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Wind power in Antarctica
– a feasibility study for Wasa

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Wind power in Antarctica - a feasibility study for Wasa

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Abstract

The Swedish Polar Research Secretariat maintains two research stations in Antarctica, Wasa and Svea. They are both small, summer-only stations that are manned a few months at a time during the regular expeditions to the continent. Recently, Swedish scientists asked for the possibility to make around-the-year measurements with automatic equipment at the two stations. Since Wasa and Svea are only manned occasionally, this request implies the need for a new power supply system. The demands imposed on this new, separate system are hard. The continent is the coldest, windiest and driest on earth and the power supply system must be designed to withstand the harsh conditions. Since there is no personnel present during the Antarctic winter, the system also has to be autonomous and very reliable.

The environment in Antarctica is sensitive and protected by strict regulations that all members of the Antarctic Treaty are obliged to follow. More and more nations are revising their power supply systems in order to find substitutions for the conventional diesel generators, and wind power has been installed at several stations and has worked well in many cases. This master thesis project is a feasibility study aimed at investigating whether wind power is a convenient solution in a separate power supply system at Wasa.

During the project, wind data from weather stations in Antarctica have been used to map the wind resources at the two research stations. Although more accurate wind measurements would be needed for a complete evaluation of the wind resources, it can be seen that the prerequisites for wind power are good at Wasa. The wind is very directional, the wind speeds are moderate and the temperatures not too low. A wind turbine modified for the climate in Antarctica should function well at Wasa, in combination with a battery bank with NiCd batteries.

Two turbines that fulfil most of the demands imposed on them and that seem to perform well in the conditions at Wasa were found, one 6 kW unit and a smaller 1 kW turbine. The choice between the two different models is a compromise between the benefits of a system with a few large turbines and the benefits of a system with a greater number of small units.

Contents

Part I
Introduction

1 Introduction

The Swedish Polar Research Secretariat is a government agency that promotes and organises Swedish research in the polar areas. It is responsible for giving Swedish scientists and companies access to Antarctica and the Arctic, and co-operates with universities and organisations involved in polar research programmes. The secretariat maintains the research stations Wasa and Svea in Antarctica. Both stations are summer-only facilities that are occupied just a few weeks during the regular expeditions to the continent.

Recently, Swedish scientists asked for a possibility to make around the year measurements at the stations. Since Wasa and Svea are unoccupied the larger part of the year, this request means that a new, autonomous power supply system would be needed to provide the measurement equipment with power. The remote locations and harsh conditions at the stations impose high demands on the power system. Besides from being autonomous, it has to be extremely reliable to ensure continuous measurements and it should have a minimum need for maintenance. Since transportation is a complicated matter in Antarctica, the equipment needed must also be easy to transport. The system must be able to withstand the climate in Antarctica and be cheap enough for the limited budget of this project. It also needs to be environmentally friendly, since the Antarctic environment is very unique and protected by strict regulations.

Wind power has many of the qualities requested above, and is one of few alternatives that are possible to implement in Antarctica. Fossil fuels should be avoided because of the emission of pollutants, which means that the conventional diesel generator is not an attractive solution. Fuel cells are expensive and still not fully developed. A system with photovoltaic cells can be used during the austral summer but is not an option during the dark winter months, and all kinds of nuclear activities are forbidden according to the Antarctic Treaty.

Although wind power seems like one of the most advantageous options for a new power supply system, there are difficulties that have to be solved. The turbine has to be designed to withstand extremely cold and strong winds. The demands on the turbine are discussed in this thesis, as well as possible solutions to problems that can occur due to the climate. The report is also an attempt to summarise earlier experience of wind energy in Antarctica, to evaluate the wind conditions at the stations and to give a foundation for a decision on whether to install wind turbines at Wasa.

2 Objective

The objective of this project is to investigate the feasibility of using wind turbines at the Swedish research station Wasa in Antarctica. The station has presently a power supply system consisting of diesel generators, photovoltaic cells and a battery system. This system is operated during the austral summer only, when the station is manned. The objective is not to replace this system, but to investigate whether wind power could be used in a separate, autonomous system that would provide automatic measurement equipment with power around the year.

Several other countries have performed assessments of the potential for wind energy harnessing in Antarctica. These studies have mostly been aimed at reducing the dependency on fossil fuels and/or lower the costs for energy production, a cost that is normally high at the Antarctic research stations. The objective of this survey is different, since the intention is not to replace or extend an existing power supply system. This means that the amount of power needed will be significantly smaller than for most other stations, and that the demands on our system will differ from demands imposed on bigger systems. While other countries need solutions that will be economically beneficial, this is not the main demand on the Swedish system, although a low cost is of course preferred. More important is a reliable system that ensures a continuous and sufficient production of energy.

The intention was originally to investigate the feasibility for wind power at both Wasa and Svea, but since the data set from the weather station close to Svea was too incomplete for the design of a power supply system, focus has been put on Wasa.

The amount of energy that will be needed for the automatic measurements is not known exactly, since different measurements will take place every year. It has been said that one or a few kW would be sufficient, and that the research conducted would have to be adjusted to the amount of energy available. During this project, the rated powers of the evaluated turbines have ranged between 1 and 6 kW.

A brief introduction to the technique used when harnessing energy from the wind is given in the beginning of the report. This is not aimed at giving a complete explanation of wind energy systems, but to give the reader a picture of the wind energy basics. The interested reader will find more information in the literature listed in the references. The same is true for the short introduction to Antarctica and the explanation of wind patterns.

3 Methodology

The main method used during the first part of this project has been to search for existing reports and relevant literature, which has been read, evaluated and summarized in the report. Databases, books, e-mail and Internet have been used for this purpose. Contact has been established with people from most national polar research programs to investigate if wind power has been used at their stations or if wind power feasibility studies have been conducted.

During the second part of the project, data were analyzed to evaluate the wind resources and weather conditions at Wasa. Large amounts of data were treated and Matlab® was used to perform the calculations and to create graphs.

A market investigation was performed and different turbine models were evaluated and compared. The expected yearly energy production was calculated, as well as capacity factors and other relative variables.

Based on information gained during the entire project such as

- Experience gained during early attempts to use wind energy in Antarctica
- Experience from present installations and surveys carried out recently
- Site specific weather conditions and wind resources
- Information from manufacturers of wind turbines
- Knowledge about cold climate issues
- Economics

the report has eventually resulted in a concrete suggestion on what kind of turbine that would be appropriate for the needs at Wasa.

Part II
Theory

4 Antarctica

The Antarctic is the coldest, windiest and driest continent. It is also the highest elevated continent, with an average height of 2300 meters, more than three times as high as most continents. Approximately 98 percent of its surface is covered by an ice cap that contains almost 70 percent of the world's fresh water resources. If the ice would melt, the ocean level would rise with almost 70 meters. Since ice reflects more than 80 percent of the incoming radiation from the sun, this explains why the continent is so cold. The yearly average temperature is almost $-40\,^{\circ}\mathrm{C}$, and the coldest ever temperature on earth, $-90\,^{\circ}\mathrm{C}$, has been recorded at Vostok station in Antarctica. The continent has an absolute humidity lower than that of the Sahara Desert, which makes Antarctica the world's biggest desert. Today there are more than 70 research stations on the continent. [11, 12]

4.1 Historical Background

The Greek philosophers during the antique understood that the earth was spherical after observing that the stars circled the poles. They predicted the existence of a continent in the Southern Hemisphere that would act as a counterweight for Arctica, a continent that Ptolemaios and other famous philosophers explored approximately 150 A.C. They called this theoretically predicted continent "terra australis incognita", or Antarktos. Many attempts to find the undiscovered continent were made. The famous explorer James Cook crossed the Antarctic Circle, but he did not spot the continent. Instead, he found resources such as whales and seals, a discovery that lead to an extensive hunt that nearly extinguished the species in the area. Antarctica was finally discovered in the 1820's, when at least three different expeditions claimed to have found the continent.

In the end of the 19th century, many Antarctic expeditions took place. There was a lot of prestige in polar research, and researchers competed for the money given out by governments for expeditions to the South Pole. The explorers were celebrated as heroes when returning from their adventurous journeys.

In 1911, the Norwegian Roald Amundsen was the first man to reach the geographical South Pole. Robert F. Scott, from England, arrived only a few weeks after Amundsen just to find the Norweigian flag at the pole and realise that he had been defeated by his competitor. Scott's expedition, as many others during this time, ended in disaster when all the men who had accompanied him during his attempt to reach the pole died. Today, the conditions for polar research are totally different and it is possible to perform advanced scientific research in Antarctica. [11, 13]

4.2 Swedish Research in Antarctica

Sweden has a long tradition of polar research, although it has been focused on the Arctic instead of Antarctica due to the distance. The first Swedish expedition to Antarctica took place in 1901-1903 under the command of Otto

Nordenskiöld. In 1949-1952, a large expedition to Dronning Maud Land was arranged by Sweden, Norway and Great Britain. SWEDARP, (Swedish Antarctic Research Programme) started in 1987/88, when a small research station, Svea, was built in Dronning Maud Land. One year later the station Wasa was built and since, expeditions have been organised regularly.

The Swedish Polar Research Secretariat was founded in 1984. It is a government agency with the purpose to promote and organise Swedish polar research. The secretariat is responsible for giving the Swedish scientists and companies access to the Arctic and Antarctica, and maintains the research stations Wasa and Svea in Antarctica. The secretariat does not perform research in the polar areas, but co-operates with universities and other organisations involved in research programmes. [13]

4.3 The Swedish Research Stations

There are two Swedish research stations in Antarctica, Wasa and Svea. **Svea** was built in 1987-88 in the Heimefront Range at (74°35'S, 11°13'W). It is a small station, with four beds and a pantry. It consists of two joined glass fibre modules. The station is used periodically during the austral summer season.

Figure 1: The research station Svea.

Wasa was built one year later and is located at the nunatakk Basen, at (73°03'S, 13°25'W). This is where the inland ice transits to shelf ice and the nunatakk would, if there was no ice, face the ocean. The station is built 460 meters above the sea level, on the south slope of the 580 m high mountain. It is a relatively small station consisting of nine buildings. In addition to the main building, which is called the Radio House, there are four living modules, a generator house, a workshop, a garage and a laboratory module. The Radio House consists of four bedrooms, a common room, a kitchen, a sauna, a shower and a laundry room. The station can accommodate up to 30 people using the mobile living modules, but normally only 12-16 people live at the station. The station is built on 1.5 m high poles in order to avoid the accumulation of drifting snow.

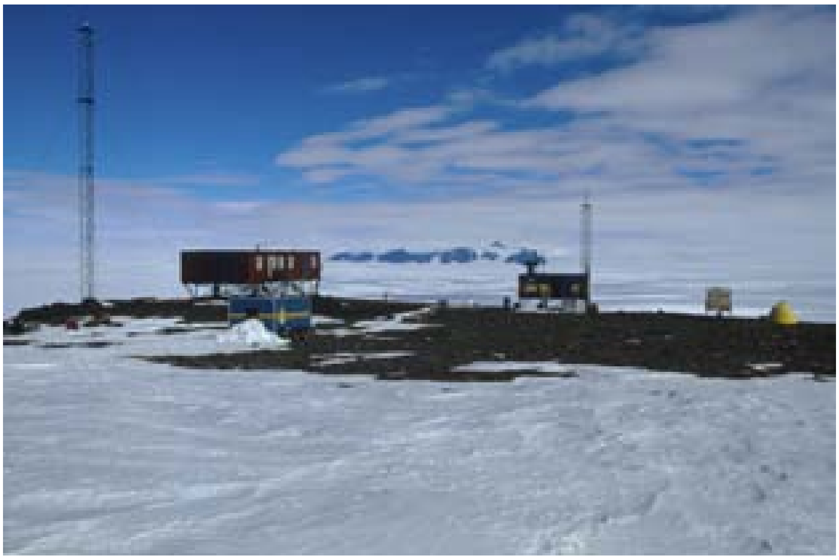

Figure 2: The research station Wasa. Picture: A. Modig

Originally, diesel generators produced all energy used at Wasa station. After a revision of the energy system, two LPG (Liquefied Petroleum Gas) generators were installed in 1996. These generators did not provide enough power, and are not in use today. Solar panels, 48 units with an output of 55 W each, provide the station with most of the energy consumed. The diesel generators are still used, but only as a back-up system. The 20.6 m^2 of solar panels charge a set of Ni/Cd-batteries stored underneath the main building. The battery bank has a total charge capacity of 1200 Ah and deliver electric power at 24 V. The energy produced by the solar panels is used for electrical equipment such as computers and communication equipment, and cover 95% of the energy needed for this purpose.

The climate in the area is characterized by low temperatures, low humidity and sparse precipitation. During the summer months, the temperature varies between $0\,^{\circ}$C and $-20\,^{\circ}$C, and the wind speed ranges from 2 m/s to 50 m/s. During the winter, the average temperature is approximately $-20\,^{\circ}$C and wind speeds up to 57.6 m/s have been measured. The direction of the wind is mainly north easterly. [13, 14, 15, 16, 17]

4.4 The Antarctic Treaty

The Antarctic Treaty is a unique legal agreement ensuring that member countries work together in Antarctica for peaceful and scientific purposes.

In the beginning of the 20th century, Great Britain was the first country to claim territorial sovereignty in Antarctica. The following decades, a number of other nations followed, among them Argentina, Chile, France and Norway. The

United States of America and the old Soviet Union decided not to recognise any other state's right of claim to territorial sovereignty. Disputes raised and the need for an agreement became obvious, especially as the conflict between Argentina and Great Britain, who claimed overlapping territories, grew deeper. During the Second World War, Antarctica became interesting for reasons of security policy, even more after the American expedition "Operation Highjump" in 1946-47, an expedition in which scientific research was combined with military exercise. The US established a base at the South Pole in 1956, while the USSR established several bases all over the continent. Nations realised that without a legal system, disputes could not be resolved. In 1957-58, during the International Geophysical Year, the twelve countries that cooperated on global scientific research in Antarctica suggested that the co-operative spirit and peacful use of Antarctica as a giant scientific laboratory should be continued. Hence, the Antarctic Treaty was drawn together. The Antarctic Treaty was signed by these twelve countries in 1959, and came into force on June 23rd 1961. In May 2004, the Treaty had been signed by 45 countries. 28 of these countries are Consultative Parties, 17 Acceding States. Consultative status can be gained by any country who has demonstrated commitment to the Antarctic by conducting significant research by building a research station in Antarctica or by arranging expeditions to the area. Sweden became a consultative party in 1988.

The Treaty covers everything south of 60 °S, and its main objectives are

- to demilitarise Antarctica, and to establish it as a zone where nuclear weapons and disposal of radioactive waste are prohibited
- to promote international scientific co-operation in Antarctica
- to set aside disputes over territorial sovereignty

A Protocol on Environmental Protection to the Antarctic Treaty and four other international agreements, have been added to the original Treaty [13, 16, 18].

5 The Wind

5.1 Global Wind Patterns

The wind is produced by the heat of the sun. When radiation from the sun reaches the earth, the air surrounding the planet and the earth itself is heated. Since the angle of attack is smaller far from the equator than close to it, the planet and the atmosphere are unevenly heated. Areas close to the equator are warmer than areas at greater latitudes. Clouds also contribute to variations in temperatures between different locations, by stopping some of the radiation from reaching the surface of the earth during daytime and preventing the planet from cooling down during the night. Since the sea absorbs more heat and is cooled down more slowly than land areas, the geography of the planet is another reason for the uneven heat distribution, which is the main cause of wind.

A pressure gradient arises that causes the air to move from high-pressure areas towards areas with lower pressure. The gravitational force normally cancels the vertical component of the pressure gradient force, causing the wind to blow predominately in the horizontal direction. Warm air is less dense than cold air and thus, warm air rises at the equator while cold air sinks close to the poles. The warm air drifts north or south until the movement ceases about 30 °N and 30 °S, when the air has been cooled down and sinks towards the ground. The cool air travels back in the lowest layers of the atmosphere, and the cycle is repeated. [3]

The Coriolis force, F_c, is a fictitious force caused by measurements with respect to the rotating reference frame. It is defined as $\overline{F_c} = f\overline{U}$ where $\overline{U}$ is the wind velocity and f is the Coriolis parameter defined by $f = 2\omega sin(\phi)$ where ϕ represents the latitude and ω is the angular rotation of the earth.

The Coriolis acceleration acts perpendicularly to the motion of the wind and deflects the flow to the right on the Northern Hemisphere and towards the left on the Southern Hemisphere. [4, 5] The effect of the Coriolis acceleration is zero close to the equator, and large at the poles. Thus, the wind blowing far from the equator is more deflected due to the Coriolis force than the wind close to the equator. This phenomenon in combination with the ice-skater effect described below causes the atmospheric motion above Antarctica to be characterised by westerly winds at high altitudes and easterly winds close to the ground. [3, 6]

The ice skater effect, an increase in the rate of rotation when the skater's arms are contracted and vice versa, could be applied on bodies of gas as well as rigid bodies. Sinking motion is associated with an inflow of air at high altitudes and an outflow of air in the lower layers. Rising motion is associated with an inflow of air at low levels and an outflow at higher altitudes. Around the pole, air is constantly cooled. Since cool air is denser than warm air, the air starts to sink creating an inflow of air at upper levels and an outflow at lower levels. Due to the Coriolis effect, which deflects the wind in the Southern Hemisphere to the left, air flowing inwards forms a clockwise spiral and the outward flow forms an anticlockwise spiral. This explains why the atmospheric motion above Antarctica is characterised by westerly winds at high altitudes and easterly or north-easterly winds close to the ground. The process is less legible during the summer, when more radiation from the sun reaches the continent and the air is warmer.

The centrifugal force acts in the same direction as the Coriolis acceleration,

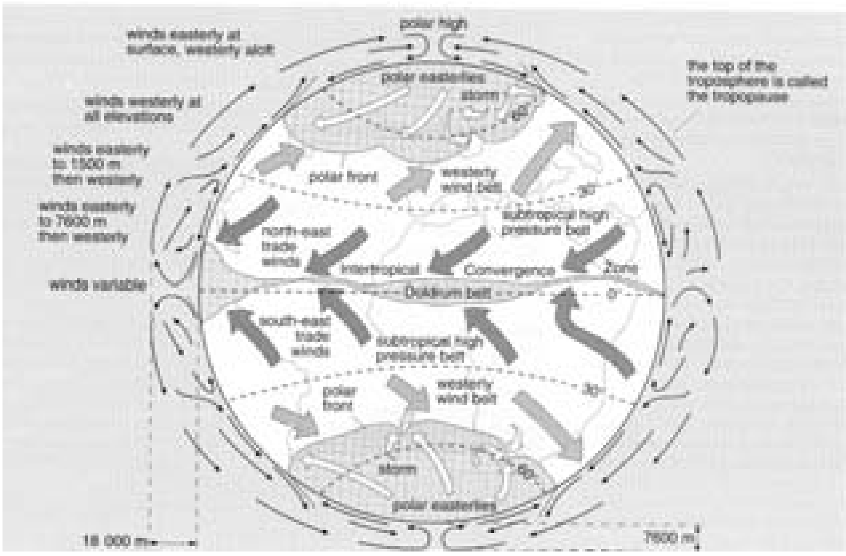

Figure 3: A simplified model of the world wind circulation. **Source:** Renewable Energy - Power for a Sustainable Future, Boyle 1996

but is weaker and does not contribute much to the deflection of the flows. The inertia of the air when the earth rotates also affects the wind.

5.2 Local Wind Patterns

Gravity and friction are other forces that affect the wind, gravity by pulling the air particles towards the ground and friction by slowing the wind down close to the ground. Where there are many trees and other obstacles the friction force is high and slows down the wind more than in areas with smooth terrain. Not only the speed is changed, but also the direction of the wind since the friction force affects the balance between the pressure gradient force and the Coriolis acceleration. Thus the friction force and the gravity contribute to small-scale changes in the wind. [5, 2]

5.3 The Wind in Antarctica

Although the wind on the Antarctic high plateau can be rather moderate, the air often moves with a tremendous speed close to the coastline. This high velocity wind is called the katabatic wind and is a gravity-driven phenomenon. The lowest layers of the atmosphere are in contact with the extremely cold ice cap, which cools the air to very low temperatures. Cool air is denser than warm air and the air contracts and becomes even heavier when it starts moving under the effect of the incline of the ice cap. As long as the slope is not too steep, the prevailing wind direction in the region is easterly as described above and the wind moves almost parallel to the contour lines of the ground. At this point, the winds are called inversion winds. When the wind approaches the coastline, the slopes are steeper and the wind accelerates to great speeds. As the speed is increased, the air starts following the line of greatest slope, which is from south to north. These high velocity winds are called katabatic winds from the Greek word katabasis that means descend. Katabatic winds could be observed at any latitude where the course of the cooled air meets a significant slope, but they are nowhere as strong as they are in Antarctica. The katabatic winds are especially active during the winter. [7, 8]

5.4 Wind Shear

Close to the surface of the earth, the air particles move randomly and the resultant velocity of the air is zero. The velocity of the wind increases with height, most rapidly close to the ground and slower with greater height. The extent of this phenomenon depends on the roughness of the terrain and is more obvious in areas with a higher surface roughness, i.e. a greater friction between the air and the ground. At a height about 2 km above the ground, the wind speed does no longer change with increased height.

When investigating the wind energy potential at a site, one is interested in the velocity of the wind from a few meters above the ground to a height of approximately 100 meters. Based on experience, different functions to determine the wind speed profile, i.e. the vertical variation of the wind speed, have been developed. Two of the most common functions are the Power law profile and the Logarithmic profile, both developed for flat and homogenous terrain.

Power law profile
The wind speed at height z, V(z), is given by the expression

$$V(z) = V_r \left(\frac{z}{z_r} \right)^{\alpha} \tag{1}$$

where z is the height above the ground, V_r is the speed at reference height z_r above the ground level and α is the surface roughness exponent. [3, 5, 9]

Logarithmic profile
Similarly, the wind speed at height z, V(z), is given by

$$V(z) = V_r \left(\frac{ln(\frac{z}{z_0})}{ln(\frac{z_r}{z_0})} \right) \tag{2}$$

where V_r is the speed at reference height z_r and z_0 is the surface roughness length, which characterises the roughness of the terrain. [3]

Terrain Description	Surface roughness exponent, a	Surface roughness length, z_0 [mm]
Very smooth, water or ice	0.10	0.01
Snow surface	-	3.00
Low grass	0.14	8.00
Rural with obstacles	0.2	250.00
Suburb	0.25	1500.00

Table 1: Surface roughness exponents and lengths for different ground conditions

5.5 Turbulence

The instantaneous wind speed u can be described by the expression

$$u = < u > + \widetilde{u}$$

where $< u >$ is the mean wind speed and $\widetilde{u}$ is a fluctuating wind component. Although the wind might have a relatively constant mean speed over a period of an hour or longer, the instantaneous velocity can fluctuate significantly due to turbulence. Turbulence can be described as random fluctuations in speed and direction imposed on the mean wind and it is caused by dissipation of the wind's kinetic energy into thermal energy. The kinetic energy is transformed into heat via the creation and destruction of progressively smaller eddies or gusts. [5] The change in surface roughness is often the cause of turbulence. For example, when wind from the sea meets the coastline, the wind closest to the ground is slowed down by the increase in friction and eddies are created. The turbulent wind behind a wind power turbine is called a wake. It could affect the wind speed to a distance of ten rotor diameters. [2] The turbulence does not contribute to the power production of a wind turbine, but should be investigated and quantified for design applications based on maximum load and fatigue prediction, structural excitations, control design and system operation. [5]

5.6 Available Wind Power

The energy contained in the wind is kinetic energy, which is given by the expression

$$E = \frac{mv}{2}$$

where m and v is the mass and the velocity of a given volume of the wind, respectively. The kinetic energy flow per unit time, i.e. the power, is given by the expression

$$P = \frac{1}{2}\frac{dm}{dt}v^2 \tag{3}$$

The mass flow of the air through the rotor with area A is

$$\frac{dm}{dt} = \rho A v \tag{4}$$

Equations (1) and (4) combined give an expression for the power of the air that flows through the disc

$$P = \frac{1}{2}\rho A v^3 \tag{5}$$

The actual power production potential of a wind turbine is not equal to the power contained in the wind. Since the air is flowing freely, it would be stopped before the turbine if the air behind the rotor had a velocity equal to zero.

The power potential of the air is proportional to the density of the air. In cold climates, the density is increased and the air contains more energy. This fact is important to remember when designing wind turbines for cold climates, since a higher power potential means heavier loads and increased risk of fatigue damage. In Antarctica, this effect is partly reduced by lower atmospheric pressure, since the density is proportional to the pressure. The atmosphere tends to bulge at the equator due to the rotation of the Earth, which means an increase in pressure at the equator and a decrease at the poles.

5.7 Obstacles

According to the most basic classification, terrain is divided into flat and non-flat terrain. Flat terrain is smooth terrain with few irregularities such as forests and large-scale elevations or depressions. Non-flat, or complex, terrain has irregularities such as those described above, canyons, hills, ridges and valleys. This kind of terrain can be divided into two categories, isolated terrain and mountainous terrain, with small- and large-scale irregularities respectively. The flow in terrain with large-scale features such as valleys and canyons, mountains and ridges is complicated to predict and few quantitative flow predictions have been made. The flow over isolated features such as ridges is easier to predict, and resembles the flow around obstacles. The slope of the ridge, its orientation and shape are important parameters when predicting the suitability for locating a wind turbine on the ridge. A region of high wind shear is created on top of a flat-topped ridge due to the separation of the flow. [5] The flow over smooth hills can be accelerated or decelerated depending on the slope. When the hill is too steep, with a slope greater than approximately 40%, turbulence is created and the speed of the wind is decreased. The flow around hills that are smooth and not too steep is accelerated until a certain height, and decreased on the other side of the hill. This means that locating a wind power turbine on top of a hill can be advantageous, if the hill is smooth and has a slope that is not too steep. In flat terrain, houses and other man-made objects are often approximated by rectangular blocks, and a common approach is to consider the flow around the object to be two-dimensional. [5] The flow is affected a long distance after the obstacle, but also the flow before the obstacle is affected, when the wind is slowed down. [2]

Figure 4: The flow around obstacles. The grey area indicates where strong turbulence occurs, the direction of the wind is according to the arrow. **Source:** Vindkraft i teori och praktik, Wizelius 2002

5.8 Wind Measurements and Instrumentation

When estimating the wind energy potential at a site, the mean wind speed as well as the turbulence, wind direction, temperature and pressure have to be measured and quantified. The measurements have to take place over a longer period of time, since the conditions vary between seasons, years and even longer periods. The amount of energy contained in the wind can differ with up to 30% from decade to decade. [2]

The wind speed is measured with an anemometer, a device that comes in different models. The two most common models are the cup anemometer and the propeller anemometer. Both models use their rotation, which is proportional to the wind speed, to generate a signal that is measured by photoelectrical switches, mechanical counters registering the number of rotations or voltage changes. Cup anemometers, usually devices with three cups on a small shaft, use the drag force in the wind to rotate. The cups can never move faster than the speed of the wind, unlike the blades in a propeller anemometer. This can be a disadvantage in cold climates where icing occurs, since a higher tip-speed ratio decreases the risk of icing. A number of problems such as icing or blowing dust can reduce the reliability of cup and propeller anemometers. In Antarctica, where ice blasting is common, ice crystals can lodge in bearings and cause an increase in friction, reducing the accuracy of the measurements. For areas where icing is common, heated anemometers are available and should be used. [10] These heated models have the disadvantage of requiring a separate power source, thus eliminating one of the main advantages of the simple cup and propeller anemometers.

A third model of anemometer is the sonic anemometer, which is based on the principle of acoustic backscattering. Acoustic pulses are transmitted from the anemometer and backscattered from small temperature inhomogeneties in the air. The recorded Doppler shift in the frequency is proportional to the wind speed along the beam axis. This kind of anemometer has no moving parts, which is an advantage in the low temperatures in Antarctica. [3]

Wind vanes are used for measuring the wind direction. Icing, blowing dust, salt and other environmental problems affect the accuracy of wind vanes as well. For temperature measurements in cold climates, thermometers adjusted for extreme conditions should be used.

6 Wind Energy Basics

6.1 Historical Background

People have used the wind as a source of energy for thousands of years. At first, the wind was only utilised for sailing. The old Greeks used sailing boats for transportation, but the rudder had not yet been invented, meaning that a number of men were needed to steer the boats in the correct direction, and the wind was not used very efficiently.

The first well-documented windmill was built in Persia 947 AD. It had a vertical axis on which a number of vertical screens were mounted. One half of the rotor was covered to make it start rotating, a model that was possible to use since the wind in this area varies according to a regular pattern and the wind direction stays almost constant for long periods of time. The only way to regulate the mill was to close a gate in front of the rotor to stop it when the wind was too strong. The first European windmills were constructed in the end of the 12th century in the Mediterranean area. These mills had a horizontal axis instead of a vertical, a solution far more complicated than the one mentioned before. To be able to extract energy from the wind, the rotor has to be turned towards the incoming wind. The use of a gearwheel was necessary because the axis of the mill stones had to be vertical.

During the 13th century, wind power underwent a great technical evolution and soon became one of the most important sources of energy in Europe. The rotor diameter was increased as well as the power of the mills. In the middle of the 19th century, there were more than 20 000 mills in France, 3 000 in Denmark and a great number in the rest of Europe. Before the steam engine was taken into use, wind power supplied half of the energy consumed in Europe, waterpower the other half. The mills in Europe had a maximum total effect of 1500 MW, a level that was not reached again until in 1988. In America, wind power was used for water pumping and was important to people living on the prairie, far from rivers and lakes. It also played a great role during the construction of the railway through the country. Since the trains were powered by steam engines, access to water was necessary along the route and the wind pump made it possible to travel greater distances. The pump was also important in the Netherlands, were it helped drain large parts of the country, increasing the land area. Even today, there are some million wind pumps in use around the world.

During the 1930's wind power came to play another role. As electrical devices such as the radio were invented, there was a growing demand for electrical power. For people living on the countryside far from the rare electrical grids, wind power was used for battery charging. This way of using the energy in the wind is still in use in locations far from electrical grids, for example on oilrigs and distant locations such as the polar areas. During the late 20th century, the need for new energy sources was growing and people started realising that the supply of fossil fuels was not unlimited. The oil crises catalysed the need to find alternative energy sources, sources that were environmentally friendly, cheap and reliable. Wind power was one of the alternatives that came up, and since then, wind power has gone through a major technical improvement. [1, 2]

6.2 Technology

6.2.1 Turbine Design

Drag or lift devices
There are two different types of wind energy converters, those that depend mainly on aerodynamic lift and those that depend mainly on aerodynamic drag. The latter kind of device is normally a low speed machine, its rotor blades move slower than the wind. The torque at the rotor shaft in a drag device is high compared to the torque in a lift device, which is normally a high-speed machine. The rotor blades in a high speed wind turbine normally move several times faster than the wind. This type of turbine has a higher aerodynamic efficiency, and generally extracts considerably more power than a drag type turbine. The high speed, which is desired for the generation of electricity, and the efficiency of the lift devices are the main reasons for utilizing turbines that rely on lift in stead of drag devices for electricity production. Windmills and other traditional devices such as water pumps are examples of low speed turbines that rely on drag. [3, 5]

Vertical or horizontal axis turbines
Wind turbines can also be divided into horizontal-axis (HAWT) and vertical-axis wind turbines (VAWT). The modern VAWT has a number of advantages such as operating independently of the wind direction, meaning no yawing system is needed, and the possibility of situating gearbox and other heavy equipment at ground level. In addition to this, there is no fatigue stress on the blades due to gravitational forces. There are also a number of disadvantages. For example, the turbines are not easily self-starting, the torque fluctuates with each revolution when the blades move into and away from the wind and regulating the speed in high winds can be difficult. The VAWTs are less common than the HAWTs, and less developed. They have so far proven to be less cost-effective than the horizontal-axis turbines, which is one of the main reasons that more research has been performed on HAWTs than on VAWTs.

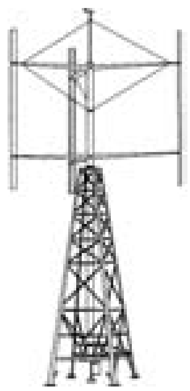

Figure 5: An example of a vertical axis turbine. **Source:** Vindkraft i teori och praktik, Wizelius 2002

Variable or constant speed
The turbines can be classified depending on whether the rotor is allowed to run

at variable or constant speed. For large-scale turbines connected to an electrical grid with a fixed frequency, a constant rotor speed is most common. In turbines used for battery charging and other small-scale operations, a variable rotor speed is most favourable. These variable-speed turbines could be used for electricity generation in connection with a power electronic frequency converter. Variable-speed turbines have an increased aerodynamic efficiency compared to constant-speed machines. This can be seen when plotting the power coefficient C_p, see appendix I, against the tip speed ratio, i.e. the blade tip speed through the speed of the undisturbed wind. In such a graph, it can be seen that the maximum power coefficient is achieved at a particular tip speed ratio. By allowing the rotor to run at variable speed, the tip speed ratio could be optimized for maximum efficiency independently of the wind speed. In a constant speed machine only a specific wind speed will lead to a high efficiency. [3]

Upwind or downwind turbines
Finally there are upwind turbines and downwind turbines. Downwind turbines do not need a yaw orientation system since they self-align with the wind, but they suffer from the effect of tower shadow. Each time a rotor blade passes the tower there will be a slight drop in power that can cause fatigue damage. Upwind turbines have an active yaw orientation. This solution is technically more complicated, but has many advantages over the passive yaw orientation system. When the turbine has rotated a number of times in the same direction, the cables inside the tower need to be untwisted in order to avoid cable breaks. With an active yaw orientation system, the rotor is stopped and the turbine is rotated in the opposite direction. In a downwind turbine without active yaw, the problem with twisted cables is more difficult to solve. Downwind turbines are also noisier than their upwind counterparts. Today, the upwind turbine is the most common model. [5]

6.2.2 Power Regulation

There are basically three ways of regulating the power when the speed of the wind is too high. The most common principle is pitch-regulation, but there is also stall-regulation. In pitch-regulated machines, the rotor blades can be rotated around their long axis. When the wind speed is above the rated speed, the blades are rotated so that the angle of attack is decreased and the power does not exceed rated power. In this way, the loads on the turbine are reduced. When the speed of the wind exceeds the safety stop wind, the blades are rotated even more, and the rotor stops since the lift force no longer affects the blades. [5, 2]

Stall-regulated turbines have fixed blades with a profile that creates turbulence on the upper side of the blade as the wind exceeds the rated speed. This causes a decrease in lift and increase in drag, and the rotor is slowed down. Designing a rotor blade for optimum stall regulation is difficult, and the stall effect will be noticeable even at lower wind speeds. Turbines with active stall, where the blades are rotated to increase the angle of attack and thus increase the effect of stall have been developed. [2]

Yaw control, also denoted furling, is a third possibility for regulating the power in high winds. This principle is very simple, the rotor is rotated horizontally out of the wind. This control method is rare on larger electricity-generating wind turbines. [3]

6.2.3 Turbine Parts

A brief description of the main components of a turbine, shown in figure 6, will be given below. Only horizontal-axis turbines will be considered in this discussion, since most research about wind turbines have been done on this type of machine, and because it is the most common type of wind turbine.

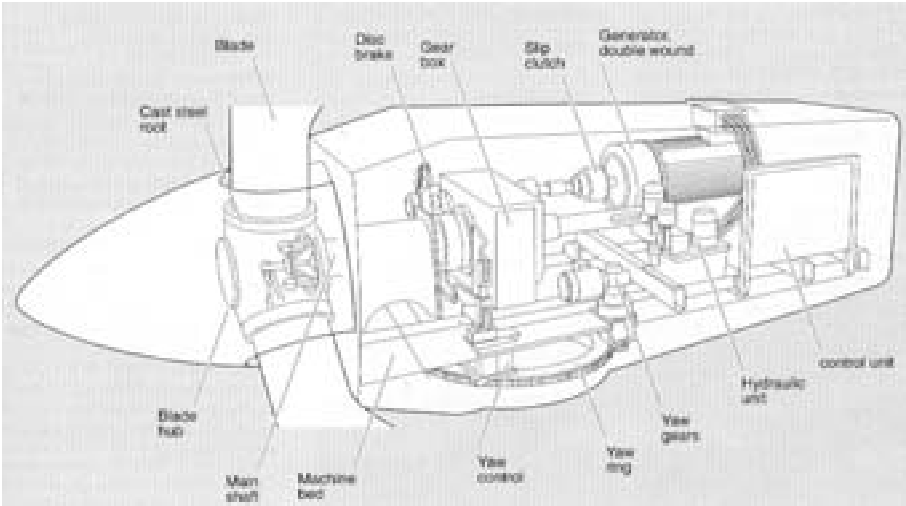

Figure 6: The machinery and nacelle of a Vestas V27/225 kW wind turbine. Source: Renewable Energy - Power for a Sustaiable Future *edited by G. Boyle* Oxford University Press.

The rotor

Most turbines have two or three rotor blades, although there are also single-bladed models with a counterweight for balance. The rotor blades are expensive, and fewer blades lead to a cheaper wind turbine. However, a rotor with two blades will have to rotate faster in order to extract the same amount of energy from the wind. This increase in tip speed ratio also means an increase in noise, and an aesthetically less pleasing solution. In addition, the forces are more evenly balanced in a three-bladed rotor than in a two-bladed one. This has led to a tendency to choose three-bladed rotors over two-bladed or single-bladed models.

Rotor blades have been constructed from glass reinforced plastic, solid wood, wood laminate, carbon fibre reinforced plastic, steel and aluminium. Blades made of glass reinforced plastic are most common today. When selecting material for the blade, fatigue strength, weight, processing costs, stiffness, noise and design difficulties are factors that have to be considered. [3] Designing the rotor blades for optimum aerodynamical performance is very difficult, and will not be discussed in further detail. More information about this topic can be found in [5].

Drive train
The drive train, or the transmission system, transmits the power generated by the rotor blades to the generator. The system is located in the nacelle, and consists of the rotating parts of the turbine; the gearbox, couplings, generator and a braking system to bring the rotor to rest. In some models, there is no gearbox. This can be advantageous in remote locations with harsh climate, since the gearbox often causes maintenance problems. [3, 5]

Generator
A generator converts the mechanical power produced by the rotor into electrical power. There are two types of generators used for wind energy applications, synchronous and asynchronous generators. A synchronous generator operates at the same frequency as the network to which it is connected. An asynchronous generator, also called an induction generator, rotates at a frequency that is slightly higher than the frequency of the network. Synchronous generators are somewhat more effective than the induction generators. More information about generators can be found in [5]. For wind turbines without gearboxes, there are large-diameter direct-driven generators that rotate with the same speed as the rotor blades. Their design allows them to generate at the required frequency. [3]

Control and monitoring system
For operation and protection of the turbine, an automatic control system is needed. The system is used to monitor power production, wind speed, operational status etc. It also controls start-up, shutdown and the blade pitch mechanism. The control system has to be protected from extreme temperatures, rain, ice and drifting snow.

Braking system
In high winds, the forces acting on the turbine components are too high and the rotor has to be slowed down and the power be limited. Normally, there are two separate braking systems in a wind turbine, each capable of bringing the turbine into a condition that ensures safe turbine operation. One of the braking systems is normally a mechanical brake, which is pneumatically, hydraulically or spring applied. There are also electro-dynamic brakes, a type that is electrically based and less common, and aerodynamic brakes. [3, 5]

Gearbox
Most wind turbines have a gearbox that increases the speed of the input shaft to the generator. This is needed since the speed of the wind turbine rotor is much slower than required by electrical generators. The gearbox is one of the most expensive and heaviest components in a wind turbine. Parallel-shaft gearboxes and planetary gearboxes are the most common types used in wind turbine applications. [3]

Yaw system
A yaw orientation system keeps the rotor shaft aligned with the wind. The system could be active or passive, as described in section 6.2.1. In an active system, a wind vane mounted on top of the nacelle senses the relative wind direction, and a signal is sent to the control system. The nacelle is turned according to the actual wind direction. The yawing has to be done at a slow rate to avoid

large gyroscopic forces. [3, 5]

Nacelle
The nacelle houses the main components of the wind turbine, except the rotor. It includes the main frame, which is the structural piece to which the generator, gearbox and brake are attached. It maintains the proper alignment among the components by providing a rigid structure, and acts as a point of attachment for the yaw bearing. The nacelle cover protects electrical and mechanical components that could be affected by the weather. It is normally made from reinforced fibreglass or other lightweight materials. [5]

Tower and foundation
The tower height is normally 1 to 1.5 times the rotor diameter. The most common types are the free-standing types constructed from steel or concrete, normally lattice or tubular types. Guyed towers are sometimes used for smaller turbines. The lattice type tower is not as common as the tubular type, but has many advantages. Less material is needed, which means lower weight and reduced investment costs. They also let some of the wind through, which means that the stress on the turbine is decreased. A disadvantage is that they have many bolted connections, which have to be checked periodically.

The stiffness of the tower is an important factor in tower selection, because of the risk of coupled vibrations between the rotor and the tower. A stiff tower has a natural frequency that is higher than the blade passing frequency, soft towers have a frequency that is lower than the blade passing frequency but higher than the rotor frequency. A soft-soft tower has a natural frequency that is below both the rotor frequency and the blade passing frequency. This means that for a soft tower a transient resonance will be excited each time the rotor is run up to speed, but since this resonance has a very short duration, the movement generated in the nacelle will not cause any problems. The soft towers are cheaper but allow more movement and hence suffer higher stresses. [3, 5]

The foundation carries the weight of the wind turbine and acts as a counterweight to keep the turbine upright. It should be designed so that its natural frequencies do not coincide with the frequencies induced by the rotor. [2]

6.3 Environmental Impacts

If a turbine were installed at Wasa, it would not replace any component of the existing power system. Instead, it would be a part of a separate power system. This means that it would not contribute to a lowered emission of exhaust gases or decrease the dependency on fossil fuels by replacing a conventional diesel generator, but it would provide the automatic equipment with clean power and make sure the dependency is not increased. An alternative power source would probably have more serious negative environmental effects than wind power.

Although wind power is a relatively clean power source, there are a number of environmental impacts that should be considered before installing a turbine. These are briefly described below.

Visual impact
The windiest locations in European countries are often considered to be the most beautiful places and the visual impact is one of the most common public objec-

tions to wind turbines. Larger turbines have a slower rotational speed, which gives a more harmonic impression. A few larger turbines give a less disturbing impression than many small machines.

At Wasa, inhabited by scientists and personnel from the Swedish Polar Research Secretariat a few months per year, the visual impact of a wind turbine should not be a problem.

Flickering
Reflexes and shadow casting from a turbine can be disturbing to people living close to a turbine. At Wasa, this would not be a problem, see above.

Sound emissions
Sound is generated aerodynamically by the rotor and mechanically by the moving parts in the drive train. The mechanically generated sound can be avoided to a great extent, and modern turbine blades are designed to produce a minimum of noise. The noise is most noticeable in low wind speeds when the sound of the wind in trees and other surrounding obstacles is low. In wind speeds exceeding 8 m/s, the sound from the turbine is often completely masked by the sound of the wind itself.

In Antarctica, the sound emissions should not be a great problem. During the winter when the station is unmanned, noise will not be a problem at all. Little sound is heard upwind from the generator, and since the wind direction is very stable at the station, it is not very difficult to place the turbine in a way that minimises the sound level at the station.

Birds
Birds are rarely bothered by wind turbines. It has been shown that they change their flight route to avoid the rotor and collisions seldom occur. Another danger is potential disturbance in breeding, nesting or feeding habits. Caution should be taken when planning to install a turbine close to an area where those activities take place.

There is a bird preservation area 4 kilometres from Wasa, but the birds should not be bothered by a turbine at such a great distance.

Flora and fauna
Installing a turbine can affect the local ecosystem, and research has to be performed before installation in order to avoid disturbing species under threat of extermination. At Wasa station, a turbine should not affect any endangered species.

Disturbance to telecommunications
The plane of the rotor disc can act as a mirror and reflect signals from a receiver and thus cause disturbances on radio communications. The problem is not very large, except when the signals are weak, the turbine is placed on the line of sight between the transmitter and the receiver and the quality of the receiver and transmitter is poor. The problem with electromagnetic interference can be avoided if the turbine is carefully sited to circumvent microwave routes. [3][62]

Part III

Research

7 Present Surveys and Installations in Antarctica

The presence of wind turbines in Antarctica has been studied, as well as wind power feasibility studies performed by countries that run research stations in the continent. A summary of the investigations is presented below.

7.1 Finland

The Finnish base Aboa (73°03'S, 13°25'W) in Queen Maud Land is a relatively small base, only used during the summer. To be able to offer Finnish and Swedish scientists the opportunity to do around-the-year measurements with automatic equipment, the energy supply system has recently been revised. A 24 V / 1200 Ah battery system that is charged by the main diesel generator has been built. To make sure the experimental equipment has power at all times, additional charging systems, consisting of 26 m^2 of solar panels and three wind generators have been installed.

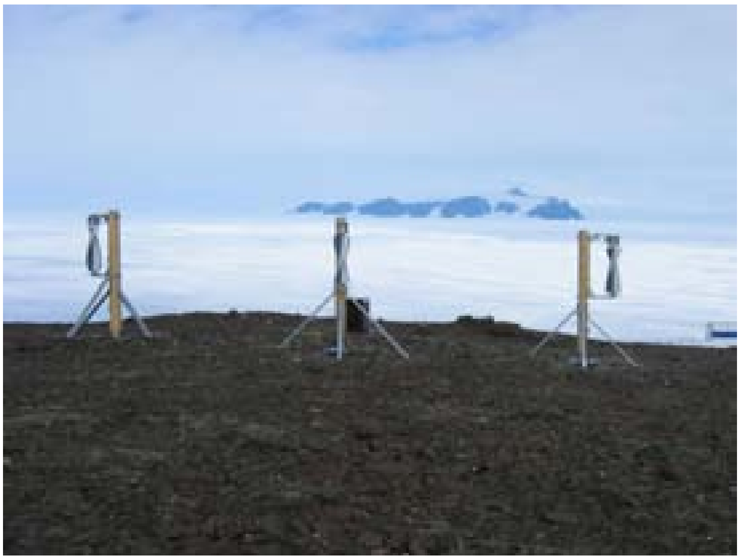

Figure 7: The three Windside turbines at Aboa station

The wind generators were manufactured by the Finnish company Oy Windside Production Ltd. The Windside generator is a vertical axis model, with a helix shaped rotor, see figure 7. The model installed in Antarctica is called WS-0,3A, a model that has a rated power of 90 W at wind speed 18 m/s and is especially developed for harsh climates. The swept area is 0.3 m^2 and the tower is 3 meters high. The turbine has been tested in wind tunnels to withstand wind speeds up to 60 m/s, and produces energy in speeds as low as 3 m/s. There is no need for a braking system, since the design prevents heavy loads on the turbine, or a yawing system. The generator does not have a gearbox, which means that less maintenance is needed, an advantage in remote locations.

The turbines were installed only a short time before this report was written, so there is no information about the performance of the turbines nor is statistics available. [21, 22]

7.2 South Africa

The South African Research station SANAE IV (71 °40'25"S, 2 °49'44"W) is a full-year station that can accommodate 20 people over winter. It is situated in the western part of Queen Maud Land, where the South African research stations have been located since 1960. Unlike the old stations, SANAE IV is built on a nunatakk instead of on the ice itself. The base was completed in 1997/1998. It is presently powered by three 180 kW diesel electric generators. One generator is run continuously, the second generator is automatically switched on when the power demand exceeds 162 kW and switched off when the demand drops below 140 kW. The third generator is a standby power source. The amount of energy produced yearly by the three generators is 1153 MWh, which means that large amounts of fossil fuel have to be bought and transported to the base each year. The cost of powering the research station by diesel generators is high and the South African National Antarctic Program (SANAE) has begun to search for new solutions in order to reduce the dependency on fossil fuels. In an assessment performed in 2002, in which the potential of wind power at the base was studied, it was concluded that the purchase of a wind generator would be a good solution to reduce the fuel consumption. Both economical and technical aspects were considered during the feasibility evaluation, presented briefly below.

The analysis procedure followed during the assessment was extensive. Wind speed and direction data covering more than a year was recorded by the existing weather station run by SAWS, the South African Weather Service. The wind speed was measured with 16 handheld anemometers on different locations around the base and the ground was surveyed on these locations. The energy demand was mapped and wind turbine characteristics were studied to find a generator suitable for the base. Cold weather issues were discussed, as well as environmental aspects. The wind data were analyzed and an economical analysis was performed. The power demanding snow smelter on the base was identified as a possible energy dump, a sink for excess electrical energy produced by the wind turbine. Although the smelter is not used constantly, there is always water in it that has to be heated before being pumped via unheated pipes to the base.

The wind generator North Wind NW100/19 has been developed for harsh climates and was the only generator that met the requirements regarding cold weather issues. It was found to be the only generator, out of five selected models, suitable for the South African base. It has a rated power of 100 kW at a rated wind speed of 13 m/s, and an operating range between 4 and 25 m/s. Its rotor diameter is 19.1 m and there are three options for hub height, depending on customer demand and site properties. Although the average power density and average wind speed increase with height, the operating time could decrease since the wind speeds more often exceed the cut-off speed at higher altitudes.

The North Wind NW100/19 has a direct drive system to eliminate the need for a gearbox, and a minimum of moving parts. It can be operated with an ice accretion up to 30 mm, but since there is almost no precipitation at SANAE IV and the temperatures are very low, the risk for icing is low. The only problem identified by the authors of the assessment except for the extreme temperatures was the risk for snow accumulation in the nacelle due to drifting snow. It was concluded that this problem could be solved by generating a pressure inside the nacelle higher than the pressure of the surrounding air, or by fitting deflectors to the ventilation openings.

The authors identified the visual impact as the only environmental effect of installing a wind generator.

It was concluded that North Wind NW100/19 is a very attractive solution to decrease the dependency on fossil fuels, both from an economical and a technical point of view. It is able to meet 35% of the energy demand of the station and can reduce the cost per kWh produced by up to 20%. The payback time is about 10 years, which is approximately one third of the turbine's design life. [23, 24]

7.3 United Kingdom

The British Antarctic Survey runs four full year stations and one summer only station in Antarctica. The research stations are heavily dependent on fossil fuels and the more remote locations are powered by solar panels. The British Antarctic Survey has had limited success with the use of wind power for their remote scientific experiments. The turbines installed have been small, low power units (< 50 W) aimed at the yacht/boat market, not developed for the harsh conditions in Antarctica.

One of the biggest problems has been speed limitation in low temperatures. In one of the models used, the rotor blades were supposed to feather elastically to stop the rotor from overspeeding, but the material in the blades did not feather very well at low temperatures. Another generator, a Marlec FM910, utilized a method called furling for speed control. This is a mechanical method to limit rotor speed in which a tail is used to flip the turbine out of the wind. Two generators of this kind were used down to 84 degrees south at the British automatic geomagnetic observatory sites with reasonable success, but one or both needed change of parts or replacing every year.

Resonance and vibrations are other problems that have occurred, mainly since it is difficult and operationally expensive to provide a structure that can have a generator mounted on top and that can be easily assembled at the most remote sites. Guyed poles have been used frequently, but resonance occurs easily in these towers when there is a slight imbalance in the turbine construction.

Vertical axis models, Forgen 500 and 1000, have been tried with limited success. The turbines have worked well in moderate temperatures and low wind speeds, but have suffered in temperatures below -20 °C and strong katabatic winds. The engineers at the British Antarctic Survey are working with the manufacturers to improve the design of these wind turbines.

Recently, a larger wind turbine was installed at King Edward Point in South Georgia. The turbine is a Proven WT6000 with a rated power of 6 kW at wind speed 12 m/s. The cut-in wind speed is 2.5 m/s and there is no cut-out speed. The blades are installed with a spring system to feather in winds that are too strong to ensure safe operation. The rotor diameter is 5.6 m and the hub height is 9 m. The Proven WT6000 is a downwind model, which means that no active yawing system is needed. It is direct driven and has no gearbox. The only problem that has occurred is that the steel welds at the base have been weakened by katabatic winds. [25, 26, 27]

7.4 Germany

Neumayer (70 °38'00"S, 08 °15'00"W) is a full year station located under the snow surface in Queen Maud Land. The station was built in 1981 and rebuilt in March 1992. Neumayer accommodates up to 50 people during the summer using seven living containers, and 9 persons during the winter. The research station is powered by two diesel generators and a 20 kW wind generator.

Since 1988, the Alfred-Wegener-Institute for Polar and Marine Research (AWI) has promoted efforts to use wind generators in order to reduce the fuel consumption and emissions. The wind generator used at Neumayer station, a vertical axis model called HMW 56, was developed in a joint project between AWI, Germanischer Lloyd, Hamburg, Hochschule, Bremerhaven and Heidelberg Motor, Starnberg. It was installed at Georg von Neumayer station in 1991 and moved to the new Neumayer station in 1993, where it is still used. The wind generator, which is a prototype, was developed especially for the harsh Antarctic climate. Since the wind generator is a vertical axis model, there is no need for a yawing system or pitch control devices. The turbine has been mechanically simplified and the rigid rotor is the only rotating part. It is direct-driven and does not have a gearbox, which means that the maintenance work needed is minimized. The generator is a permanent-magnet field type, integrated in the steel structure, and there is a converter to ensure that the frequency and output voltage are independent of the rotor speed. The rotor speed is controlled by a brake system using eddy currents. The turbine is mounted on a foundation consisting of three base frames that can be raised in order to avoid snow accumulation. The tower is mechanically liftable by a small winch. The wind turbine has an operating range between 7 and 23 m/s and a rated power of 20 kW at wind speed 14 m/s. The survival wind speed is 68 m/s and the minimum operating temperature -55 °C. The rotor diameter is 10.0 m, the swept area 56 m^2 and the hub height 10 m above the snow surface.

The converter and control unit had to be replaced after three years of operation, but no mechanical damages have occurred and very little maintenance work has been needed. The turbine produces in average 35 000 kWh per year and contributes with approximately 6% of the energy consumed at the station. Studies are focused on the possibility to increase the fraction of energy from the wind generator.

There is no possibility to store the electrical energy produced by the wind turbine at the Neumayer station. [28]

7.5 Australia

In 1993, a joint French-Australian project called "Alternative Energy Systems for Antarctic Stations" was initiated. It was aimed at evaluating the possibility to use renewable energy and decrease the dependency on conventional fossil fuels

Figure 8: HMW 56. **Source:** Operational Experience with Wind Power Technology at Neumayer-Station, S. El Naggar et. al.

in order to save money and to reduce the emission of polluting exhaust gases. Traditionally, diesel generators and boiler sets have been used for production of electrical and thermal energy for the French and Australian research stations.

Although the potential for wind power was identified many decades ago and small turbines were tested as early as during the first post-war expeditions of the 1950's, the lack of success during these attempts discredited wind power and its ability to provide the stations with power. High failure rates, energy storage problems and the constant need for complete back-up systems led to a withdrawal of the wind generators, except for a few units used in small remote installations. Because of the bad results in the past, other solutions have been chosen when installing power supply systems. During the last decades, wind power has evolved a lot and turbines have been successfully installed and operated in Antarctica. The surveys conducted within the French-Australian project identified wind power as the most promising solution for immediate implementation.

In the surveys performed, weather data were evaluated and several reference installations were studied. Preliminary investigations in 1993 showed that wind turbines could be operated with a capacity factor of up to 0.7 and that the kinetic energy in the wind could be converted into electricity with 25 % efficiency.

The French-Australian cooperation has been aimed at using renewable energy instead of conventional power sources to decrease the dependency on fossil fuels. The units needed to make a significant contribution to the production of electrical and thermal energy would be very large and not of interest for the Swedish stations. However, the experience gained during the investigations could still be important when deciding if wind generators should be installed at Wasa and Svea.

At Heard Island (53 °06'S, 73 °57'E) a Sub-Antarctic island, two Furlmatic 600 units and a 10 kW horizontal axis Aérowatt UM70X turbine were installed and tested in 1992/93. The Furlmatic 600 units were unable to survive the harsh conditions on the island due to insufficient design strength, but the Aérowatt unit was operated successfully for three months. The same turbine was reerected at Casey Station (66 °17'S, 110 °32'E) in 1995 and later replaced by a Vergnet

GEV7.10, a two bladed machine with a rated power of 12 kW at wind speed 11.5 m/s and a rotor diameter of 7 m. The turbine is especially designed for extreme wind conditions and has survived 90 m/s wind gusts. The rated survival wind speed is 110 m/s. The turbine is an upwind model, with a passive yawing system consisting of a wind vane from the blade shaft. The cut-in wind speed is 4.5 m/s, and the turbine has a passive pitch system. It can be operated in temperatures as low as -30 °C.

The Vergnet GEV7.10 turbine has also been operated successfully at Kerguelen Island (79 °21'S, 70 °14'E).

Mawson (67 °36'17"S, 62 °52'15"E), opened in 1954, is a full year station in MacRobertson Land in Eastern Antarctica. It consists of 35 buildings and can accommodate 20 people over winter, and around 60 during the austral summer. Large amounts of fuel are consumed every year at the Australian stations, and in order to reduce the emissions and fuel costs the Australian Antarctic Division, AAD, decided to invest in wind generators. The wind resources at the Australian stations Casey, Davis Mawson and Macquari Island were investigated and it was concluded that Mawson and Macquari Island have the best conditions for generation of wind energy. To produce the desired amount of energy, a choice between a few larger units and many small generators had to be made. Since a large number of smaller units could cause maintenance problems and the amount of available space is limited at the base, a decision was taken to invest in a few larger turbines despite the logistical difficulties.

An investment was made in three E-30 machines produced by the German company Enercon. Powercorp Pty Ltd of Darwin has developed and installed the system's technology. The E-30 turbine is available commercially, but the turbines bought for the Australian research station Mawson have been slightly modified to withstand the harsh conditions in Antarctica. Their rated power is 300kW at wind speed 12 m/s, and the operating range is between 2.5 and 28-34 m/s. The turbines have a rotor diameter of 30 meters and the hub height is 33 meters, reduced from the standard 50 meters. Enercon E-30 is an upwind machine equipped with an active pitch control and an active yaw system. The turbines are variable-speed machines that are designed to feather their blades in winds that are too strong to prevent the rotor from overspeeding. The machines are gearless and use a ring generator that rotates with the same speed as the rotor. The nacelle and the hub have special sealings to prevent any ingress of drifting snow and the electrical boxes are heated.

Two of the three turbines have been installed so far, the third unit is stored on site until the foundations have been completed. The turbines have worked well, with few failures and problems. The downtimes have been planned due to maintenance work or software upgrades with one exception, when a super-capacity battery that provides power to the pitch control motor in case of black out was out of order.

The turbines were delivered with a European storm software version that was supposed to stop the rotor in certain wind/temperature combinations to prevent icing. However, icing will not be a problem at Mawson because of the dry air, cold temperatures and prevailing wind directions, and the software had to be modified for the conditions in Antarctica in order to decrease the number of downtime hours. The turbines were also equipped with infrared heat lamps under the wind instruments to stop icing, but the lamps were destroyed in the first 40 m/s blizzard and were not replaced since they were not considered necessary. Adjustments also had to be made to the software since the weak electrical grid at Mawson does not absorb a variable power output, which means that the wind turbines had to be power limited. [29, 30, 31, 32, 33, 34, 35, 36]

7.6 France

In 1986-88, a vertical axis turbine of the Darrieus type was tested in the sub-Antarctic island Amsterdam Island. The turbine was designed and constructed by the Centre d'Etudes Nucléairs de Grenoble, and had a rated power of 30 kW at 13.5 m/s. The turbine worked well in moderate winds and produced 400 kWh of energy daily. However, high winds led to failures and serious braking problems that were never solved.

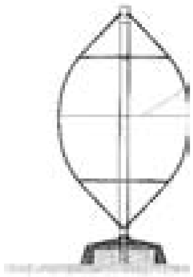

Figure 9: The Darrieus turbine. **Source:** Vindkraft i teori och praktik, Wizelius 2002

Recently a 12 kW turbine, especially developed for the conditions in Antarctica, was installed at Dumont D'Urville (66 °39'46"S, 140 °00'05"E). The full year station was established in 1956, and accommodates 100 people during the summer and 26 over winter. The turbine installed, a CH Cap Horn 10/POL turbine, was developed in cooperation with CITA, Compagnie Internationale de Turbines Atmosphériques, after a study of a 3 kW prototype of the model and a vertical axis model. The Cap Horn turbine met all the demands regarding robustness, climate rating, mechanics and environmental aspects, and was the choice for the French research station.

The Cap Horn turbine has a rated capacity of 12 kW at wind speed 13 m/s, and an operating range of 3 to 30 m/s. The rated survival speed is 90 m/s. It is direct driven which minimizes the need for maintenance. The rotor diameter is 4.4 m and the hub height is 8.5 m. The turbine has an unusual design, with a deflector around the rotor, see figure 10. [37, 38]

7.7 India

Maitri station (70 °45'57"S, 11 °44'09"E) situated in Queen Maud Land is a full-year station that accommodates 65 people during the summer and 25 over the winter. The station was opened in 1989, after the old station Dakshin Gangotri had been taken out of use.

The Department of Ocean Development initiated a wind power assessment study during the XVI expedition that took place in 1996. The objective was

Figure 10: The Cap Horn turbine. **Source:** French Polar Institute Paul Emile Victor- IPEV

to investigate whether wind power could be used as a supplementary power source, in addition to the modified diesel generators and boiler sets used at the station. The need for a way of charging batteries at remote locations was also important. The batteries used in the field had simply been replaced when fully discharged before. The results of the assessment were positive, and NAL, the National Aerospace Laboratories, were encouraged by the Department of Ocean Development to continue the work. It was decided that NAL would perform a detailed analysis including wind resource investigations and a study of the land available for installation of a turbine.

During the XVI expedition in 1998, a wind monitoring station was installed at Maitri. It consisted of a 28-meter mast, with three heated anemometers at heights 12, 22 and 28 meters. Two heated direction sensors were also mounted on the mast, at heights 12 and 28 meters. The data logging started in January 1997. The result of the assessment was that there are good conditions for wind power at the Indian station. There is enough land and equipment such as cranes available for installation of a 10-20 kW turbine.

A few small turbines have been installed at Maitri and in field locations during the years. They have performed reasonably well for some months, but have all been destroyed due to the harsh conditions in Antarctica. [12, 43, 44, 45, 46]

7.8 The United States

The U.S. Antarctic program is trying to reduce the dependency on fossil fuels and extend the use of solar and wind power, especially in the field.

McMurdo (77°50'53"S, 166°40'06"E) was established in 1956 and is today the biggest full year station in Antarctica. It accommodates more than 1100 people during the summer, and about 250 over winter. Originally, the base consisted of a few buildings, but has grown to a facility of more than 100 structures. Because the volcano mountain Mount Erebus behind the station prevents contact between McMurdo and the communication satellite, a communication center has been established on Black Island, 30 kilometers from the base. Black Island is unmanned and difficult to access, which means that a highly reliable system with little need for maintenance was necessary. The initial system selected was installed in 1985 and consisted of a 3 kW NorthWind HR3 wind turbine, a 1.2 kW closed cycle vapor turbine generator and a 24 V DC-battery bank. As the base has grown and the means of communications have evolved, the energy demand has increased. Today, the system consists of 4 NorthWind HR3 turbines in combination with 3 diesel generators, a 10 kW photovoltaic array and a 24 V DC-battery bank

The NorthWind HR3 is a horizontal axis turbine, with rated power 3 kW at wind speed 12.5 m/s and a rotor diameter of 5 m. It has a rated survival speed of 74 m/s and has been operated successfully in wind gusts of up to 71 m/s. The availability of the system has exceeded 99.99%, and no failures have been reported. A maintenance trip is performed twice every year and no unscheduled maintenance trips have been needed.[39, 40, 41, 12, 38]

7.9 Spain

The Spanish station Juan Carlos 1 (62 °39'46"S, 60 °23'00"W) is a small summer-only station, situated on Livingston Island, South Shetland Islands. Juan Carlos 1 was opened in 1988 and accommodates up to 14 people over the summer. It is powered by conventional diesel generators in combination with solar cells and three wind generators, one 2 kW unit and two 1 kW generators. However, no information on the turbines has been found. [12, 48]

7.10 Japan

Syowa station (69 °00'25"S, 39 °35'01"E) is a full year station opened in 1957. The station is situated on East Ongul Island in eastern Antarctica and accommodates 110 people during the summer and can host 40 people over the austral winter.

A 10 kW wind turbine was installed at the station in January 2000. In July 2000, the turbine went out of order because of strong wind gusts (53.6 m/s), but the model has now been improved and is currently tested in northern Japan. According to the plan, the modified turbine will be installed at Syowa in December 2004. [12, 47]

7.11 Russia

The Russian base Novo (Novolazarevskaya) (70 °46'26"S, 11 °51'54"E) situated in Queen Maud Land is a full year station that accommodates 70 people during the summer and 30 people over winter. It is powered by three diesel generators. Wind generators have been used in the past, but the turbines are out of order and no longer in use. There is no technical information available since the turbines are very old (more than 15 years). [42]

7.12 Summary

Wind power has been used in Antarctica by different countries and with different results. The turbines installed during the early years of polar research did not function for long periods of time, due to insufficient design strengths and lack of knowledge. Most early turbines seem to have been models not designed for the extreme weather conditions. The UK for example, installed turbines aimed at the boat market and not for Antarctica. These turbines were all destroyed by strong winds or vibrations due to resonance effects. Recently, a turbine designed for harsh conditions was installed by the UK. This turbine has been operated with satisfactory results.

Germany, the US and Australia have all installed turbines after conducting profound feasibility studies. The units installed have worked well and few reparations have been needed. France has also performed investigations before installing their new turbine at Dumont D'Urville.

Studies performed by different national polar research programs have all shown that wind power is a feasible solution for power production in Antarctica.

8 Data Analysis

When planning to install a wind turbine, the wind resources must be carefully investigated and evaluated. Variables such as wind speed, wind direction, temperature and pressure must be mapped. This is done by extensive measurements at the site over a sufficiently long period, since the wind can vary significantly over long periods. An overestimation of the wind resources will lead to a production lower than expected, while an underestimation can lead to severe damages on the turbine due to loads heavier than designed for. For companies with commercial interests, this mapping is very important since a lower production than expected could mean that the investment is not beneficial. Since the Swedish Polar Research Secretariat is only interested in providing the automatic equipment with power, the exact output of the turbine is not very important as long as a certain lowest level can be guaranteed to ensure continuous measurements. However, since the stations are unmanned the bigger part of the year, it is also important to know that there will not be any failures due to unexpectedly high gusts or low temperatures.

8.1 Data Sources

FINNARP, the Finnish Antarctic Research Programme, has had an automatic weather station installed at Aboa station 200 meters from Wasa since 1989. Values of temperatures, pressure, wind directions and wind speeds have been measured and transmitted to a satellite every three hours. The mean wind over ten minute intervals has been calculated, and the maximum gust strength over three hours has been measured. FINNARP has been very helpful and provided the Swedish Polar Research Secretariat with the data collected at Aboa.

During the 1990's, a number of Dutch AWS, Automatic Weather Stations, were installed in Antarctica. The stations are designed to measure a number of meteorological variables in harsh climates and remote locations. Two of the stations, AWS 5 and AWS 6 were placed close to the Swedish research stations. AWS 5 is situated close to Wasa and AWS 6 close to Svea. Both weather stations have been operated since 1998 and are still in use. Dr. Carleen Reijmer and Michiel van den Broeke at the University of Utrecht in Holland have shared their extensive data collection, including two hourly averages of wind speed and wind direction, sensor height, pressure, humidity and other variables. [49, 50, 51, 52]

8.2 Limitations

There are a number of factors that can affect the accuracy of the data used in the calculations below. Due to a programming error, the wind speeds from AWS 5 and AWS 6 are somewhat underestimated before year 1999 (AWS 6) and 2000 (AWS 5). This means that the wind speeds calculated below are probably too small for the two weather stations.

None of the sensors used are heated or equipped with extra sealing to prevent ice accretions and snow ingress, which can affect the reading of the sensors. On some occasions, the wind direction remains constant for long periods of time, which can indicate that the vane has frozen. Because of the large amounts of data, no attempt has been made to find the incorrect values.

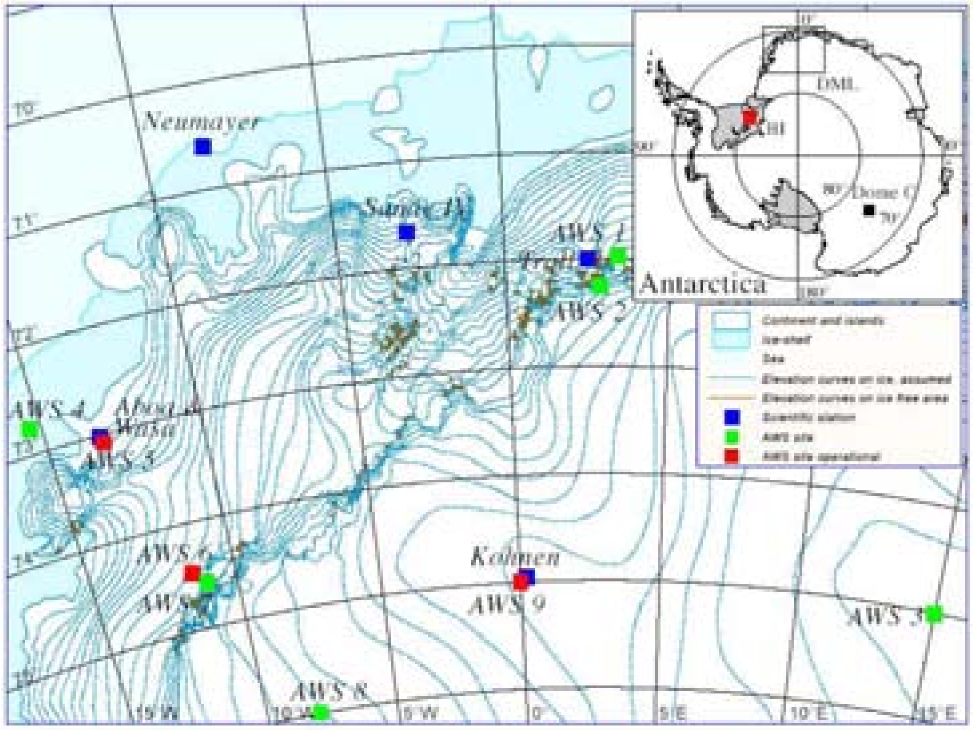

Figure 11: Map over the Automatic Weather Stations. Svea is situated close to AWS 6

Erroneous values had to be removed in all three data sets, which has led to a decrease in number of readings. Some months, the number of data values has been significantly reduced due to erroneous values.

Although the data collections are extensive, measurements from even longer periods would be needed to ensure that the actual wind potential does not differ from the estimated figures.

The data from the Dutch weather stations contained only two hourly averages and lacked information on maximum wind gusts. The data given in table 2 is therefore the maximum two hour average. To be able to choose a turbine suitable for the conditions at Wasa and Svea, it is very important to know the maximum wind strength at the site.

The measurements from Aboa did not contain information on exact sensor height, which means that the height had to be approximated. This should not affect the resulting value too much. However, the sensor was placed on top of a building, which means that the airflow could have been turbulent at the site for measuring, which could lead to an underestimation of the wind speeds.

The power law used to extrapolate the wind speeds to a height of ten meters is only valid for flat and homogenous terrain. Although Wasa is situated on a mountain, it has been used in the calculations to demonstrate that the wind speed is considerably higher at greater heights above the ground. However, the slope in which Wasa is located is not very steep and there are no big obstacles around the station, so the power law could probably be used as an approximation.

The thermometers used by AWS 5 and AWS 6 are not rated for extreme temperatures, which means that sometimes the temperature has been below the lowest operating limit. Corrections have been made later for temperatures below the specified operation range. The temperature sensors used at the Aboa station should in principle work well in the climate, but there are still several possible sources for errors. For example, sun radiation that has been reflected from the snow surface could have reached the sensors despite radiation shields.

The temperature sensors at Aboa have been calibrated during the austral summers, but the wind sensors are more difficult to calibrate and have simply been replaced regularly. The sensors used in AWS 5 and AWS 6 have been tested but not calibrated before use. [49, 50, 51]

The wind speeds from Aboa were given in integers, which means that the number of significant figures was very small.

Since the data sets only contained information on average winds and maximum wind gusts (Aboa) there is no information on turbulence nor the distribution of wind gusts. For wind energy applications, an average over 10 seconds is normally preferred for feasibility estimations.

8.3 Statistics and Graphs

For wind energy applications, a directional wind is advantageous. A wind that changes direction constantly will cause a lower energy production, since the rotor will be facing the wind a smaller part of the time. To investigate whether the wind at the Swedish station is directional, wind roses were created. The wind rose based on data from AWS 5 can be found in figure 12, wind roses based on the two other data sets can be found in appendix II.

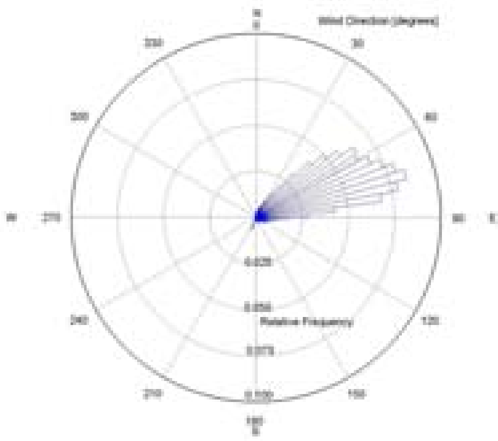

Figure 12: Wind rose based on data from AWS 5

The wind at the weather stations is very directional, which means that the conditions for wind power generation are excellent in this aspect. The prevailing wind direction, north-easterly, is in agreement with the explanation given in section 5.1.

In order to choose a wind turbine that will work well under the specific wind conditions at the research stations, the wind resources should be compared to the information on operating ranges, rated wind speeds and power curves given by the manufacturers. Since the values found in power curves and product sheets are valid for winds in normal weather conditions and at hub height, it is necessary to compensate for the specific conditions at the measurement locations as well as for tower heights. The data set from the Dutch researchers contain information about the sensor's height above the snow surface, which makes it possible to use the power law function described in chapter 5.4 to calculate the speed at 10 m above the ground. The data from Aboa does not contain information about the exact sensor height, which has varied between 4 - 5.5 meters above the ground depending on season. In the calculations performed, an approximate value of the height was set to 5 meters. The parameter α used in equation 1 was set to 0.1, since the weather stations are located on snow surface (see table 1).

As described in chapter 5.6, low temperatures and low air pressure affect the density of the air. The density of air is

$$\rho \approx 1.2929 \frac{273.15p}{0.1013T} \tag{6}$$

where p is the pressure in MPa and T is the temperature in Kelvin. The average temperature and average pressure were calculated for the three sites. Since the power produced is proportional to the density of air and to the cube of the wind speed, the wind speeds were multiplied with a factor k described by

$$k = \left(\frac{\rho_{calculated}}{\rho_{normal}}\right)^{1/3} \tag{7}$$

to compensate for the low temperatures and low pressures. The standard pressure is 1013 hPa and the standard temperature 15 °C. The obtained wind speeds could then be compared to the turbine specific data given out by manufacturers.

Since the load on the turbine is proportional to the square of the wind speed, the root mean square defined as

$$RMS = \sqrt{\frac{1}{N}\sum {v_k}^2} \tag{8}$$

was calculated for load predictions. The root mean cube defined as

$$RMC = \sqrt[3]{\frac{1}{N}\sum {v_k}^3} \tag{9}$$

was also calculated based on the data from Aboa. This value can be used for energy calculations, since the energy produced by the turbine is proportional to the cube of the wind speed. The results of the calculations can be found in table 2.

A graph presenting the average speed for each month was created to see how the mean speed varies over a year. As expected from the reasoning in section 5.3, the average speed is higher during the winter than during the summer season, which can be seen in figure 13.

Variable	Aboa	AWS 5	AWS 6
Average temperature [°C]	-15.05	-17.10	-20.50
Minimum temperature [°C]	-41.50	-41.10	-44.50
Average pressure [hPa]	926.79	941.72	855.26
Average speed [m/s]	7.37	6.59	6.77
Average speed at 10 m height [m/s]	7.89	6.71	7.97
Average standard speed at 10 m [m/s]	7.94	6.81	7.87
Root-mean-square (standard speed) [m/s]	10.75	-	-
Root-mean-cube (standard speed) [m/s]	13.67	-	-
Maximum speed [m/s]	57.60	32.42	29.72
Maximum speed at 10 m height [m/s]	61.75	33.03	35.01
Maximum standard speed at 10 m [m/s]	62.19	33.53	34.57

Table 2: Weather statistics from the three weather stations. The standard wind speed refers to the wind speed equivalent in standard temperature and pressure.

When determining the potential for power generation, frequency distributions graphs are used. When narrowing the intervals, the graph resembles a probability density function, typically the Weibull distribution for wind power applications. However, when an extensive data set is available, as is the case here, there is no need to fit a probability distribution function.

The mechanical load on the turbine is roughly proportional to the square of the wind speed, which means that even though the average load on the turbine is low, the turbine can occasionally be exposed to extremely high loads that can damage it. It is therefore important to investigate how frequently the wind is very strong. This is also important when calculating the approximate power output, since strong winds contribute more to the amount of power produced than moderate winds. The power in the wind varies with the cube of the wind speed, which means that a doubling of the speed will lead to an increase in power available by eight times. A frequency distribution graph was created, and is presented in figure 14. The numerical values of the frequency distribution can be found in table 4 in appendix III. Note that the first bin only includes the zero values, and the last bin includes all values over 40 m/s.

An energy distribution graph was created by multiplying the occurence of each wind speed in figure 14, with the median speed in each interval. The resulting graph can be found in figure 15. It can be seen that although strong winds are not very common, as seen in the frequency distribution graph, their contribution to the total energy available in the wind is substantial. Note that winds stronger than 40 m/s have been excluded in this graph. Numerical values of the energy distribution can be found in table 4 in appendix III.

Figure 13: The average and maximum wind speeds at Aboa station.

Graphs presenting the diurnal and seasonal wind speed variations were also created for the years 1992-96 and 1998. These graphs can be found in appendix II. A graph with annual and diurnal variations over all six years is shown in figure 16 for comparison. The graphs were created to investigate whether the mean wind speed varies over the day and between different years. These graphs can be used to illustrate that the wind resources change substantially from year to year, but general conclusions are hard to draw from them. It can be seen that the mean wind speed a specific month can vary with 5 m/s over 24 hours.

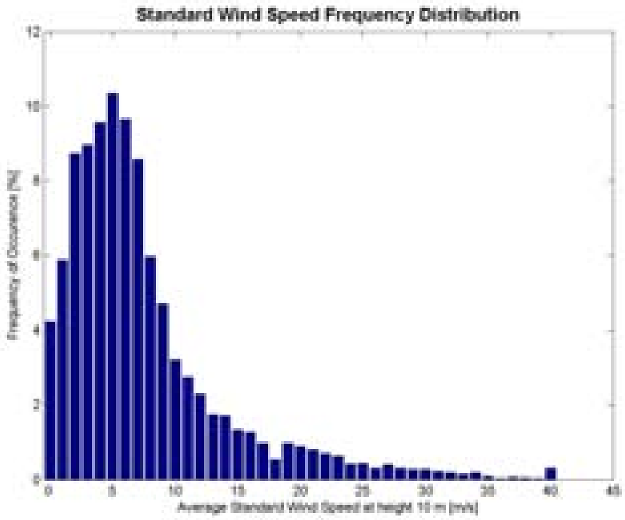

Figure 14: Wind speed frequency distribution.

9 Wind Turbine Characteristics and Energy Production

9.1 Cold Climate Issues

The operation of wind turbines in cold climates and remote locations imposes high demands on the design of the machines. They have to be reliable, survive strong winds and heavy loads and need a minimum of maintenance.

9.1.1 Icing

Ice accretions on the rotor blades increase the load imposed on the rotor and destroy the aerodynamic blade profiles. It can change the resonance frequency of the turbine and thus cause resonance induced damages. Icing can also lead to delayed stall and cause overproduction, which can damage the generator. Though icing of the rotor blades is a big problem in northern Europe, there is generally a low risk of icing events in Antarctica. Icing appears frequently in areas with temperatures around the freezing point and high humidity. Since the temperature in Antarctica is normally below zero, and the air is very dry, the risk of icing events is low and no adaptations should be needed to protect the turbine from ice accretions.

To make sure the risk for icing events is minimized, there are some measures that can be taken. There are effectice blade heating systems that can be used. The problem with these systems is that they require an energy supply. This is easily solved during operation, when some of the energy produced by the turbine can be utilized without lowering the energy production significantly. When the turbine is not operated, a separate energy source would be needed.

Using black colored rotor blades that absorb more heat from the sun reduces

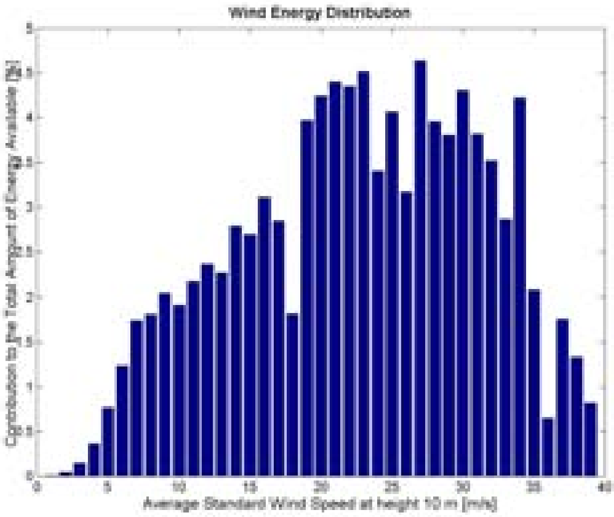

Figure 15: Wind energy distribution at Aboa station. It can be seen that although strong winds are not very common, their contribution to the total energy available is substantial.

the risk for icing during the summer months, but this method is useless during the dark winter months.

Covering the blades with a water repellent material also decreases the risk for icing events. This reduces the contact area between water drops and the blade, thus making the small ice crystals formed during freezing easier to remove. It also means that the water from melted ice does not stay on the blade as easily, which decreases the risk for icing even more.

9.1.2 Extreme Temperatures

The material properties are changed in low temperatures. Metals are more fragile and less resistant to fatigue, some materials shrink and the viscosity of lubricants increases. These changes can all have a great impact on the lifetime and performance of the turbine and need to be considered when designing a turbine for cold climate applications. Cold rated materials should be used to ensure a long lifetime and safe operation. Steel especially developed for use in extreme temperatures is not much more expensive than regular steel, and should be used in wind turbines. Synthetic lubricants rated for cold climates should be used in parts where lubrication is needed.

There are many problems connected with the use of gearboxes in cold climates and direct driven turbines without gearboxes need less maintenance and are often cheaper than models with gearboxes. Instead of a gearbox, a frequency converter can be used to ensure a stable frequency output.

A minimum of moving parts is preferred in turbines used in cold climates.

Electronics is sensitive to low temperatures and should be heated. Heat from the generator, a rest product when converting mechanical energy into electrical

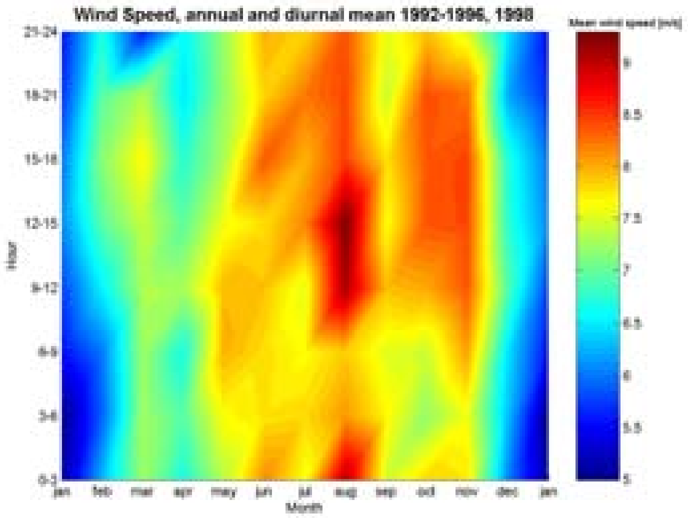

Figure 16: Annual and diurnal variations of the wind speed at Aboa station, 1992-96 and 1998.

energy, can be used to heat the electrical boxes. However, a separate power source is required when the turbine is not operated. In the nacelle, heat from the drive chain keeps the temperatures moderate during operation.

As described in chapter 5.6, low temperatures also mean a higher air density. The amount of power produced is proportional to the density, which means that a turbine designed for operation in standard temperatures will produce more energy in Antarctica than in other continents due to the low temperatures. The power needs to be limited to protect the generator from overproduction, but a shut down of the rotor means less energy is produced. One solution is to limit the load on the turbine by allowing the rotor to run with partial load. [19]

9.1.3 Strong Winds

The load on the rotor is proportional to the square of the wind speed and thus the strong winds in Antarctica impose high loads on the turbine, which can lead to fatigue damages. The rotor area and the hub height could be decreased for cold climate applications to avoid overproduction. Since the wind in Antarctica is generally stronger than in other areas, the operating range for wind turbines needs to be expanded to make sure the turbine is not cut off too frequently. It is also important to be aware of the high wind speeds when designing a turbine to be able to avoid resonance frequencies.

9.1.4 Static Electricity

Due to the dry atmosphere and the dry drifting snow, static is built up on cables and structures and earthing practices have to be used. [20]

9.1.5 Snow Ingress

The fine snow in Antarctic blizzards has a habit of getting into everything. The nacelle and hub have to be properly sealed to prevent the drifting snow from getting in. The yawing system is also sensitive to drifting snow that can stop the yaw mechanism from aligning the rotor with the wind. [20]

9.1.6 Logistics, Transportation and Erection of a Turbine

A turbine exposed to strong winds and harsh conditions needs to have a foundation that can act as a counterweight and withstand the loads on the turbine. The permafrost ground conditions make the use of concrete structures complicated and a high level of quality control is needed during construction. When building Wasa, water was used instead of concrete.

Turbines are normally erected with the help of cranes, but there are models that are self-erecting, which is an advantage in remote locations such as Antarctica.

Since there are no roads in Antarctica, the transport of bigger structures is complicated and should be considered when choosing wind turbine model.

9.1.7 Maintenance

Though maintenance is not really a cold climate issue, many of the turbines installed in cold climates are located in remote areas. Wasa is only occupied during a few months per year, which means that no personnel are able to perform maintenance during the austral winter. A turbine installed at Wasa should be highly reliable to minimise the need for maintenance. The design should be kept simple and the number of moving parts small. A direct driven generator needs less maintenance and is thus preferred over a turbine with a gearbox.

9.2 Market Investigation

Based on information from other Antarctic research programs, information on cold climate issues and wind potential assessments carried out, there is enough information available to search the market for suitable wind turbines. The demands on the turbine are summarized below.

- Annual maintenance sufficient
- Materials classified for cold climates
- Synthetic lubricants rated for cold climates
- Preferably direct driven generator
- A minimum of moving parts
- Heated electronics
- Sealing to protect from snow ingress
- Possible to erect without use of cranes
- Survival in wind gusts of approximately 60 m/s
- Possible to operate in low temperatures ($< -42\,^{\circ}$C)

An investigation was carried out and a large number of manufacturers and possible wind turbine models were found. Temperature and wind speed operating ranges were compared, as well as experience of the turbines in cold climates. It was investigated which turbines that fulfilled most of the demands listed above, and which turbines that were of appropriate size for Wasa, i.e. that one or a few units would be sufficient to cover the energy demand. At last, some possible turbines were omitted because there was not enough information available about them. An attempt was made to contact the manufacturers of the turbines that seemed interesting, but since some of them did not answer email or return telephone calls their turbines were simply omitted due to lack of information.

Some of the models considered to be interesting were investigated more thoroughly. These models are briefly described below. All turbines examined are horizontal axis models, if nothing else is explicitly stated.

Northern Power Systems' North Wind HR3
The HR3 turbine has been operated successfully at Black Island since 1985 and is of appropriate size for Wasa. Unfortunately, Northern Power Systems does no longer manufacture this turbine. [53]

Proven WT6000
Proven WT6000 is a 6 kW pitch controlled downwind turbine, recently installed at King Edward Point in South Georgia by the British Antarctic Survey. It has been operated successfully since, with few problems, see chapter 7.3 for more information. Its cut-in wind speed is 2.5 m/s, the nominal speed 12 m/s and the survival wind speed is 65 m/s. Its rotor diameter is 5.6 meters. The turbine is direct driven, an advantage in cold climates, and maintenance is only

required once a year. It comes with two different hub-heights, 9 or 15 m. The turbine can be ordered with specific demands on temperature operating range. In Norway, Proven turbines with a lowest operating limit of -50 °C have been installed. Available outputs are 48 V, 120 V and 240 V AC. [54, 63]

Westwind 3kW
The Australian company GP & Hill Pty Ltd manufactures a series of turbines called the Westwind Wind Turbines. Their smallest turbine is a 3 kW three bladed, upwind model. Its nominal speed is 14 m/s and the cut-in speed is 3.5 m/s. There is no information on its survival wind speed. The rotor has a diameter of 3.7 meters, and the tower is available in two heights, 18 and 24 meters respectively. The nacelle is completely sealed to stop ingress of foreign particles. The rotor is protected from overspeeding with an auto-furling mechanism that turns the rotor away from the wind at 17 m/s. There is no gear box in the generator. The output voltages available are 48 V, 96 V, 110 V and 120 V DC. A low temperature version is available, with a temperature range of -30 ° to 50 °C. The rotor blades are constructed of the same pultruded fiberglass that Bergey use (see below). [55]

Vergnet GEV 5/5
The Vergnet GEV 5/5, manufactured in France, is a twin bladed upwind turbine with a rated power of 5 kW at wind speed 14 m/s. Its rotor diameter is 5 meters, and the tower height is 12 or 18 meters. The turbine has a cold climate option, which makes it possible to be operated in temperatures down to -30 °C, and a simple design. The cut-in wind speed is 4 m/s and the survival wind speed is 85 m/s, probably the highest on the market. At 60 m/s the tower is tilted to protect the turbine from extreme loads. The rotor is turned to face the wind by a passive yawing system. This turbine has a gearbox with ratio 5.78. Since the Vergnet turbines are produced to fulfil the demands of the customer, there are several options for output voltage.

The Vergnet GEV 7/10, a turbine with the same design as the GEV 5/5 but with a higher rated power, was considered the best alternative for operation in Antarctica by the French-Australian joint project "Alternative Energy Systems for Antarctic Stations", for more information see [36]. The GEV 7/10 turbine has been tested at Heard Island and Kerguelen Island with satisfactory results. [56]

Eoltec Scirocco E5.5-6
The Scirocco E5.5-6 turbine is a twin bladed upwind turbine manufactured by the French company Eoltech. It has a rated power of 6 kW at wind speed 12 m/s, a cut-in speed of 2.8 m/s and a survival wind speed of 60 m/s. The rotor diameter is 5.5 meters, and there are three different tower heights; 18, 24 and 30 meters. The power is regulated via active stall. The turbine has a passive yawing system, consisting of a down-wind tail. The Scirocco E5.5-6 is direct-driven and requires only an annual inspection. It is fully sealed to prevent ingress of snow or sand. The voltage output is 48 V DC. The standard version is possible to operate in temperatures above -20 °C, but operation in colder temperatures is possible with a few adaptations, such as different component materials. These adaptations would increase the price by approximately 40 percent. [57, 58]

Bergey BWC XL.1
The Bergey turbine is designed for high reliability, low maintenance and operation in harsh conditions. It is a 1 kW direct driven model with a minimum of moving parts. The power is regulated by furling, i.e. by mechanically flipping the rotor out of the wind. Survival wind speed is 54 m/s, nominal wind speed is 11 m/s and the furling wind speed is 13 m/s. The cut-in wind speed is 2.5 m/s, but a speed of 3 m/s is required for start-up. The rotor diameter is 2.5 meters, and there are several options for tower height; 9, 13, 20, 26 and 32 meters. The temperature range is -40 °C to 60 °C. XL.1 has a three-bladed upwind rotor with blades constructed of pultruded fiberglass, a material that Bergey claims to be twice as strong as normal steel. The turbine is offered with a tubular tilt-up tower, available in heights from 9 to 32 meters. The voltage output is 24 V DC. [59]

SVIAB VK240
The three-bladed VK240 turbine is manufactured by the Swedish company SVIAB. It is a small unit aimed at battery charging, delivered with an electronic regulator that ensures that the battery bank is not overloaded. The voltage output is 12 V or 24 V. The turbine has a cut-in speed of 2-3 m/s, and a rated power of 750 W at nominal speed 11-12 m/s. As the wind speed exceeds 10 m/s the rotor is turned partly away from the wind with the help of a tail. At 20 m/s, the rotor is turned completely away from the wind. There is no information about maximum survival speed nor temperature operating range for this turbine. The generator is direct-driven, which minimizes the need for maintenance, and completely sealed. The VK240 is known for its long life time and small need for service. However, when used at Wasa in 1988/89, the turbine was destroyed by the strong winds at the station. The model manufactured today is exactly the same model that was used earlier at Wasa. [64, 65]

Windstream Power Systems
Windstream Power Systems in the US has developed turbines used in Antarctica before. They do not have a model ready for production, but could design a turbine with help of their prior experience. The cost for a cold climate turbine would be approximately $10-12 per W of capacity. [60, 61]

9.3 Calculations

Power curves distributed by the manufacturers and the wind speed frequency distribution displayed in figure 14 were used to calculate the energy produced over a year for all six turbines. Note that these calculations are numerical approximations. The obtained power distribution curves were nomalized to make it possible to compare units with different rated powers. The normalization was done by dividing the output from each turbine with its rated power in W times the number of hours in a year to create a dimensionless number for comparison. The resulting power distribution curves can be found in figure 17. Another means of comparing the turbines is the capacity factor, derived in appendix I, which gives a picture of the turbine's performance. The capacity factor is the actual annual energy output divided by the theoretical maximum output, i.e. the amount of energy that would be produced if the turbine were running at rated power 8760 hours. The capacity factor is normally 25-30 percent, which is roughly true for all turbines investigated with the exception of the Westwind and the SVIAB turbines. Depending on wind conditions and turbine prices, a large capacity factor does not necessarily indicate an economical advantage. However, a high capacity factor indicates a relatively stable power output, close to the design limit of the machine, which is an advantage in weak grids. It also indicates relatively stable winds. [62]

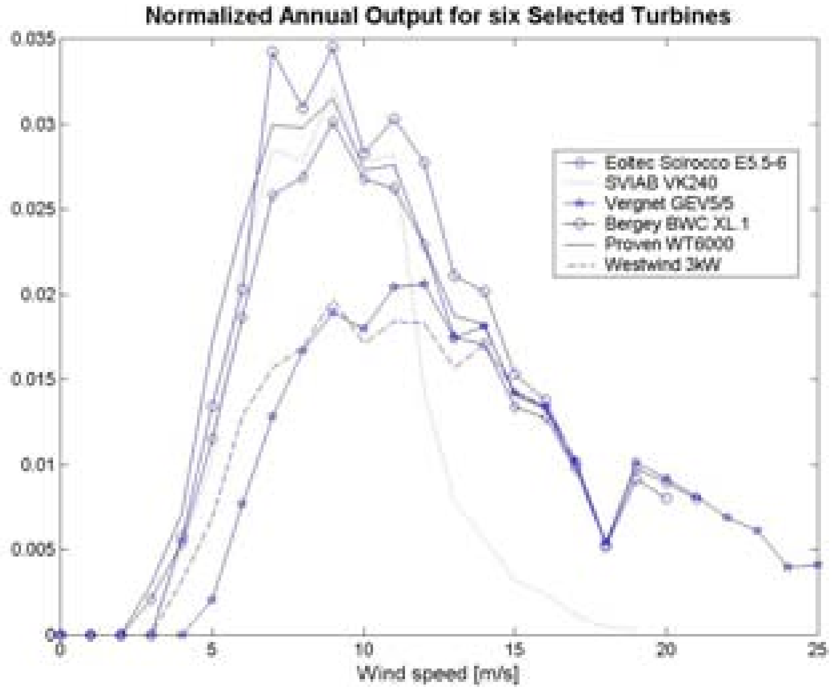

Figure 17: Normalized power distribution curves.

The number of operating hours for each turbine was also calculated, based on knowledge about the turbines' operating ranges and the frequency of occurrence for winds outside these limits. This number has been divided by the number of hours in a year, 8760, and is displayed as operating percentage below. Note that this percentage is an estimation.

At last, the number of operating hours was calculated taking temperature operating range into account. Even when the wind is moderate, it might be impossible to run the turbine due to temperatures that are too low to ensure safe operation. Taking this into account lowered the operating percentage significantly. It should be noted that the standard version of the Scirocco turbine is only operable in temperatures higher than -20 °C. However, a cold climate version of this model could be manufactured on demand, see section 9.2. An extended temperature operating range would mean an increased operating percentage and a higher price. It should also be noted that since there was no information on temperature operating range for the SVIAB turbine, the number of operating hours taking both temperature and wind strength into account could not be calculated for this turbine.

The results of the calculations can be found in table 3.

Wind turbine	Scirocco	Westwind	Proven	Vergnet	Bergey	SVIAB
Rated power [kW]	6	3	6	5	1	0.75
Swept area [m^3]	23.8	10.75	24.63	19.63	4.91	4.52
Total energy/year [kWh]	14809	4758	16707	10322	2904	1427
Capacity factor	0.28	0.18	0.32	0.24	0.33	0.22
Operating percentage	81	61	81	72	81	66
Operating %, temperature included	57	55	81	66	77	-

Table 3: Capacity factors, operating percentage and total amount of generated energy for six turbines.

The six turbines evaluated in this assessment were all chosen because they seemed to be well adjusted for the harsh conditions at Wasa. In the calculations performed above, it can be seen that there are big differences in performance between the models.

The rated capacities and total amount of energy produced in a year are figures that can be used to compare the different models. It can be seen in table 3 that the Bergey XL.1 turbine and the Proven WT 6000 both have capacity factors exceeding 30 percent, which is a relatively high number and significantly better than for the other models. The Westwind 3 kW turbine has the lowest capacity factor (0.18) while the Scirocco turbine, the SVIAB turbine and the Vergnet GEV 5/5 have capacity factors between 20 and 30 percent.

The operating percentages, when the temperature range is taken under consideration, vary from 55 percent to above 80. If the Scirocco turbine could be delivered with a wider temperature operating range as promised by the manufacturer, its percentage would be considerably higher and the turbine would be a good alternative to Proven WT6000 and Bergey XL.1 in this aspect. The Westwind turbine has the lowest operating percentage, followed by Scirocco (standard version) and Vergnet GEV 5/5. The operating percentage for the SVIAB turbine is missing due to lack of information.

9.4 Economics

The budget for the power supply system is limited, and the cost has to be minimized. Comparing the prices of the turbines is not as straightforward as could be expected, since the wind turbine assemblies do not always include all the necessary equipment and that additional investments have to be made. Most often, the price for a tower is not included but has to be added. During this comparison, the price given is for a wind turbine assembly that includes the turbine and the generator, if nothing else is explicitly stated. The Westwind turbine has been excluded from this comparison, since it does not seem like a promising alternative when it comes to performance under the existing conditions.

The price for a Proven WT6000 is approximately €11,340, which means that the price per kW is €1,890. A Scirocco 6 kW turbine assembly costs €13,000 (excluding VAT) for a machine that is operational in winds up to 60 m/s and standard temperatures. This gives a cost per kW of €2,167. The smallest turbine, the Bergey XL.1 costs €2,150. The Sviab turbine is the most expensive one, since it costs approximately €2600 for 750 W, which means that the price per kW is €3500. No information about Vergnet's prices has been received yet.

As can be seen above, the price per kW is approximately €2,000 for all turbines in the comparison, except for the SVIAB turbine, which is much more expensive than the other turbines investigated. If one of the smaller turbines is chosen, a larger number of turbines would have to be installed, which would mean that a larger number of towers would have to be bought. It should also be remembered that the standard version of the Scirocco turbine can only be operated in temperatures down to -20 °C, and if a low temperature rated machine is desired, the price will be higher than for the other turbines.

Wind Steam Power Systems mentioned in section 9.2 has manufactured turbines used in Antarctica before, and could develop a turbine rated for the conditions at Wasa to a price of $10-12 per W, i.e $10,000-12,000 or €8150-9750 per kW, which is substantially higher than for the other turbines evaluated.

10 Storage of Excess Energy

Although new methods of energy storage, such as hydrogen systems and fuel cells, seem promising, they are not fully developed and have not been tested in extreme conditions. Batteries on the other hand, have been used for many years in all kinds of climates. They are inexpensive, reliable and they have a high power density. For the Swedish station Wasa, a storage system consisting of batteries is probably the best alternative for storing excess energy.

The technique used in a battery is well known and will not be explained in this report. In case more information about batteries is needed, see [66]. The intention with this chapter is to mention some aspects connected to using batteries in a harsh climate and to describe the benefits and drawbacks of some types of batteries. A more profound investigation of the storing possibilities has already been conducted in a master thesis project carried out by two students at the Royal Academy of Technology in Stockholm, see [48].

10.1 Different Kinds of Batteries

There are a number of different kinds of batteries; all of them have characteristics that vary. Finding a battery that fulfils all demands imposed on it is difficult, and deciding to buy a specific type of battery is most often a compromise since no single battery offers a fully satisfactory solution.

For use in a wind energy system in Antarctica, a battery system that can resist low temperatures, needs little maintenance, is relatively cheap and can be transported to and stored at the site is needed. Since the environment in Antarctica is very sensitive and protected by strict environmental regulations, a battery that is environmentally friendly would of course be preferred over a battery that contains toxic substances.

The first criterion is maybe the most difficult one to fulfil, since all batteries perform best in room temperature. The performance drops drastically in temperatures below the freezing point, and even though it might be possible to discharge a battery in such low temperatures, charging often requires higher temperatures. Among the most well known types of batteries, Nickel-Cadmium and modern Lithium-ion batteries are the kinds that perform best in cold climates. [66] Therefore, focus will be put on these two types of batteries during this brief survey.

10.1.1 Nickel-Cadmium Batteries

The Nickel-Cadmium, NiCd, battery was invented in 1899 and eventually evolved towards the modern sealed NiCd battery. It has a good performance in harsh climates and allows recharging in low temperatures. It is quickly charged and can be stored for long periods of time. The NiCd battery is relatively cheap and has a high number of charge/recharge cycles. There are also a number of drawbacks, such as a relatively low energy density, a rather high self-discharge and that it contains toxic metals. The memory effect, when large crystals are formed on the cell plates in case a full periodic discharge is neglected, affects the NiCd battery and gradually lowers its performance. The battery needs maintenance in form of regular full discharges, or the number of cycles may be reduced by a factor of three.

According to [66], NiCd batteries can be used in temperatures as low as -40 °C. In temperatures this low, the discharging rate is limited to 0.2 C, i.e. one fifth of the maximum rate, and the charge rate is reduced to 0.1 C.

There is already an energy storage system at Wasa, consisting of 80 1.2 V NiCd batteries and a regulator. The batteries are kept in insulated boxes underneath the radio house, see figure 18. The system has only been used during the austral summer, which means that it has not been run under the lowest temperature periods. It is therefore not known whether the insulation is sufficient during the winter months.

Figure 18: The battery bank at Wasa station.

According to Northern Power Systems, the manufacturer of the equipment (wind turbines, batteries etc) used at Black Island (see 7.8) and other locations with extreme cold conditions, NiCd batteries outperform other types of batteries in cold weather applications. [67]

10.1.2 Lithium-Ion Batteries

The first non-rechargeable lithium batteries were commercially available in the 1970s, but it was not until in 1991 that a rechargeable model was invented. The lithium-ion battery has a higher energy density than NiCd batteries, typically two times as high, and the self-discharge is less than half compared to NiCd batteries. No maintenance is required, but aging is a major problem and failures after two or three years are common. There is no memory effect, but a protection circuit is required to maintain voltage and current within safe limits. The battery is relatively friendly to the environment. The price for a lithium-ion battery is about 40 percent higher than that of NiCd models.

Standard lithium-ion batteries can be discharged in temperatures down to -20 °C, but charging should not be carried out in temperatures that low. There are modified models that can be operated in temperatures as low as -40 °C, but these are new and still under development. The price of the rather expensive battery will probably be even higher for the modified model.

The rapid aging of lithium-ion batteries is a major disadvantage, especially for applications in remote locations. Since the battery is expensive, the price per load cycle is very high compared to the price of a NiCd battery. [66]

10.2 Discussion

NiCd batteries have been used with satisfactory results in Antarctica before and the technology used in the battery is simple and well know. The battery has many advantages, such as being possible to operate in harsh conditions, a low price and many operating cycles. Another advantage is the existence of a battery bank with NiCd batteries at Wasa that might be possible to use in combination with additional batteries during the winter months, an alternative that would be a lot cheaper than investing in a large number of new batteries. Lithium-ion batteries are interesting but not fully developed and their price is substantially higher than the price for NiCd batteries. Their main benefits are the lack of toxic metals, the minimized need for maintenance and the high energy density. However, since reliability is one of the most important demands on the new power supply system, a well-known technique which could last for many years is desired and the NiCd battery is probably the best alternative for storage of excess energy at Wasa.

Part IV
Conclusions

11 Recommendations

During this master thesis project, the answers to two different questions are investigated. The first question is whether wind power is a feasible and realistic solution for a new power supply system at Wasa. After evaluating prior experiences with turbines in Antarctica, wind resources at the site and a number of other parameters, it is now time to answer this question.

There are many advantages with using a wind power system at Wasa despite of the harsh conditions in Antarctica, for example

- The wind at Wasa is very directional.
- The wind resources are excellent. Although extremely strong wind gusts occur, they are not very common. The wind is stronger than 40 m/s less than 0.5 percent of the time. Several of the turbines compared above still produce energy in winds stronger than 40 m/s.
- Other countries have used wind turbines in Antarctica with satisfactory results.
- Wind power is a clean energy source, with few environmental impacts compared to conventional power sources such as diesel generators.
- Wind power is relatively cheap.
- Icing, a phenomenon that threatens to destroy turbines in cold climates in the rest of the world, is not very frequent in Antarctica.
- The location is suitable for installation of a turbine, since the slope where Wasa is located is not very steep, there are few obstacles and there is enough space available.

As all means of generating power, wind energy has disadvantages, such as

- The generation of wind energy is very weather dependent.
- It is difficult to transport large equipment, for example turbine towers, where there are no roads.

Compared to other power sources, the disadvantages with wind power are few. Since photovoltaic cells would not work during the austral winter, diesel generators are environmentally unfriendly and fuel cells are expensive and not yet fully developed, wind power is one of the few alternatives that could provide the automatic equipment at Wasa with power around the year without major problems.

The answer to the first question is therefore that wind power would in fact be a suitable solution for the generation of power at Wasa.

The second question is what the new system would look like? Which turbine would be best at covering the energy need at Wasa? Would one large turbine be preferred over a number of small units?

In section 9.3, it was concluded that the Proven WT6000 and the Bergey XL.1 turbine have the best capacity factors of the turbines compared. The same turbines have the highest operating percentages, which is a very important parameter since a continuous power production is requested. Their prices per kW are comparable. The Scirocco turbine has a relatively high capacity factor and operating percentage, but the price for the cold climate version is higher than for the two turbines mentioned above. The Vergnet turbine has a lower capacity factor and a lower operating percentage, but a larger unit of the same model has been tested in Antarctica with satisfactory result and it was the turbine recommended in the joint French-Australian evaluation. The SVIAB turbine has been used with limited success at Wasa before, and is much more expensive than the other turbines in the comparison. It also has a low capacity factor and a rather low operating percentage, although it must be remembered that the temperature operating range is unknown, which means that it is impossible to compare the operating percentages when taking temperature into account.

Since the Proven and the Bergey turbines seem to perform best of the turbines evaluated, one of them should be chosen for Wasa. The Proven turbine, which is also available in smaller versions, has been used by the British Antarctic Survey in the area and has performed well. The Bergey turbine has not been tested in Antarctica.

Since the wind speeds vary considerable between different years, a turbine with a rated power 20-30% higher than needed should be installed at Wasa, to ensure continuous measurements.

Installing one or a few turbines would be cheaper than installing a number of smaller units, and it would also require a smaller area. In addition, it is an advantage to have few turbines when it comes to maintenance. On the other hand, when it comes to transport and elevation, smaller units are more practical than larger ones. A larger number of small units would also increase the reliability of the system, since the failure of one unit would not automatically mean that no power is produced, nor a drastical decrease in production. However, the turbines evaluated in this thesis were chosen because they seemed well adapted for the conditions at Wasa, and they should be operable in the harsh climate without reliability problems. Chosing between a system with one or a few larger units and a system with a number of smaller units is an adjustment between the different advantages mentioned above, and giving advice on which kind of system that should be chosen is hard.

Since the British Antarctic Survey has had problems with resonance and vibrations, stiff towers discussed in section 6.2.3 would be recommended for the turbines installed at Wasa. These towers should be constructed of a cold rated material, as discussed in section 9.1.2. A tower constructed of several parts is easier to transport than a tower consisting of one piece only. The height of the tower also needs to be optimised. Increasing the tower height is the cheapest way of increasing the energy production, but a higher tower also means stronger wind speeds at hub height and higher loads.

Since the prevailing wind direction is known, locating the turbine/turbines in such a way that the builings at the station area do not act as obstacles is easy. Turbulence occurs a distance of two times the obstacle's height before the obstacle and twenty times the height after the obstacle, which is illustrated in section 5.7. This means the turbines should be placed at least two times the height of the buildings upwind of Wasa, or at least twenty times the height downwind of the station. The latter location would mean that less noise from the turbine would be heard at Wasa. On the other hand, it would also mean that longer cables would be necessary, which would increase the cost for the installation.

As discussed in chapter 10, a battery bank with NiCd batteries would probably be the best alternative for storage of excess energy.

12 Future Work

The most important task remaining is to determine the energy demand more exactly and to optimise the composition of the system for this energy level. For this purpose, a simulation tool could be utilized.

Once a more precise minimum power output has been determined, negotiations with the different manufacturers could take place. Vergnet, for example, does not have a price list that is followed strictly, but the prices of their units depend on the demands imposed on the machines. This is true for most of the manufacturers, since the turbines are often modified slightly for the buyer's specific demands. Thus, the Swedish Polar Research Secretariat has to invite tenders for complete systems, including towers, from all manufacturers.

A simulation tool could also be used to calculate the duration of time intervals with wind speeds insufficient for energy production, and the duration of storms. This information is important when determining the size of the battery bank, which must be able to deliver energy to the measuring equipment during the longest periods of insufficient wind speeds, and in temperatures as low as -45 °C.

The lack of data on maximum wind speeds at Svea made it difficult to evaluate the feasibility for wind power at the station. Since the scientists who came up with the request to make around the year measurements were also interested in experiments at Svea, the maximum wind speeds should be measured and the wind resources should be evaluated. It would also be a good idea to map the station area in order to find a location suitable for a wind turbine.

To be able to calculate the wind resources more exactly, the wind speeds should be measured over considerably shorter time intevals. Short-term variations in wind speed need to be quantified for fatigue prediction and other turbine design considerations such as structural excitation and power quality. For wind energy applications, a 10 second average is preferred.

Since more and more nations install wind power in Antarctica, there will be valuable information about the installations available in a near future. These facts should be collected and evaluated, so that the information on hand is up-to-date at all times.

Part V
Acknowledgements

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Part VI
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Part VII
Appendix

13 Appendix I - Derivation of the Betz Limit

The flow of air through a stream tube, see figure 19, is considered. The air velocity is denoted U and A is the cross-section area of the tube.

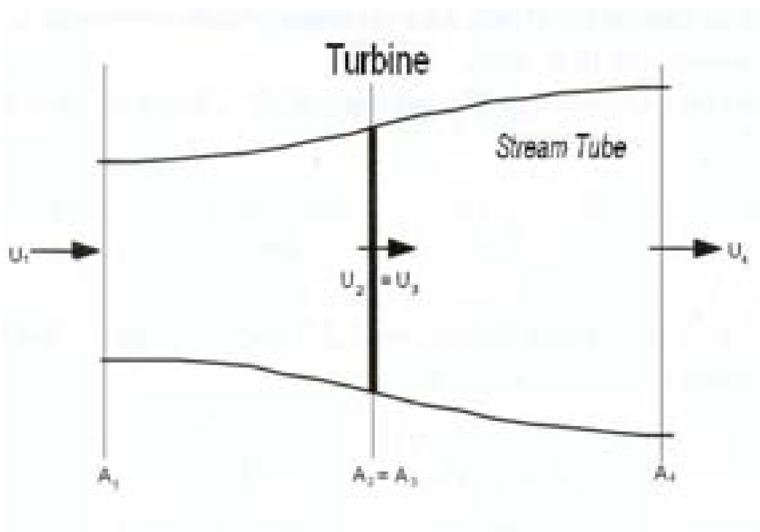


Figure 19: The flow through a stream tube with the rotor situated at position 2.

Ideal conditions are assumed;

- The air can be considered an incompressible, homogenous fluid
- The flow of air is static
- There is no friction between the air and the tube
- The number of rotor blades is infinite
- Non-rotating, non turbulent wake
- The air pressures a long distance before and a long distance after the tube are equal to atmospheric pressure
- The turbine can be approximated by an ideal disc

The mass flow is conserved through the tube, i.e.

$$\frac{dm}{dt} = \rho A_1 U_1 = \rho A_2 U_2 = \rho A_3 U_3 = \rho A_4 U_4 \tag{10}$$

The pressure on the air in the tube, T, is given by

$$T = \frac{dm}{dt}(U_1 - U_4) \tag{11}$$

Under the assumption of ideal conditions, Bernoullis theorem, given below, can be applied

$$p + \frac{1}{2}\rho U^2 = constant \tag{12}$$

For the tube in figure 19, this means that

$$p_1 + \frac{1}{2}\rho U_1^2 = p_2 + \frac{1}{2}\rho U_2^2 \tag{13}$$

$$p_3 + \frac{1}{2}\rho U_3^2 = p_4 + \frac{1}{2}\rho U_4^2 \tag{14}$$

The pressure on the air in the tube can also be expressed as

$$T = A_2(p_2 - p_3) \tag{15}$$

where p_2 is larger than p_3.

From equations (13) and (14) an expression for $(p_2 - p_3)$ is obtained

$$(p_2 - p_3) = p_1 + \frac{1}{2}\rho U_1^2 - \frac{1}{2}\rho U_2^2 + \frac{1}{2}\rho U_3^2 - p_4 - \frac{1}{2}\rho U_4^2. \tag{16}$$

From the initial assumptions, it is known that $p_1 = p_4$. It is also known that $U_2 = U_4$. These expressions can be used to simplify equation (16), which gives

$$(p_2 - p_3) = \frac{1}{2}\rho(U_1^2 - U_4^2) \tag{17}$$

Equations (15) and (17) give

$$T = A_2(p_2 - p_3) = \frac{1}{2}\rho A_2(U_1^2 - U_4^2) = \frac{1}{2}\rho(U_1 - U_4)(U_1 + U_4) \tag{18}$$

A combination of (11) and (18) gives

$$\frac{dm}{dt}(U_1 - U_4) = \frac{1}{2}\rho A_2(U_1 - U_4)(U_1 + U_4) \tag{19}$$

Equation (10) and equation (19) give

$$\rho A_2 U_2(U_1 - U_4) = \frac{1}{2}\rho A_2(U_1 - U_4)(U_1 + U_4) \tag{20}$$

This expression can be simplified to

$$U_2 = \frac{U_1 + U_4}{2} \tag{21}$$

which means that the air speed at the rotor is the average of the speed of the undisturbed air and the speed after the rotor.

The decrease in velocity of the air from point 1 to point 2, the axial interference factor, is denoted a, i.e.

$$a = \frac{U_1 - U_2}{U_1} \tag{22}$$

which can be rewritten as

$$U_2 = U_1(1-a). \tag{23}$$

Equations (21) and (23) give

$$U_4 = U_1(1-2a) \tag{24}$$

The turbine's power is given by the expression

$$P = TU_2 \tag{25}$$

A combination of equations (18), (21), (24) and (25) gives

$$P = \frac{1}{2}\rho A_2 a 4 U_1^3 (1-a)^2 \tag{26}$$

In order to find the a that maximizes P, P is differentiated with respect to a

$$\frac{dP}{da} = \frac{1}{2}\rho A_2 4 U_1^3 \left[(1-a)^2 - 2a(1-a)\right] \tag{27}$$

This equals zero if the expression in the parenthesis is equal to zero, which is the case if a equals one third. Insertion of $a = 1/3$ yields

$$U_2 = \frac{2}{3}U_1 \tag{28}$$

$$U_4 = \frac{1}{3}U_1 \tag{29}$$

These results can be inserted into equations (10), which yields

$$A_1 = \frac{2}{3}A_2 \tag{30}$$

$$A_4 = \frac{3}{2}A_2 \tag{31}$$

The maximum theoretical power is obtained by inserting

$$a = \frac{1}{3}$$

into equation (26), which gives us a maximum power equal to

$$P_{max} = \frac{8}{27}\rho A_2 U_1^3 \tag{32}$$

The maximum power coefficient, C_p, the rate between the maximum theoretical power output and the power in the undisturbed wind through A_2 is given by

$$C_p = \frac{P_{max}}{\frac{1}{2}A_2 U_1^3} = \frac{16}{27} \approx 59.3\% \tag{33}$$

The turbine efficiency, η, the maximum theoretical power output divided by the supplied power is given by

$$\eta = \frac{P_{max}}{\frac{1}{2}\rho A_1 U_1^3} = \frac{\frac{8}{27}\rho A_2 U_1^3}{\frac{1}{2}\rho \frac{2}{3} A_2 U_1^3} = \frac{8}{9} \tag{34}$$

14 Appendix II - Figures

Wind roses were created from all three data sets used during the project. In figure 20 the wind rose based on data from Aboa is displayed and in figure 21 the wind rose based on data from AWS 6, close to the station Svea, is presented. Note that the classes used in the data from Aboa are broader.

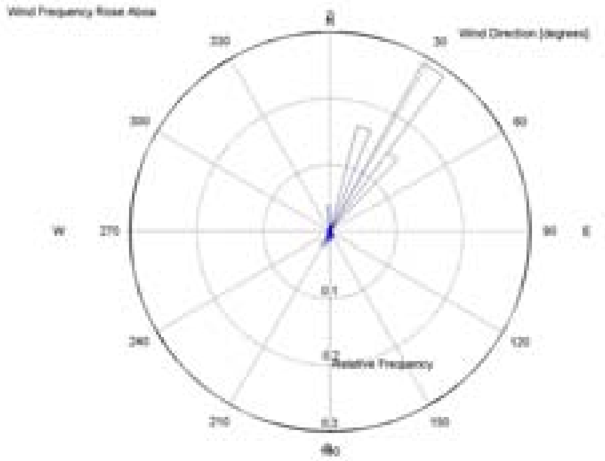


Figure 20: Wind rose based on data from Aboa.

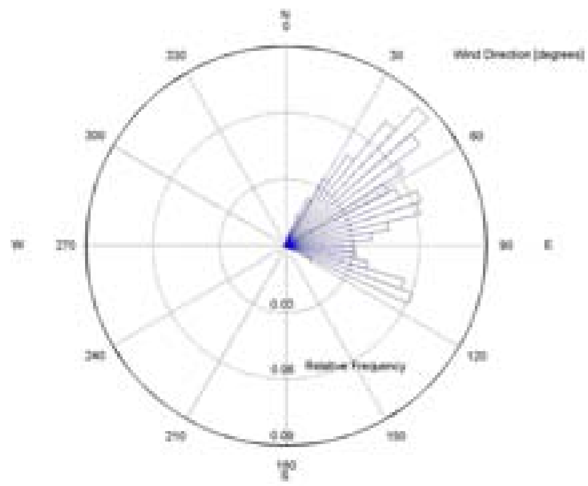
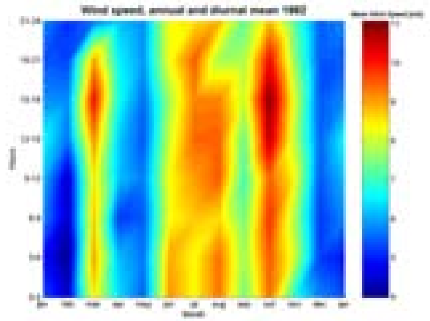
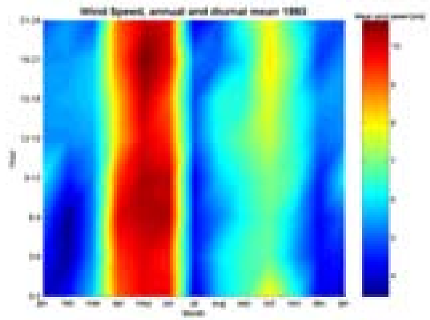
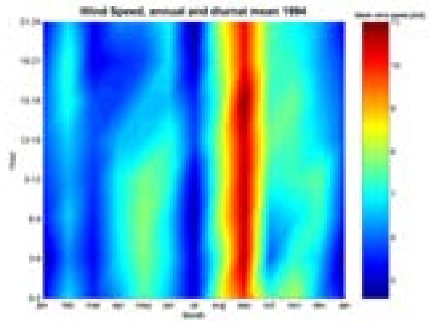


Figure 21: Wind rose based on data from AWS 6.

The graphs below display the annual and diurnal wind speed average at Aboa station for the years 1992-96 and 1998.







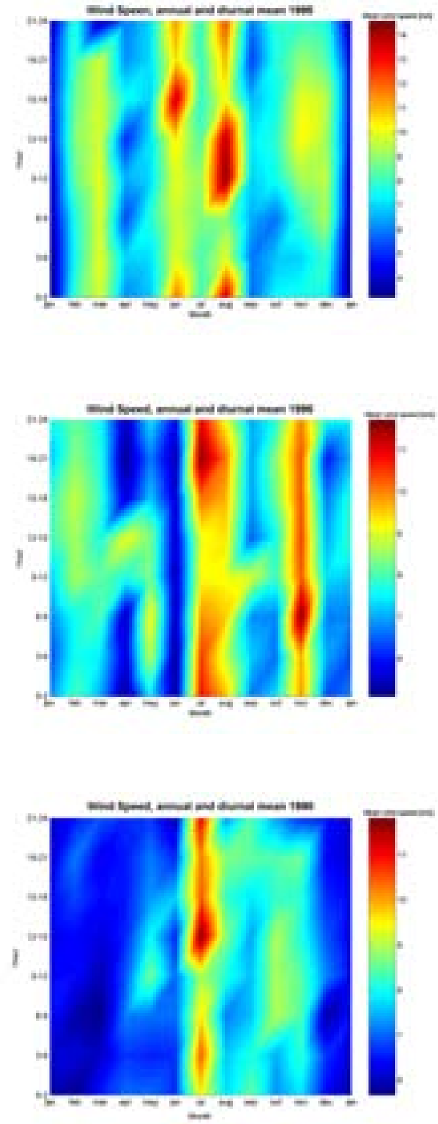


Figure 22: Annual and diurnal mean wind speeds at Aboa 1992-96, 1998

15 Appendix III - Numerical Values

The standard wind speed frequency distribution, displayed in figure 14, and the energy distribution presented in figure 15, in numerical values.

Wind speed [m/s]	Occurence [%]	Energy contribution [%]
0-0.5	4.2447	0
0.5-1.5	5.8714	0.0035
1.5-2.5	8.7167	0.0414
2.5-3.5	8.9499	0.1436
3.5-4.5	9.5563	0.3635
4.5-5.5	10.3376	0.7680
5.5-6.5	9.6496	1.2388
6.5-7.5	8.5534	1.7438
7.5-8.5	5.9530	1.8116
8.5-9.5	4.7286	2.0489
9.5-10.5	3.2126	1.9095
10.5-11.5	2.7579	2.1817
11.5-12.5	2.2914	2.3534
12.5-13.5	1.7433	2.2765
13.5-14.5	1.7084	2.7862
14.5-15.5	1.3410	2.6901
15.5-16.5	1.2769	3.1086
16.5-17.5	0.9737	2.8433
17.5-18.5	0.5248	1.8190
18.5-19.5	0.9737	3.9696
19.5-20.5	0.8921	4.2418
20.5-21.5	0.7988	4.3969
21.5-22.5	0.6880	4.3543
22.5-23.5	0.6239	4.5116
23.5-24.5	0.4140	3.4014
24.5-25.5	0.4373	4.0611
25.5-26.5	0.3032	3.1673
26.5-27.5	0.3965	4.6384
27.5-28.5	0.3032	3.9559
28.5-29.5	0.2624	3.8034
29.5-30.5	0.2682	4.3041
30.5-31.5	0.2157	3.8199
31.5-32.5	0.1807	3.5203
32.5-33.5	0.1341	2.8644
33.5-34.5	0.1807	4.2224
34.5-35.5	0.0816	2.0802
35.5-36.5	0.0233	0.6467
36.5-37.5	0.0583	1.7554
37.5-38.5	0.0408	1.3311
38.5-39.5	0.0233	0.8223
39.5-	0.3090	-

Table 4: The standard wind speed frequency distribution and the energy distribution in numerical values.