and justify the existent demographic distribution. Its inhabitants live in settlements which used to be fishing refuges in the old days, or small inuit communities, most of them located in the milder areas of the western coast of the island. They are normally separated by many kilometers from one another and no roads exist conecting them. This particular distribution strongly conditions the logistics and the energy systems in the region and also involves environmental problems related to waste. In what concerns energy, and since grid extensions are most of the time technically unfeasible or extremely expensive, most of the settlements are fuel dependent and suffer high operation costs due to the constant fuel supply by boat. Except in the case of small isolated villages where diesel generators are used for power production, bigger settlements have their own fuel power production plants and storage tanks for energy generation. Although there has been an increasing tendency in utilizing hydro power in the recent years as a renewable, not as vulnerable and reliable energy source (successful projects have be achieved: in Sisimiut for example), this technology cannot be implemented everywhere since not all the existing settlements have hydro power potential. Thus, energy supply remains in most of the cases fuel dependent and vulnerable to fuel availability and price. This also involves environmental issues since fuel power plants are very pollutive.

In some cases, some of this energy problem (or fossil fuel dependency) could be solved or reduced when utilizing other renewable energy technologies as solar or wind energy. Indeed, and when referring to wind power, it's implantation becomes interesting specially in small villages or in isolated locations, with no hydro power potential but with wind potential and where all year long demand is needed (because of the absence of sun during the winter months, solar energy becomes unfeasible if all year long supply is demanded).
Many challenges have to be faced though, in order for wind energy to succeed in the harsh arctic climate.

- Icing issues during the winter time seriously affect the wind turbine aerodynamic forces decreasing and even nullifying its the power output. In particular, rime icing conditions, which are known to be the worst case scenario, have to be faced frequently in these regions. These happen when a constant cool and humid flow coming from the ocean is cooled a lot bellow zero when going up a mountain or when mixing with colder continental air. Wind turbine blades are really affected loosing all of their aerodynamic efficiency since ice is able to build up to incredible levels. The corresponding weight of the ice can negatively affect the blades by increasing its fatigue. See Fig. 59 to get a visual example of a rime icing scenario affecting a telecommunication tower.
- More robust and resistant wind turbine designs are needed so they are able to withstand extreme wind conditions (as the so-called Foehn wind for example: see section2 for more details) which are observed in many of the isolated locations in Greenland where wind energy could be feasible. These locations also present intense turbulence as they are generally located on mountains or near them.

It is important to state that Wind Energy in Greenland is in a primitive stage of development nowadays, but that due to the huge development and progress this technology has experienced in harsh climates in the recent years (especially in icing related problems) and because of the increasing interest of wind turbine installation in cold areas (Russia, Canada, Finland etc.) a lot of effort is put in this field through companies and research institutions and major advances are expected in the near future. This project is thus relevant since it contributes to the development of wind energy in Greenland through field work that was performed in three different locations. The installation of a new met.mast in Sarfannguaq or the maintenance work and connection of its Proven [8] wind Turbine to the local grid are among some of the contributions provided during our stay. Besides this, useful new data analysis in these locations was carried out and suggestions of improvement for future applications or for further investigations are also discussed and examined in detail through the report. Furthermore, an interesting new idea is suggested in what concerns the applicability of vertical axis wind turbine in Greenland. As it will be discussed in the following subsection, exploring and testing a vertical axis turbine for a particular applications was the first goal of our project.

1.2 Project overview

When starting the project, the initial idea was to take part in the design and manufacturing of a vertical axis wind turbine mounted with a special generator. Our goal was for the turbine to work in tandem with the diesel generator to reduce the fuel consumption, thus reducing the amount of refueling trips. The design focus was extreme winds and icing, with icing being the most critical. This required us to explore many different concepts, which include aerodynamics, structures and material science. In addition to these mentioned topics, there are many others that need to be addressed as listed below.

- Interaction of wind turbines and radio communication systems
- Design choices for wind turbine and power system
- Battery capacities
- Control Strategy
- Prototype design and testing under Greenland's extreme environment

However given the limited time and rather large scope of this project, it was difficult to match up our fieldwork to these topics (no vertical axis wind turbine could be tested). So ultimately, due to the lack of related work to VAWT's in the arctic, we had to rely on a literature study of its feasibility combined with a more extensive overview of the current applications which some of them were implemented during field work.

2 Climatology and wind in Greenland

2.1 The synoptic-scale climatically different regions in Greenland

Greenland suffers the arctic climate which meanly refers to the presence of harsh conditions during most part of the year making it impossible for forest or other kind of vegetation besides low plants or tundra to grow. Nevertheless and from a synoptic-scale point of view, since Greenland is so vast and big, seven climatically different regions can be distinguished as it can be seen in Fig. 1.

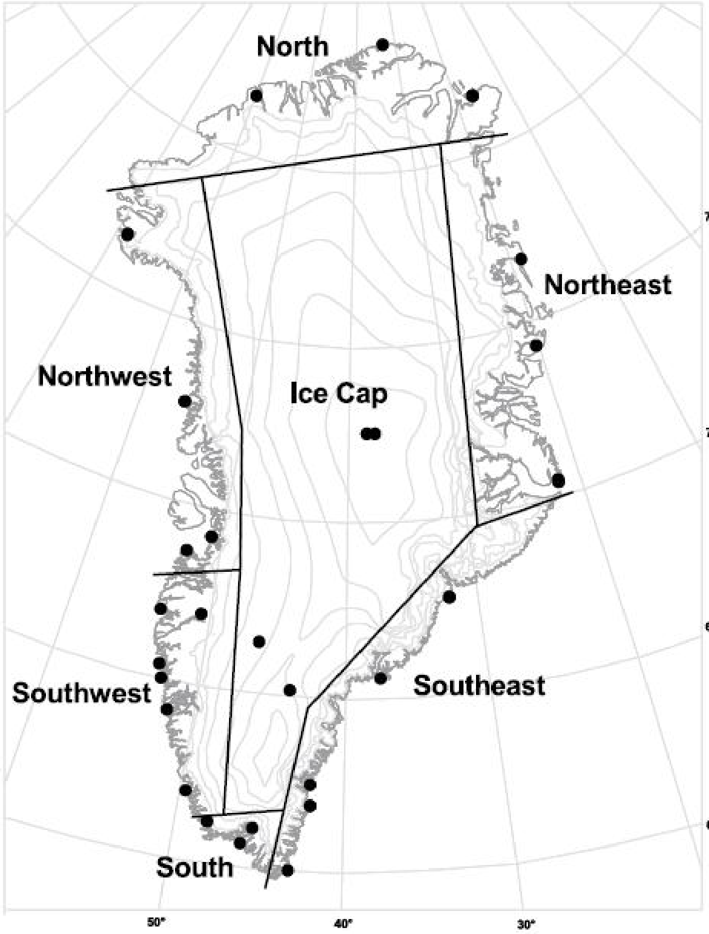
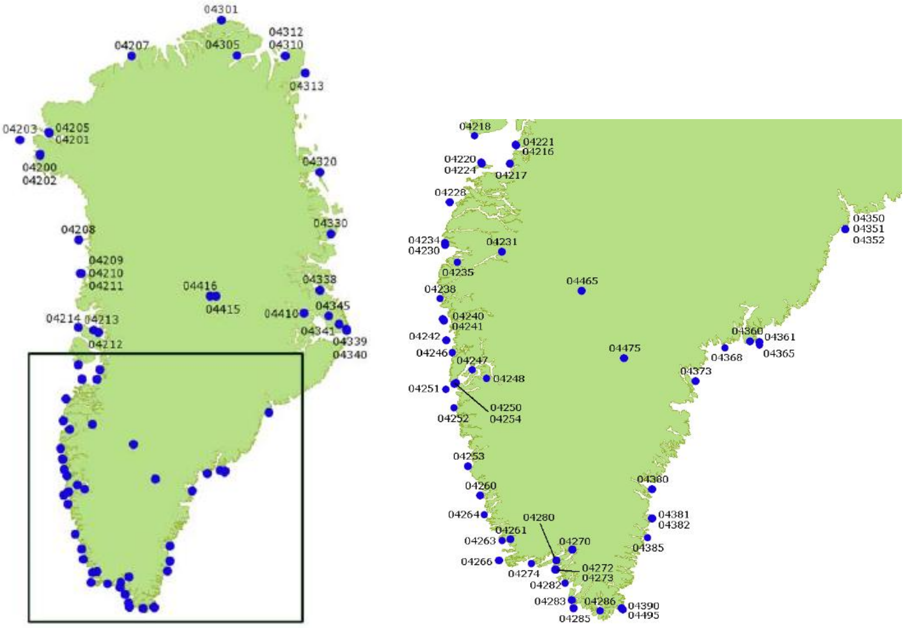


Figure 1: The seven synoptic-scale climatic regions in Greenland.

Climate and weather can be very different all across Greenland. In general trends, precipitation is more abundant and frequent in the south and in the coastal areas in detriment of fjord interior areas (like Kangerlussuaq for instance), the icecap and northern regions where they can be almost inexistent (arctic desert climate). In terms of temperature, the interior of Greenland suffers extremely cold weather, even in the summer. The southern and western coast though, (especially southwestern) has milder weather and it's where most of Greenland's population is concentrated since the living conditions are not as extreme. A broader and more detailed mesoscale description of the climate of this area will be reported later on, since most of the projects related to wind energy would be conducted here.

2.2 The existing met.stations and data availability in Greenland

DMI (The Danish Meteorological institute, see [10]), has a broad network of meteorological stations all across Greenland, as it can be seen in Fig. 2. The southwestern and southern stations can be seen in more detail in the right hand side of it. The oldest locations are recording data since 1874. Generally these stations provide good meteorological assessment (wind assessment and temperature characteristics are the main interest in wind projects in arctic climate) in the nearby areas but, unfortunately for remote location oriented projects, they are insufficient since these locations are usually far away from the stations and sometimes located near mountains (on in them). Indeed, the south and western coast of Greenland are quite irregular and mountainous and it is well known that constant changes in the orography and steep terrain make it difficult particularly for wind assessment since the flow pattern can become very complicated. A broader discussion related to wind resource and assessment will be treated in the next subsection.



(a) (b)

Figure 2: DMI Met.Station location in Greenland. (a) In the whole Greenland (b) In the southern regions

On the other hand, a climate change research group (Steffen research group) from the University of Boulder, Colorado, and financed by NASA, installed in 1999 18 automatic weather stations in the greenlandic icecap (See [13]). There lifetime was around five to six years and they were able to provide useful meteorological knowledge as well as useful wind assessment in this inhabited and isolated area. The exact locations of these stations is shown in Fig. 3

2.3 Wind resource in Greenland

Unfortunately, no wind atlas was found for Greenland in the internet. Nevertheless, if one combines the data provided by all the different met.stations in Greenland with topographical and roughness inputs, one would be able to simulate and create an atlas using Wasp or similar programs. Unfortunately and due to the fact that none of our group members had Wasp available in their computer (the license we once possessed expired in july), we decided that a company could do it for us. So we managed to do simulations for the entire Greenland, and for areas of the south and southwestern coast. We also decided to check the accuracy of the obtained atlas by looking at the mean wind speeds at the

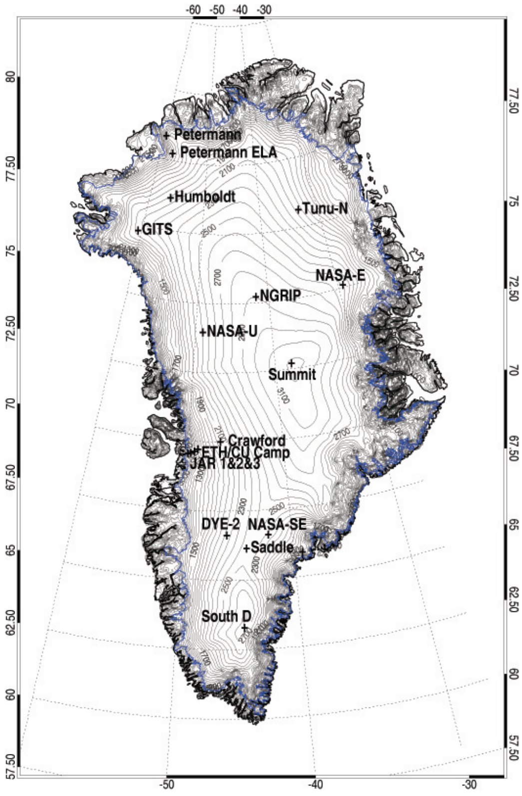


Figure 3: Automatic weather stations in the ice cap (from 1999 to 2005 approximately).

locations we did field work. It was found that the results were not very accurate and that the wind speed was the same when moving 300 meters or more around a picked point. The main reasons for this were thought to be:

- Very low grid resolution resulting in a considerable inaccuracy in the results since no high resolution topographical maps exist and thus can be used in Greenland. SRTM maps, which are widely used for wind resource assessment (1, 3 or 30arc-second in the worst case) are not available in this part of the world since these cover latitudes smaller than 60 ° north or south. Only GTOPO30 maps can be used to grid the topography but they are not as precise as SRTM maps and their resolution is low (30 arc-second or 1km grid resolution).
- Many areas of Greenland which are interesting for wind energy are far away from the met. stations (Sarfannguaq for instance, or the telecommunication tower locations where vertical axis wind turbines could be suitable).

An available GTOPO30 map was downloaded from the NASA website at [12] and processed with SAGA-GIS. The grid resolution was checked and it was found to around 1km as expected. A topographic map of the entire Greenland is shown in Fig. 4 and a zoom to southern part of the peninsula is shown in Fig. 5 where 100 meter contour lines where added. It is important to mention that better topographic map resolutions can be digitalized locally when wind resource needs a better estimate.

Besides all of these limitations, the wind atlas of Greenland shown in Fig. 6, can give an idea of the areas with wind potential. Indeed, although not precise, one can observe that the ice-cap has a high wind potential as well as the south tip of Greenland (See Fig. 7) and other small areas in the southwestern coast (more interesting for wind power projects). Nevertheless and when observing the data from the DMI stations and when refering to the south and southwestern coast the wind pattern is quite irregular. Not only observations are quite different from year to year, making it difficult for assessment when one year or two of two of data is available, but in what concerns smaller time scales, and in general trends, many periods of calm are observed as in many locations. Some of the western

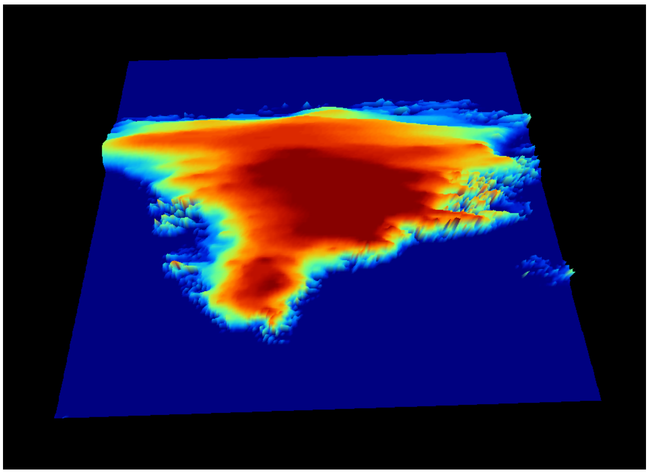


Figure 4: GTOPO30 topographic map for Greenland (30 arc-second resolution).

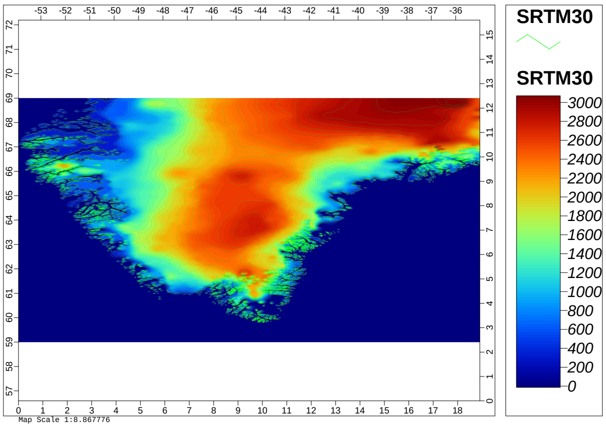


Figure 5: GTOPO30 topographic map of Southern Greenland.

coast location even exceed 50% in periods of calm. At the same time, severe gales are seen as well along the year.

2.4 Wind related mesoscale phenomena affecting the South and Southwestern coast

The South and Southwestern coast are composed by hundreds of fjords that settle beneath sharp and steep mountains that can easily go up to 1500 metres right above the sea level. This particular orographic setting makes it difficult for local wind assessment, as it has been mentioned before, since wind characteristics can be quite different from one fjord to another (even if they are very close in distance). Nevertheless, common wind patterns can be observed when doing a mesoscale analysis.Indeed, they are strongly related to the existent meteorological situation and can be mainly divided in two groups. They will be analyzed for the south and southwestern coast separately since the regimes are slightly different.

2.4.1 In the South Coast

- Wind regimes associated to cyclon passages:
  - During the winter, typical low pressure passages from the southwest to the northeast result in moderate easterly winds at the beginning changing to northwestly winds after the

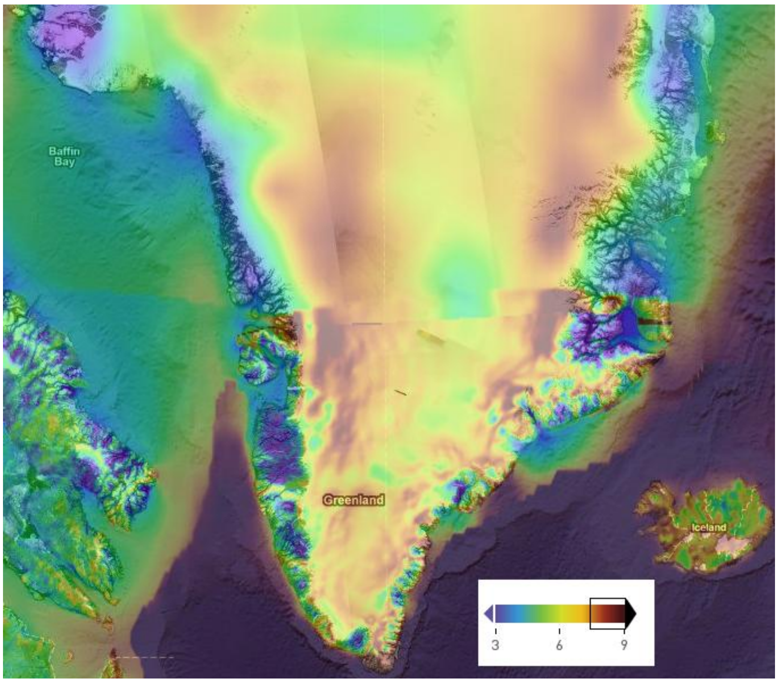


Figure 6: Wind Atlas of Greenland.

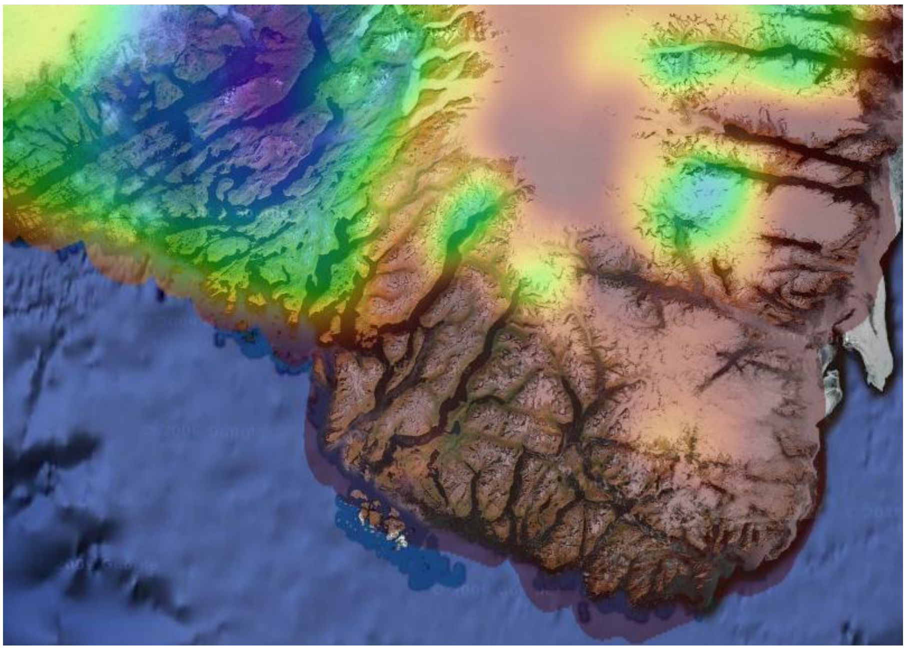


Figure 7: Southern tip of Greenland Wind Atlas.

passage.

  - Stationary lows at the south of Greenland are more rare but they are able to produce, because of their stationarity, dry, warm (around 10 °C in average) and very strong easterly Foehn winds right from the ice cap, that will blow right through the fjords till the coast. These wind are quite dangerous since they can last for a long period of time and are accompanied by gale and even hurricane gusts. In these situations, the ice on the fjords will generally break and the snow will melt.
  - The typical stationary low in Iceland causes the opposite effect, with sometimes long periods of northwesterly winds and cold weather.

- Wind regimes associated with calm weather

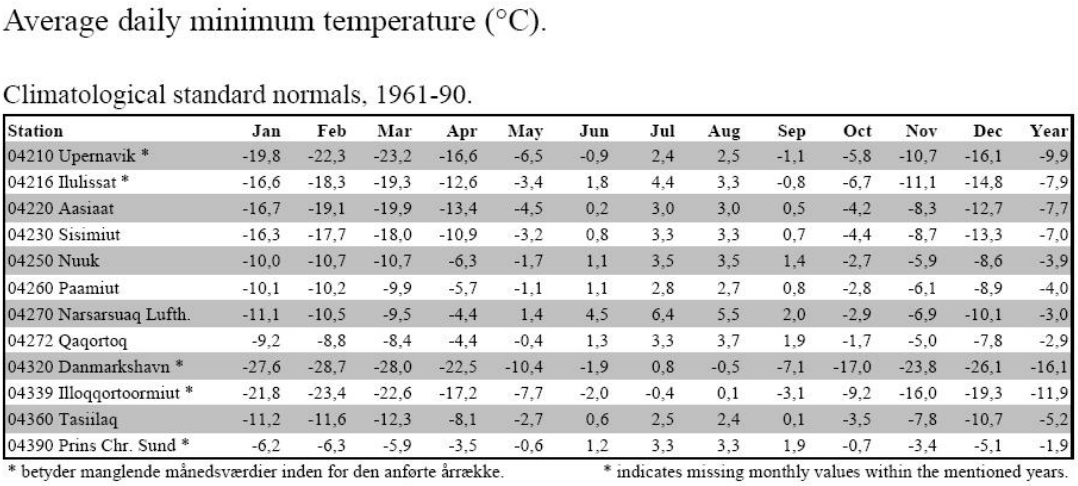
  - In the summer time, the cold temperature of the sea in contrast with the interior land heat will produce a breeze regime that can be long lasting if stable weather persists. This breeze is often not strong.
  - In the winter time, in contrast, a land breeze or the so-called katabatic wind system of the ice cap is the main pattern in stable weather since the interior land remains colder than the seaside. This also happen in daily time-scales during warmer months, when the air temperature of the ice-cap has decreased. Indeed, land and sea breezes can altern in the daily basis.

2.4.2 In the Southwestern Coast

- Wind regimes associated to cyclon passages:
  - During the winter and also through the summer, low pressure passages through the south are common and can often produce very strong southerly winds with gale force and even hurrican level force in the coast line. This wind is best known as the 'Nigersuaq' in Nuuk, when it is combined with local Foehn and temperatures can rise up to 15 °C.
  - Polar lows developing in the open sea are also possible during the winter time and can produce strong winds and heavy snow in the coast-line.
- Wind regimes associated with calm weather
  - In the winter time, northerly winds are predominant, but never strong and usually bring clear and cold weather.
  - As in south Greenland, sea and land breezes are also common in this area

2.5 Low temperatures and icing in the South and Southwestern coast

Important information concerning low temperatures, humidity and cloud covering in South and Southwestern coast locations can be found in the DMI website [10]. This data can be useful to predict potential icing in a hypothetic wind turbine located in the met. mast locations. It is seen that near the sea and at the sea level, temperatures will rarely go beneath $-20\,°\mathrm{C}$ as average minimals in a normal winter. Fig. 8 shows the average minimum temperatures for some of the locations in that area from data collected though almost 30 years. Sisimiut or Nuuk have their average minimum temperatures at $-18\,°\mathrm{C}$ and $-10.7\,°\mathrm{C}$ respectively. The most extreme temperatures ever recorded in these location are shown in the appendix. On the other hand, Fig. 9 shows the average cold days per month and per year (that is when the minimum temperature is under $-10\,°\mathrm{C}$) and Fig. 10 shows the average ice days (the maximum temperature does not exceed $0\,°\mathrm{C}$) per month and per year as well. One can observe that in locations near the coast, in these regions, the number of cold days per year is comprised between 60 and 130 days and the number of ice days lays between 95 and 180 days. Humidity time series would be very useful to quantify icing conditions but unfortunately only data from Kangerlussuaq is available at the DMI [10]. An essential parameter that is used to quantify icing is the level of water content (LWT) which is difficult to access by measurements but can be somehow estimated with the existing visibility or cloud covering data. Cloud covering data is available at DMI and some statistics for several locations are shown equally here (Fig. 11). It can be stated, in a general way,and from this data, when comparing the cold temperatures throughout the year, the cloud-covering of the locations , and different wind speeds for the different locations the available data, that icing will be particularly severe in the southern regions close to Nuuk, where average wind speeds are higher and more cloud-covering is observed.



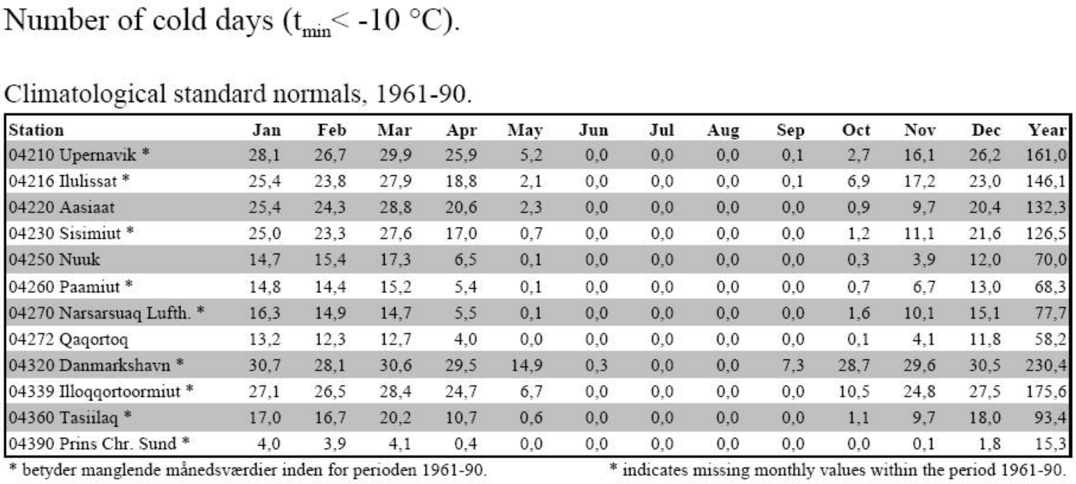
Average daily minimum temperature (°C).

Climatological standard normals, 1961-90.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
04210 Upernavik *	-19,8	-22,3	-23,2	-16,6	-6,5	-0,9	2,4	2,5	-1,1	-5,8	-10,7	-16,1	-9,9
04216 Ilulissat *	-16,6	-18,3	-19,3	-12,6	-3,4	1,8	4,4	3,3	-0,8	-6,7	-11,1	-14,8	-7,9
04220 Aasiaat	-16,7	-19,1	-19,9	-13,4	-4,5	0,2	3,0	3,0	0,5	-4,2	-8,3	-12,7	-7,7
04230 Sisimiut	-16,3	-17,7	-18,0	-10,9	-3,2	0,8	3,3	3,3	0,7	-4,4	-8,7	-13,3	-7,0
04250 Nuuk	-10,0	-10,7	-10,7	-6,3	-1,7	1,1	3,5	3,5	1,4	-2,7	-5,9	-8,6	-3,9
04260 Paamiut	-10,1	-10,2	-9,9	-5,7	-1,1	1,1	2,8	2,7	0,8	-2,8	-6,1	-8,9	-4,0
04270 Narsarsuaq Lufth.	-11,1	-10,5	-9,5	-4,4	1,4	4,5	6,4	5,5	2,0	-2,9	-6,9	-10,1	-3,0
04272 Qaqortoq	-9,2	-8,8	-8,4	-4,4	-0,4	1,3	3,3	3,7	1,9	-1,7	-5,0	-7,8	-2,9
04320 Danmarkshavn *	-27,6	-28,7	-28,0	-22,5	-10,4	-1,9	0,8	-0,5	-7,1	-17,0	-23,8	-26,1	-16,1
04339 Illoqqortoormiut *	-21,8	-23,4	-22,6	-17,2	-7,7	-2,0	-0,4	0,1	-3,1	-9,2	-16,0	-19,3	-11,9
04360 Tasiilaq	-11,2	-11,6	-12,3	-8,1	-2,7	0,6	2,5	2,4	0,1	-3,5	-7,8	-10,7	-5,2
04390 Prins Chr. Sund *	-6,2	-6,3	-5,9	-3,5	-0,6	1,2	3,3	3,3	1,9	-0,7	-3,4	-5,1	-1,9

* betyder manglende månedsværdier inden for den anførte årrække. * indicates missing monthly values within the mentioned years.

Figure 8: Average minimum temperatures per month in several locations in the Western Coast.



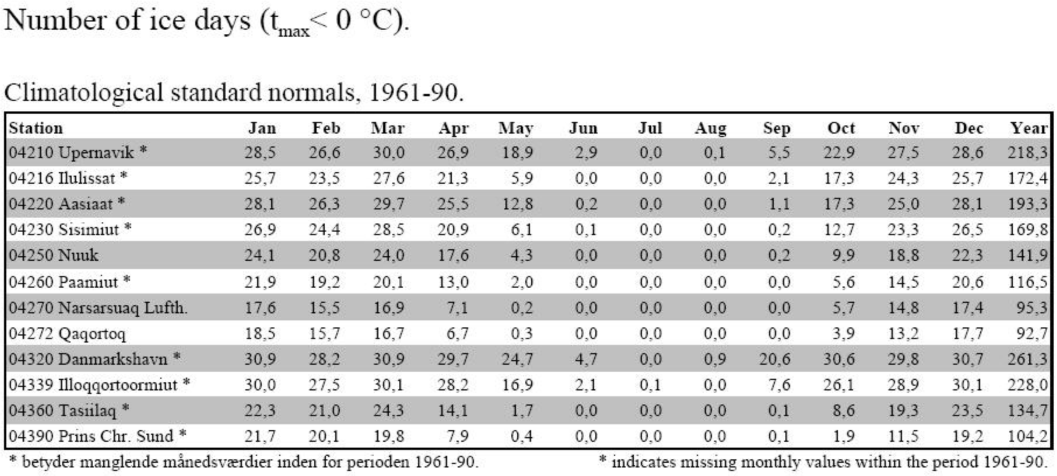
Number of cold days (t_{min}< -10 °C).

Climatological standard normals, 1961-90.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
04210 Upernavik *	28,1	26,7	29,9	25,9	5,2	0,0	0,0	0,0	0,1	2,7	16,1	26,2	161,0
04216 Ilulissat *	25,4	23,8	27,9	18,8	2,1	0,0	0,0	0,0	0,1	6,9	17,2	23,0	146,1
04220 Aasiaat	25,4	24,3	28,8	20,6	2,3	0,0	0,0	0,0	0,0	0,9	9,7	20,4	132,3
04230 Sisimiut *	25,0	23,3	27,6	17,0	0,7	0,0	0,0	0,0	0,0	1,2	11,1	21,6	126,5
04250 Nuuk	14,7	15,4	17,3	6,5	0,1	0,0	0,0	0,0	0,0	0,3	3,9	12,0	70,0
04260 Paamiut *	14,8	14,4	15,2	5,4	0,1	0,0	0,0	0,0	0,0	0,7	6,7	13,0	68,3
04270 Narsarsuaq Lufth. *	16,3	14,9	14,7	5,5	0,1	0,0	0,0	0,0	0,0	1,6	10,1	15,1	77,7
04272 Qaqortoq	13,2	12,3	12,7	4,0	0,0	0,0	0,0	0,0	0,0	0,1	4,1	11,8	58,2
04320 Danmarkshavn *	30,7	28,1	30,6	29,5	14,9	0,3	0,0	0,0	7,3	28,7	29,6	30,5	230,4
04339 Illoqqortoormiut *	27,1	26,5	28,4	24,7	6,7	0,0	0,0	0,0	0,0	10,5	24,8	27,5	175,6
04360 Tasiilaq *	17,0	16,7	20,2	10,7	0,6	0,0	0,0	0,0	0,0	1,1	9,7	18,0	93,4
04390 Prins Chr. Sund *	4,0	3,9	4,1	0,4	0,0	0,0	0,0	0,0	0,0	0,0	0,1	1,8	15,3

* betyder manglende månedsværdier inden for perioden 1961-90. * indicates missing monthly values within the period 1961-90.

Figure 9: Average cold days per month and per year in some locations in Greenland.



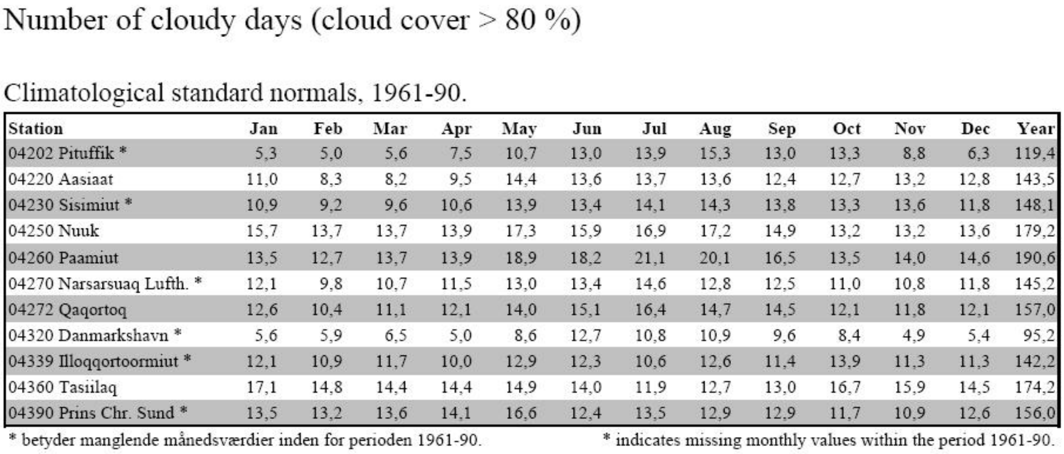
Number of ice days (t_{max}< 0 °C).

Climatological standard normals, 1961-90.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
04210 Upernavik *	28,5	26,6	30,0	26,9	18,9	2,9	0,0	0,1	5,5	22,9	27,5	28,6	218,3
04216 Ilulissat *	25,7	23,5	27,6	21,3	5,9	0,0	0,0	0,0	2,1	17,3	24,3	25,7	172,4
04220 Aasiaat *	28,1	26,3	29,7	25,5	12,8	0,2	0,0	0,0	1,1	17,3	25,0	28,1	193,3
04230 Sisimiut *	26,9	24,4	28,5	20,9	6,1	0,1	0,0	0,0	0,2	12,7	23,3	26,5	169,8
04250 Nuuk	24,1	20,8	24,0	17,6	4,3	0,0	0,0	0,0	0,2	9,9	18,8	22,3	141,9
04260 Paamiut *	21,9	19,2	20,1	13,0	2,0	0,0	0,0	0,0	0,0	5,6	14,5	20,6	116,5
04270 Narsarsuaq Lufth.	17,6	15,5	16,9	7,1	0,2	0,0	0,0	0,0	0,0	5,7	14,8	17,4	95,3
04272 Qaqortoq	18,5	15,7	16,7	6,7	0,3	0,0	0,0	0,0	0,0	3,9	13,2	17,7	92,7
04320 Danmarkshavn *	30,9	28,2	30,9	29,7	24,7	4,7	0,0	0,9	20,6	30,6	29,8	30,7	261,3
04339 Illoqqortoormiut *	30,0	27,5	30,1	28,2	16,9	2,1	0,1	0,0	7,6	26,1	28,9	30,1	228,0
04360 Tasiilaq *	22,3	21,0	24,3	14,1	1,7	0,0	0,0	0,0	0,1	8,6	19,3	23,5	134,7
04390 Prins Chr. Sund *	21,7	20,1	19,8	7,9	0,4	0,0	0,0	0,0	0,1	1,9	11,5	19,2	104,2

* betyder manglende månedsværdier inden for perioden 1961-90. * indicates missing monthly values within the period 1961-90.

Figure 10: Average ice days per month and per year in some locations in Greenland.



Number of cloudy days (cloud cover > 80 %)

Climatological standard normals, 1961-90.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
04202 Pituffik *	5,3	5,0	5,6	7,5	10,7	13,0	13,9	15,3	13,0	13,3	8,8	6,3	119,4
04220 Aasiaat	11,0	8,3	8,2	9,5	14,4	13,6	13,7	13,6	12,4	12,7	13,2	12,8	143,5
04230 Sisimiut *	10,9	9,2	9,6	10,6	13,9	13,4	14,1	14,3	13,8	13,3	13,6	11,8	148,1
04250 Nuuk	15,7	13,7	13,7	13,9	17,3	15,9	16,9	17,2	14,9	13,2	13,2	13,6	179,2
04260 Paamiut	13,5	12,7	13,7	13,9	18,9	18,2	21,1	20,1	16,5	13,5	14,0	14,6	190,6
04270 Narsarsuaq Lufth. *	12,1	9,8	10,7	11,5	13,0	13,4	14,6	12,8	12,5	11,0	10,8	11,8	145,2
04272 Qaqortoq	12,6	10,4	11,1	12,1	14,0	15,1	16,4	14,7	14,5	12,1	11,8	12,1	157,0
04320 Danmarkshavn *	5,6	5,9	6,5	5,0	8,6	12,7	10,8	10,9	9,6	8,4	4,9	5,4	95,2
04339 Illoqqortoormiut *	12,1	10,9	11,7	10,0	12,9	12,3	10,6	12,6	11,4	13,9	11,3	11,3	142,2
04360 Tasiilaq	17,1	14,8	14,4	14,4	14,9	14,0	11,9	12,7	13,0	16,7	15,9	14,5	174,2
04390 Prins Chr. Sund *	13,5	13,2	13,6	14,1	16,6	12,4	13,5	12,9	12,9	11,7	10,9	12,6	156,0

* betyder manglende månedsværdier inden for perioden 1961-90.

* indicates missing monthly values within the period 1961-90.

Figure 11: Average cloud cover in some locations of Greenland.

2.6 Extreme wind observations: Piteraq and Foehn winds

The particular orography of Greenland, which gradually steepens from the base of the fjords till the top of the icecap, and the low roughness in the icecap are perfect ingredients for extreme wind conditions to take place. Indeed, in particular locations of the coast, katabatic downward wind can get extremely powerful in the proximities of the inland ice mainly because of local canalization due to orography. Two types of wind are depicted and described here and mainly differ in the climatic conditions that generate them.

2.6.1 The Foehn wind

This wind generally occurs in stable conditions and when the cold and dense air in the icecap region starts to accelerate downwards, driven by gravity and by density difference (or diffusion) since air at the sea level is warmer and thus much lighter. As air is moving down, it will experience an adiabatic expansion because of the encountered positive pressure gradient which makes it warm up fast. This process decreases the acceleration of the wind and moderates the wind speed. Most of the time Foehn winds will arrive warmer to the base of the fjord (especially in the western coast) being quite powerful but will barely make it to the coast line since neither gravity or density difference can drive them. On the other hand, if the katabatic wind arrives colder than the fjord air temperature, it will continue its way through the coast and arrive to the coastline. These winds can go up to 30 m/s in some situations.

2.6.2 The Piteraq wind

This wind is a katabatic 'fall' wind, meaning that it arrives cold to the fjord and coast but unlike the Foehn wind it is generated in special conditions. It normally occurs when very cold Canadian air arrives to the top of the icecap via western greenland and driven by a low. As it blows towards the eastern coast. Since it carries a lot of inertia and has extremely cold caracteristics, when it descends towards the east coast it is accelerated by gravity, by density difference and by local orographic patterns. It can become extremely powerful and usually reaches wind speeds up to 50 m/s. Eventually even higher wind speeds have been recorded in Eastern Greenland, especially at the location of Tasiilaq as it can be seen in the time series Fig. 12. A Piteraq storm struck here in 1970 and the fastest wind speed recorded was above 70m/s before the anemometer was blown away. Some say it blew 90m/s that day! Fig. 13 shows a Piteraq wind event in the east coast; one can observe its trace in the sea and can easily guess its direction. It is also usual that this wind strikes after a long period of calm. This phenomenon is rare in the west coast, simply because the gradient from elevated areas of the icecap till the coast is smoother when compared to the one in the southeastern coast (near Tasiilaq the orographic conditions are ideal for this extreme wind) and the distance to the coast line is much larger too (longer fjords exist in the western coast).

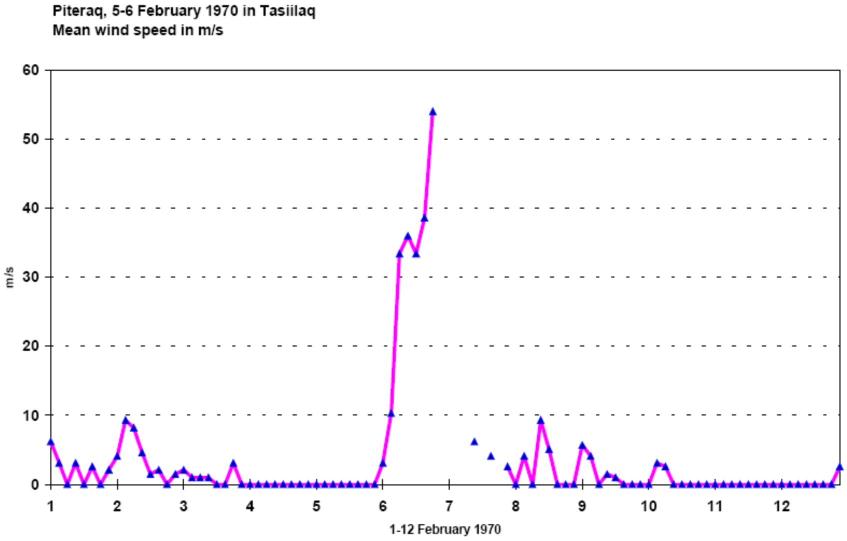


Figure 12: Piteraq event reflected in the time series at Tisiilaq.

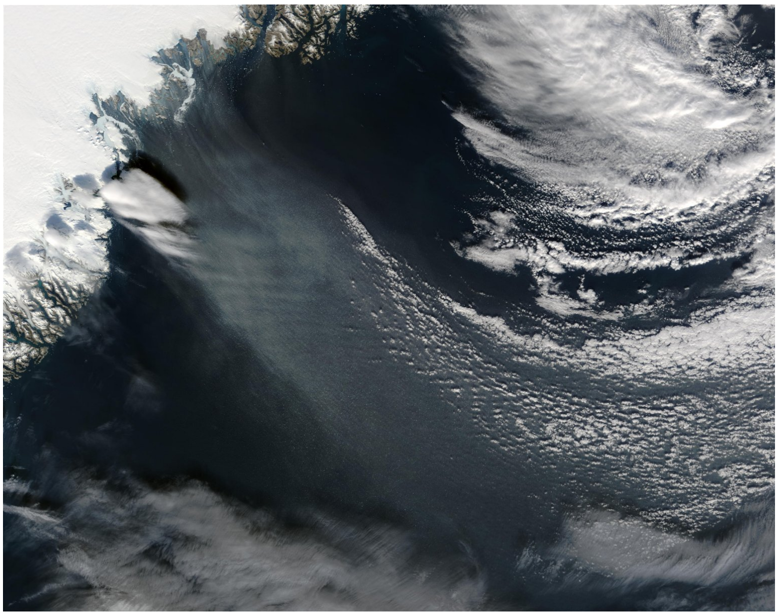


Figure 13: Satellite picture of the Eastern coast of Greenland when Piteraq strikes.

3 Current situation of Wind Energy in Polar environments

Given the uniqueness of the application coupled to the environment it is essential that research is made to gain as much knowledge as possible. However, information in this area (wind power in Greenland) is limited, so the search criteria had to be enlarged to cover both Arctic and Antarctic regions. Also the type of turbine used had to be broadened. With the new search criteria, enough information was found to establish a general understanding about the history, troubles and successes of wind energy in the most extreme polar climates. The locations and turbine types are as follows:

- Summit Station, Greenland - [9] Proven 6kW (HAWT)
- Sarfanguaq, Greenalnd - [9] Proven 6kW (HAWT)
- West shoulder of Mt. Erebus, Antarctica - [9] Southwest Windpower 400W (HAWT)
- Mawson Station, Mac.Robertson Land - [9] Enercon E30 300kW (HAWT)
- Whitehorse, Canada - [9] Vestas V47 660kW Bonus Mark III 150kW (HAWT)
- Assaqutaq, Greenland - [9] Windside 100W (VAWT) Ampair 100W (HAWT)
- Camp Raven, Greenland - [9] Bergey 1500 150W (HAWT)
- Lake Bonney, Antarctica - [9] Aerogen 360W (HAWT)
- Mt. Erebus, Antarctica - [9] Southwest Windpower 400W (HAWT)
- New Harbor, Antarctica - [9] Bergey XL1 1000W (HAWT)
- Dronning Maud Land, East Antarctica - [9] Proven 6kW (HAWT)
- Aboa Base, Antartica - [9] Windside (VAWT)
- Nuuk, Greenland - [9] Ropatec WRE.005 500W (VAWT)

For this section of the report only a couple of locations will be discussed in detail, to be able to make a broad overview about severe wind and icing and then later in the report the VAWT's in Greenland will be discussed.

3.1 Summit Station, Greenland

Located at the highest point above sea level (3250 meters) in the Greenland ice cap, is the Summit Station. The environment in this area has been known to reach wind speeds in excess of 40 m/s and have temperatures drop to -70 degrees Celsius. It is one of the primary research facilities operated year-round by the National Science Foundation's Arctic Program. Directly due to the lack of anthropogenic pollution sources, it is the perfect location to conduct studies of snow and atmospheric chemistry, ice core analysis and other research focused on the environment.

Before any installation of renewable energy sources diesel generators, powered by modified jet A-1 fuel, supplied all of Summit's electrical needs. This type of power production has its drawbacks though. The reason for the location of this site was for its clean and undisturbed environment, but with the burning of fossil fuels can severely compromise the data being collected, defeating the purpose of locating such a site in a remote area. To combat this issue, the installation of a 6kW Proven wind turbine began in 2006. This turbine was chosen primarily for its existing track record within the United States, more specifically in Alaska. This Scottish designed and built machine has a 'survival speed' of 67 m/s. This is possible because the roots of the blades are hinged and are able to stay in place due to the tension provided by springs. As the wind speeds increase, the force on the blades increase causing them to furl out of the wind, thus stalling out and allowing them to maintain a steady power production even at high wind speeds.

Figure 14: Summit Station location.

Figure 15: Putting up the Proven Wind Turbine at the Summit Station, Greenland.

Besides the extreme winds, other challenges specific to this location where the foundation construction and icing. For the foundation construction, there was no bedrock to directly anchor to since it was more than 3000 meters below the snow surface. To get around this, a platform was created out of wood and with the combination of wetting the snow with water an 'arctic concrete' was made that created a solid foundation (see Fig. 16). Also, while originally designed as a guyless monopole tower, 13 mm steel guys were added to ensure rigidity due to the high forces of the wind over time (See Fig. 15).

With regards to the wind turbine's performance, the extreme cold and elevation affected it in a couple of ways. These are lower air density and icing, which both affect the final power output. The air density at Summit Station's elevation has had a greater effect on power output than anticipated. In 2007, the maximum output was about 4,6 kW. This was with wind speeds of 18 m/s or greater. It can be noticed on the Proven power curve shown in Fig. 17 that peak power is produced at approximately 13 m/s. However this is at sea level where the density of air at room temperature is $1.205 kg/m^3$ when compared to $0.919 kg/m^3$. So even though you would have even denser air at colder temperatures the high altitude severely affects density and because of this there is less power to extract per cubic meter of air passing through the turbines blades. To compensate for this, the team at Summit, increased the spring tension on the blades. This caused the blades to pitch out later and resulted in a new

Figure 16: foundation strategie for the Proven Wind Turbine at the Summit Station, Greenland.

maximum output of approximately 5200 Watts.

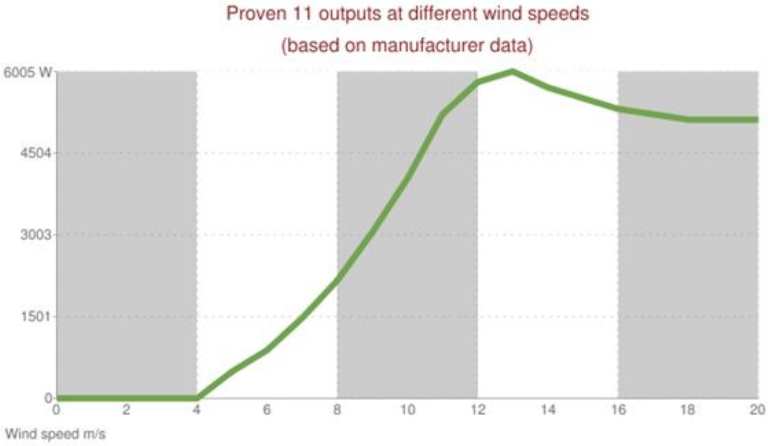


Figure 17: Proven 6kW Power curve.

As a consequence, the increase in power has an undesirable side effect. During periods of sustained high wind speeds, the inverters have cut out a few times. This was only seen when the cumulative power output was 5kW or more for several hours.

The ice buildup at Summit can be problematic at times. The specific ice that commonly precipitates at this location is hoar frost and this has a tendency to collect on any and all surfaces, including wind turbine blades. However, because of its delicate nature, it was believed that the frost would have fallen off once the wind was strong enough to move the blades. In reality, it is rather unyielding. It turned out the centrifugal force of the blades caused the frost to densify, making it harder to shed. As can been seen in Fig. 18, the buildup can become so severe at times that it is enough to lower power output to almost nothing at times. The icing on the left noticeably reduced power production, while the level of buildup on the right reduced power output to approximately 80%.

There were also issues where ice entered into the nacelle through the front ventilation ports. This caused some damage to the slip rings through arcing. Also, with prolonged exposure to the sun, the nacelle's black plastic body would warm causing the ice inside to melt. The runoff from this would accumulate at the bottom of the stator. This then would refreeze, locking the rotor with the only solution being to lower the turbine and melt it out. The last time this happened at Summit, it remained 'frozen' for almost 8 weeks before any repairs could have been made. Since then, a porous filler material was epoxied in the ventilation ports, which has seemed to resolve this specific issue. This allowed the machine to cool during the summer and then plug up with frost during the winter, preventing any ice intrusion. To combat the ice buildup on the blades, a chemical compound called ICEX II was applied. This coating is developed by the Goodrich company and is marketed towards de-icing of aircraft propellers. The result in this application is a significant improvement in the wind

Figure 18: Two different ice buid-up levels in the Proven wind turbine.

turbine's performance. Before this compound was used the cumulative power production was around 1% (2007), but after the production rose to 5% (2008). Unfortunately, at this current moment there are no active blade de-icer's available for smaller machines (100kW or less), making the only way to apply this compound is manually. For more information realted to the Summit station project refer to [6]

3.2 Whitehorse, Canada

Located in the North-Westerly part of Canada, Yukon, lies immediately East of Alaska. The city of Whitehorse is situated in the South central part of Yukon and has a population estimated at 33,000, of which two-thirds live in the capital city. The climate in this area is sub-arctic. The average daily temperature low is $-25\,^{\circ}\mathrm{C}$ with the lowest occasionally reaching $-45\,^{\circ}\mathrm{C}$. Also rime ice is seen quite regularly during winter, with the most severe occurring between the months of October and December. In Fig. 20, one can observe that some wind monitoring equipment severely covered in rime ice.

Figure 19: Whitehorse, Canada.

Electrical energy is usually supplied by two hydro-electric plants, while peaking energy, capacity and small communities are supplied by diesel generators. Since the goal was to produce power at costs

Figure 20: rime ice on met.mast.

below the costs of diesel generation, a wind study was performed in the early 1980s using two wind monitoring stations and data from an airport. Later, in 1990, a subsequent analysis of the upper was performed and with the addition of 20 meter met mast at location west of the city called Haeckel Hill. At this location it was discovered that the annual mean wind speed was close to 7 m/s. In 1992 it was decided to take advantage of the wind potential at the Haeckel site and a program to adapt commercial wind turbines to the local climate was implemented. Bonus Energy's (now Siemens) 150kW MARK III unit was chosen because of the manufacturer's willingness to work with Yukon Energy on modifications and the available hinged tower design that eliminated the need for a large crane. This particular turbine is a conventional three bladed, horizontal axis, up wind and of the stall regulated type.

During the consultation process with Bonus a number of modifications where made to the original design in anticipation of the rime icing and the colder climates in general. These modifications are listed below:

- Hinged, winch up 30 meter tower
- Low temperature steels in the tower sections and other components
- Use of synthetic lubricants throughout
- Electric heaters installed in the gearbox, generator, computer control cabinet and radio communications cabinet
- Heating strips in the blades
- Anemometer and wind vane were equipped with heated bearings
- Ice detector to turn the blade heating on and off

The turbine was erected 6 months after ordering (July of 1993) with a power production target of 300,000kWh per year that represents a capacity factor of 22.8%. Of the toughest challenges to overcome was the rime icing effect described earlier. The problems encountered throughout the turbines use where:

- Heated bearing anemometer and wind vane were still immobilized by rime
- Overhead power line had approximately 5 outages per month due to accumulation of ice
- Ice detector was not working effectively

- Due to tip breaks, poor electrical contact between the two portions of the blade heaters
- Icing of the blades

The severity of the rime are depicted in Fig. 21 to Fig. 23.

Figure 21: rime ice on the rotor of the 150 kW Mark III turbine.

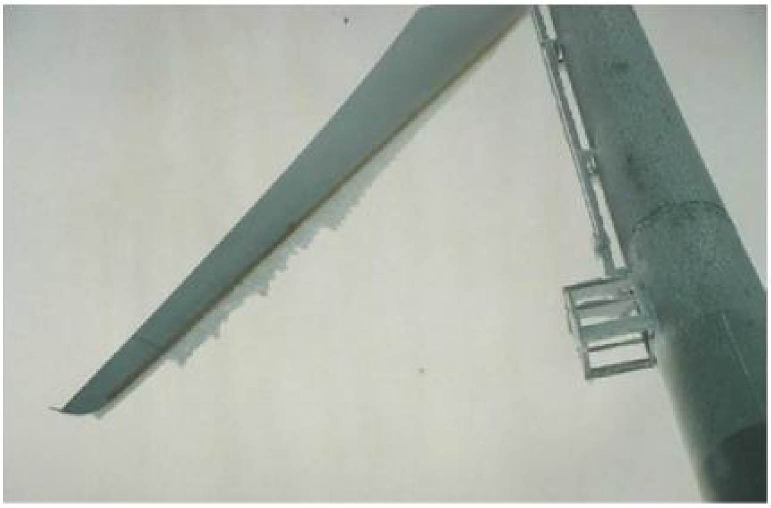


Figure 22: rime ice building up in the trailing edge of a blade of the 150 kW Mark III turbine.

To combat this problem several solutions where implemented throughout the operation.

- The wind vane and anemometer where replaced with a fully heated Hydro-Tech instruments
- Leading edge heaters where replaced with 300mm wide strips, compared to 150mm as before.
- Blades where coated with a black compound called Sta-Clean®. See [4] for more information.

Once the measurement instruments where replaced with the new type, there have been no issues since. As with the addition of 300mm wide strips, it did keep portions of the blade clear. However under heavier icing conditions ice would accumulate right up to the heater. Also with the addition of the Sta-Clean®it greatly improved the production output of the turbine. This can be contributed to the solar heating and the low surface adhesion of the compound (see Fig. 24).

During operation and without the blade heaters, the ice heavily builds up on the leading edges with the buildup increasing as the distance from the blade root increases. When the turbine is shut

Figure 23: rime ice building up around the blade of the 150 kW Mark III turbine.

Figure 24: Ice breack off with StaClean®.

down, the ice builds up on the edges of the blade's surface facing the wind. It has been estimated that the annual losses due to rime were to be approximately 65000 kWh per year or about 20% of the production target. As a progression of this project, a second turbine was installed in mid-September of the year 2000. This time it was decided to go forward with a low temperature version (rated down to −30 °C) of Vestas 660 kW V47 LT II. All of the modifications made successfully to the previous Bonus turbine have been made to this one. The experience with the stall regulated turbine have convinced them that a pitch regulated machine would be affected less by rime since they can be pitched at higher speeds so that maximum output can be achieved. Also since there are no tip brakes, effective heating to the very tips would no longer be a problem. Through the experience gained through this project, a list of recommendations or suggestions for similar applications has been made.

1. Lower temperature steels
2. Low temperature synthetic lubricants and fluids

3. Equipment heaters (gearbox, generator, control cabinets)
4. Fully heated wind instruments
5. Black colored fluorourethane (Sta-Clean®) coated blades
6. Full surface blade heating if available (minimum 300 mm wide)
7. Pitch or active stall regulation

As it can be seen, the effect of rime icing on the turbine was something not to be ignored. Whatever the scenario, buildup on all and any part of the turbine hinders power production significantly. More information related to the performance of these turbines can be found at [11].

Figure 25: 660 kW Vestas and 150kW Mark III wind turbines at Whitehorse, Canada.

4 Field work

The field work carried out by our group during the month of august 2010, mainly consisted in contributing in the improvement of some of the wind energy related installations. Installing new measurement equipment, doing maintenance work in a existing wind turbine, performing calculations related to wind assessment with fresh new data are some examples of the contributions provided during our stay. In total, three locations were visited:

- **Assaqutaq**: A abandoned village located 13km east of Sisimiut
- **Sarfannguaq**: A small settlement with approximately 130 citizens located 43km east of Sisimiut at the foot of the Amerloq fjord.
- **Itilleq**: A small settlement located in the municipality of Qeqqata south of Sisimiut and counting with approximately 116 inhabitants.

Independent work was performed in each of these sites. In principle, and since there is no link connecting the existing projects in the mentioned locations, the field work description and analysis will be presented in separate subsections, each one corresponding to one of the locations.

4.1 Assaqutaq

Assaqutaq which lays in a small island, just under the Kællingehætten mountain south face (see **??**), lost its only inhabitant not long ago, and is now an abandoned village mainly used as a summer camp for children during the summer. It is also regarded as a DTU test facility for hybrid systems in the arctic climate. Indeed, it involves photo voltaic panels and two small wind turbines (a vertical axis and a horizontal axis). These are combined with a diesel generator and supply power to a refrigeration system of rated consumption: 66 + 66 = 132 Watts. A magnetic commuter is used to switch from the Hybrid system to the generator whenever it is needed.

(a) (b)

Figure 26: The settlement of Assaqutaq. (a) From the main land (b) From the island

4.1.1 Field work description

Two separate activities were carried out during our stay in Assaqutaq:

- **Putting down the existent met. mast and analyzing the recorded data**:
  The met. mast had been installed in early march that same year and was equipped with two cup anemometers (at the heights of 6 and 13 meters) and one wind vane at 10 meters height. Since the location apparently had bad wind resource, it was thought to put it down and erected in

Sarfannguaq for better wind assessment there (these aspects will be discussed further on, in the field work description section concerning Sarfannguaq). The data analysis and wind assessment for Assaqutaq using these 5 months and a half of data was one of the first tasks to work on. Hence, the purpose of the analysis was to verify that the location had a poor wind resource even if knowing that the accuracy of the results would not be excellent since a small amount of data was available. The met. mast was placed in one of the most exposed locations to wind in the island, at approximately 500 meters distance from the wind turbines. So, if the results show a bad resource there, it is certain that where the turbines are erected it will be worse since they are less exposed and they are surrounded by obstacles.

- **Installing a new anemometer and wind vane in the roof of the test facility building** For better knowledge of the wind near the wind turbines, a new hall effect anemometer and wind vane were installed at the roof of the building as it can be seen in Fig. 27. Unfortunately, there were several problems encountered once the installation was finished:

Figure 27: Installing the anemometer and wind vane.

  - First, and because of a problem related to the inverters in the DC-source center, the monitoring system had to be turned-off enabling us to record data.
  - Second, five days after the installation, and because the wrong anemometer was installed in the first place, two of our group members were obliged to go back to Assaqutaq from Sarfannguaq to install the correct anemometer: the 'Hall-effect' anemometer which has a three cable connection instead of two suiting the electrical connection to the monitoring system. Once there, we observed that the wind vane was not changing its direction. It was somehow 'stuck' in the same place showing the same direction all the time. After getting on the roof again, we realized that the wind vane was broken and that one of the most likely reasons would be related to the action of a crow, which could of had sit on the top of the wind vane. This suspicion become even bigger when we saw some of them flying around the island. Knowing that the system would not be able to record any data because of the malfunction of the DC-source center, and because of the bird issue, we decided that there was no need to get on the roof again to replace the anemometer and take the wind vane down. Furthermore, a new location for wind measurements show be thought for next year, and therefore the existing installation should be put down again.

4.1.2 Data analysis: Wind resource assessment

The data from the met. mast was processed and the main parameters that characterize the site are shown in Tab. 1. It is important to mention that all the calculations were done using the 13 meter height anemometer and that the Weibull parameters where not extrapolated to 10 meters height. The data consists in ten minute average values for wind speed and wind direction.

Table 1: Assaqutaq main wind characteristics from the 5.5 month time series at H=13m.

Mean Wind speed [m/s]	2.79
Std Wind speed [m/s]	2.29
Max Wind speed [m/s]	15.80
Mean Turb. int. [%]	15.51
Mean dir. [deg]	148.09
Std dir. [deg]	90.08

The Weibull parameters and Weibull distribution for the time series was found using two different methods:

- The first one consists in using Matlab's weibull fit function giving the A and k when inputting a wind speed time series. The method used is a linear regression fit of the cumulative function of the wind speed (y=Cx+D). This can easily be seen when considering the basic weibull cumulative function (1) and doing some simple manupulations shown in (2). The expressions used are shown in (3) and (4).

$$F(U) = 1 - e^{-(\frac{U}{A})^k} \tag{1}$$

$$ln[-ln(1 - F(U))] = klnv - klnA \tag{2}$$

$$k = C \tag{3}$$

$$A = e^{\frac{-D}{C}} \tag{4}$$

- The second method consists in using Justus numerical estimation when knowing the standard deviation of the 10 minute time series and its mean value. The equations used are shown in (5) and (6).

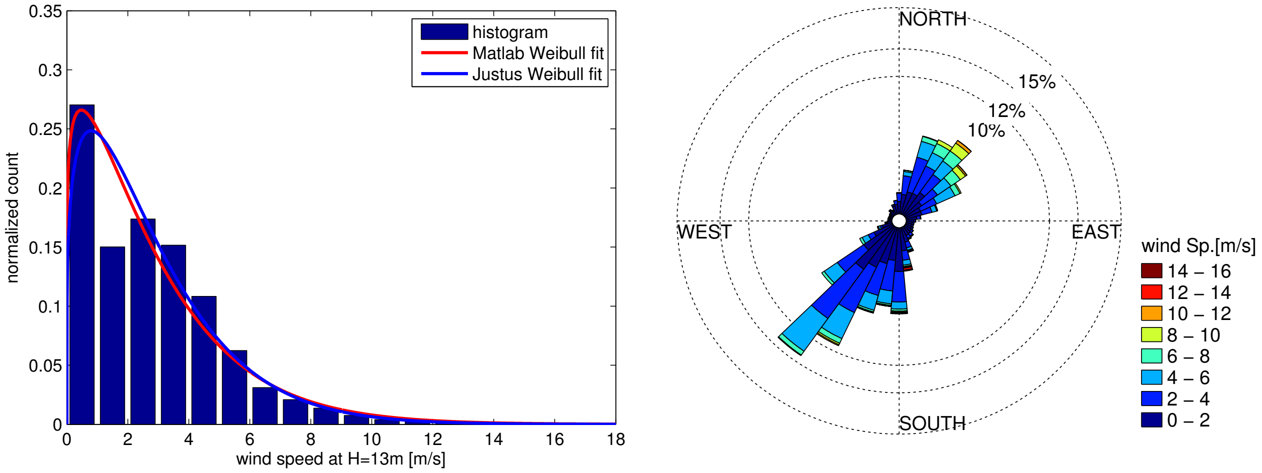
$$k = (\frac{\sigma(U)}{\overline{U}})^{-1.086} \tag{5}$$

$$A = \frac{\overline{U}}{\Gamma(1 + \frac{1}{k})} \tag{6}$$

The two Weibull fits and the corresponding wind rose of Assaqutaq are shown in Fig. 28. The different Weibull values are shown in tableTab. 2.

Table 2: Weibull parameters using the two different methods

	Matlab fit	**Justus fit**
A [m/s]	2.923	2.993
k	1.143	1.239



(a) (b)

Figure 28: Weibull fit and wind rose at Assaqutaq:. (a) Weibull fit (b) Wind Rose

An important parameter that allows one to characterize the wind potential at a certain cite is the mean of the wind power per m^2 defined in (7)

$$WP = \frac{\overline{P}}{A} = \frac{1}{2}\rho\overline{U^3} = \frac{1}{2}\rho F_e(\overline{U})^3 \tag{7}$$

where ρ was calculated using (8) with Sisimiut's mean temperature from march to august (T=−2.28 °C) and with the approximative value of 30 meters for the site height (h=30m). F_e was calculated from the Weibull density function and is given in (9)

$$\rho = 1.225\frac{288}{T+273}e^{\frac{-h}{8435}} \tag{8}$$

$$F_e = \frac{\overline{U^3}}{(\overline{U})^3} = \frac{\Gamma(1+\frac{3}{k})}{(\Gamma(1+\frac{1}{k}))^3} \tag{9}$$

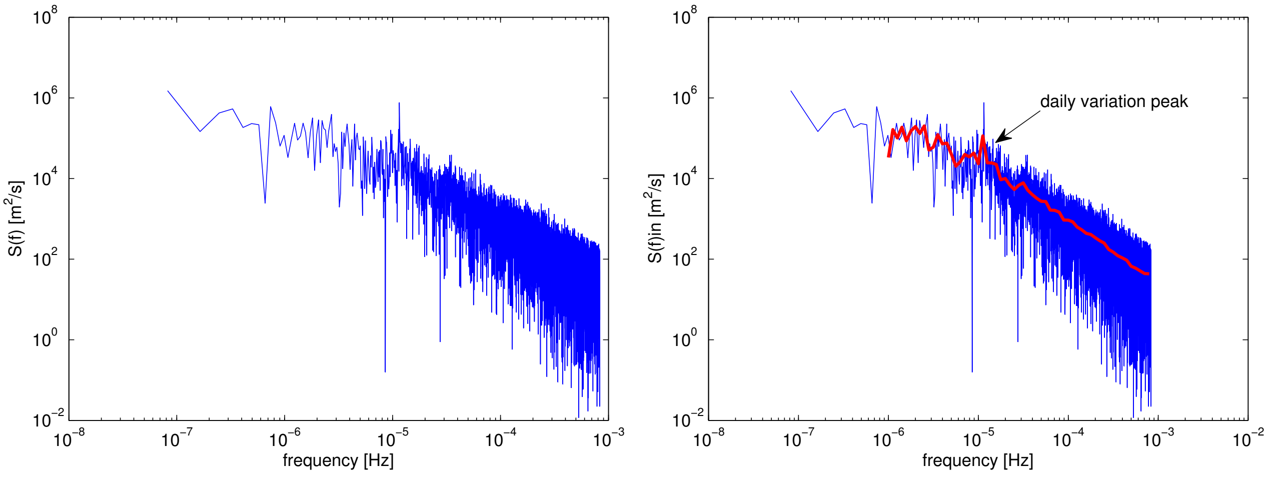
The value estimated for wind potencial with the two different Weibull fit methods is shown in Tab. 15

Table 3: Wind Potencial at Assaqutaq

	Matlab fit	**Justus fit**
Wind Potencial $[W/m^2]$	62.43	53.07

Tab. 1 and Tab. 15 confirm that the site has a poor wind resource with an average wind speed under $3m/s$ and a wind potential under 100 W/m^2. As seen from the wind rose in Fig. 28, the wind mainly blows from two directions: Southwest and Northeast. Northeastern winds are the strongest but not the more frequent and they could possibly be explained by the local over speeding effect caused by the mountainous orography at the north of the settlement. On the other hand, southwestern winds are the most frequent. Their low to moderate intensity and more or less constant direction combined with the observation of a daily peak in the filtered Spectrum in Fig. 29 allows us to state that the island during this period is mainly governed by sea breezes. Indeed, during spring and summer, there is a big temperature difference between the inland (warmer) and the coast line (colder) because of the

cold temperature of the sea. Inland convection creates suction that induces western to southwestern winds in the fjord. Other than that, long periods of calm exist (between 25 and 30% of the time) as it can be seen in the Weibull fit of Fig. 28.
It is well known that the amount of data is insufficient and that it would be preferable to continue recording data for better estimations but a bigger priority was established for measurements at Sarfannguaq since it has more possibilities for wind energy development.



(a) (b)

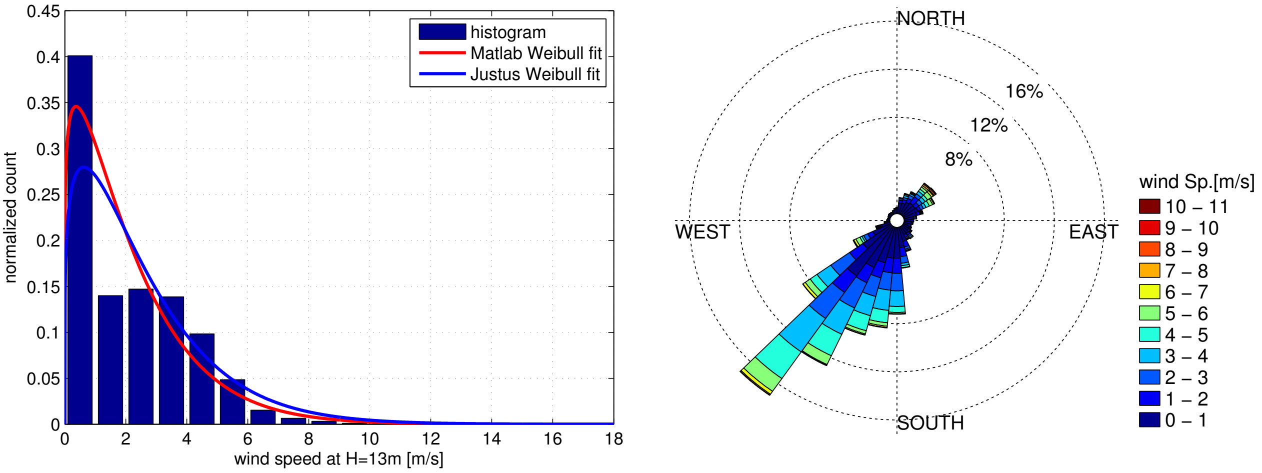
Figure 29: Energy spectrum at Assaqutaq. (a) Non-Filtered (b) Filtered

4.1.3 VAWT and HAWT performances if placed at the met. mast site

The Vertical axis wind turbine (VAWT) and the horizontal wind turbine (HAWT) are placed far away from the met. mast (approximately 500 meters away) enabling a reliable estimation of energy production and therefore performance of the turbines at their site. Moreover, the irregular orography and the obstacles (3 or 4 houses) that lay between them make it even more difficult (the test facility building is the biggest obstacle for both of the turbines: The VAWT is placed right behind the turbine meaning that it is really influenced and the the HAWT is placed on the roof with less influence but still affected). It was thought that Wasp could maybe be useful for these predictions but is was found that since the orographic maps of the area had bad resolution and that obstacles play a bigger role in this case-study, it would be too inaccurate. Perhaps CFD codes for local wind assessment in rough terrain could be used for this. But no further research was done here.
The point is that the met. mast was placed in that exposed area with the purpose of obtaining general wind resource information of the island and not aiming for energy production or performance calculations of the turbines. In fact, the installation of the wind vane and cup anemometer at the roof of the test facility building had these goals. Nevertheless, a quick calculation one could carry out is the energy production the turbines would output if they were placed at the met. mast site, at a height of 13 meters. This would represent a top limit value, since the energy production would be less in the turbine sites (because the location is less exposed and because of the many obstacles). Suggestions for energy production improvements (using different wind turbines with power curves that fit better the site, for example) could be successfully extracted from this analysis.

For this calculation, a new Weibull curve was calculated using the warmer months data (may, june and july) since it is expected that the wind turbine power output could be used for the summer camps.

The Weibull fit and the wind rose for these months are shown in Fig. 30 and the corresponding monthly wind characteristics are shown in Tab. 4



(a) (b)

Figure 30: 3 month Weibull fit and wind rose at Assaqutaq (may, june and july). (a) Weibull fit (b) Wind rose

Table 4: 3 month wind characteristics at Assaqutaq

	Mean Wind speed [m/s]	**Std Wind speed [m/s]**	**Mean dir. [deg]**	**Std dir. [deg]**
may	3.29	2.76	160.55	84.79
june	2.07	1.82	174.09	71.33
july	2.21	1.78	179.45	68.03

It can be seen in Fig. 30 that southwestern winds are prevailing during this period, and that the stronger northeastern wind blew earlier, in april or march. Indeed, since we are considering the warmer months, the sea breeze it the principal wind mechanism/pattern.
Moreover, perturbations passages which temporally stop this wind pattern every once and a while, generally affect the area from the west-southwest as well, and hence with their associated west-southwest winds. See section2 for more details in wind mesoscale patterns and tendencies in the south and southwestern coast of Greenland.
Another interesting aspect to mention is related to the fitting of the curve. It can be seen that in this location Weibull fitting is not as convenient. Nevertheless, and since we are not seeking for accuracy in this part of the analysis, we will pursue with the calculations using this fit and Justus coefficients since they seem to lead to a slight overestimation. This will be formally correct since our results will show an overestimation related to the site (performance estimations done at the met. mast site) and to the fit which will still lead to a poor performance of the turbines, so one should expect even worse results at the turbines site.

The VAWT and HAWT power curves (108 Watts and 100 Watts of rated power respectively) are shown in Fig. 31 and were extrapolated from the power curves given by the different manufacturers (power curves available at [3] and [14]). It can be seen that they have relatively high cut-in wind speeds (specially the VAWT) and that they don't start producing significant power till much higher wind speeds. It is also seen that the rated power is reached for very high wind speeds (around $20m/s$). From the graphs one can observe that the HAVT is likely to produce more power for mostly all of the wind speeds. In general trends it can be stated that these wind turbines are not ideal for Assaqutaq since they are designed to perform well in higher wind speeds.

The performance characteristics are shown in Tab. 5 and Tab. 6. The number of hours the refrigerators could use the wind turbine power output is shown for each case and when considering the

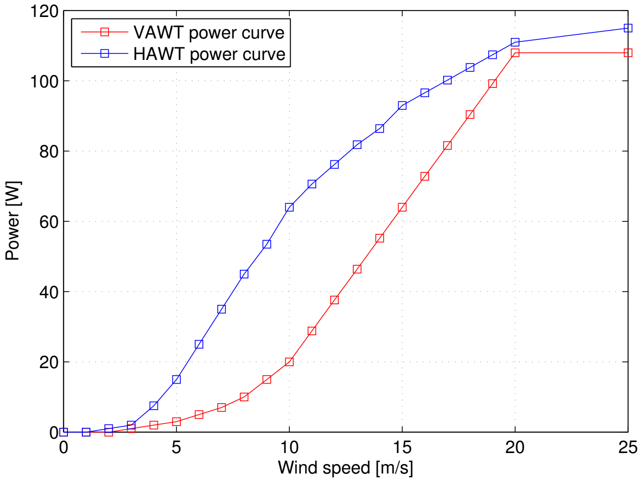


Figure 31: VAWT and VAWT power curves.

total output of both turbines in Tab. 7.The operational factor (portion of time the wind turbines are producing power), the full load hours (number of hours needed to produce the calculated output energy if the turbine is generating power at the rated power level) and the capacity factor (ratio of the full load hours with respect to the total hours) are shown as well. This last parameter is of crucial importance when trying to estimate a wind turbine performance at a given site. Standards of the capacity factor exist and can be referred in the appendix.

The annual energy production can be found using (10) and (1).

$$AEP = F(U)P(U) * 365 * 24 \tag{10}$$

where P(U) is the average Power between U and U+1 (U is an integer).

Table 5: Vertical Axis wind turbine (VAWT) performance at the met. mast site at H=30m.

VAWT	**Justus fit**
3-month energy [kWh]	3.28
132W. fridge hours [h]	24.86
fridge ratio hours [%]	1.13
Full load hours [h]	28.54
Capacity factor	0.013
Operational factor [%]	31.89

Table 6: Horizontal Axis wind turbine (HAWT) performance at the met. mast site at H=30m.

HAWT	**Justus fit**
3-month energy [kWh]	12.89
132W. fridge hours [h]	97.65
fridge ratio hours [%]	4.42
Full load hours [h]	112.09
Capacity factor	0.051
Operational factor [%]	49.63

Table 7: VAWT and HAWT combined energy coverage for the refrigerator system if turbines located at the met. mast site at H=30m.

	132W. fridge hours [h]	**fridge ratio hours [%]**
HAWT+VAWT	122.51	5.55

The analysis confirms what was already expected: even when overestimating (turbines at the site and using an overestimated fit), the capacity factor remains extremely low (CF=0.051 in the best case (HAWT) which still remains very far away from the standard limiting value for poor or insufficient performance (Standards of the Capacity Factor can be found in the appendix). Combining the two wind turbines, they will only be able to supply power to the refrigerators 5.55 % of the time (overestimated). Other than that, the operational factor is bellow 50(%) in both cases.

4.1.4 Further investigations and suggestions of improvement

Although it is well known that this site should be regarded as a test facility and that performance in the hybrid system is not the main goal, after this analysis, we came out with a couple of suggestions for a better performance of the wind turbines.

- replace the existing wind turbines with new models that will have a better performance in low wind speeds and therefore will make the capacity factor increase.
- if possible relocate them so that they are exposed to southwestern and northeastern winds with no obstacles influencing in these directions.

Further investigations related to wind energy in Assaqutaq would be mainly focused in finding a new strategy for wind measurements (speed and direction) near the test facility to avoid the problems encountered in our field work (a crow most likely destroyed the wind vane). Besides that, documentation should be carried out concerning low power wind turbines and focusing in finding the ones that best fit the location. If possible, simulate with a CFD program the flow pattern in the test facility building with the data at the met mast.

4.2 Sarfannguaq

Sarfannguaq is a small village located 43km East of Sisimiut on an island near the mainland. The main source of income for the inhabitants of this location comes mainly from fishing. Most of the locals are self-sufficient with fish and reindeer or muskox from the landscape around the village. Currently, there are around hundred inhabitants living permanently in this location, a school and a shop which provides the locals and the hikers with a large variety of products. The main consumption of energy in this location comes from the fish factory, which processes the fish to be exported, dwellings,a workshopand service buildings. Since there is mutual interest from the population andfrom the local commune to keep this place as pure and in harmony with the environment as possible a 6kW wind turbine has been raised in this island to help on reducing the consumption of diesel of two generators.

(a) (b)

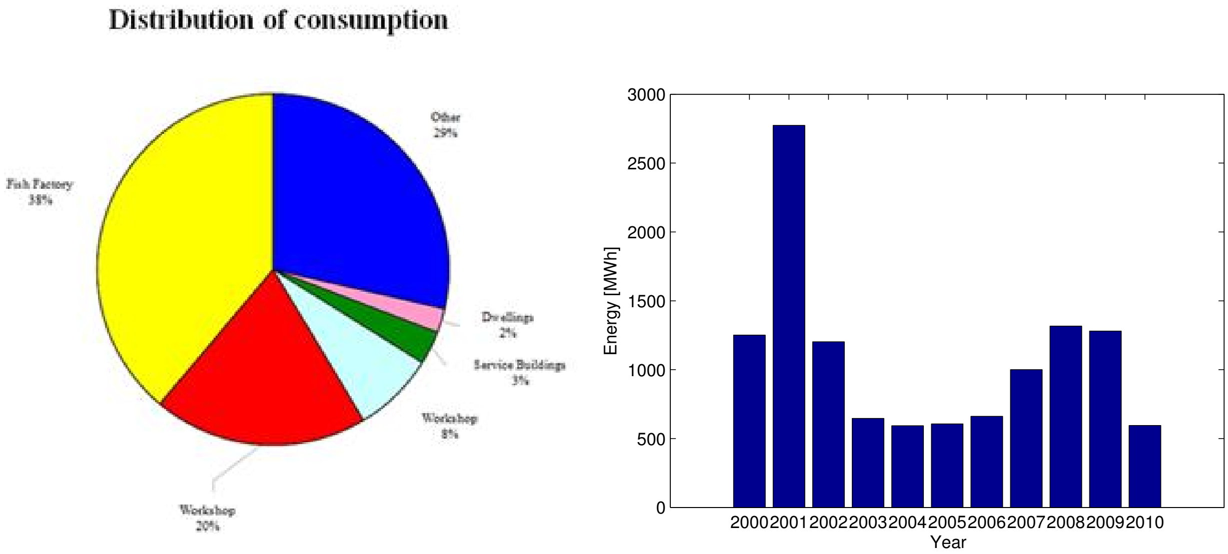
Figure 32: Map of Sarfannguaq. (a) Zoomed view (b) In the Greenland scale

4.2.1 Power consumption and distribution in Sarfannguaq

Fig. 33 gives a general idea of how the consumption of electricity is distributed along the different active sectors in the village. It is noticeable that the activity with bigger influence in the consumption of electricity is the industry, although this sector has been decreasing activity, mainly due to the fact that the fish factory in the area is not operating at full power anymore. For such a remote and isolated village like this one, it makes sense to integrate wind energy in the production of electricity to contribute to the overall power budget, though an assessment of the wind potential in the area must be done to evaluate if the investment is economically effective especially because of the arctic climate that can compromise the performance of the wind turbines.

4.2.2 Description of the Wind Turbine

The wind turbine already installed in this site is a Proven WT6000 downwind turbine. It is a 6kW machine (rated power) with a permanent magnetized rotor. It can produce from 7 to 18MWh per year depending on the wind resource available in site. Fig. 34 shows a picture of the turbine during field work and Fig. 35 shows its corresponding power curve and power coefficient curve. The connection system is shown in Fig. 36.



(a) (b)

Figure 33: Distribution and consumption of the electricity in Sarfannguaq. (a) Distribution (b) Consumption per year

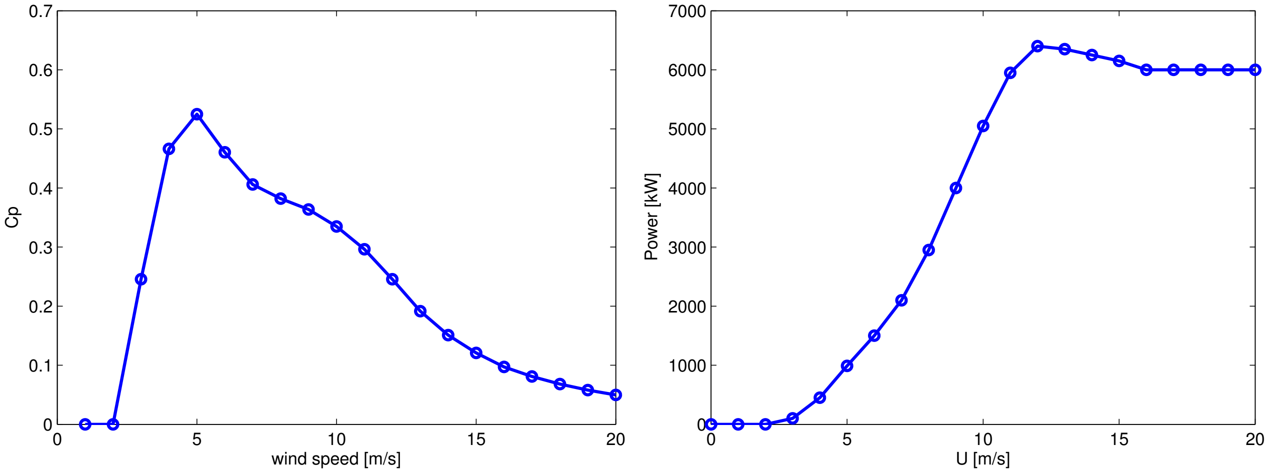
Figure 34: Proven WT6000 in a bright day this summer.

4.2.3 Maintenance work and flaws encountered on the turbine

Consistent maintenance work has to be performed on the wind turbine to guarantee optimal operation reducing losses of power. The maintenance work takes place mainly on the nacelle part and for this kind of turbine, consequently the entire structure has to be lowered; such operation required a winch and a tripod to keep the turbine close to the ground as possible and avoiding damaging the rotor.

The regular maintenance consists of lubing the main bearings and an overall inspection especially to the components that are more exposed to wear, such as breaking pads and slip rings.

After inspecting all these components it was found that the breaking pads were uneven tuned.



(a) (b)

Figure 35: power curve and power coefficient curve of the Proven WT6000. (a) Power coefficient curve (b) Power curve

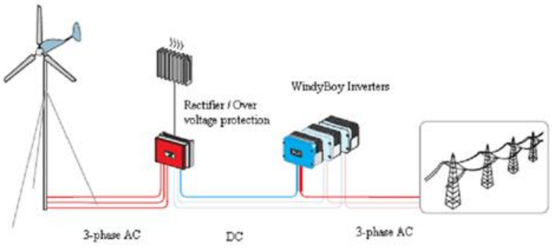


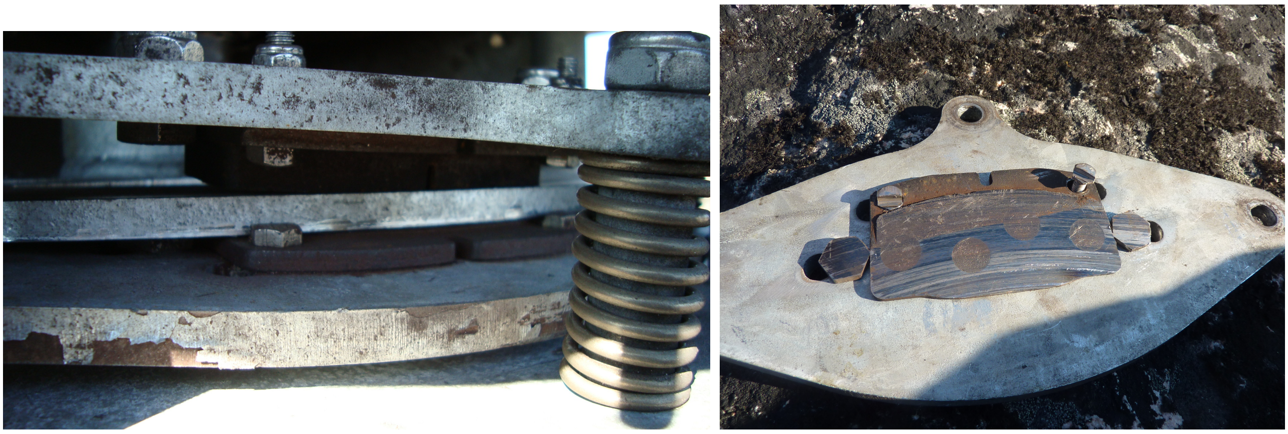
Figure 36: PROVEN 6000 electrical connection.

(a) (b)

Figure 37: Works on existing turbine and met. mast. (a) process of pulling down the turbine and placing the tripod at the right position (b) Working on the existing mast

The lower pad was completely worn out and scratching the braking disk with the bolts that keeps the pad in place, while the top one was completely new. Because we weren't prepared with spare pads, the solution found to provisionally fix this problem, was just switching the pads so the braking disk doesn't touch the bolts anymore. Since, only the lower pad seems to be applied when the brake is activated, we mounted the worn pad on the top to avoid the bolts that holds the braking pad to touch the brake disk.

Figure 38: Lubing the bearings.



(a)

(b)

Figure 39: Condition of the braking system before maintenance. (a) Breaking system (b) Breaking pad

After a more thorough inspection, this time to the generator we found lumps of magnet dispersed all over the casing that covers the generator rotor. This might be caused by the unbalanced rotor discs... a problem that has been already reported in [2]. This issue is illustrated in Fig. 40. Not much could have been done to fix this problem. We tried to remove all the lumps we could reach inside the casing to avoid future damage on other components in the nacelle.

Finally, some snaps was encountered on the surface of one of the blades, probably caused by flying chunks of broken magnet spewed from the generator, due to big centrifugal forces when the turbine was operating. This was provisional fixed by applying a kind of resin for boats that we found in the local shop, over of the crack (see Fig. 40). Since we were not prepared with the right products for this kind of malfunction not much could have been done to fix the cracks, but this patch it will prevent further deterioration of the blade especially by infiltration of moisture into the fibers of the blades.

4.2.4 Meteorological mast field work

A 10 m mast was already erected in this site since august 2004, equipped with all the meteorological instrumentation required to assess the wind potential available. Prior to our intervention, the mast had


(a) (b)

Figure 40: Maintenance work on the turbine. (a) Lump of magnet from the generator (b) Patch applied on the cracked blade

mounted a wind vane (NRG 200P) to measure the wind direction, one cup anemometer (NRG 40) to measure the wind speed, one thermometer (NRG 110S), one pyrometer (LiCOR High-stability silicon photo voltaic detector) for measuring global radiation from the sun, a barometer and a hygrometer for measuring the relative humidity.

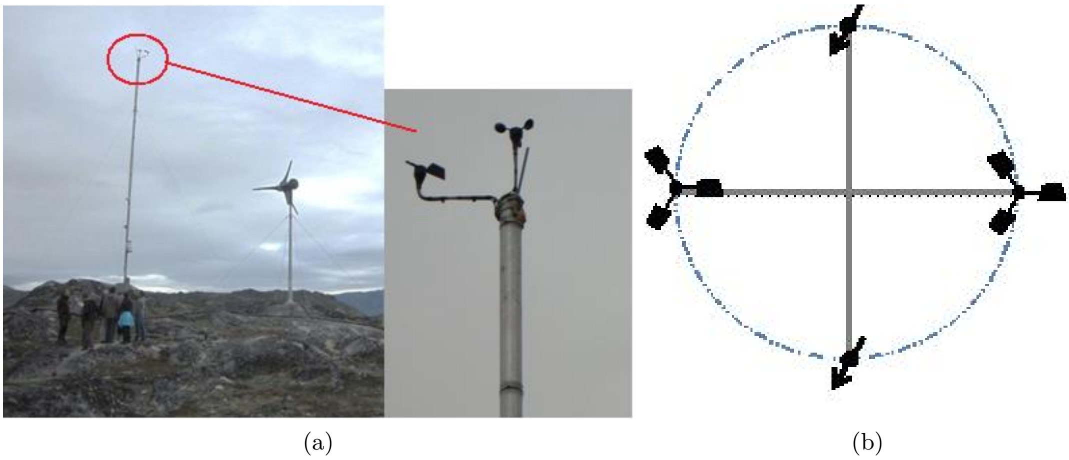

(a) (b)

Figure 41: Existing met. mast field work. Existing met. mast before improvements (b) Scheme of the new displacement of the instruments on the mast

The main purpose of the field work in this location was to update the mast, mounting on one more cup anemometer and a wind vane in other to obtain more accurate data, consequently the displacement of the instrumentation had to be changed.It was chosen to mount two booms with a 90 deg offset between them. In this way one can have readings with fewer protuberances from the mast no matter the direction of the wind.

Apart from the implementation of this new setup, the old cup anemometer and wind vane were replaced by new ones of the same kind. It was also found that the old data logger wasn't working properly, so it had to be replaced by a new one. Another modification performed was to power the logger and the GSM transmission unit directly to the antenna station which is just next to the mast, eliminating the need of batteries.

After finishing the work on the existing mast, a new location had to be found to erect the mast brought from Assaqutaq. Having two met masts in the area will give a better understanding of the wind characteristics in this place and also its behavior, due to the roughness and ruggedness of the surrounding landscape. The selected location for the new met. mast can be seen in Fig. 42.

Figure 42: Location of the met masts.

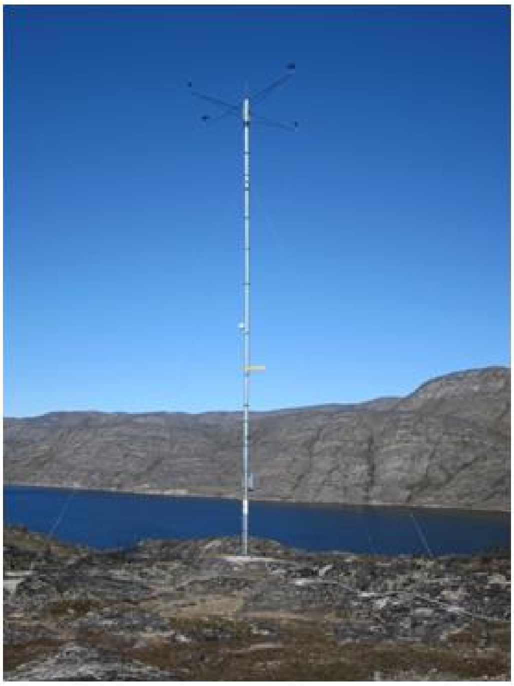


Figure 43: The existing met Mast after the modifications.

This new met mast was equipped with one wind vane, three cup anemometers at 4, 8 and 11.65 m respectively, one pyrometer, a thermometer, a hygrometer and a barometer. All of the instruments are the same kind as the ones on the existing mast to be compatible with the NRG logger and GSM unit. Since the new data logger in the existing met mast wasn't working properly, this new met mast was left provisional without any data logger, until further visit to the site by a member of the DTU - Arctic Technology.

4.2.5 Data analysis and turbine performance estimations

To perform the wind analysis of this site we retrieved 10 minutes average data at H=10m , from 2004 to august 2010, from the existing met. mast prior to our modifications, plus the data acquired from the same mast after the changes. This includes three months more (August to October of 2010) to the overall available data. The data from the new erected mast couldn't be evaluated because the sensors weren't connected to any logger as mentioned before. Tab. 8 shows the main wind characteristics of the site. In this case, the wind measurements are quite representative with respect to the ones the

(a) (b)

Figure 44: New met. mast erection process. (a) Drilling the holes to anchor the guy wires of the new met mast (b) New met mast erected at Sarfannguaq

wind turbine will experience. Although, there could be errors related to speed ups at certain heights depending on the wind direction since the site is on the top of a hill. This should be taken into account when constructing a Power curve from the wind measurements and power output. All of this will be discussed later on, in the future investigations part of this section.

Table 8: Sarfannguaq main wind characteristics evaluated from more than 6 years of measurements at H=10m.

Mean Wind speed [m/s]	5.72
Std Wind speed [m/s]	3.29
Max Wind speed [m/s]	25.80
Mean Turb. int. [%]	14.01
Mean dir. [deg]	180.55
Std dir. [deg]	104.6

The monthly wind speed means and their corresponding standard deviations are shown in Fig. 45

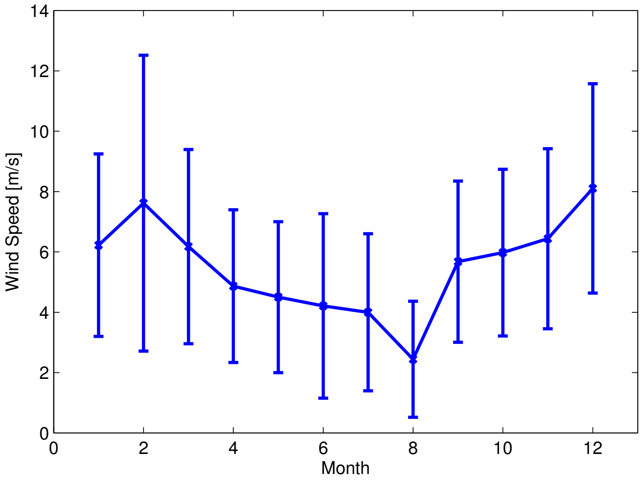
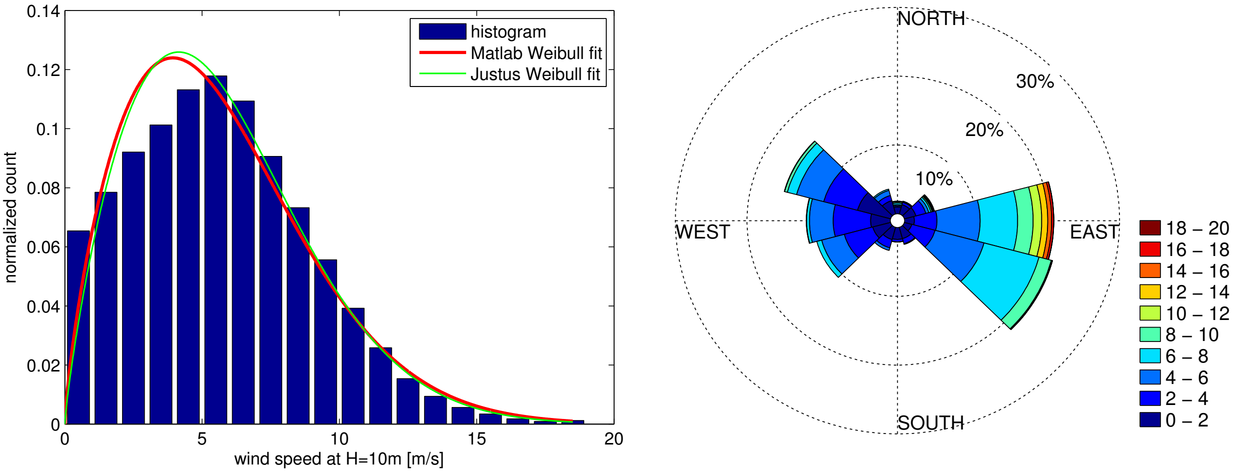


Figure 45: Monthly Wind Speeds at Sarfannguaq.

From Fig. 45, it can be seen that the highest winds ,in average, are recorded in December. The lower winds are in general recorded in August.

The Weibull fit and correspond wind rose are shown in Fig. 46 and the Weibull parameters for Justus and Matlab's fit are shown in Tab. 9. It is important to mention that some errors where found in the wind rose in the west sector. The wind vane on the existing mast wasn't properly align with the north, meaning that there are values missing in the east sector, which are actually wrong distribute along the west sector. For comparison purposes, this can be checked with the 3TER [1] wind rose found in the appendix. The remaining Weibull parameters per sector are shown in the appendix.



(a) (b)

Figure 46: Weibull fit and Wind rose at Sarfannguaq. (a) Weibull fit (b) Wind rose

Table 9: Weibull parameters for Sarfannguaq using the two different methods

	Matlab fit	**Justus fit**
A [m/s]	6.39	6.43
k	1.75	1.82

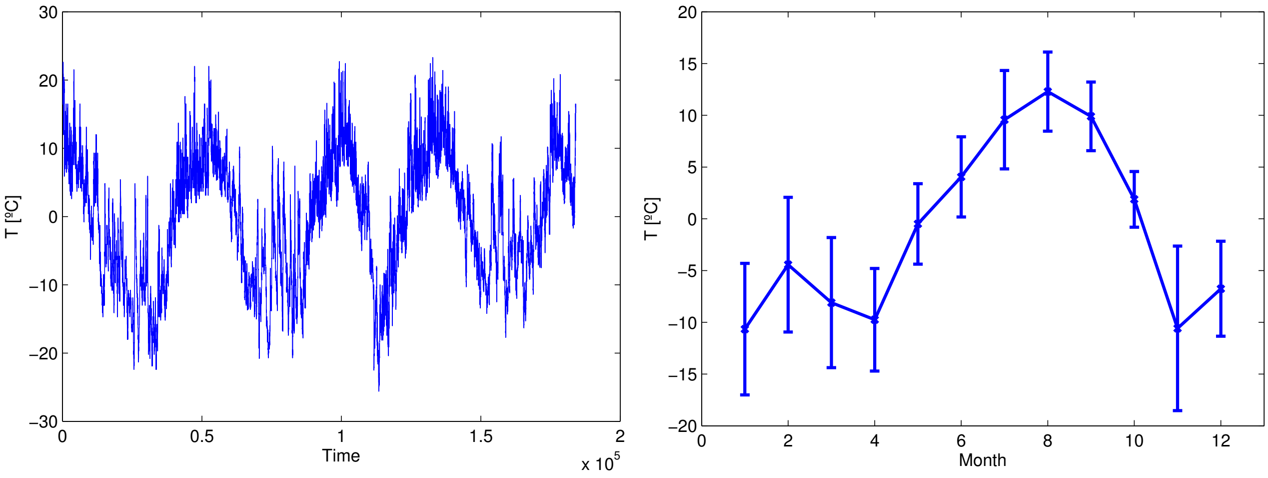
The wind potencial is calculated using Eq. (7) as in Assaqudaq case study. The corresponding values was calculated with Justus and Matlab's built-in function and then averaged as shown in Tab. 10. It can be seen that the wind power density for Sarfannguaq at 10 m is 259 W/m2 which is significalty better than Assaqutaq's wind potential.

Table 10: Wind Potencial values at Sarfannguaq

	Wind Potential $[W/m^2]$ at 10 m
Justus fit	252
Matlab fit	265
Mean	259

From the main parameters shown in Tab. 8, one can affirm that Sarfannguaq has a decent wind resource (near 6m/s mean wind speed is a decent average) with a nice distribution of quite high speed winds.

Temperature measurements are available for 6 years as well and can be useful to estimate the icing periods. The time series and the corresponding monthly mean temperatures are shown in Fig. 47.

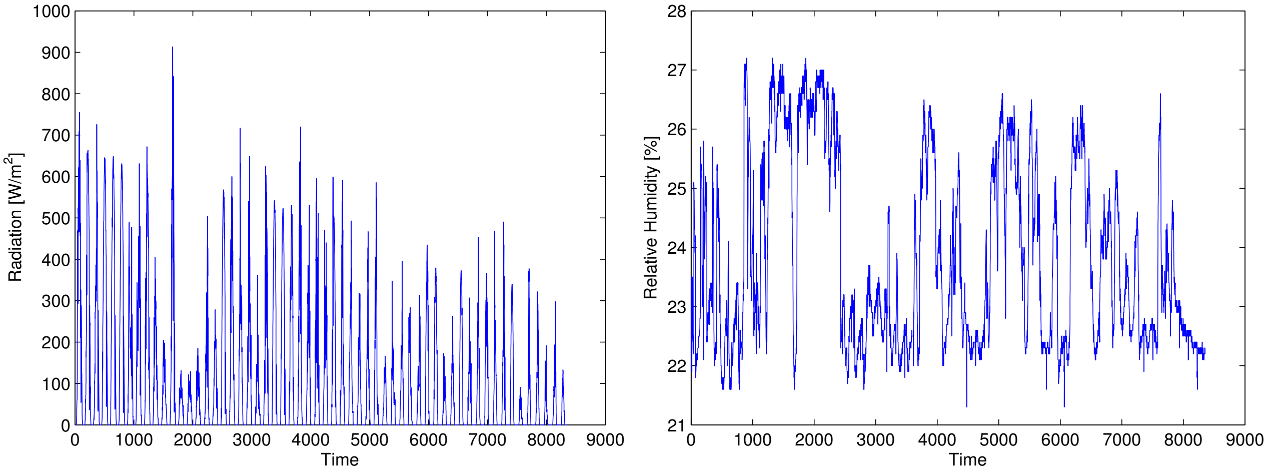


(a) (b)

Figure 47: Temperature measurements at Sarfannguaq. (a) 6 year temperature measurements at Sarfannguaq (b) Monthly Temperatures

It can be seen that there are 7 months per year, the average temperatures are under zero. This is an important issue since icing conditions could be present and lead to wrong wind measurements (icing on the back surface of the cup anemometers) and to a substantial output power reduction (reduction of the aerodynamic efficiency due to icing on the leading edge).

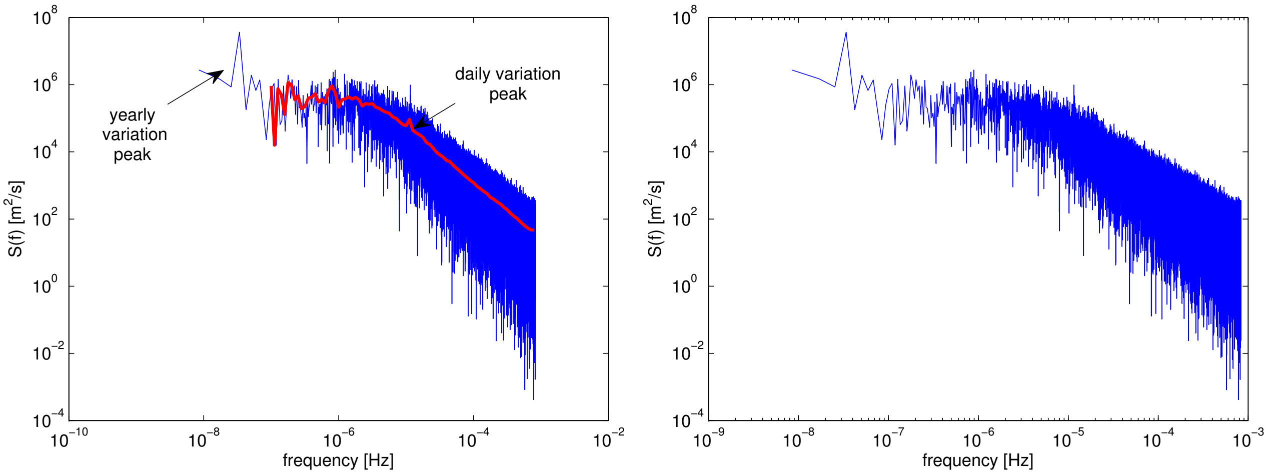
The relative humidity and solar radiation time series shown in Fig. 48 represent the latest period (august to middle of October 2010), so were recorded after the changes done in existing met. mast. No records for solar radiation and relative humidity were available before. When more data is available and when combining relative humidity records, with temperature and wind measurements, it would be possible to estimate the icing periods and their duration. Some suggestions will be exposed in the last section ('further investigations') for icing prediction improvements. When observing the relative humidity time series it can be seen that its variation is extremely small and limited to values between 21% and 27%. This indicates us that there is a possible error in the calibration of measuring device. It should be checked whenever possible and changing the present values of gain and offset values.



(a) (b)

Figure 48: Solar radiation and relative humidity time series (barely 3 months of data). (a) Solar radiation (b) Relative humidity

On the other hand, another interesting aspect to mention in what concerns the wind resource in this location can be addressed when analyzing the energy density spectrum (shown in Fig. 49)



(a) (b)

Figure 49: Sarfannguaq energy density spectrum. (a) Non-filtered (b) Filtered

As in the case of Assaqutaq the daily peak can be observed, but in this case it is not as pronounced meaning that the daily wind pattern is not as strong. The annual variation peak can be observed as well, since the spectrum was performed with more than one year of data; this peak does not provide us with attractive information since it is pretty much present in all of the wind time series.

In what concerns the wind turbine performance, our study produced the following energy distribution Fig. 50 for the available wind resource in the site. To compute the energy, (10) was used. The Weibull parameters from Tab. 9 where used.

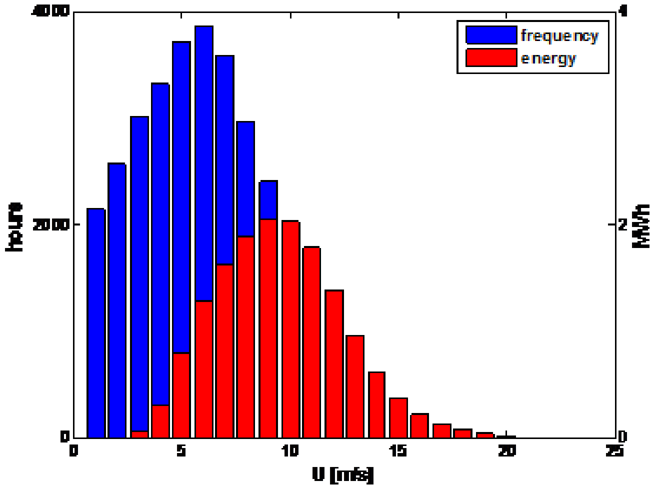


Figure 50: Distribution of wind speed (blue) and energy (red) in Sarfannguaq, based on data (2004-2010).

The annual energy production of the PROVEN WT6000 at this site in Sarfannguaq with a 9m tower would be 15.6 MWh at normal operation conditions.

The other important performance parameters for the turbine on this site are shown in Tab. 11

Table 11: Turbine performance indicators for the site

	Matlab fit
Annual Energy Production [MWh]	15.55
5*1300W. House hours [h]	2392
House ratio hours [%]	27.31
Full load hours [h]	2591.30
Load factor	0.30
Operational factor [%]	88

To better identify the potential of this turbine on this site we find an equivalent number of hours that would be needed for 5 average houses in the US to consume the total annual energy production as it can be seen in the second line of Tab. 11. According to EIA (Energy Information Administration, Official energy statistics from the US government) an average home in the US consumes 936kWh/-month, dividing this value by the number of hours in one month gives that one average US home consumes 1300 W. Dividing the annual energy production of the turbine by the equivalent power necessary to power five US homes (5 homes *1300 W) gives that 2392 hours would be necessary for these 5 homes to drain all the energy produce during one year by the PROVEN 6000 WT in Sarfannguaq. This means that this turbine in this site can power five average US homes 27% of the year. Since an average home in Sarfannguaq uses maybe 1/3 of the energy of an average US home, this turbine can actually power 5 houses during 80% of the year. The observed load factor gives according to the standards shown in the appendix (Fig. 93), a so-called 'good' performance at this specific site. On the other hand, the Operational factor is close to 90% meaning that it will be operating most of the time unlike in Assaqutaq's case.

4.2.6 Further investigations and suggestions for measuring improvement

As it was mentioned previously, the reliability of wind measurements is still not proven since the cup anemometers can be often influenced by icing effects (see Fig. 47 where it can be seen that average temperatures are bellow zero more than half of the year) This issue can easily be tracked by replacing one of the two existing anemometer by a heated anemometer. This will not only provide us with more reliable measurement but it can also be a very useful indicator for icing events. Indeed, when a continuous and constant difference between wind speeds measured by the two cups is found in the time series, icing is occurring and can be therefore detected. We suggest to use the already installed power supply from the telecommunication facility next to the turbine to power the heated anemometer.

Besides this, the performance of the turbine has to be checked: this is done by plotting the power curve (10 minute averaged power output of the turbine) with respect to the wind speed but more data is needed. When this is done, one can estimate how much the production is being affected by the cracked magnets and other related maintenance problems.

In what concerns the new met. mast, once new data is available, CDF codes in rough terrain can be applied to yield better estimations of the flow in the area and more accurate assessment of the exact wind speed at the rotor plane.

4.3 Itilleq

Itilleq is an island in central-western of Greenland,located 45km south of Sisimiut.At the present there are 112 inhabitants living in this settlement who's main activity consist of fishing and hunting, with a fish factory being the main employer. In the island no freshwater is available and for this reason the settlement makes use of a desalination plant to serve its population with water. There is also an all-purpose shop and school which has recently extended its facilities. Due to the remote location of this settlement electricity is produced by diesel generators with the desalination plant having a big cut on the total consumption of the island therefore increasing by a lot diesel demand. In this report we only focus on the wind resource on the island based on data from an existing met mast which has been erected in august 2009 and comment on issues and modifications done to the mast. A study for a possible integration of wind energy in this settlement has been prepared by our colleague Gabriele Bedon, who came along and collaborated with us in this expedition to Itilleq.

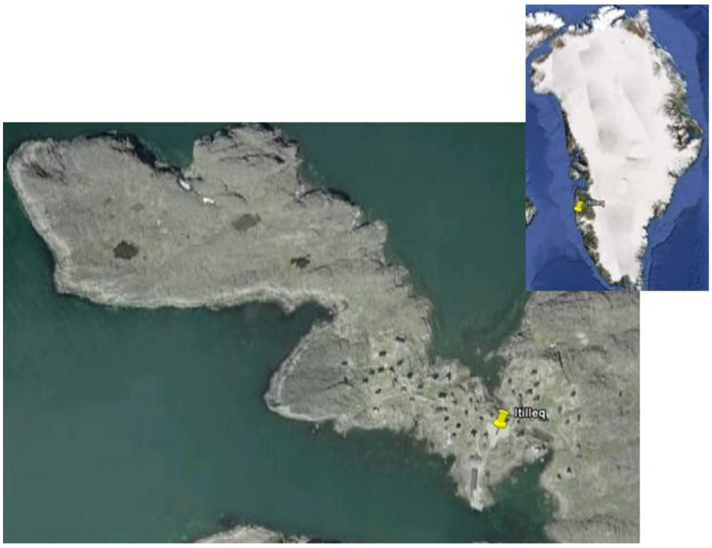


Figure 51: Satellite view of Itilleq.

4.3.1 Work done on meteorological instrumentation

This mast has been erected on august 2009 with the intention to evaluate the wind characteristics and potential on the island.Some issues were found regarding mast location and sensors set up. We think the location where it is mounted is not proper and will definitely affect the results, as it will be discussed later on, when the data analysis for this site is performed because the mast was erected on the hillside of the highest hill on the island. Another problem encountered is how the anemometer and the wind vane were set up on the mast. As can be seen in Fig. 52, the anemometer is not six tower diameters away from the tower like the guide lines suggest. Same problem with the wind vane since it's mounted to close to the mast. The mast has mounted a wind vane (NRG #200P) to measure the wind direction, one cup anemometer (NRG #40) to measure the wind speed and one thermometer (NRG 110S). The maintenance work done consisted of changing the old anemometer and wind vane for new ones and the installation of two photovoltaic panels to power the logger and the GSM unit, one orientated towards southwest the other facing southeast.

Both new sensors were mounted on the mast on a new higher boom so this way the guide lines are fulfilled. See Fig. 53.

Figure 52: Itilleq mast (before changes).

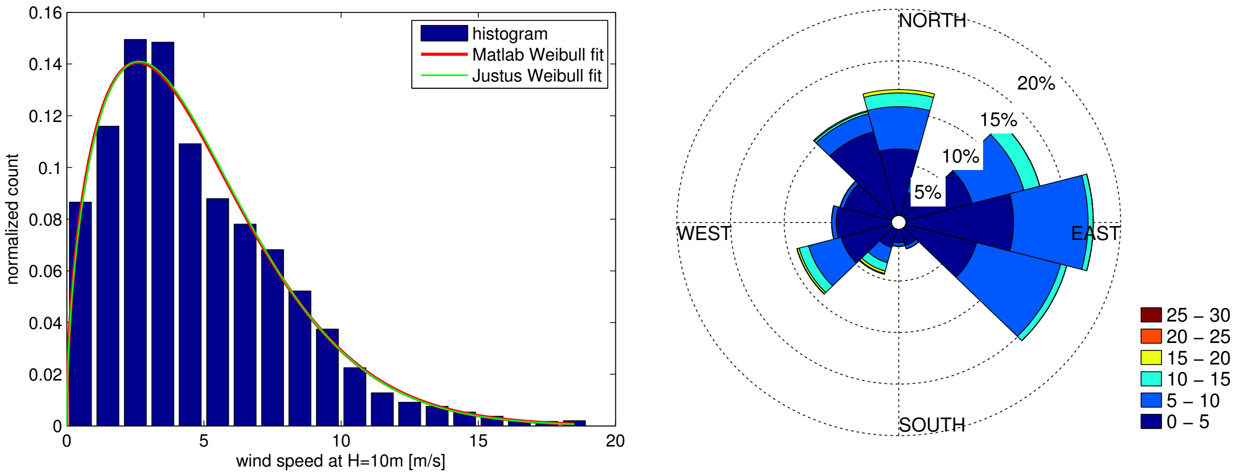
Figure 53: Itilleq met mast (after changes).

4.3.2 Data Analysis for Itilleq's site

Wind data is retrieved as 10 minutes averages, since august 2009 to august 2010 (one full year). The most important wind characteristic parameters are shown in Tab. 12. The Weibull distribution and the wind rose are shown in Fig. 54. The value of the Weibull parameters are shown in Tab. 13. The wind potential of the site is shown in Tab. 14.

Table 12: Itilleq main wind characteristics evaluated at H=10m.

Mean Wind speed [m/s]	4.78
Std Wind speed [m/s]	3.24
Max Wind speed [m/s]	26.00
Mean Turb. int. [%]	17.00
Mean dir. [deg]	176.78
Std dir. [deg]	111.10



(a) (b)

Figure 54: Weibull and wind rose at Itilleq.

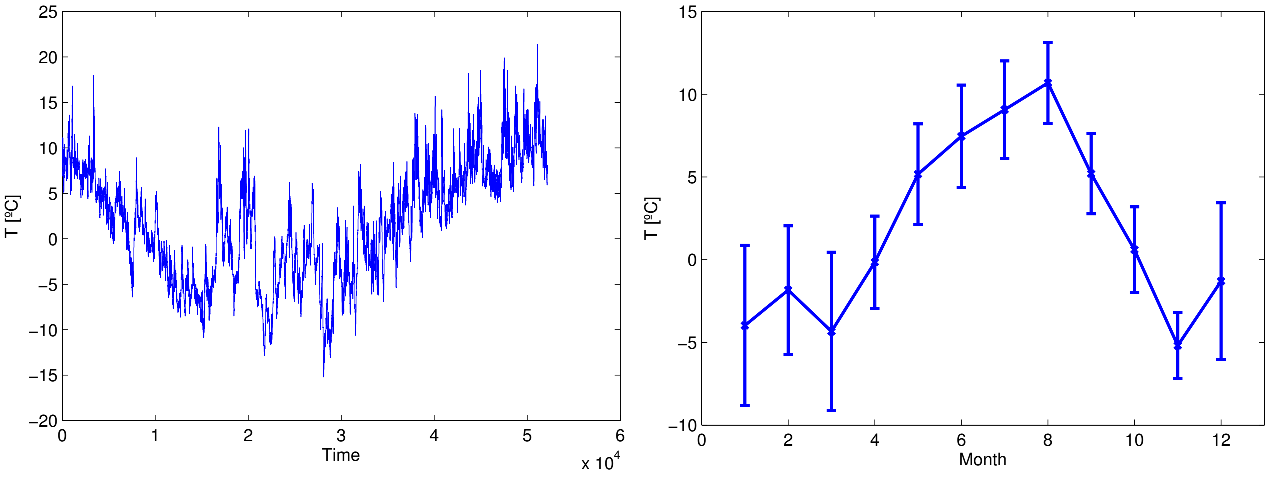
Table 13: Weibull parameters for Itilleq using the two different methods

	Matlab fit	**Justus fit**
A [m/s]	5.30	5.31
k	1.51	1.52

Table 14: Wind Potencial values at Itilleq

	Wind Potential $[W/m^2]$ at 10 m
Justus fit	185.7
Matlab fit	188
Mean	186.89

On the other hand, temperature measurements were also extracted from the met. mast and are shown in Fig. 55. They could be useful in the future to predict icing if wind energy is finally developed here. It can be seen that the values are not as extreme and do not vary as much as in Sarfannguaq's case. The reason behind this it that, Itilleq's temperature is regulated by the open sea and Sarfannguaq is regulated by the temperature of the water of the fjord which varies much more and gets a lot colder during the winter time when compared to the open sea temperature. The opposite happens in the summer where Itilleq is likely to have cooler temperatures.

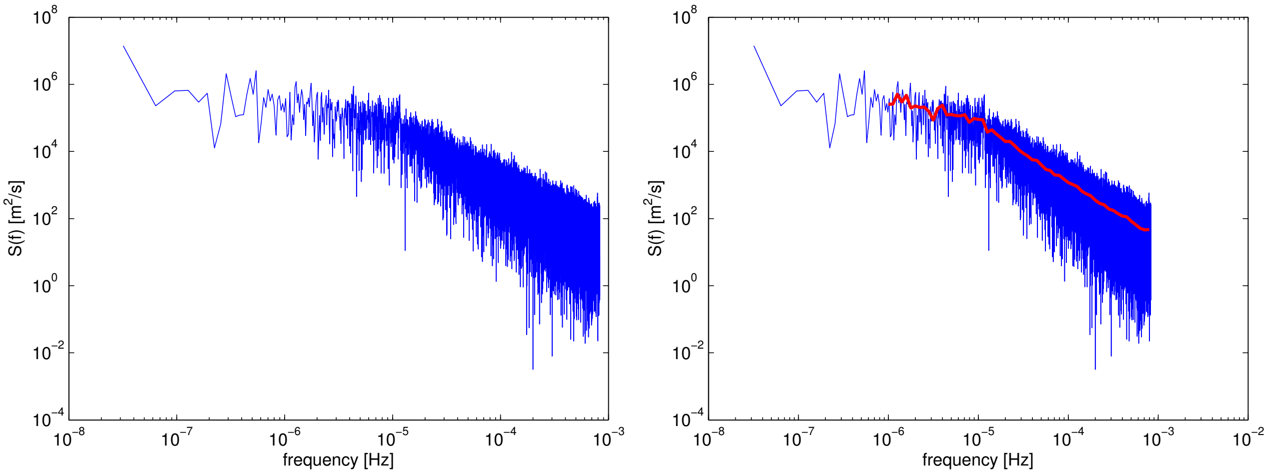


(a) (b)

Figure 55: Temperature data. (a) Time series (b) Montly mean temperatures and std's

In general trends, it can be stated that Itilleq has a relatively acceptable wind resource with a averaged mean speed slightly bellow 5 m/s. It is not as good as Sarfannguaq but wind energy implementation is still possible. It is important to mention that better wind measurements are needed since the met. mast is partially blocked by a hill and prevents us from getting reliable data from a certain direction. In the 'further investigations part' this problem is detailed.

On the other hand, the energy density spectrum was also plotted (in Fig. 56). It can be seen that, unlike in the locations of Sarfannguaq and especially of Assaqutaq, the daily variation peak is almost not present. A possible explanation of this can be related to the fact that Itilleq is not located inside the fjord but closer to the open sea, were the breeze and local daily wind patterns are not as pertinent. It is more exposed to the sea conditions which do not vary that much in a daily basis.



(a) (b)

Figure 56: Energy spectrum of Itilleq. (a) Non-filtered (b) Filtered

4.3.3 Further investigations and suggestions

As it can be seen in the appendix, in the wind parameter by sectors of Itilleq (table and graphs), the turbulence intensity of the 7th sector is quite high combined with a rather small measured wind speed (if compared with sector 6 and 8). By the looking at the geography of the location, it can be seen that there is a quite substantial effect in the wind measurements due to a hill which matches the highest point of the island. One suggestion for future field work would be to move this mast to the top of this hill. Surprisingly this was already been done recently as it can be seen in Fig. 57.

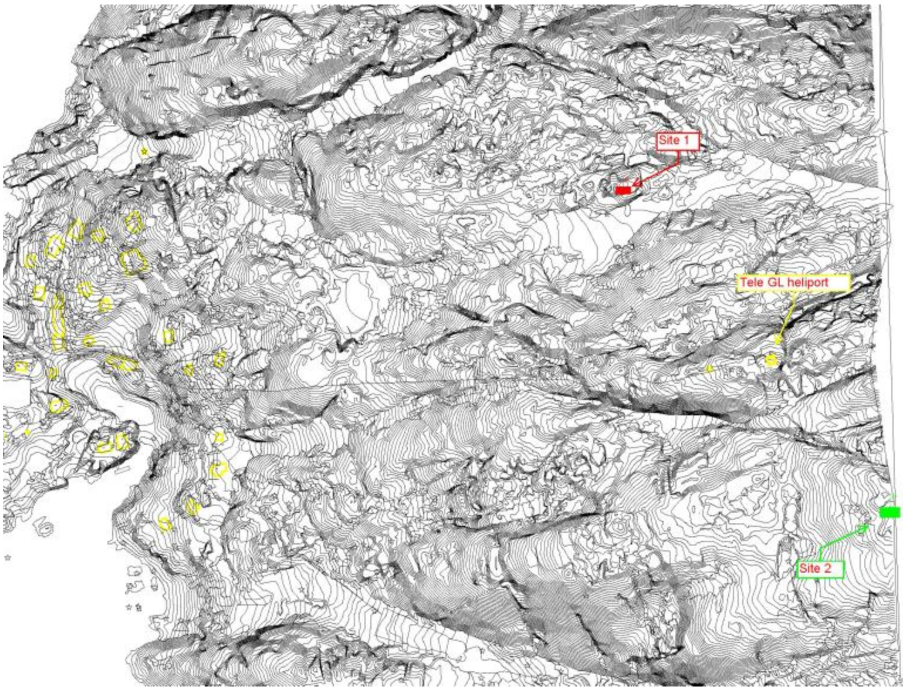


Figure 57: New location of met mast in Itilleq.

5 Vertical Axis Wind Turbine guidelines for Telecom

5.1 Introduction

On the western coast of Greenland there are approximately 40 telecommunication towers. The locations of the towers are usually midway between settlements or cities and are placed at high elevations because the towers need a clear line of sight to be able to relay messages from one city to the other. This makes them remote and unfortunately the locations of these towers experience very extreme climates, which push their operational capabilities to the limits. Currently the main source of power supplied is by diesel generators that are located onsite.

5.2 Issue

Power generation through the use of diesel is proving to be very expensive. On some sites operated by TELE Greenland (TG), the fuel cost for each kWH is in the region of 50 DKK. This price includes the cost for the fuel and the transportation cost. An average TG site has a typical power consumption of approximately 1 kW, which equals 438.000 DKK per year. The reason for this is because the only way to transport the fuel to these locations is by helicopter. So if there is a way to eliminate or reduce the dependence of power produced by these diesel generators with the introduction of a sustainable energy source, then the operation costs could be greatly reduced.

5.3 History and Experience with wind energy

TELE Greenland has tested approximately 3 different types of wind turbine manufacturers since 1995. These are:

- **TG Custom**:
  For TG's own production type, they were a horizontal upwind design that began running, at various sites, in 1995. Approximately 15-20 units were used with only one still being used today. Eventually though they will be phased out due to them requiring too much maintenance. There was never a power rating supplied by TG but by the size in the supplied picture (Fig. 58) and the year that it came online it can be assumed to be around the 200W range.

Figure 58: TG's first venture in a wind turbine; picture provided by TELE Greenland A/S.

- **Southwest Windpower**:

  Southwest Windpower is a manufacturer of wind turbines aimed at supplying the needs of small independent power systems and have been in the market since the mid 80's. This coupled with a proven operational history in various environments, it was decided by TG to use them in a few locations. These turbines, specifically the Air X models, are advertised to have a minimum survival wind speed of 50 m/s and a robust construction (See Fig. 59. After installation at the TG sites they have experienced various issues. One of the first issues encountered was a design flaw. To be able to reduce the rotor speed the turbines would essentially load the generator internally which can lead to a buildup of internal heat decreasing their life spans significantly. The manufacturer later added an external heat sink to overcome this issue. Other issues where with blade failure due to the sudden and high wind gusts. See [7] for more details.

Figure 59: Affected turbine in a very remote location: notice how the turbine has no blades.

- **Ropatec**:

  The wind turbine manufacturer Ropatec, produces VAWT's. They are a hybrid of Darrieus-Savonius turbines that have the potential to produce high amounts of power at high rotational speeds and for some models produce nominal power from 14 m/s - 56 m/s. The companies aim since 1996 was to develop a product that was absolutely reliable and durable through testing of prototypes under extreme weather conditions atop the Alpine peaks. However after installation there have been several issues of the blades failing with recorded wind speeds that began at 40 m/s. Below in Fig. 60fig Ropatec.jpeg is a relay station at Nuuk using a Ropatek model VRE.007, 750VA.

5.4 TG Input and final recommendation

Through TG's experience, there were several topics that were recommended to be the most important when considering the design of a turbine to be used in Greenland's environment.

- Ice issues
- Survival wind speed of 70m/s
- Low maintenance
- No slip rings
- Low average wind speed
- Maximum wind speed is either too high or turbulent
- Need real strong construction

Figure 60: picture of the Ropatec VAWT provided by TELE Greenland A/S.

- Passive high speed protection

Upon review the best direction to would be to use a VAWT using a Savonius design. These types of turbines are inherently less efficient than HAWT or even Darrieus systems which can be a benefit in storm-prone regions since a system like this cannot have rotation speeds that exceed the wind speed. This is because as the energy of the wind is split between two forces. The first force is turning the turbine while on the opposing side of the turbine the second force resists rotation. A large drawback with the inefficiency of this design, along with the combination of the low mean wind speed, is that the swept area will have to be increased to be able to generate the needed power. This can be done but it has to be remembered that the turbine will experience wind loads that are close or even over the survival wind speed and these loads are what have caused failure with the past turbines. It has been recommended that in polar conditions to de-rate the survival speed by 25% (See [7]) Another major issue will be icing. The first and foremost task that should be completed before anything else is to get specific site measurements regarding icing conditions. There might locations where the icing is so severe that it will be impossible, with current technologies, or too expensive to maintain a wind turbine. So before continuing further icing has to be assessed because it is very specific to each site.

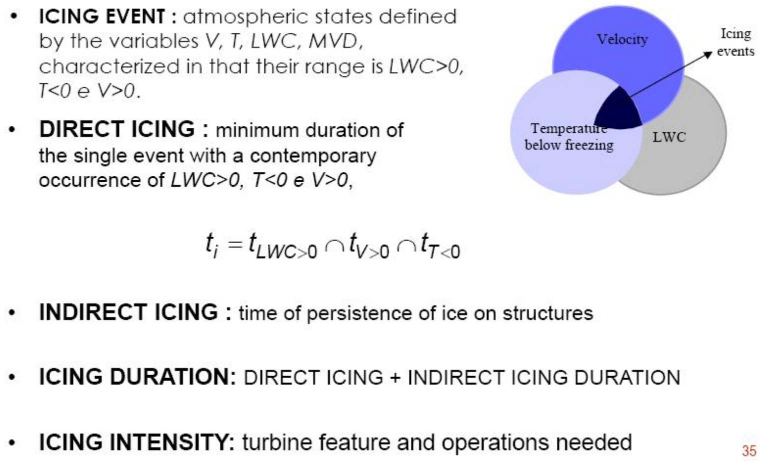
5.5 Importance of field measurements for icing and speed survival estimations

It has already been stated throughout the whole report that sites located in remote and mountainous areas have extremely local wind and climatic characteristics, that can change widely in space and time. It is therefore recommended that general field measurements are conducted in the specific telecommunication tower locations were it is certain that conditions will be very different from one tower to the other. With the gathered results, and depending on the icing intensity, and wind measurements, different strategies can be adopted where existing or inexisting (so designs to develop) wind turbines may be feasible. The most important measurements to be conducted are related to icing estimation (intensity, nature and period) and to severe wind gusts (maximum wind values).

- **ESTIMATING ICING IN SOUTH AND SOUTHWESTERN GREENLAND**:

  According to all the data available and extracted from DMI, it can already be stated that extreme icing conditions (especially rime-icing) occur in the western coast, and they are more intense the southern you go (Tele Greenland test Wind turbines confirm that). This is because icing generally occurs with the combination of three main parameters as it can be seen in Fig. 61 and which are:

- moderate to high wind velocity
- the liquid water content (LWC) in g/m^3
- Droplet size (MVD)
- temperature bellow zero (T<0 Celcius)



- **ICING EVENT :** atmospheric states defined by the variables *V, T, LWC, MVD*, characterized in that their range is *LWC>0, T<0 e V>0*.
- **DIRECT ICING :** minimum duration of the single event with a contemporary occurrence of *LWC>0, T<0 e V>0,*

$$t_i = t_{LWC>0} \cap t_{V>0} \cap t_{T<0}$$

- **INDIRECT ICING :** time of persistence of ice on structures
- **ICING DURATION:** DIRECT ICING + INDIRECT ICING DURATION
- **ICING INTENSITY:** turbine feature and operations needed

Figure 61: Predicting Icing events: main parameters involved.

This usually happens inside a cloud, in what is called the 'in-cloud icing'.

Since LWC and MVD measurements are not evident to estimate (sometimes done with Sonars and usually estimated with visibility values) and thus, making icing conditions hard to analyze, an easy and cheap way to obtain general information about icing conditions in a specific site is by doing wind measurements with a heated and with a non-heated cup anemometer at the same time. Ice will deposit in the unheated cup when icing occurs resulting in a slower rotation. The constant value between wind speed measurements of one cup with respect to the other should be detected in the time series and therefore the length and intensities of these events calculated.

- **RECORDING THE MAXIMUM WINDS IN SOUTH AND SOUTHWESTERN GREENLAND: important for design purposes**:

  As it has been mentioned earlier on in the report, some of the problems Tele-Greenland encountered with the already installed wind turbines were related to severe gusts or very high constant wind speed. Normally these wind, as it has been seen in the previous sections, would be related to Foehn or katabatic winds. It is important, thus, for design purposes (resitance to certain wind speeds) that the maximum wind speeds are known in the sites so 50 yearly and 1 yearly average maximum wind speeds can be estimated.

5.6 Strategies to combat icing and to incoporate in the design phase

Once the extreme wind speeds and icing intensity has been estimated in a specific site, the most proper assessment to anti-icing or de-cing strategies should be addressed. There are currently many strategies that are been used in the wind turbine industry but they are still quite new and a lot of research has to be done in this field since not much was found in what concerns vertical axis strategies.

In general trends, it is important to mention that, in what concerns the results shown from [5] basically applied to normal HAWT when temperatures become extreme, constant heating from a local

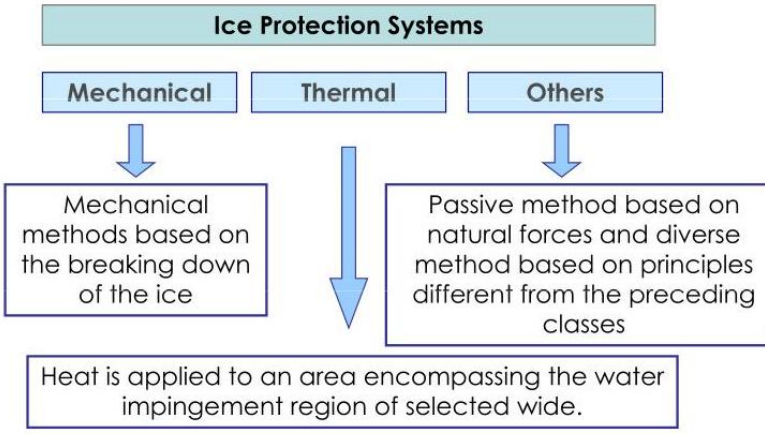


Figure 62: Different mechanisms of ice prevention.

source (normally hot air source) is required which is not very efficient since it extracts a lot of power. On the other hand, it states that the proportion of energy needed for heat becomes higher when the rated power decreases, and since Tele-Greenland needs small powered VAWT's it becomes even more difficult. Thereby, all of these aspects should be investigated in the near future since by looking it from an economical perspective it is still not very promissing.

Conclusion

Greenland is in a early stage in the development of wind energy but it has a very big potential in the near future, as icing strategies are becoming more efficient and designs are getting more robust. Although wind resource is not promising throughout the inhabited areas (south and southwestern coast), where generally low mean winds are found with very irregular patterns (many periods of calm alter with periods of intense winds) fjords and orography may sometimes play a beneficial role and higher wind speeds may be observed at some sites and thus making it possible for Wind Power development. A big effort should be therefore addressed to wind assessment, especially in remote areas where hydro power is unfeasible because of lack of the resource.

References

[1] 3TIER. *www.3tier.com*. 3TIER, 2010.

[2] Mahmoud Ali Adel. *Wind Turbine Testing and Installation*. DTU.

[3] Ampair. *www.boost-energy.com/ampair/productsproduct3.asp*.

[4] Sta-Clean antifreeze. *www.stacleanantifreeze.com/company.html*.

[5] Lorenzo Battisti. *Ice prevention course*. DTU, 2007.

[6] Tracy Dahl. *Summit Station Wind Power Pilot Project*. CH2M Hill Polar Services, 2009.

[7] Tracy Dahl. *Wind Power Systems*. PolarPower.org, 2010.

[8] Proven energy. *www.provenenergy.co.uk*. 2010.

[9] National Science Foundation. *www.polarpower.org*. CH2M Hill Polar Services, 2004-2009.

[10] Danish Meteorological Institute. *DMI technical report on Greenland*. DMI, 2001.

[11] John F. Maissan. *Wind Power development in sub-arctic conditions with severe rime icing*. Yukon Energy Corporation, March 2001.

[12] SRTM maps. *http://dds.cr.usgs.gov/srtm/*. USGS: US Geological Survey.

[13] Greenland Climate network (GC-net). *http://cires.colorado.edu/science/groups/steffen/gcnet/*. Coorporative institute for Reaearch in environmental sciences.

[14] Windside. *www.Windside.com*.

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Appendices

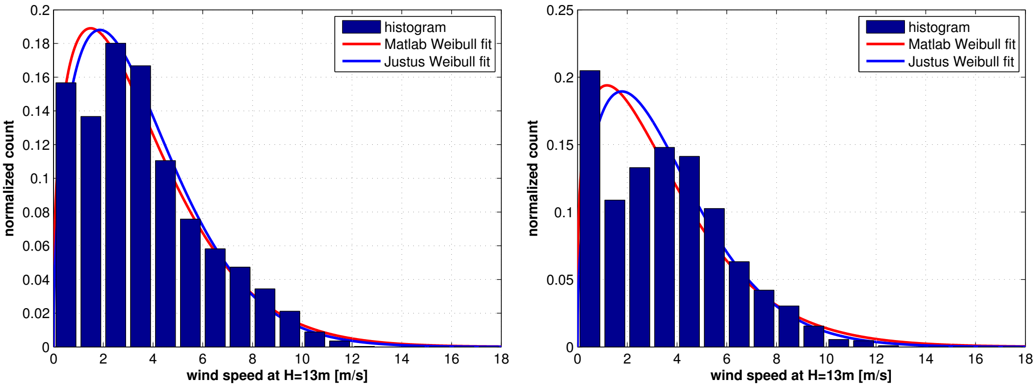
A Weibull Distributions per sector

See the following pages.

A.1 At Assaqutaq

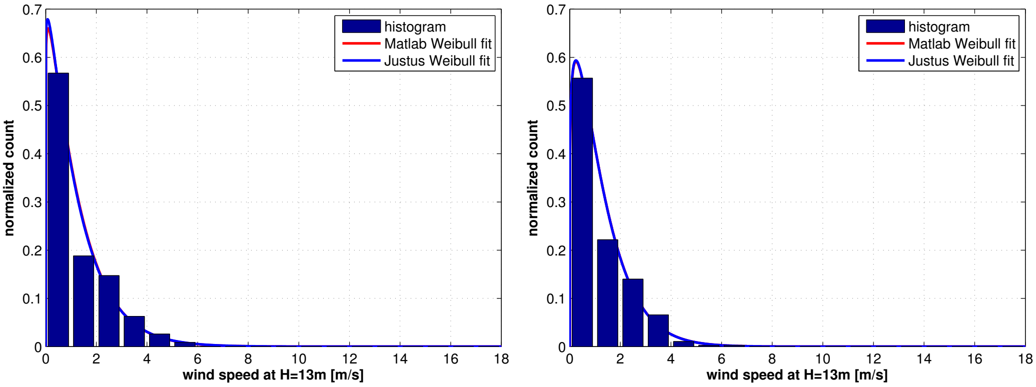
Table 15: Wind Potencial at Assaqutaq per sector

	mean U sec [m/s]	std U sec [m/s]	A sec jus [m/s]	k sec jus	A mat [m/s]	k mat
sector 1	3.572679477	2.481648388	3.952815343	1.48546914	3.884604547	1.369814228
sector 2	3.541474865	2.493523837	3.910827609	1.463775637	3.799617951	1.287187074
sector 3	1.241060606	1.182566036	1.267076169	1.053830591	1.275016914	1.06740089
sector 4	1.220897098	1.057498415	1.28881503	1.168868566	1.292481359	1.17078341
sector 5	2.101749347	2.497550082	1.901228954	0.829129664	2.027579757	0.931295654
sector 6	2.588643298	2.563766464	2.599994378	1.010542099	2.628262652	1.037677886
sector 7	2.794896627	1.929141776	3.094916737	1.495711186	3.000775602	1.299558099
sector 8	2.438742515	1.952224179	2.629167484	1.273347619	2.527432866	1.108765771
sector 9	2.149295775	2.693446619	1.866705096	0.782634095	1.778922193	0.749436129
sector 10	2.648563536	3.127887845	2.406473507	0.83473095	2.197590256	0.744243858
sector 11	1.499670659	1.351436633	1.563085956	1.119663254	1.581621777	1.153165393
sector 12	1.982752373	1.435017924	2.180323882	1.42064809	2.15474101	1.344453054



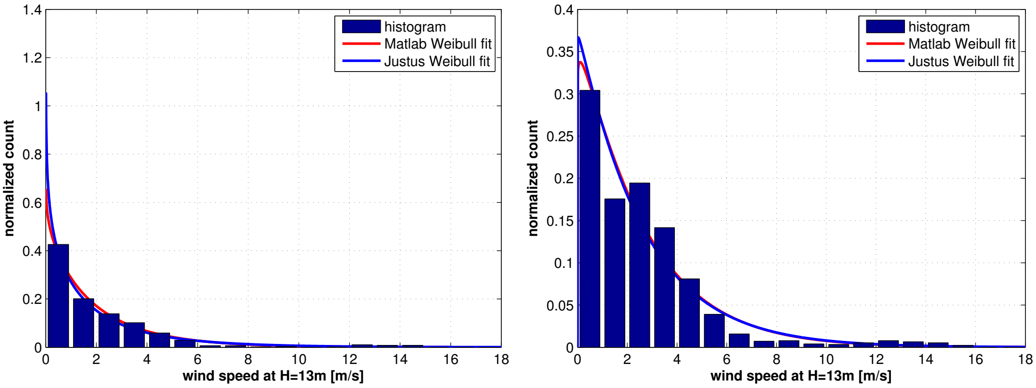
(a) (b)

Figure 63: Weibull fit for Sector 1 and 2. (a) Sector 1 : 15 ° to 45 ° (b) Sector 2: 45 ° to 75 °



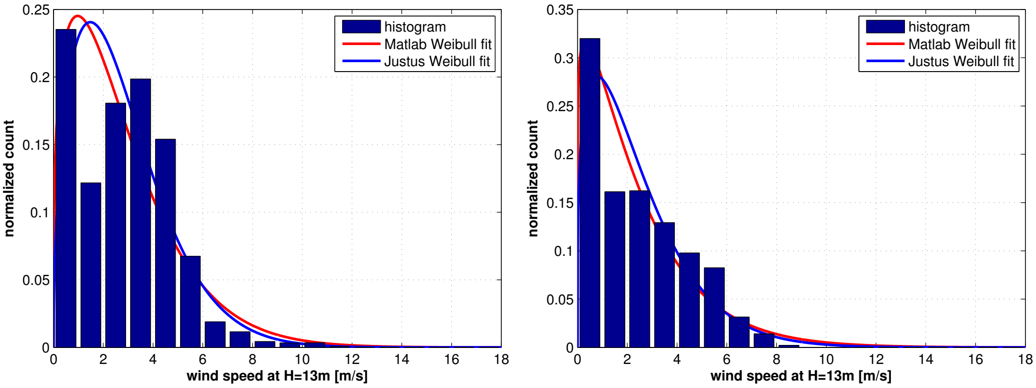
(a) (b)

Figure 64: Weibull fit for Sector 3 and 4. (a) Sector 3 : 75 ° to 105 ° (b) Sector 4: 105 ° to 135 °



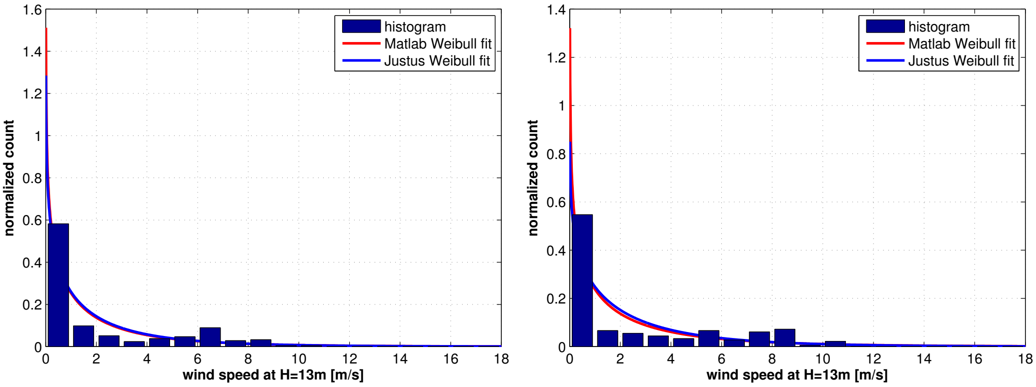
(a) (b)

Figure 65: Weibull fit for Sector 5 and 6. (a) Sector 5 : 135 ° to 165 ° (b) Sector 6: 165 ° to 195 °



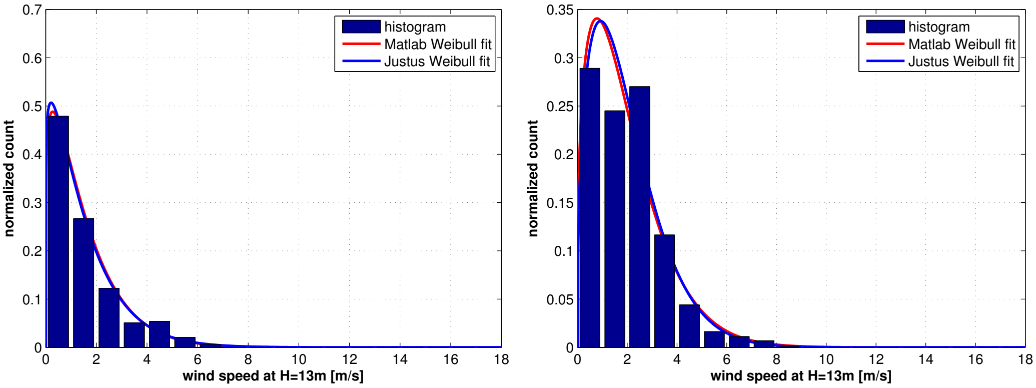
(a) (b)

Figure 66: Weibull fit for Sector 7 and 8. (a) Sector 7 : 195 ° to 225 ° (b) Sector 8: 225 ° to 255 °



(a) (b)

Figure 67: Weibull fit for Sector 9 and 10. (a) Sector 9 : 255 ° to 285 ° (b) Sector 10: 285 ° to 315 °



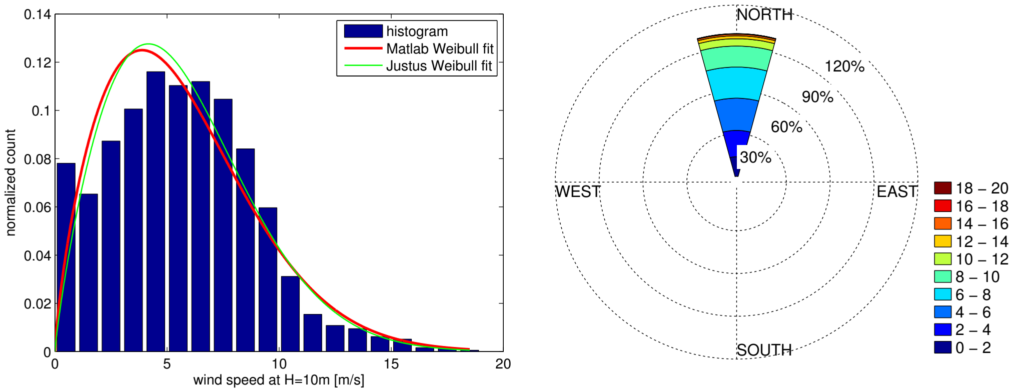
(a) (b)

Figure 68: Weibull fit for Sector 11 and 12. (a) Sector 11 : 315 ° to 345 ° (b) Sector 12: 345 ° to 375 °

A.2 At Sarfannguaq

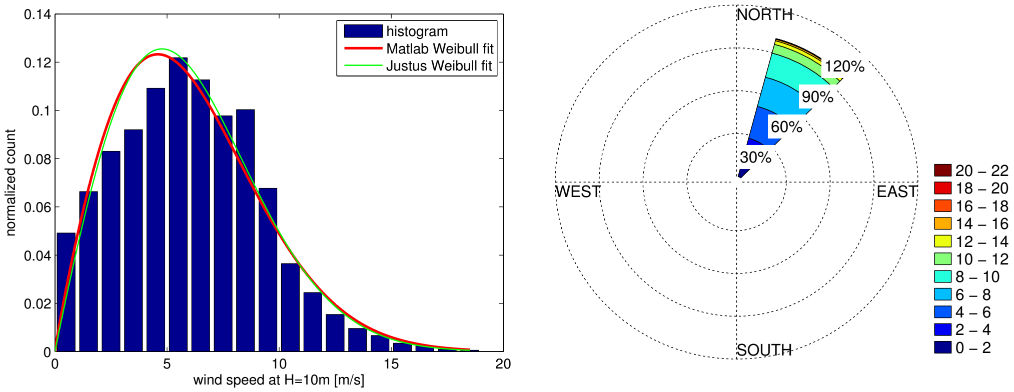
Table 16: Wind Potencial at Sarfannguaq per sector

	mean U sec [m/s]	std U sec [m/s]	Turbulence Inten.	A sec MATLAB [m/s]	k sec MATLAB
sector 1	5.673	3.2367	17.529	6.3316	1.7436
sector 2	6.025	3.2073	16.792	6.7619	1.9114
sector 3	6.134	3.3453	16.591	6.8749	1.8533
sector 4	6.052	3.4524	16.352	6.7698	1.7611
sector 5	5.868	3.3607	16.870	6.5792	1.7767
sector 6	4.956	3.0317	18.424	5.5193	1.6306
sector 7	4.897	3.0559	17.921	5.4445	1.5972
sector 8	4.692	2.9909	18.237	5.2083	1.5644
sector 9	4.855	2.9610	18.090	5.4206	1.6579
sector 10	5.477	3.3842	17.274	6.1073	1.6353
sector 11	5.809	3.2249	16.913	6.5178	1.8352
sector 12	5.955	3.1783	17.029	6.6906	1.9174



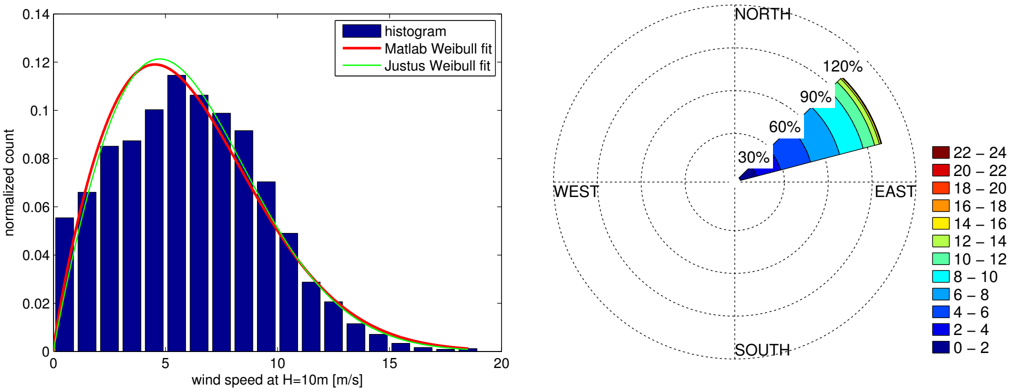
(a) (b)

Figure 69: sector 1.



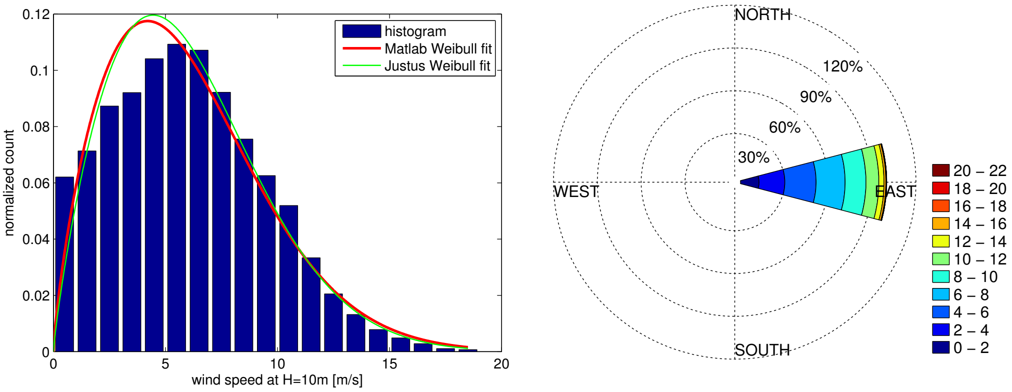
(a) (b)

Figure 70: sector 2.



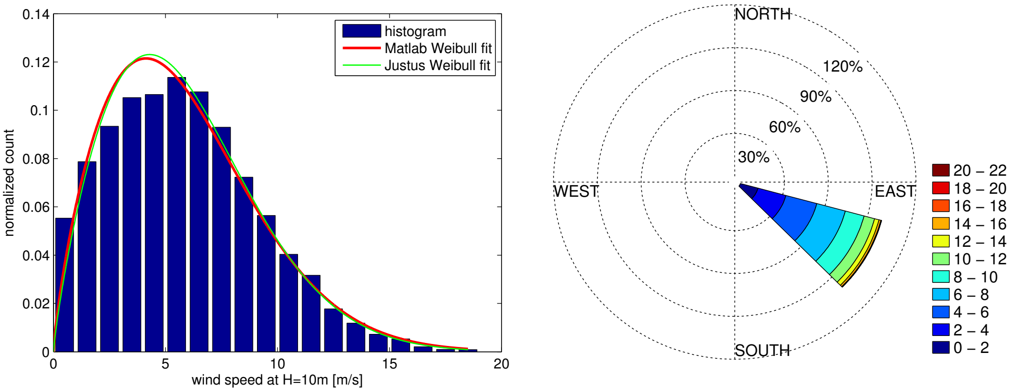
(a) (b)

Figure 71: sector 3.



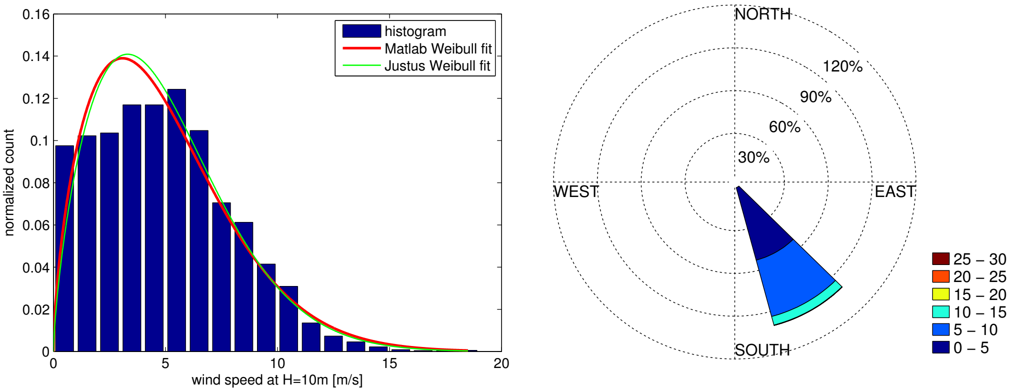
(a) (b)

Figure 72: sector 4.



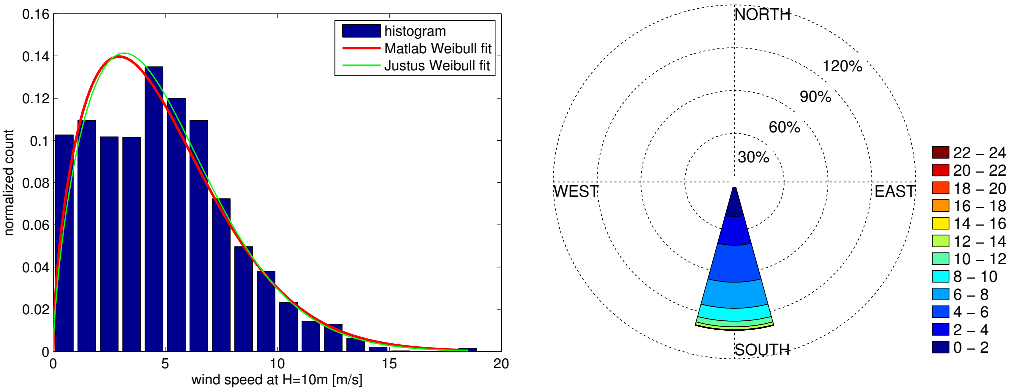
(a) (b)

Figure 73: sector 5.



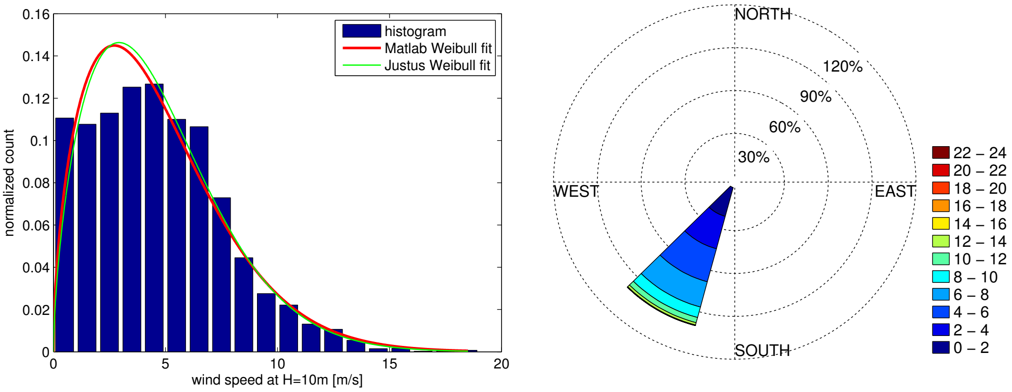
(a) (b)

Figure 74: sector 6.



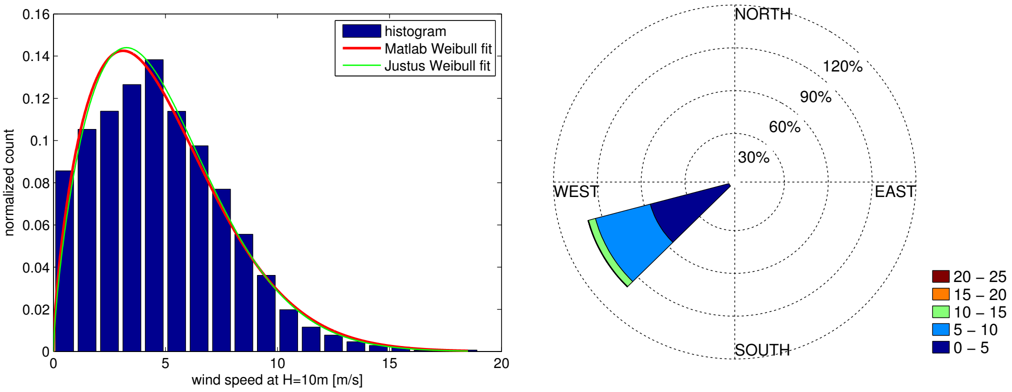
(a) (b)

Figure 75: sector 7.



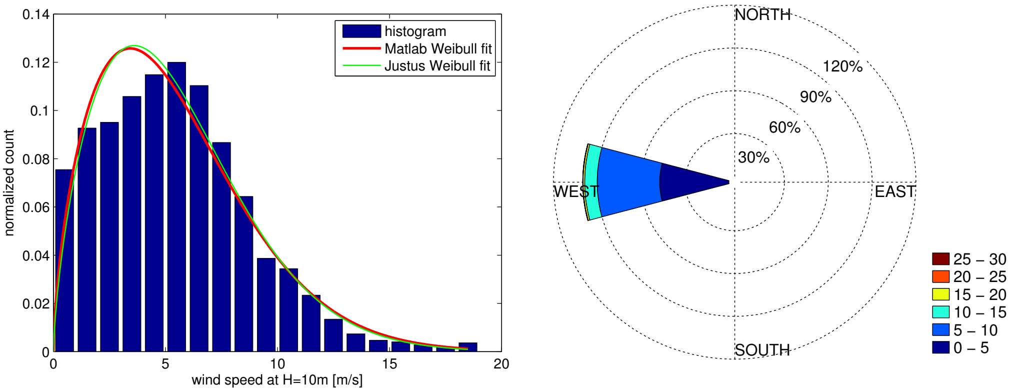
(a) (b)

Figure 76: sector 8.



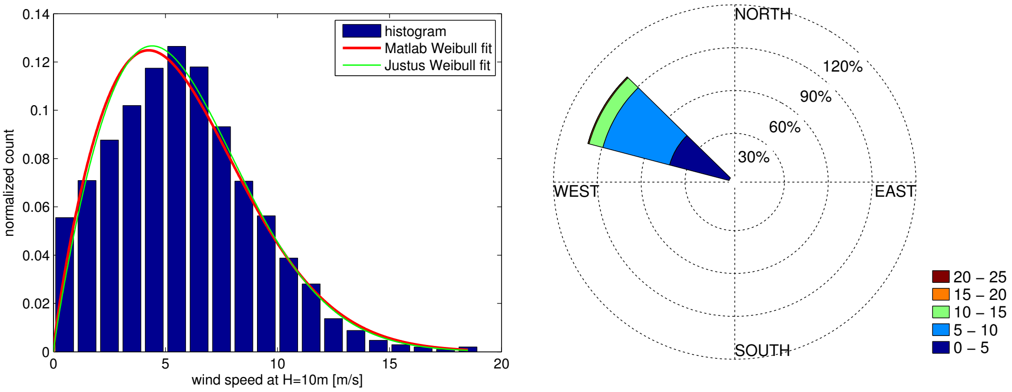
(a) (b)

Figure 77: sector 9.



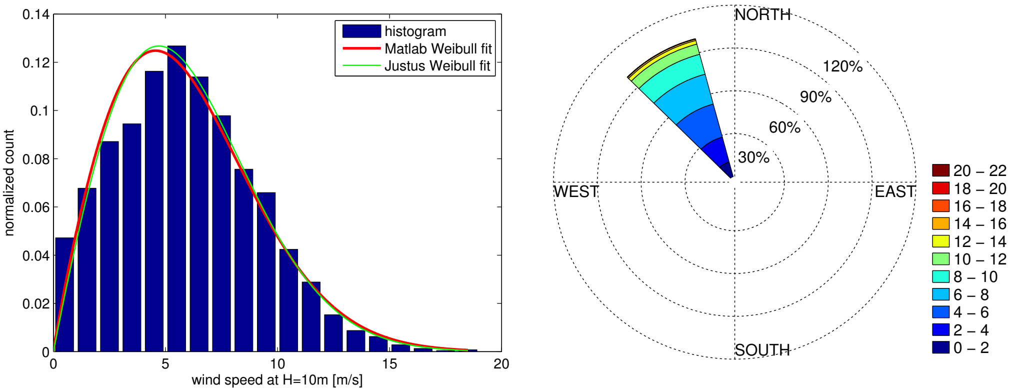
(a) (b)

Figure 78: Sector 10.



(a) (b)

Figure 79: Sector 11.



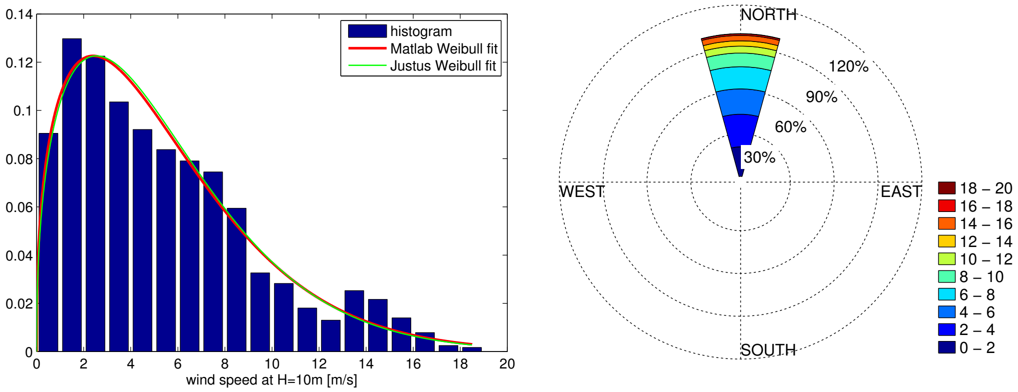
(a) (b)

Figure 80: Sector 12.

A.3 At Itilleq

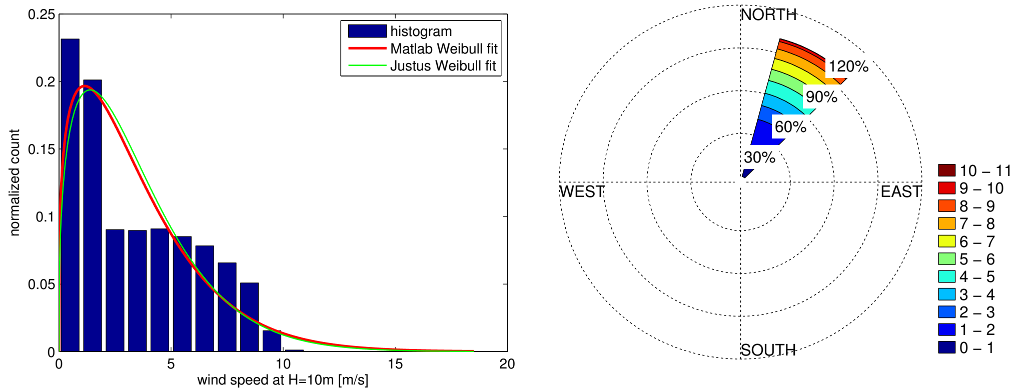
Table 17: Wind Potencial at Itilleq per sector

	mean U sec [m/s]	std U sec [m/s]	Turbulence Inten.	A sec MATLAB [m/s]	k sec MATLAB
sector 1	5.466	3.9656	10.501	5.9941	1.3889
sector 2	3.475	2.6373	14.430	3.7513	1.2796
sector 3	5.482	3.405	12.520	6.0974	1.6
sector 4	4.774	2.5742	11.218	5.3814	1.9278
sector 5	5.472	2.5216	12.455	6.1644	2.2935
sector 6	2.969	1.8574	19.520	3.3213	1.6392
sector 7	3.243	2.4541	20.938	3.5539	1.3651
sector 8	7.009	4.859	13.794	7.6864	1.4159
sector 9	5.404	3.6799	11.865	5.9848	1.4966
sector 10	2.947	1.5957	12.773	3.3216	1.926
sector 11	2.872	1.6158	14.741	3.2305	1.8469
sector 12	3.539	2.8153	12.494	3.8634	1.3352



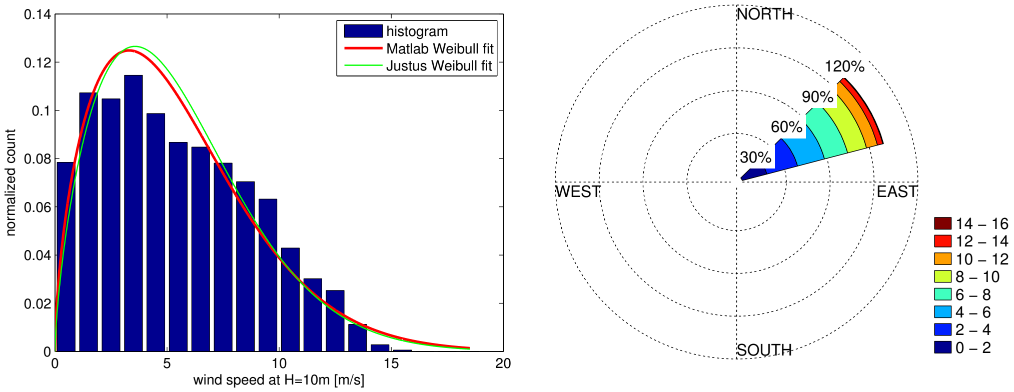
(a) (b)

Figure 81: Sector 1.



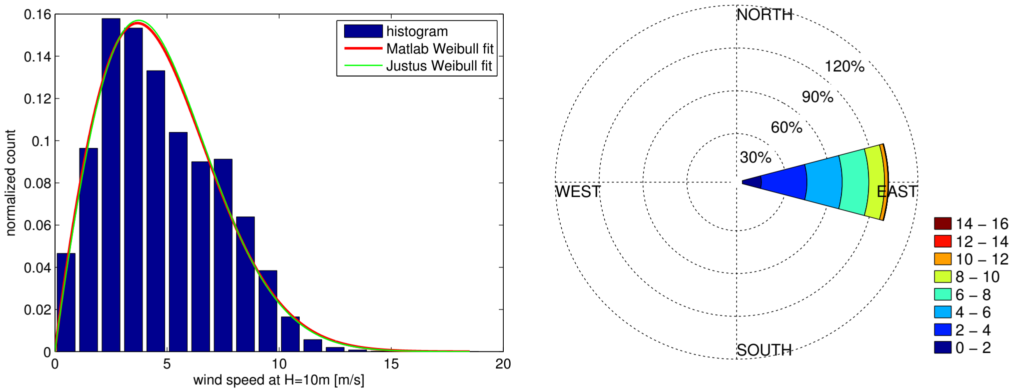
(a) (b)

Figure 82: Sector 2.



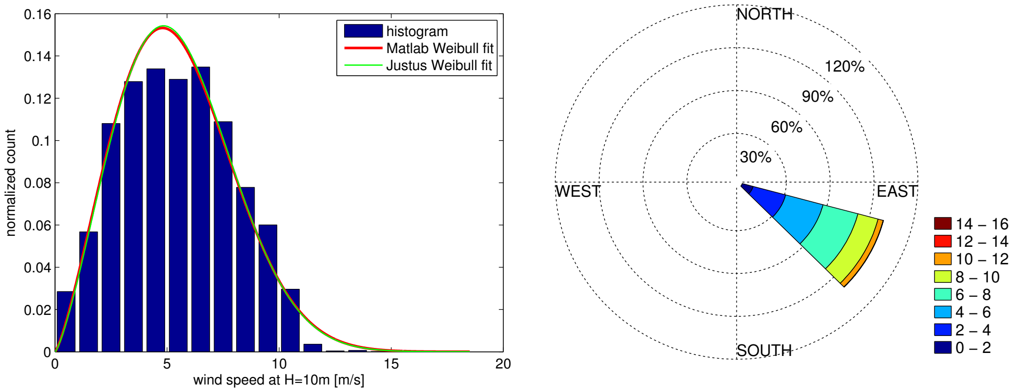
(a) (b)

Figure 83: Sector 3.



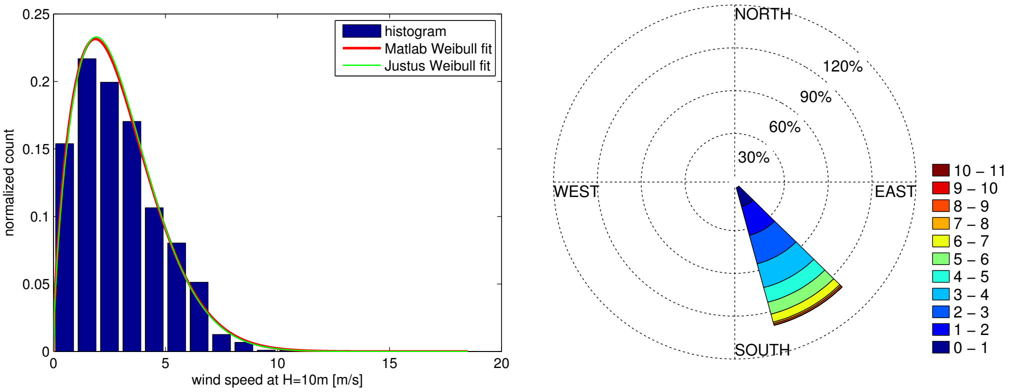
(a) (b)

Figure 84: Sector 4.



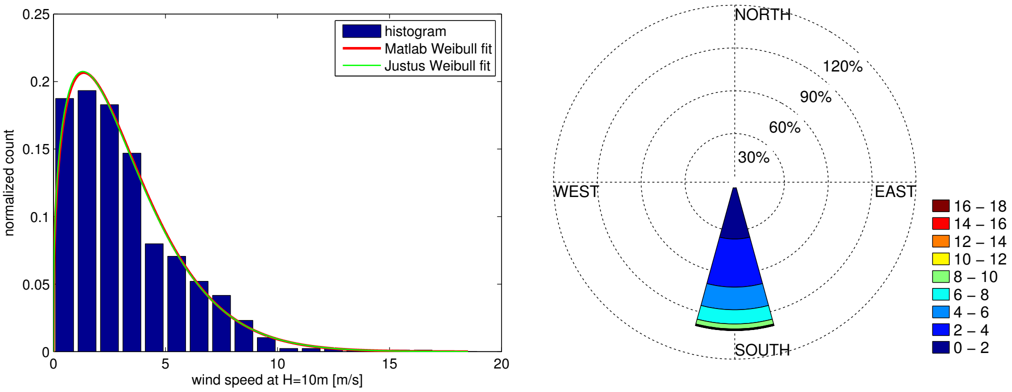
(a) (b)

Figure 85: Sector 5.



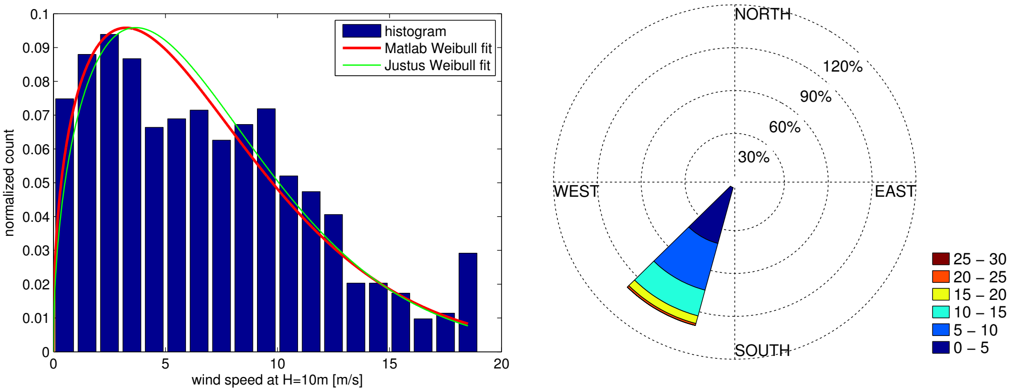
(a) (b)

Figure 86: Sector 6.



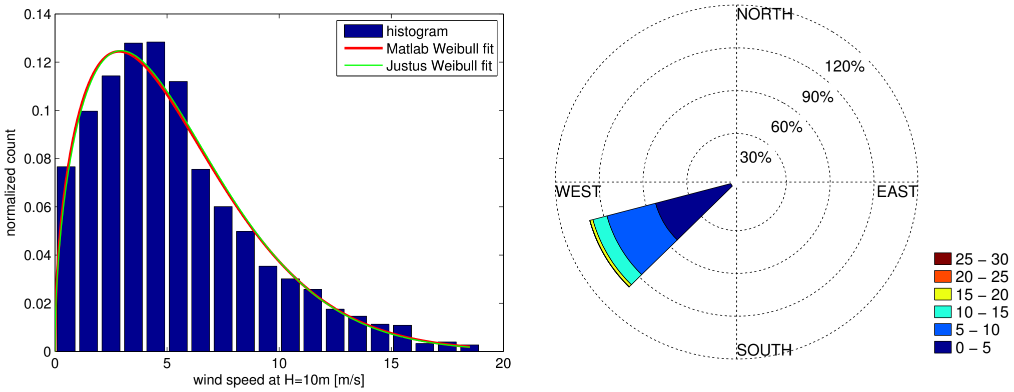
(a) (b)

Figure 87: Sector 7.



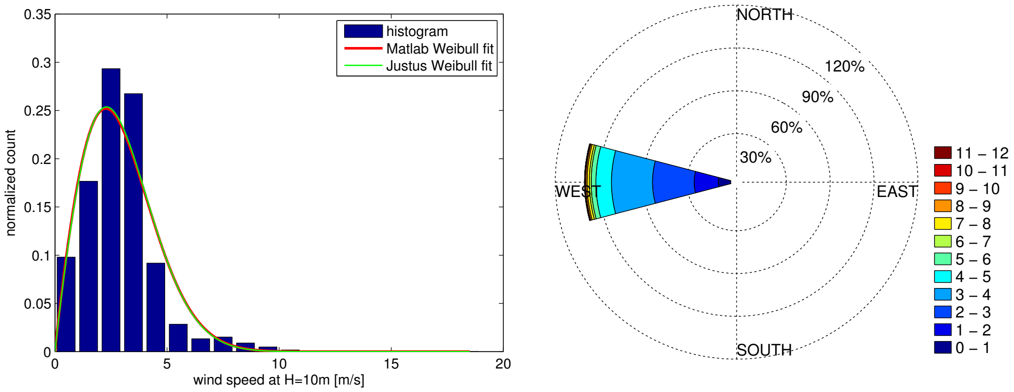
(a) (b)

Figure 88: Sector 8.



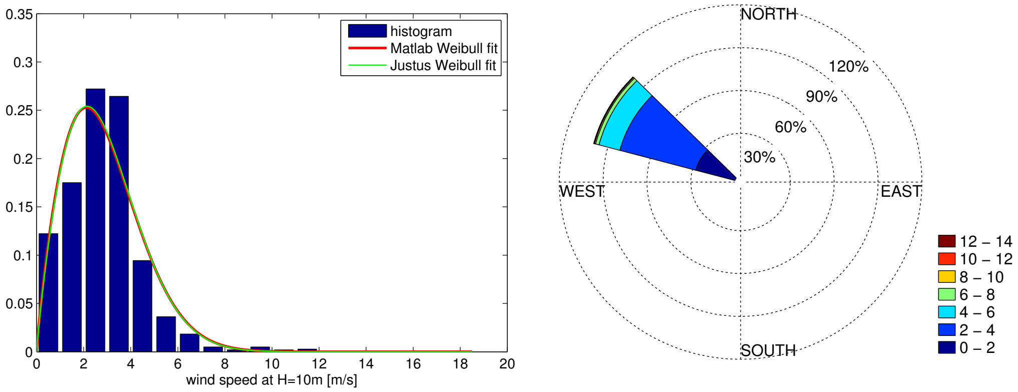
(a) (b)

Figure 89: Sector 9.



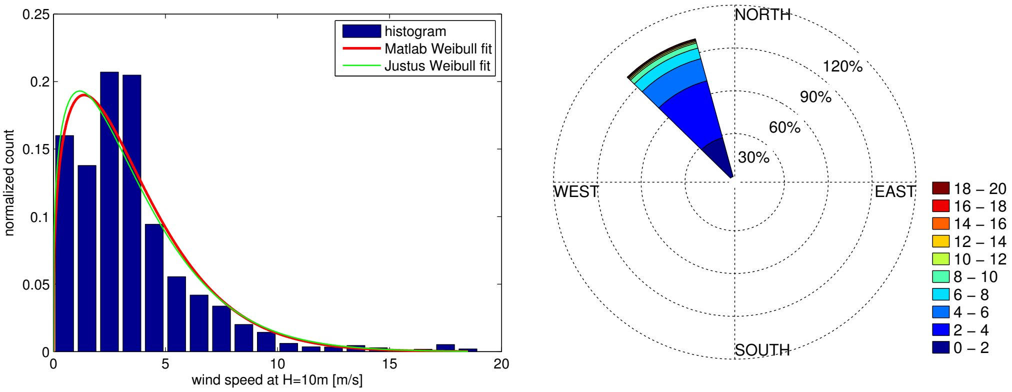
(a) (b)

Figure 90: Sector 10.



(a) (b)

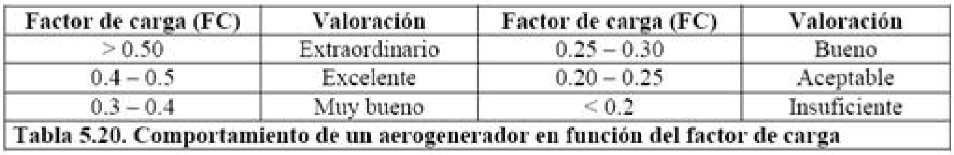
Figure 91: Sector 11.



(a) (b)

Figure 92: Sector 12.

B Capacity factor standards

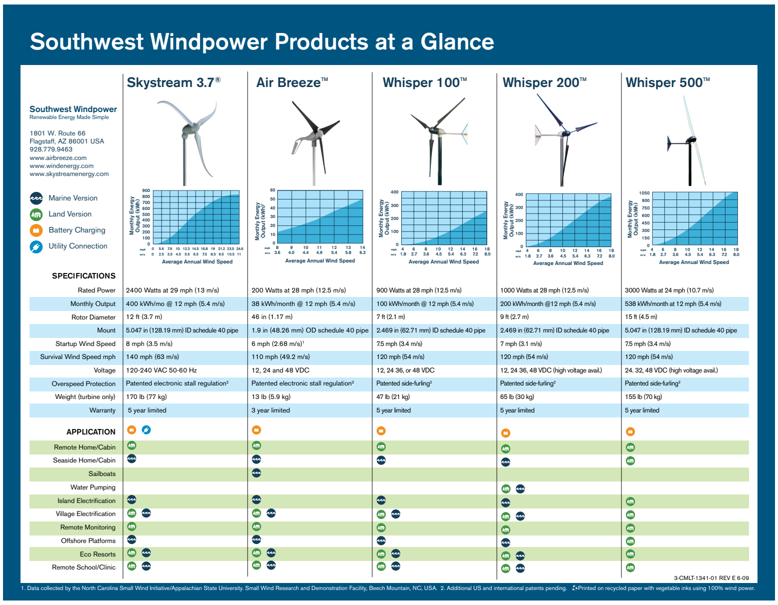


Factor de carga (FC)	Valoración	Factor de carga (FC)	Valoración
> 0.50	Extraordinario	0.25 – 0.30	Bueno
0.4 – 0.5	Excelente	0.20 – 0.25	Aceptable
0.3 – 0.4	Muy bueno	< 0.2	Insuficiente

Tabla 5.20. Comportamiento de un aerogenerador en función del factor de carga

Figure 93: Capacity factor standards.

C Related files to Wind Turbine developement in Greenland



Southwest Windpower Products at a Glance

Southwest Windpower
Renewable Energy Made Simple

1801 W. Route 66
Flagstaff, AZ 86001 USA
928.779.9463
www.airbreeze.com
www.windenergy.com
www.skystreamenergy.com

- 🌊 Marine Version
- 🏠 Land Version
- 🔋 Battery Charging
- 🔌 Utility Connection

SPECIFICATIONS	Skystream 3.7®	Air Breeze™	Whisper 100™	Whisper 200™	Whisper 500™
Rated Power	2400 Watts at 29 mph (13 m/s)	200 Watts at 28 mph (12.5 m/s)	900 Watts at 28 mph (12.5 m/s)	1000 Watts at 28 mph (12.5 m/s)	3000 Watts at 24 mph (10.7 m/s)
Monthly Output	400 kWh/mo @ 12 mph (5.4 m/s)	38 kWh/month @ 12 mph (5.4 m/s)	100 kWh/month @ 12 mph (5.4 m/s)	200 kWh/month @12 mph (5.4 m/s)	538 kWh/month at 12 mph (5.4 m/s)
Rotor Diameter	12 ft (3.7 m)	46 in (1.17 m)	7 ft (2.1 m)	9 ft (2.7 m)	15 ft (4.5 m)
Mount	5.047 in (128.19 mm) ID schedule 40 pipe	1.9 in (48.26 mm) OD schedule 40 pipe	2.469 in (62.71 mm) ID schedule 40 pipe	2.469 in (62.71 mm) ID schedule 40 pipe	5.047 in (128.19 mm) ID schedule 40 pipe
Startup Wind Speed	8 mph (3.5 m/s)	6 mph (2.68 m/s)[1]	7.5 mph (3.4 m/s)	7 mph (3.1 m/s)	7.5 mph (3.4 m/s)
Survival Wind Speed mph	140 mph (63 m/s)	110 mph (49.2 m/s)	120 mph (54 m/s)	120 mph (54 m/s)	120 mph (54 m/s)
Voltage	120-240 VAC 50-60 Hz	12, 24 and 48 VDC	12, 24 36, or 48 VDC	12, 24 36, 48 VDC (high voltage avail.)	24. 32, 48 VDC (high voltage avail.)
Overspeed Protection	Patented electronic stall regulation[2]	Patented electronic stall regulation[2]	Patented side-furling[2]	Patented side-furling[2]	Patented side-furling[2]
Weight (turbine only)	170 lb (77 kg)	13 lb (5.9 kg)	47 lb (21 kg)	65 lb (30 kg)	155 lb (70 kg)
Warranty	5 year limited	3 year limited	5 year limited	5 year limited	5 year limited
APPLICATION	🔋 🔌	🔋	🔋	🔋	🔋
Remote Home/Cabin	🏠	🏠	🏠	🏠	🏠
Seaside Home/Cabin	🌊	🌊	🌊	🌊	🏠
Sailboats		🌊			
Water Pumping				🏠 🌊	
Island Electrification	🌊	🌊	🌊	🌊	🏠
Village Electrification	🏠 🌊	🏠 🌊	🏠 🌊	🏠 🌊	🏠
Remote Monitoring	🏠	🏠	🏠	🏠	🏠
Offshore Platforms	🌊	🌊	🌊	🌊	🏠
Eco Resorts	🏠 🌊	🏠 🌊	🏠 🌊	🏠 🌊	🏠
Remote School/Clinic	🏠 🌊	🏠 🌊	🏠 🌊	🏠 🌊	🏠

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1. Data collected by the North Carolina Small Wind Initiative/Appalachian State University. Small Wind Research and Demonstration Facility, Beech Mountain, NC, USA. 2. Additional US and international patents pending. ♻Printed on recycled paper with vegetable inks using 100% wind power.

Figure 94: South West wind products at a Glance.

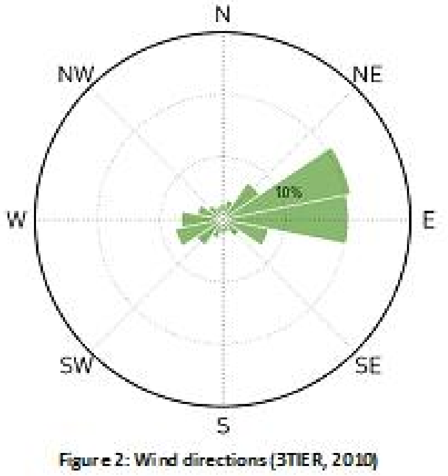

Figure 2: Wind directions (3TIER, 2010)

Figure 95: 3Tier wind rose at Sarfannguaq.