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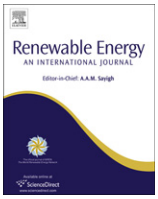

Energy efficiency and renewable energy under extreme conditions: Case studies from Antarctica

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ABSTRACT

This article showcases a range of small and large scale energy efficiency and renewable energy deployments at Antarctic research stations and field camps. Due to the cold and harsh environment, significant amounts of fuel are needed to support humans working and living in Antarctica. The purchase, transportation and storage of large amounts of fossil fuel entail significant economic costs and environmental risks and have motivated developments in energy efficiency and renewable energy deployment. Over the past three decades, improved building design, behavioral change, cogeneration, solar collectors, solar panels and wind turbines have been found to be effective in Antarctica, demonstrating that harsh environmental conditions and technological barriers do not have to limit the deployment of energy efficiency and renewable energy. The ambition to run entire stations or field camps on 100% renewable energy is increasingly common and feasible. While the power requirements of Antarctic research stations are small compared to urban installations on other continents, these case studies clearly demonstrate that if energy efficiency and renewable energy can be deployed widely on the coldest, darkest and most remote continent of the world, their deployment should be more widespread and encouraged on other continents.

1. Introduction

Antarctica is the coldest, darkest, and least populated of the seven continents on Earth. The Antarctic continent covers 13.8 million km^2, a surface area of land 50% larger than the United States. More than 99% of this land is covered by glacial ice which can be up to 4000 m thick. High on the inland plateau, mean annual temperature is about −50 °C, and Vostok station on the Antarctic plateau has recorded the lowest ever temperature in nature on Earth, a sobering −89.2 °C.

Despite its remoteness and harshness, however, humans have visited Antarctica since the late 1700s as explorers and then fishers, sealers, whalers, scientists and tourists. Since there is no indigenous population in Antarctica, the most permanent human presence in Antarctica comes from 75 active research stations providing maximum simultaneous accommodation capacity for just over 4000 people in the summer [1] (See Fig. 1 and 2). In the summer the tourism industry brings an additional 74,000 people (including paying passengers, crew and staff during the 2007/8 season), the majority of whom travel to Antarctica in cruise ships [2]. In winter, 38 stations still operate and provide space for about 1000 people.

Antarctica is governed internationally by 28 Countries under the Antarctic Treaty System (ATS). Under the ATS, Antarctica is designated as a “natural reserve, devoted to peace and science”, where military activities, nuclear explosions, disposal of radioactive waste, as well as mining are prohibited. As a result of its geographical location, unique natural features and relatively undisturbed natural

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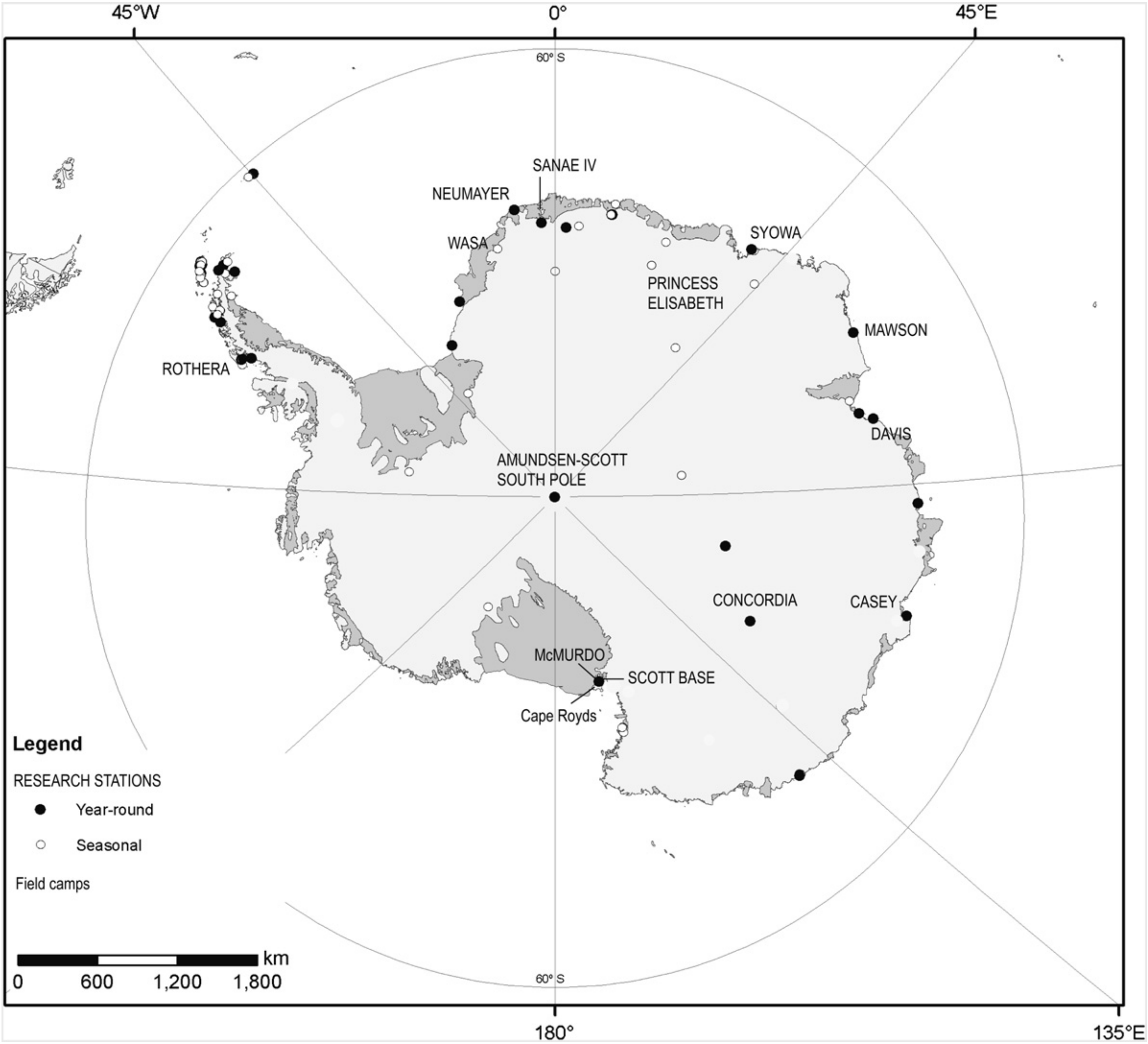

Fig. 1. Map of Antarctic research stations and field camp locations.

environment, Antarctica has been seen as an ideal laboratory for understanding natural processes, many of which have global implications. Biology, geology, astronomy, glaciology, global climate change and many other disciplines are studied in Antarctica.

In this article, we focus on energy use in Antarctica associated with science and its supporting logistical activities. At research stations, electricity generators provide the energy needed for science equipment, lighting, space heating, water pumping and purification, and waste systems. Gasoline, diesel, and jet fuel are also used to power aircraft, ships, boats, and land based vehicles. Many Antarctic stations are isolated and inaccessible for nine months of the Antarctic winter due to sea-ice cover and a single ship visit each year is often the only opportunity to resupply the stations with food, equipment and fuel. A few stations have also been constructed inland, over 1000 km away from the coast. In some cases, the resupply of fuel, equipment and personnel is performed by overland vehicles, which undertake roundtrip voyages of 2–3 weeks at a time. For example, US's Amundsen-Scott South Pole station, which is located far inland, has, until recently, been resupplied completely by aircraft from McMurdo station, which is situated on the coast. This has resulted in the price of fuel being more than seven times higher at South Pole than at McMurdo [3].

Transporting fuel and oil to Antarctica is therefore a costly and sometimes risky exercise. Fuel spills have occurred in the past due to the particular difficulties in pumping fuel ashore and the fragility of the bulk fuel tanks and fittings in the frigid temperatures, although the use of double skinned fuel tanks and improved safety procedures has greatly reduced the problem. The fuel requirements of a research station range from several hundred thousand to several million liters per year depending on the activities, the length of the open season, staff size and the diligence of onsite personnel. Most stations have been designed to accommodate up to approximately 50 people, while the larger stations can accommodate 100–200 people, the largest permanent station in Antarctica, US's McMurdo station, has power requirements of 16,000 MWh/yr to provide for a peak population of 1000 people in the summer and a winter population of 250 (See Fig. 3). McMurdo also serves as the primary logistics hub of the US Antarctic Program, where multiple small research camps are originated and supplied by air or overland. At McMurdo nearly 5 million liters of fuel are used annually for electricity production and additional fuel is needed for heating [3]. The Australian stations, Casey, Mawson and Davis are also relatively large stations, serving as logistical hubs for field activities in the East Antarctic region. Combined, they can accommodate up to 200 people in the summer and 62 in the winter. By the year 2000, these three stations were using 2.1 million liters of diesel fuel annually to provide power and heating. On a smaller scale, South Africa's SANAE IV station which was designed to accommodate up

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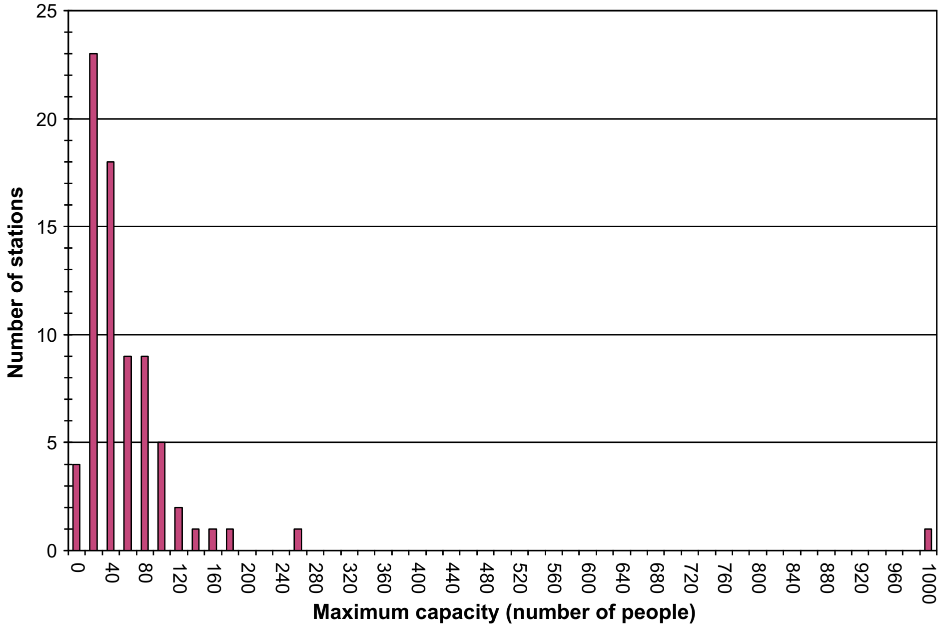

Fig. 2. Maximum summer capacity of Antarctica's 75 active research stations.

to 80 people in the summer and 10 people in the winter has an annual diesel consumption of about 300,000 l. During winter, about 72 kW of power is needed to keep the station at a temperature of 18 °C, and the power needed for heating can more than double during very cold periods [4]. The fuel for SANAE IV is transported from Cape Town and transportation and logistical costs increase the price of the fuel to approximately three times that of the purchase price [5].

This article showcases two broad categories of case studies of energy efficiency and renewable energy applications in Antarctica. The first focuses on energy efficiency and renewable energy at permanent research stations. The second category of case studies focuses on energy efficiency and renewable energy deployments at field camps and for scientific instruments. Field camps are summer-only camps that are set up at sites remote from permanent stations and can vary in size. At one extreme, they can provide hard structures as living and working quarters for 40–60 people, at the other they can be just a tent for as little as 2 people. Since the energy demands of field camps and scientific instruments are smaller than those of entire stations, their energy efficiency and renewable energy applications also tend to be smaller, more portable, and require less infrastructure than those deployed at permanent stations. These two broad categories demonstrate the wide spectrum of energy efficiency and renewable energy applications that are being used in Antarctica.

Fig. 3. Winter sunrise over McMurdo station. Photo by Chad Carpenter, National Science Foundation.

The purpose of this article is to encourage the exchange of ideas and information on energy efficiency and renewable energy between the polar and the non-polar circles. Information on energy efficiency and renewable applications in Antarctica is not often distributed widely in circles outside those of the polar regions. We hope that more colleagues working in the polar world would publish their work and inform a wider audience. At the same time, we would like to encourage non-polar colleagues to share their experience and also learn from polar examples. The remoteness of Antarctic research stations and facilities makes them similar to other rural areas where energy use occurs in relative isolation. Put another way, how energy facilities managers have saved energy and promoted renewables in Antarctica offers insight into how energy is used in other harsh and remote environments, such as offshore, in the Arctic, in outer space, or off-grid. Furthermore, even though energy consumption, carbon dioxide emissions and pollution from Antarctic operations are small in the global context, as the only continent internationally collectively managed for "the benefit of mankind" and playing an important role in the study of global climate change, some would argue that there is an ethical importance of reducing emissions and leading by example using best practice [6].

2. Energy efficiency and renewable energy at permanent stations

2.1. Energy efficiency

Rothera is the largest of the UK's research stations in Antarctica. It was built in 1975. The site is open throughout the year and has a maximum population of just over 100 people during the summer. In the winter, occupancy drops to 22. Temperatures at Rothera are likely to be between −5 °C and −20 °C in winter with possible lows of −40 °C.

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The site has developed since the 1970s with a range of different styles of buildings and structures to accommodate varying requirements. The energy efficiency of the earlier buildings is often poor and a concerted effort has been made to replace these buildings where possible and when affordable, with newer designs and technologies. By enhancing the insulation within buildings, a reduction in energy budgets needed to operate the site has been achieved. Modern buildings also have building management systems, improved boilers and other engineering equipment to maximize efficiency and reduce fuel burn. Solar collectors are used on newer buildings and have been a very useful addition for hot water production.

Perhaps the most effective and simplest of the energy efficiency measures that have been taken is a cap on electricity use. Electricity continues to be produced primarily with fossil fuel based generators, but facility managers have slowly reduced the average electrical load from 280 kW in 2000 to 220 kW in 2007 and plan to reduce it further. To facilitate this reduction, space heating in several of the buildings was changed from electrical to hot water, reducing electrical power and improving the efficiency of heating via direct use of fossil fuels rather than via an electrical system. Lighting systems were retrofitted, freezers fitted with energy saving devices and staff encouraged to actively reduce the use of power.

When designing new buildings, care has also been taken to ensure that structures are optimized for minimum snowdrift. Winds blowing across a structure in polar regions carry snow which is then deposited either on the structure or on the downwind side as the wind loses velocity while transiting the building. By developing a snow-blow model and making physical scale models, it has been possible to design the new buildings for minimum snow build-up. Snow clearance is a very energy intensive process. Reducing the need for snow clearance greatly reduces the energy needs of the station.

In comparison to Rothera, the Swedish station, Wasa, is smaller and newer. Built in 1989 to accommodate up to 30 people in the summer and closed during the winter, it was designed with energy conservation in mind. Walls and ceilings have 30–50 cm rock wool insulation, all windows are tripled glazed and there are no windows facing south. A heat exchange system distributes warm air generated by, for example, cooking or sauna from one part of the building to another. This system is very efficient and it is in the only early or late season that it is sometimes necessary to use external Liquefied Petroleum Gas (LPG) heaters. Stoves, refrigerators, freezers and sauna also run on LPG.

Energy efficiency was also the main design parameter for the French–Italian Concordia station. Built in 1997 to accommodate up to 60 people in the summer and 13 in the winter, Concordia is located over 1000 km from the coast. All equipment is transported long distance by tractor trains then stored onsite. The quantity of fuel consumed at Concordia must be strictly limited both to limit local environmental impacts and limit the quantities of fuel to be transported. All space heating needs are met using diesel generator sets where waste heat is recovered from the jacket water cooling system and the exhaust. At full load, 155 kW of waste heat is recovered in the powerhouse and distributed inside the three station buildings through the heating circuit. Additional heat is generated within the buildings by all electrical appliances. The external insulation and ventilation system have been designed to ensure that heat loss will remain under 70 kW even under the most unfavorable conditions in order that the two main buildings can be sufficiently heated without the need for additional heat to be generated [7]. Annual consumption of diesel fuel remains low at 200 m^3 and thermal cogeneration permits heating of the 1800 m^2 covered space and preparation of the daily potable water ration of 250 l [8].

While improving energy efficiency and reducing fuel burn requires significant technical input, it is widely acknowledged that staff education and encouragement of behavioural change are a simple and effective way of reducing the use of fossil fuels at stations. New staff members working at the Australian stations undergo education and training programs alerting them to the costs of energy at the stations and suggesting ways they could conserve energy at their work, living and recreational places. For instance, the simple fact that the cost of energy in Antarctica could be at least five times its cost to a residential consumer in Australia made a noticeable difference to the attitude of many staff members. At Wasa station, most of the power at the station is generated by solar panels. Scientists and logisticians are very conscious about the limited power that they have at their disposal, and they get together to discuss their energy needs, energy conservation and alternatives prior to each summer field season. At Rothera, the opportunity was taken to encourage staff to be far more energy efficient; switching off lighting when not in use, using washing machines when electric cookers are not being used, encouraging energy saving wherever possible. Realizing that the sustainability of the site was crucial to maintaining the station in a cost effective way, the staff responded and the average load is now around 220 kW, including a new laboratory.

2.2. Wind farms

Wind energy has, up to now, been the renewable energy that has been exploited at the largest scale in Antarctica. Two wind turbines of 300 kW have been able to provide much of the energy needs of Australia's Mawson Station since 2003 (see Fig. 4). A new wind farm is being constructed on Ross Island with the eventual goal of providing 100% of the energy of New Zealand's Scott Base and meeting part of the power requirements of US's McMurdo station.

Wind energy has taken off in Antarctica in part because of favorable environmental conditions (such as strong winds all year-round), the availability of off-the-shelf wind units that can be easily adapted to the special technical conditions in Antarctica, and a readily available, highly educated workforce with a strong background in science and engineering. However, technical challenges still need to be overcome in order to meet Antarctic conditions, such as extreme cold, extremely strong winds, and snow accumulation. In the case of the wind turbines at Mawson, after a decade of data collection and studies, the issues and solutions were reduced to:

- Annual average wind speeds of 11.2 m/s (at 10 m), recorded wind gusts regularly exceeding 70 m/s and an annual average

Fig. 4. Wind Turbines at Mawson Station. Photo by Peter Magill.

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temperature of −12 °C implied high risk of damage from strong winds and cold temperatures.

- Expected high grid penetration (up to 100%) demanded high degree of turbine control. Consequently, variable speed, variable pitch wind turbine design was preferred.
- Experience with a smaller machine at Casey station showed that gearboxes/hydraulics/oil-seals were high maintenance items in Antarctica. Consequently, a gearboxless design was preferred.
- Limited ice-free land at Mawson dictated a small number of “large” turbines, but turbine size was limited by the maximum size of mobile crane which could be shipped to Mawson.
- Only one manufacturer was willing to consider the project and modify a standard design to meet the specifications.
- Need to pour 65 m^3 mass concrete foundations in sub-zero temperatures.

The Australian Antarctic Division worked closely with German turbine manufacturer, Enercon, and Australian company, Powercorp, to design a high penetration renewable energy solution for Mawson, sized to allow operation of the station, free of fossil fuels. The outcome was a wind farm based on three Enercon E-30, “off-the-shelf” 300 kW wind turbines modified as follows to meet the unusual Mawson conditions:

- low temperature steel used in all tower sections, castings, and structural components;
- 34 m tower which is shorter than normal due to high winds and crane restrictions;
- control software modifications to ramp-down output power when the wind speed was in the range of 25 m/s to 34 m/s (a high proportion of winds at Mawson are above 15 m/s);
- special cold-porch attachment at tower entrance to exclude snow; and
- The need for de-icing systems eliminated due to the dry atmosphere.

A 100 tonne mobile crane was delivered to Mawson, along with foundation material and a concrete agitator truck. The turbines and powerhouse control system were installed and commissioned over a six-week period in early 2003 with minimal problems.

Since commissioning, wind penetration of the station energy load has consistently exceeded 90% when steady winds above 12 m/s have occurred. Annual wind penetration during the first six years of operation has averaged 35%, equating to fuel savings of around 32% per annum above the baseline year of 2002 (Table 1). Monthly fuel savings have been as high as 58% compared with the corresponding month in 2002.

Table 1
Statistics for operation of Mawson station Wind Farm (March 2003–December 2008).

Average wind penetration of station load	35%
Maximum monthly average wind penetration	60.5% (April 2006)
Minimum monthly average wind penetration	10.5% (Dec 2007)
Average annual fuel saving (compared to 2002)	32%
Maximum monthly average fuel saving (compared to same month in 2002)	58.1% (April 2006)
Minimum monthly average fuel saving (compared to same month in 2002)	8.1% (Jan 2006)
Maximum average monthly wind speed at hub height	20 m/s (72 kph)
Minimum average monthly wind speed at hub height	9.6 m/s
Availability of turbines (excludes low and high wind stoppages)	93%
Tonnes CO_2 saved	2918

Six years of successful operation of the Mawson wind farm has demonstrated that even in the world’s most hostile environment, well-engineered commercial-size wind turbines can make a substantial contribution to fuel and cost savings in Antarctic operations with the consequential environmental benefits. However for the Antarctic stations that are located on the (usually moving) continental ice-sheet or on ice-shelves, foundations required for large commercial wind turbines at those sites would be technically difficult and costly. As in the case of Germany’s Georg von Neumayer station on the Ekström ice shelf, engineers had to design special wind turbines with lightweight and efficient materials that could be installed without using heavy cranes or heavy lifting gears.

Neumayer station accommodates up to 50 people in the summer and at most 10 people in the winter. As Fig. 5 depicts, the wind energy potential here is very high and is about 165 W/m2 with mean wind speeds of 10 m/s and a maximum wind speed between 30 and 40 m/s. Higher wind speed categories contribute significantly by more than 60% to the total wind speed. Fig. 6 shows a 20 kW prototype Vertical Axis Wind Turbine (VAWT) that has been operating at Neumayer since 1991. It has been specially developed for minimum operating temperature of −55 °C, to survive wind speeds of up to 68 m/s and withstand a snow accumulation rate of 70 cm/year. The rotor is rigid and there is no transmission gearbox between the rotor and generator. The foundation consists of three base frames. Several triangles in the structure provide high mechanical stability of the construction. The base frame can be raised according to the snow accumulation.

The performance of the VAWT exceeded expectations, and it operated with no mechanical damages or faulty functions except for the need to replace one control component. During the main operation period, the wind generator is providing, on average, about 4 kW daily of electrical power (35,000 kWh/year) which is directly fed into the energy supply system of the station. The mean fuel consumption was, on average, reduced by about 6%, or 12,000 l per year, with reductions of 10–13% in the winter (due to the lower energy demand associated with fewer staff) (See Fig. 7).

After more than 18 years of operation, a new special 30 kW horizontal axis wind turbine was designed in co-operation between Alfred Wegener Institute for Polar and Marine Research (AWI), the Bremerhaven University of Applied Sciences (BUAS), and Enercon. A special ice foundation and a special mast construction were developed to meet the logistical requirements to lift the wind turbine by about 1 meter every year to compensate the snow accumulation, and the turbine was rated to provide about 120,000 kWh at a mean wind speed of 9 m/s (See Fig. 5). Another innovative feature of this wind turbine, apart from being constructed without heavy machine and to operate on an ice shelf, is its ability to operate at wind speeds ranging from 2.5 m/s up to 40 m/s.

The success of these two turbines has convinced the operators of Neumayer to expand the supply of wind energy even further to create a base-load renewable energy system. Five separate 30 kW wind turbines coupled with a 160 kW diesel generator are being constructed to meet all of the electricity needs of the station. The diesel generator would only serve to backup the wind turbines, and it is expected that only 25% of its full output will be needed over the course of the year. The first wind turbine has been installed in February 2009 and the other four are due to be completed by the end of 2011.

2.3. Solar energy and combined systems

Solar energy is increasingly being used to increase the renewable content of energy supply at research stations as well as at smaller seasonal field camps. In most cases, solar power is

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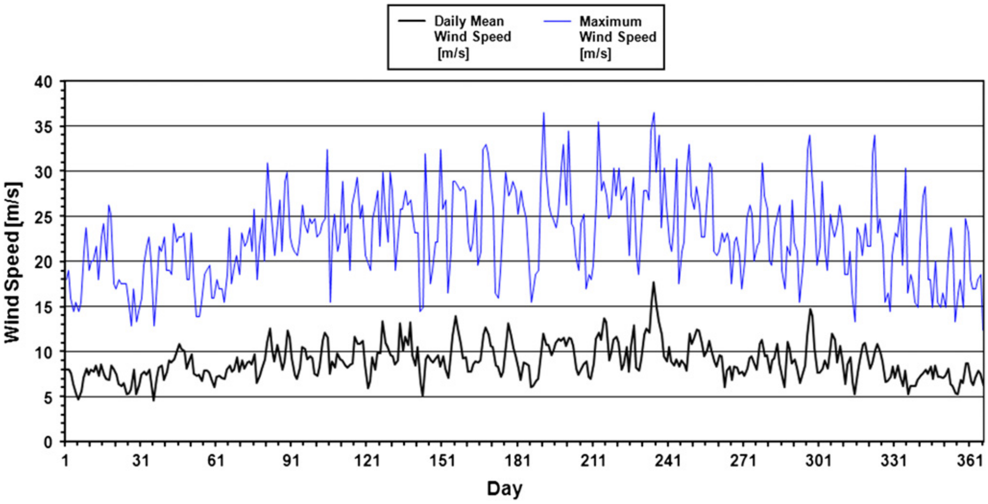

Fig. 5. 10 Years of Average Maximum and Daily Mean Wind Speeds at Neumayer Station at 10 m for the period of 1998–2008. Source: Dr. Gert Koenig-Langlo, Alfred Wegener Institute.

combined with wind turbines and diesel generators to meet energy needs. In a few cases, such as in the one below for Wasa station, solar panels can meet the bulk of the energy demands. Solar thermal energy is also often used to provide air and water heating.

At Wasa station, 48 solar panels manufactured by Neste/Fortum, each with a nameplate capacity of 55 W produce the power to meet most of the operational power needs of the station. The solar panels are backed up by a bank of Fiber Nickel Cadmuim (FNC) batteries manufactured by Hoppecke which can each store 1160 Ah. A diesel generator may need to be switched on very early or late in the summer season to provide supplementary energy. The heavy Antarctic winds cause the solar panels to be blasted by ice and gravel which degrades the panels' performance and shatter their outer protective glass. Despite the harsh conditions, overall the solar panels have worked well.

Japan's Syowa station is a larger facility, built to accommodate up to 110 people in the summer and 28 people in the winter, and subsequently has higher energy demands. 55 kW of solar panels produce an annual output of 44,000 kWh and displace about 3–5% of fossil fuel used by the facility, despite the long winters. The solar panels are complemented with air-type solar collectors that capture heat from sunlight and then transfer it to the walls of the facility. The solar heat collector consists of an intake fan that is powered by a 22 W photovoltaic and a collector panel of 1.1 m^2. The energy obtained from this system also displaces fossil fuel use, and produces about 86,318 MJ/year. A solar hot water system that uses evacuated glass tubes to heat water in a tank was also installed, in order to accommodate the hot water needs of the facility during the summer. The capacity of the system is 324,000 kcal/day and can heat water from 0 °C to 30 °C within one minute (see Fig. 8).

Belgium's Princess Elisabeth station opened in 2009 and was designed to be run on 100% renewable energy with diesel generators as emergency backup. Nine 6 kW wind turbines provide 65% of the estimated 140 MWh of electricity needed each year [11]. The rest is generated from nearly 300 m^2 of solar panels installed on stations walls and on rocks around the station. 18 m^2 of thermal solar panels are installed on the station roof to provide heating for the kitchen, bathroom and water treatment unit. An additional 6 m^2 of panels on top of the garages provide heat to melt snow for drinking water. The building's layout and wind arrangement have been designed so that passive solar gain would provide sufficient heating during the summer months. Princess Elisabeth is currently functioning as a summer station that is open only from November to February with space for up to 48 people. However, it has been designed to function year-round, and, in the future, may open its doors in the winter and accommodate up to 12 people.

3. Field camps and instrumentation

Increasingly small wind turbines and solar panels are being introduced to provide power at field camps to power computers, data collectors, cameras, radios etc. These portable and flexible systems reduce the significant costs associated with transporting fuel by helicopters and planes, and make it possible to have a silent

Fig. 6. 20 kW prototype Vertical Axis Wind Turbine (left) and 30 kW Horizontal Axis *Wind Turbine (right) at Neumayer Station. Photo by Saad El Naggar.*

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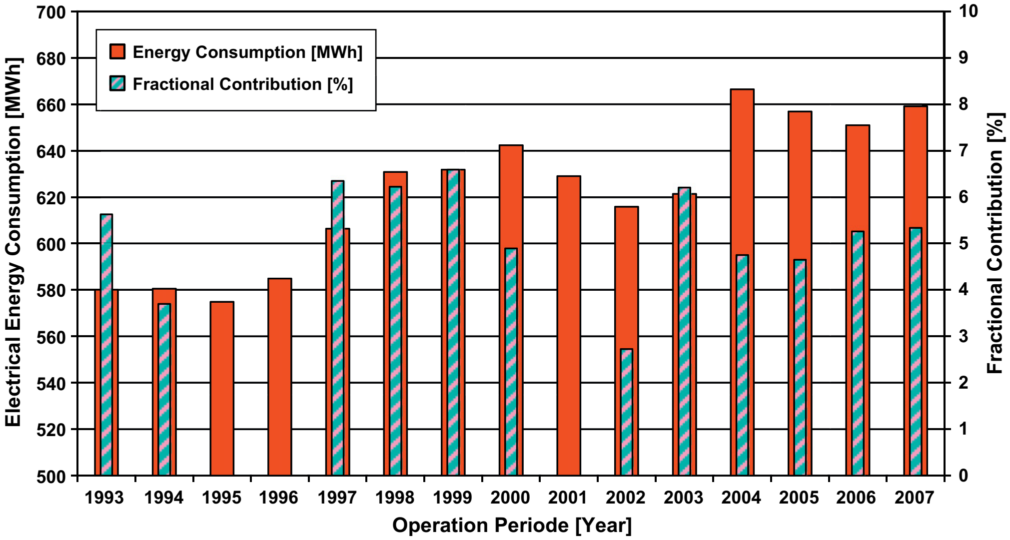

Fig. 7. Electrical energy consumption (solid bar, left axis) and the fractional contribution (dashed bar, right axis) of the 20 kW Vertical Axis Wind Turbine at Neumayer Station.

and low atmospheric emissions environment at field sites. Power systems based upon solar panels and sometimes small wind turbines allow instruments to collect data continuously and to connect to satellites for remote access and data transfer. Instruments utilising renewable energy have vastly increased the spatial and temporal sampling of monitoring possible.

At Cape Royds, a small tent camp is set up in order to facilitate the studying of a penguin colony each summer (David Ainley, Ronald Ross, personal communications). It is home to two researchers over a period of three months, in addition to any occasional visitors. The camp is powered by four 100 W panels, set up side by side on a swiveling base, and tilt is also adjustable. During the day, especially if cloudy, the orientation of the panels is changed to maximize exposure. A bank of three 12 V batteries provides storage for the energy. As long as the sun is not covered for more than 4 days, this power system provides sufficient energy for a weather station, 3 laptop computers, a charger for VHF hand-held radios, a wireless internet set up and a radio telephone (see Fig. 9). A gas generator is available as a backup and has been used solely on the few days when the solar panels have been unavailable due to storm damage. Four 35 W solar panels and a 12 V battery provide the power for a weighbridge that weighs each penguin as it leaves its colony. The weighbridge is mostly quiescent until a penguin moves and breaks the beam of photocells. Once motion is detected, the antenna reads the transponder that is implanted under penguin's skin, and then records the penguin's weight. As the penguin reaches the other side of the weighbridge, another set of photocells registers its stepping off the scale and the weighbridge returns to its quiescent state.

For renewable energy to truly be effective in providing power for instrumentation, one of the key requirements is to reduce the power consumption of the instruments. The Low Power Magnetometer – a precision instrument that measures the Earth's magnetic field in three dimensions – has been designed especially to have a power requirement of only 0.5 W [9]. The Low Power Magnetometer uses solar power over the summer and excess power is stored in batteries. 4 sets of 100 Ah lead acid batteries tide the magnetometer over the winter [9]. The network of magnetometers has been deployed far inland on the Antarctic continent where it can be dark up to five months each year, the Low Power Magnetometers can each function with full autonomy for over 400 days without interruption.

A similar rationale of reducing power demand lies behind solar-powered digital cameras designed for taking photographs of a penguin colony at regular intervals [10]. A camera controller, made of a very low power microcontroller and consumes very little power in sleep mode, controls the frequency and timing of camera operation. When operating the camera, the power consumption is dominated by the digital camera and shutter servo motor which are only operated as long as necessary to take a photograph. By focusing design effort into lowering the power consumption of the camera system, the size and mass of the solar panel and batteries are greatly reduced. Low power also rules out any kind of electrical heating, so all components must be able to function at the required

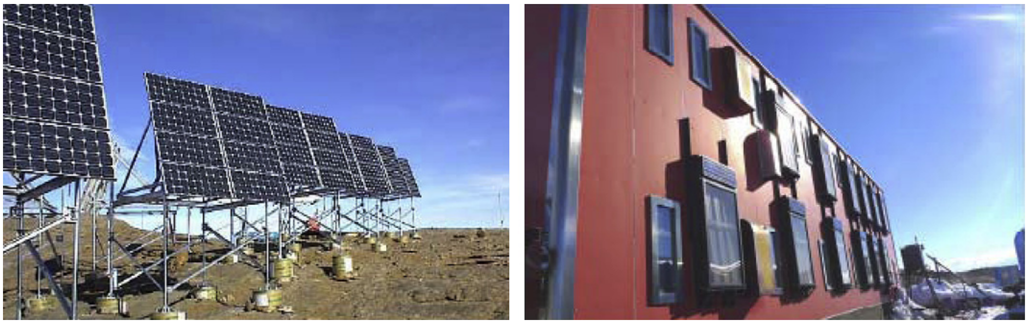

Fig. 8. Solar panels (left) and solar collectors (right) at Syowa station. Photo by Kenji Ishizawa.

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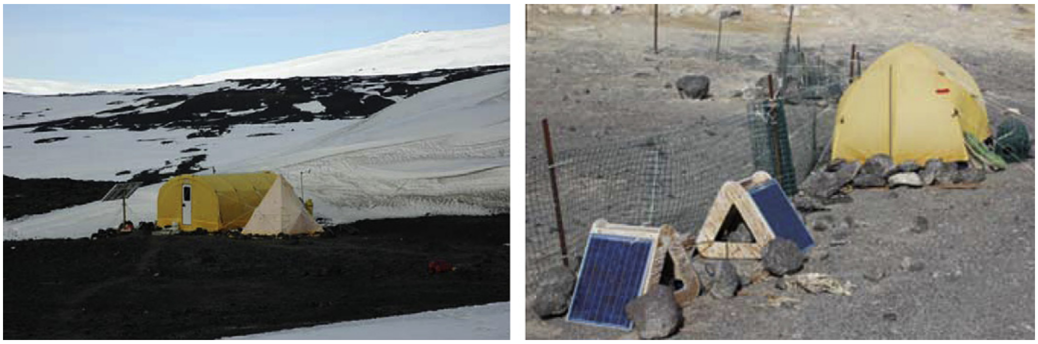

Fig. 9. Field camp at Cape Royds. Photos by David Ainley and Jean Pennycook.

temperatures. A 12 V, 2.5 Ah battery in combination with a 5 W solar panel have been proved to provide sufficient power for taking ten images a day over a period of 160 days a year [10].

4. Costs and benefits

Although subject to methodological differences and uncertainties, economic cost-benefit analyses can be useful in providing some kind of indication of the costs and benefits of introducing energy efficiency and renewable energy in Antarctica. However, in Antarctica as elsewhere, the results of such analyses should be treated with care and considered only as indicators of parts of a complex reality. Results from cost-benefit analyses are often subject to change as a result of fluctuating variables, such as changing fuel purchase prices, the cost of transporting fuel and installation costs. Conservative estimates are often employed. Cost-benefit analyses can rarely accommodate hard-to-monetize external cost savings, such as reduced risk of oil spill in transport and storage and reduced atmospheric emissions, or hidden cost savings such as annual reduced transport costs, and storage and maintenance requirements.

Despite the shortcomings of economic cost-benefit analyses, we hope that the following information provides an indication of some of the costs and benefits of renewable energy systems in Antarctica. The wind farm project at Mawson station cost around AU $8–9 million. The 3 wind turbines accounted for only 25% of the total project cost. Creating the foundation and infrastructure, purchase of plant and equipment and transportation took up the lion's share of the rest of the project cost. Undiscounted simple payback period is estimated to be from 5 to 12 years, depending on assumptions made on the cost of fuel landed and stored in Antarctica. Since commissioning, the wind farm has provided an average annual fuel saving of around 32%, equivalent to a saving of 2918 t of carbon dioxide during the first six years of operation.

The hypothetical installation of nine 100 kW wind turbines at South Pole station is estimated to cost approximately US $4.3 million and would result in potential net savings of almost US $18 million over a 20-year project life [3]. Annual fuel consumption would be reduced by almost 23%, or 440,783 l. Similarly, the possible installation of wind turbines of approximately 1 MW at McMurdo is estimated to cost US $2–3 million. Total fuel consumption would potentially be reduced by between 600,000 and 1,200,000 l/year resulting in net savings of between US$1 million and US$4 million over a 20-year project life (presuming a simple undiscounted payback rate). At South Africa's SANAE IV station, the hypothetical installation of a 100 kW turbine is estimated to reduce the cost per kWh produced by potentially up to 20%, with a simple undiscounted payback period of about 10 years [4]. Similarly, a flat-plate solar thermal system at SANAE IV could potentially save over 10,000 l of fuel annually and have a short payback period of 6 years. At the same time, it would lead to avoided emissions of 0.012 t volatile organic compounds, 0.019 t carbon monoxide, 0.471 t nitrous oxides, 0.003 t sulphur dioxides, 26 t carbon dioxide and 0.007 t particulate matter, which were not included in the economic cost-benefit analysis [5].

5. Conclusions

If there is one central lesson to be gleaned from the Antarctic experience, it is that facility managers have relied on a mix of different technologies and approaches to enhance energy efficiency and embrace renewable energy. Advanced energy management controls, robust energy efficiency measures, encouragement of behavioral change, low energy instrumentation, improved insulation, innovative snow removal techniques and cogeneration have contributed towards reducing energy demands. Solar collectors, solar panels and wind turbines have further reduced the need for fossil fuel. No single technology is used in isolation, and even in one of the world's most remote and harshest environments, where special foundations, materials, and construction techniques are often required, energy efficiency, wind, and solar can be effectively harnessed in a mix of applications and at a variety of scales. Energy efficiency measures, small-scale renewable energy applications, and management of energy needs through technical means and behavioral change have the added advantages of being flexible, portable, relatively cheap and requiring little infrastructure.

Years of successful operation at these facilities demonstrate that even in one of the world's most difficult environments, well-designed and well-engineered energy efficiency programs can make a substantial contribution to reducing energy use, displacing imports, reducing costs, and minimizing environmental damage. Indeed, our article highlights the fact that harsh environmental conditions and technological barriers do not have to limit the deployment of energy efficiency and renewable energy. Although the power requirements of Antarctic research stations are small compared to urban installations on other continents, the increasing ambition of independence from fossil fuel at Antarctic station is admirable and increasingly feasible.

In short, if energy efficiency and renewable energy can be deployed widely on the coldest, darkest and most remote continent of the world, we hope that it clearly demonstrates that their deployment should be easier, more widespread and even more encouraged on the other, more populated and less isolated continents.

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