Assessment of green power production in Antarctica

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Abstract
Traditionally, fossil fuels have been the energy source to power research stations in Antarctica. With increasing awareness of climate change and local environmental effects associated with use of fossil fuels, the demand for replacement green energy power supply have increased rapidly.

In this article, the potential for wind and solar power in Antarctica is assessed. The study is based on 34 years of reanalysis data from the Modern-Era Retrospective Analysis for Research and Applications (MERRA) focusing on the location for the experiment ARIANNA (Antarctic Ross Ice-Shelf Antenna Neutrino Array). Results are compared with the stations Mawson and Princess Elisabeth, where wind and solar power already is operational, and with the Amundsen-Scott station.

The average wind speed for the ARIANNA site is around 7.5 m/s during winter and 6.0 m/s during summer. Comparing with Princess Elisabeth, the average wind speed is approximately 5 m/s lower.

The generally low wind speeds at the ARIANNA site suggest that wind turbines with a low cut-in speed should be used. The strong influence from katabatic winds make wind direction persistent, which is preferable.

The potential for solar power production at ARIANNA is expected to be 10% lower comparing with Princess Elisabeth.

Keywords: ARIANNA, MERRA, Antarctica, wind power, wind energy, solar energy, katabatic winds

1. Introduction
The Antarctic continent, with its remoteness and extreme environmental conditions, is ideal for many scientific experiments. As the possibilities to colonize the continent and construct very large experimental setups have increased, the question of how to supply the research stations with electrical power has become a hot topic.

Traditionally, fossil fuels, have been used as the primary energy source in Antarctica. During the last decade, the knowledge and general awareness about the environmental impact from fossil fuels has increased rapidly. Thus, the need for green energy sources is a burning issue.

The original Antarctic Treaty, dating from 1959, was formulated to protect the continent from military conflicts and ensure that it would solely be used for peaceful and scientific purposes. In 1982, the agreement of Conservation of Antarctic Flora and Fauna was added to the treaty and in 1998 the Protocol on Environmental Protection came into force. The restrictions were created with the aim to safeguard the unique Antarctic biosphere and polar environment (Secretariat of the Antarctic Treaty 2013).

During the 1960s, a nuclear power plant supplied the McMurdo station, maintained by the United States, with energy. Due to spill of nuclear waste and the public opposition, it only lasted for ten years, and nuclear energy is nowadays prohibited by the Antarctic Treaty System (Reid 2005).

Replacing fossil fuels with wind turbines might be the first thing that comes to mind. For example, the two 300 kW wind turbines deployed at the Australian Mawson station account for 95% of the energy for electricity, heating and fresh water production. Any excess of energy can be used to generate hydrogen from water and stored in fuel cells, to be used when the wind drops (Australian Antarctic Division 2013).

Despite the many benefits of wind turbines, there
are several aspects to consider before construction can begin. Any anthropogenic disturbance affects the image of Antarctica as an untouched desert. Since the landscape generally is open, wind turbines will stand out and be visible from great distances. During installation, there is a large impact on the local environment as explosives are used to prepare the ground. When wind turbines are running, wildlife is affected as e.g. the Weddell seals are sensitive to low frequent sounds (Ray & deCamp 1969) and birds may accidentally get hit by the rotor blades.

The remarkable Antarctic climate causes problems unseen elsewhere. Tin et al. (2010) report that wind gusts often exceed 70 m/s at the Mawson station and that the low temperatures are a problem when constructing the foundations. Due to snow accumulation the wind turbines have to be lifted approximately one meter every year. On the other hand, advantages are the persistent strong winds and the dry Antarctic atmosphere which eliminates the need of a de-icing system for the turbines (Tin et al. 2010).

Other possible renewable energy sources are solar power, geothermal power and water power.

Solar power can be used in two ways, either for direct heating, or by using photovoltaics to convert the energy to electricity. Both alternatives cause minimal impact on nature as they can be mounted on existing buildings. However, the drawback is that there is no sunlight during the winter months.

If the temperature gradient in the ground is large enough, geothermal power is a possible energy source. It is available all year round, but the installation has a large impact on the local environment. Water power in the shape of currents, waves and tidal elevation are possible energy sources for the coastal stations in the future, when the technologies are improved (McKenzie et al. 2010).

Besides installing green energy turbines, one of the most effective ways of creating a more environmentally friendly research station is by education of the staff and encouraging a change of attitudes. For example, many Australian staff members changed their behaviour when informed that the cost of energy in Antarctica is at least five times higher than the cost to a suburban consumer in Australia (Tin et al. 2010).

In this article, the wind power potential is reviewed from a meteorological perspective, describing the general wind situation and using 34 years of reanalysis data to compare the wind resource at different research stations in Antarctica in practice. Extra attention is paid to an area centered on the Ross shelf, the location for the ARIANNA experiment (Antarctic Ross Ice-Shelf Antenna Neutrino Array).

In addition to this, the preconditions for solar power are discussed briefly.

2. Antarctic wind climate

For most places on Earth the weather and prevailing winds are determined by the movements of synoptic systems. However, Antarctica with its unique characteristics has a quite special wind pattern.

Since there is no heating from incoming solar radiation during the Antarctic winter, the surface is cooled by emitted long wave radiation. The surface in turn cools the adjacent air. The cooler air is heavier and therefore strives to sink, following the slope of the terrain downwards. These gravity winds are called katabatic winds and are described in more detail in an article by Parish & Cassano (2003).

The katabatic winds converge in narrow valleys and are channeled towards the coast. This results in a constant wind direction and, as a matter of fact, the surface winds in Antarctica are among the most persistent on Earth (Parish & Cassano 2003).

During summer, insolation counteracts the cooling of the surface, thereby decreasing the strength of the katabatic winds.

The Antarctic coastal zone is one of the most active cyclogenetic regions on Earth. Thus, in this area surface winds are affected by the wind field associated with the generation of intense low pressure systems (Parish & Cassano 2003).

3. The MERRA data set

To be able to study the Antarctic wind resource and compare the wind power potential at several scientific stations, reanalysis data from the Modern-Era Retrospective Analysis for Research and Applications (MERRA) (Rienecker et al. 2011) has been used for the calculations. The data set is provided by National Aeronautics and Space Administration (NASA) and covers the modern era, from 1979 and onwards, during which remote sensing has been dominant when collecting data about the atmosphere.

The reanalysis data is created by combining different types of measurements (such as surface observations, radio soundings and satellite data) and using a numerical model to calculate a gridded data set in a consistent way.
Table 1: Summary of the MERRA data that has been used in the calculations.

<table>
<thead>
<tr>
<th>Data product</th>
<th>Resolution</th>
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<td>Native</td>
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<td>IAU 2d atmospheric single-level diagnostics</td>
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Figure 1: Map with approximate height contours showing the location of the four research stations. The investigated area centered around the ARIANNA station is marked in blue.

In this study, data for wind speed at 2, 10 and 50 m above ground level (AGL) is used in combination with the air temperature at 2 m height and the surface pressure. In both cases, the time period is from January 1, 1979 to December 31, 2012.

The data is gridded with a latitudinal resolution of 1/2° (approximately 56 km) and a longitudinal resolution of 2/3° (approximately 28 km at 60°S with increasing resolution closer to the South Pole). The analysis is mainly based on time averaged hourly data.

The MERRA data set is covering the whole globe and is not optimized for the polar regions. Verification of the data (e.g., Rienecker et al. 2011) has shown good agreement with observations and better performance than other reanalysis data sets such as NCEP/NCAR (National Centers for Environmental Prediction, National Center for Atmospheric Research), ERA-Interim and ERA-40 (both maintained by the European Centre for Medium-Range Weather Forecasts, ECMWF) (Kalnay et al. 1996; Dee et al. 2011; Uppala et al. 2005).

The research stations selected for the survey are: Mawson (Australia), Amundsen-Scott (United States) and Princess Elisabeth (Belgium). In addition to these, the location of the research station for the ARIANNA experiment, located on the Ross Shelf approximately 100 km south of the McMurdo station, is investigated. To be able to find the site that is most suitable for wind power production an area of size 560 km x 460 km centered on this location is analyzed (76–81°S, 152–172°E). A more detailed description of the used data and the positions for the stations are given in Tables 1 and 2 and in the map in figure 1.

The Mawson and Princess Elisabeth stations are valuable in making a good estimate of wind power production at any other site since wind turbines already are installed at these stations. The Amundsen-Scott station is selected as it is the most remote station in Antarctica and manned all year round. Jet fuel is used as primary power supplier at Amundsen-Scott and since transport of the fuel is a vulnerable and costly project, the energy supply from a wind turbine would lead to great savings, both economical and environmental.

4. Metrics for wind power

The key parameter that comes to mind when evaluating the resource for wind power is the average wind speed. However, the power output $P$ of a wind turbine is

$$P = c_p \rho A U^3$$

where $c_p$ is the coefficient of performance of the wind turbine, $\rho$ the density of the air, $A$ the area swept by the blades and $U$ the wind speed. Hence it
is important to construct a measure that takes the variability of the wind speed with time into account, since this has a large influence on $U^3$ (Burton et al. 2011). One such measure is the wind power density (WPD) defined as

$$\text{WPD} = \frac{\rho U^3}{2}$$

(2)

The density is calculated using the approximation that the air is dry and behaves like an ideal gas. This gives the expression

$$\rho = \frac{p}{R_d T}$$

(3)

where $p$ is the air pressure, $R_d$ the gas constant for dry air and $T$ the air temperature.

The calculated density at 2 m height is assumed to be valid up to 50 m height. The relative error that this simplification introduces is, for the general case, estimated to be less than 1%. Since the density decreases with height, the wind power density at 50 m AGL will be slightly overestimated. It should be mentioned that the uncertainty in the MERRA-data for the wind speed is unknown and that this probably is a larger error source, due to the factor $U^3$. Despite the errors these approximations and uncertainties cause, the calculations are performed in the same way for all locations and the results should be comparable.

Since the WPD is a long-tailed distribution, it could be argued (Gunturu & Schlosser 2012) that the median WPD is a more appropriate measure than the average WPD to describe the center of the distribution. The median WPD will be used in this article.

5. Results

5.1 The Antarctic continent

The seasonal average wind speed (summer: October – March, winter: April – September) at 10 m AGL shows, figure 2, that the wind speeds are highest in the coastal zones, primarily on the easterly coast. Wind speeds are generally lower on the ice shelves and over open sea.

The effect from the katabatic winds is seen as the wind speeds clearly are lower on the mountain ridges (compare with the height contours on the map in figure 1), and that winter is the windiest season for most places.

The maps for 2 and 50 m AGL display the same pattern as for 10 m AGL, but having maximum values of 11.0 and 16.5 m/s respectively.

5.2 Comparison of wind power potential at four research stations

The time evolution of average wind speed from 1979 to 2012 in summer (January) and winter (July) is studied to see if there are any trends of increasing or decreasing wind speeds, possibly relating to a climate change. The result is shown in figure 3 where trends can be seen following the 5-year running average (black lines).

For the location of the ARIANNA experiment, there is an increasing trend in the average wind speeds during the summer months, rising approximately 1 m/s during the last 30 years. On the other hand, the time series for the winter season does not show any clear trend, but indicate that occasionally there can be periods with higher wind speeds.
Figure 3: Time evolution of the average wind speed during July (upper line) and January (lower line) for ARIANNA and Princess Elisabeth. Note the different scales.

For the Princess Elisabeth station there are no visible trends in the data, and the same is true for Amundsen-Scott and Mawson.

The large year-to-year change of wind speeds are interesting to note, in the extreme case, the average wind can increase with 50% from one year to the next. This of course highly affect the potential for wind power, as $WPD \propto U^3$.

The monthly variation of WPD at 10 m AGL, figure 4, clearly shows the higher energy content in the wind during the Antarctic winter. Princess Elisabeth is the station in the survey with greatest opportunities to make use of wind power. The wind resources are not negligible for Mawson or at the ARIANNA site, but for Amundsen-Scott the potential is highly limited, reaching a maximum of 140 W/m$^2$ during winter.

The distribution of wind speeds, figure 5, further confirms that Princess Elisabeth and Mawson are most suitable for wind power, with peak values shifted more to higher wind speeds than the other stations. A narrow curve indicates a small variability in wind speeds.

Since most wind turbines shut down and do not produce any electricity when the wind is too weak or too strong, it is important to know how often these limits are surpassed. Typically, the cut-in and cut-out wind speeds are 4 and 25 m/s respectively. Since the most common wind speeds for the Amundsen-Scott and ARIANNA stations are low, wind turbines with a lower cut-in speed should be considered. The cut-out criterion of 25 m/s is almost never met.

Extreme wind speeds can cause high loads on the turbine and, in the worst case, structural failure. Therefore, information about the highest expected possible wind speed is of interest. However, the 1 h time averaged MERRA data is not sufficient to describe these phenomena. The 70 m/s gusts reported by Tin et al. (2010) are suggested to be used as a guideline.
The shift in wind distribution with height for the ARIANNA site, shown in figure 6, is as expected. As the average wind speed increases with height the possible range of wind speed increases as well and wind speeds below 4 m/s are less common.

5.3 The ARIANNA area

The average wind speed at 10 m AGL for the area centered around the ARIANNA experiment on the Ross Ice Shelf, shown for the winter season (April-September) in figure 7, indicate that the wind speeds are remarkably higher over land than at the ice shelf. The highest summits on the Ross Island, Mount Erebus (3800 m) and Mount Terror (3200 m), can be seen as wind speeds are lower there than in the immediate surrounding.

The gradient along the coastline proves that the model used to create the MERRA data is taking the terrain into account, but the exact values at the coastal zones cannot be trusted blindly. Despite this shortcoming, the spatial distribution and absolute values can give an idea of the wind resource. In combination with a time series (covering at least one year) of observations from a weather station, the MERRA data can be adjusted to give a trustworthy long term analysis.

The maps are similar for 2 and 50 m AGL and the scales ranges, during winter, from 3.2 – 9.3 m/s and 4.8 – 14.1 m/s respectively. During summer (October-March), the average wind speed at a specific height is 20 – 25% lower than the average wind speed during winter.

Mapping the median WPD, figure 8, for the winter season shows the same spatial distribution as the average wind speed map in figure 7. During winter, median WPD is as large as 850 W/m² for some grid points in the area. During summer, the maximum value is less than 350 W/m².

Figure 7: Average wind speed in the ARIANNA area during winter. Locations for the ARIANNA (78.5°S, 165.3°E) and McMurdo (77.5°S, 166.4°E) stations are marked with black circles.

Figure 8: Median WPD in the ARIANNA area during winter.

Figure 9: Percent of time that the wind speed is less than 4 m/s in the ARIANNA area.

Figure 9 shows how often the wind speed is lower than the standard cut-in wind speed 4 m/s. The most occasions below 4 m/s occurs northwest of Ross Island. The most preferable situation is west of the Mina Bluff peninsula where, on average, the winds are lower than 4 m/s only one week every year. Again, it should be emphasized that the winds in coastal zones are complex and that the data probably is more smeared in the map than in reality.
To measure the persistence of the winds, the directional constancy is calculated. It is defined as

\[ d = \frac{\sqrt{\bar{u}^2 + \bar{v}^2}}{\sqrt{u^2 + v^2}} \]  

where \( u \) and \( v \) are the vector components of the wind and the bar denotes the average (van den Broeke & van Lipzig 2003). If \( d = 0 \), winds are equally common from all directions. The other extreme, \( d = 1 \), indicates that winds always are from the same direction (Parish & Cassano 2003).

A value close to unity is ideal when designing a wind power farm and can ensure that the blocking effect the wind turbines exert on each other is minimized, thus maximizing the electrical production. As seen in figure 10, the directional constancy is highest during winter months, due to the strong influence from the katabatic winds. The winds are mainly channeled over land, explaining the lower directional constancy over the ice shelf.

The streamlines show that the winds are generally directed northwards, away from the South Pole. There are only small differences in the average wind directions, mainly in the southeast corner of the map and northwest of Ross Island, comparing winter and summer.

5.4 Solar energy potential

The change of insolation during the year is compared for the location of the ARIANNA experiment and the Princess Elisabeth station. Since solar panels already are in operation at Princess Elisabeth, it is convenient to compare the conditions to easily give an estimation of how large the power production from sunlight can be.

The graph for the amount of incoming shortwave radiation during a year, figure 11, shows that the peak value is around 370 W/m² in December. From May to August, the Sun is below the horizon, leaving Antarctica in darkness and making power production from solar cells impossible.

The Princess Elisabeth research station is situated further away from the South Pole than the ARIANNA experiment and thus has greater opportunities to rely on solar energy, especially during spring and autumn. In total, the incoming solar radiation is about 10% lower at the ARIANNA site compared with Princess Elisabeth.

In the same manner as when finding the perfect position for a wind turbine, the local terrain should be investigated thoroughly before constructing a solar power system. To optimize the production it is important that the solar panels face the sun at a right angle and that they never are in the shade of any object.

6. Conclusions

The increasing demand on green energy production in Antarctica goes hand in hand with the growing amount of research stations on the continent. The unique Antarctic climate with persisting high wind speeds and low temperature provides conditions that are both favorable and unfavorable for wind turbines.

Using reanalysis data from MERRA, the potential for wind power at the location for the ARIANNA experiment is investigated.

![Figure 10: Directional constancy and wind directions for the ARIANNA area during winter (left) and summer (right).](image)

![Figure 11: Average monthly incoming shortwave flux for ARIANNA and Princess Elisabeth.](image)
The average wind speeds are 25-30% higher during winter compared to summertime. The potential for wind power is lower at ARIANNA compared with the Princess Elisabeth and Mawson stations where wind turbines already are operational.

The generally low wind speeds at ARIANNA suggest that wind turbines with a low cut-in speed should be considered. The average wind speed increases with a rate of 0.5 m/s per 10 m increase in height, going from 10 m AGL up to 50 m AGL.

Due to the strong influence of katabatic winds, the wind direction is almost always the same, which is preferable when designing a wind power farm.

The resolution of the MERRA data is too low to accurately depict the wind conditions in the coastal zones. However, in combination with measurements from a weather station it should be possible to long time correct the results. It is also concluded that the MERRA data is insufficient for analyzing the extreme wind gusts.

The potential for power production using solar energy is about 10% lower at ARIANNA compared with Princess Elisabeth.

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