Alternative Energy Options for Antarctic Stations

by

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"*Change is the law of life.*
And those who look only to the past or the present are certain to miss the future."
John Fitzgerald Kennedy

Declaration

I hereby declare that this thesis contains no material which has been accepted for the award of any other degree or diploma in any University, and that to the best of my knowledge and belief, this thesis contains no copy or paraphrase of material previously published or written by another person except where due reference is made in the text.

John David Steel

Abstract

The cost of powering Antarctic research stations by conventional diesel electric generator systems is high. A significant financial cost is associated with transporting fuel long distances by sea and storing and handling large quantities of bulk fuel in Antarctic conditions. Fossil fuel combustion in the power houses is the single largest local contributor to Antarctic produced airborne pollution. In addition, the serious consequences of oil spillage to the polar environment have been demonstrated recently with the *Exxon Valdez* incident in Alaska, and the *Bahia Paraiso* grounding in the Antarctic Peninsula.

The reduction of the use of fossil fuels has become an objective of nations active in Antarctica. This study has concentrated on wind turbine electrical generation systems, hydrogen production and storage systems, and fuel cell power plants as an alternative energy system designed to reduce the consumption of fossil fuels. The components of alternative energy systems were evaluated in this project to determine their potential to meet the special needs for efficient, reliable, safe and environmentally friendly power systems in Antarctica.

The study concluded that the large scale of an alternative energy system involving hydrogen as the prime 'energy carrier' is initially prohibitive. An alternative energy system centred around a wind farm producing energy for a station is the most practical means to reduce the consumption of fossil fuels. Periods of excess electrical production by the wind farm can be used for the production of hydrogen by the electrolysis of water. The hydrogen can be stored and later used by a fuel cell power plant to produce energy during periods of low electrical production by the wind farm.

The limitation of the study has been in obtaining specific data for technologies primarily in the development stage. Future research in this field will involve keeping up to date on international industrial groups and research institutions to obtain more data. Obtaining further data on the environmental conditions and energy use at Antarctic Research Stations will enable a specific design of an alternative energy system for Antarctica.

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Chapter 1

INTRODUCTION

The environmental and scientific values of Antarctica have recently received greater attention. Detection and monitoring of global environmental phenomena such as the depletion of atmospheric ozone, global warming and sea level change are now becoming priority research areas for nations active in Antarctica.

The signing of the Antarctic Treaty at the conclusion of the International Geophysical Year (IGY) in 1959 represented a significant point in the cooperation between nations involved in Antarctica. Research by Treaty Parties that is 'freely available to all mankind' includes:

Glaciological research providing information about the heat exchange budget and Antarctica's influence on weather and climate;

Geophysical research providing insight into global geological history and the formation of continents;

Upper atmosphere research studying solar-terrestrial interactions and cosmic ray research as a contribution to international programs;

Meteorological research and data acquisition improving forecasting in the Southern Hemisphere;

Biological research to document the bio diversity of terrestrial and freshwater communities and study adaptation mechanisms of organisms with their environment; and

Human biology and medicine providing information on the physiological adaptation of persons to extreme climates and isolation.

The determination of the Antarctic Treaty nations to protect Antarctica's environmental and scientific value is demonstrated in their recent adoption of the Protocol on Environmental Protection to the Antarctic Treaty (the Madrid Protocol) which designates Antarctica as a '...natural reserve, devoted to peace and science.' The Protocol was the product of four sessions of the XIth Antarctic Treaty Special Consultative Meeting (ATSCM) signed in Madrid on 4 October 1991 (Jackson 1991).

The Madrid Protocol is a comprehensive, legally binding regime for ensuring that activities parties undertake in Antarctica are consistent with the protection of the Antarctic environment and of dependent and associated ecosystems (ATCPs 1992).

During the first session of the XIth ATSCM at Viña del Mar two working groups were established. At the second session of the ATSCM in Madrid, Working Group II was called upon to review items including: 'Alternative energy uses to reduce environmental impact.' The result of the group's deliberations on this topic was a working document presented by the Italian Delegation. In essence, 'the use of alternative energies, such as solar and wind power in the Antarctic Treaty Area, and the study of a systematic way of implementing energy saving methods with the aim of reducing the use of fuels to the maximum extent possible' was suggested (ATCPs 1991). The working group further proposed a study by the Scientific Committee on Antarctic Research (SCAR) and the Council of Managers of National Antarctic Programs (COMNAP).

The ATSCM noted the importance of co-operation between SCAR and COMNAP as essential for the effective pursuit of international scientific programs of global importance as well as the implementation of relevant recommendations adopted by the ATCMs and of the Protocol on Environmental Protection (ATCPs 1992).

COMNAP, and its sub-group SCALOP (Standing Committee on Antarctic Logistics and Operations), responded to the request of the ATCPs. A sub-group on alternative energy was convened and its report to SCALOP (SCALOP 1993) included discussions under the following headings:

Identify needs and potential alternative energies;
Gather and examine on-site experiences;
Identify the needs for further developments;
Examine costs; and
Develop cooperative efforts.

The upcoming Sixth Symposium on Antarctic Logistics and Operations, convened by SCALOP in conjunction with the XXIII SCAR meeting in Italy 1994, identifies the importance of alternative energy and has made a call for papers on 'the use of alternative energy sources in Antarctica'.

Australia regards the Antarctic Treaty System as the best means of achieving its Antarctic policy interests. The Antarctic Science Advisory Committee

(ASAC) view that priority in the allocation of resources for Antarctic research should reflect Australia's policy interests in Antarctica. The 1992 ASAC Report 'Antarctic Science - The Way Forward' made recommendations on priority areas for future Antarctic science:

science that contributes to our understanding of, and decision making on, important global or regional issues;

science to support the management of activities in Antarctica (such as those aimed at the protection of the Antarctic environment); and

science that provides fundamental information not easily available elsewhere.

Environmental Management is one of six ASAC priority areas in which a key program involves Human Impact. Three of the seven major objectives of this component are:

examination of means of reducing the volume of fuel used;

investigations of critical potential pollutants and development of techniques to eliminate or minimise their risk in Antarctica; and

improved environmental technology, including efficiency of power generation systems, energy from alternative sources, water generation systems and heating efficiency (Australian Antarctic Division 1992).

The present role of the Australian Antarctic Division, as the executing agency for the Australian Antarctic Program, is 'to enhance Australia's scientific, environmental, political, strategic and economic interests (except mineral resource activity) in the Antarctic and, where relevant, the sub-Antarctic, and to preserve its sovereignty over the Australian Antarctic Territory (AAT)' (ASAC 1992).

The Engineering Section of the Antarctic Division has initiated programs of waste disposal and conservation. Attention is now being drawn to the use of fossil fuels. The reduction of the use of fossil fuels is being sought by 'means of a concerted effort on all necessary fronts within an Energy Conservation Program, for which endorsement is being sought at Ministerial level' (Wilson & Turnbull 1991).

The international and national policy framework has established the need to investigate means to reduce the use of fossil fuel by alternative energy sources under the broad umbrella of minimising the impact of Antarctic operations. The need also exists at an operational level as the logistical program represents a very large part of the expenditure for the Australian Antarctic Division.

There is a widespread perception, whether justified or not, that the logistical operations are driving the scientific program rather than responding to scientific needs (ASAC 1992). This is an increasingly legitimate concern as a decision has now been taken not to continue to charter the Antarctic resupply vessel, *Icebird*, and to rely solely on the *Aurora Australis* for logistical resupply and for science. Any opportunity to free the *Aurora* from the logistical program will now provide a significant advantage for the scientific program.

A reduction in the requirement to supply fuel to the stations has the potential to reduce the time and number of voyages dedicated to the re-supply of Antarctic research stations.

The logistical program could also be re-adjusted by integrating the shipping program with an intracontinental air service. As fuel is now the main bulk cargo, a reduction in fuel consumption at the stations and the introduction of intercontinental air transport for expeditioners and supplies would further free the ship to continue with marine scientific activities.

The Antarctic Division has done a considerable amount of work in assessing the practicality and cost of both intercontinental and intracontinental air-links. Recommendation 16 (ASAC 1992) supports the concept of an intercontinental air-link between Australia and Antarctica in the longer term, but recommends that:

no immediate moves should be made to institute an intercontinental air-link between Australia and Antarctica;

the matter should be kept under review, and a further assessment be made in five years time in the light of changing circumstances; and

this further review should include consideration of an integrated plan for air and sea transport to Antarctic stations, to be developed by the Antarctic Division.

The identification of appropriate alternative energies for the Antarctic research stations is based on the international and national policy objectives of environmental management and practical considerations to meet the special needs of the research stations.

The report from the SCALOP sub-group (SCALOP 1993) listed potential alternative energies in the following categories:

Practical; i.e. state of the art technology allowing near term application.
This category includes:
Solar Energy; and
Wind Energy.

Potentially applicable; but needs further development and research.
This category includes:
Hydropower;
Fuel Cells; and
Methane generated from the composting of waste or sewage treatment.

Exotic; somewhat theoretical or impractical.
Use of thermal gradients in the atmosphere or oceans;
Geothermal.

Nuclear: This energy source is placed in its own category due to the political controversy that may ensue by installing such systems. No member felt that the use of nuclear was prohibited, but that the cost of installation and the security involved in operation and refuelling may not make this a practical option.

Concentrating on wind energy, hydrogen and fuel cell technologies is based within these criteria and includes a mixture of well-established technologies and developing technologies. While concentrating mostly on wind energy through production of electrical power by wind turbines an assessment of solar energy and thermo-mechanical machines will also be made.

Objectives of study

The objectives of the study were to:

1. Establish the need for alternative energies based on the policy and operational objectives of the Australian Antarctic Program;

2. To assess a renewable energy, hydrogen production, and fuel cell power plant system and determine the availability and development of these technologies; and

3. To examine how these alternative energy systems can be used and determine possible options and strategies for their implementation.

The widespread interest in the project both from industrial groups and research institutions has not always translated to a willingness to provide information. This has often been on the basis that shared information on developing technologies can compromise a company's position relative to their competitors. Costing information has also been withheld as this can often be misinterpreted. The misinterpretation is mostly linked to the fact that costs have to be compared to costs of other options at the same location.

The study concentrates on the more developing technologies for an alternative energy system to demonstrate the potential for reduction of the use of fossil fuels on the Antarctic continent. Adopting conservation practices and improved technologies for diesel generator sets can also achieve the objectives of reducing the consumption of fossil fuels at the stations. These practices are currently being undertaken by the Australian Antarctic Division.

The study is arranged in the following manner:

1. An overview of the existing energy system for the Australian Antarctic stations. An analysis of the operating performance and logistical program required to support the energy system. A description of the special needs for the provision of energy to the stations.

2. A description of alternative energy system components. The performance potential and environmental benign operation of wind energy, hydrogen, fuel cell systems.

3. An assessment of available hydrogen and fuel cell power plant equipment and options on how this equipment can be used. This is based on incomplete information from industrial and research institutions and is intended only as a guide due to the assumptions that needed to be made.

4. A method to implement the system options is proposed on the basis of providing an alternative energy system that is practical and can be achieved in stages.

The study contributes to an Australian - French co-operative research project. The project aims are to investigate the current energy requirements of the

Australian and French research stations and to conduct a feasibility on the use of alternative energy systems.

Information used in this thesis is from the three permanent Australian Antarctic stations and the French Antarctic station. The focus is on Casey Station in the Australian Antarctic Territory and the French Station at Dumont d'Urville. These stations have the most complete record of current energy use and are representative of environmental conditions experienced on the East Antarctic coast.

Chapter 2

Antarctic Stations

2.1. Background

The Australian Antarctic program currently maintains and operates three permanent over wintering research stations on the harsh coast of East Antarctica. The stations lie some 3000 km south of Australia: Mawson (67°36'S, 62°52'E), Davis (68°36'S, 77°58'E), Casey (66°18'S, 110°32'E). A fourth over wintering station is established on Sub-Antarctic Macquarie Island (54°30'S, 158°57'E). Australia has a large investment in the Antarctic stations which serve the objectives of Australia's continued involvement in the Antarctic.

Australia has had a permanent presence in Antarctica since 1954 when the first station was established at Mawson. The station was a collection of second hand timber buildings obtained from a Norwegian-Swedish-British expedition to Heard Island, and some sandwich panel post-tensioned 'boxes' of small proportions made by a coolroom manufacturer in Melbourne (Turnbull 1993).

Davis Station was established in the Vestfold Hills, Princess Elizabeth Land in 1957 in readiness for the International Geophysical Year (IGY) of 1957-58. Casey Station was established between 1965 and 1969 on the coast of Wilkes Land. Nearby was the Wilkes Station which Australia had taken over from the USA in 1959. This was later closed as drift snow inundated the buildings rendering them unusable.

The first of the newly designed buildings under a major Antarctic Station Rebuilding Program, the Davis Living Quarters, was begun in 1978 and completed in 1979. The Station Rebuilding program continued through the 1980s and is scheduled to be completed by 1995 (Lyons 1991). The design philosophy has been to provide long life, properly engineered, cost efficient and maintainable facilities (Incoll 1990).

The Antarctic stations remain isolated for all but the summer months. Access is via sea with the current charter of the *Icebird* and *Aurora Australis*. Resupply is often difficult and time consuming as distances from Hobart to the stations are: Casey (3427 km); Davis (4816 km); and Mawson (5447 km). The isolation requires the stations to be totally self sufficient in the needs of the expeditioners for the period of isolation.

2.2. Antarctic Station Energy Requirements

The research stations of the Australian Antarctic program have special needs for efficient, reliable, safe and environmentally friendly power systems to provide electricity, heat and potable water. Since the 1950s and 60s when most of the major research stations were being developed the energy demands were met by diesel generators and oil fired boilers. At this time these methods were the most convenient, established and reliable means to support the needs of the stations where safety was, and still is, of highest priority.

The rationale has persisted that as the current system works there is no need to drastically change it. With the shifting environmental emphasis of the activities conducted in Antarctica, the substantial use of fossil fuels in the current energy system has come under increasing scrutiny. Technical developments in alternative energy systems have provided the opportunity to develop an energy system that is both environmentally friendly and economically sustainable.

2.3. Current Energy Systems

The generator sets typically consist of 125 kVA alternators mostly driven by six cylinder Caterpillar 3306 diesel engines. The power houses typically house four generator units with emergency generators housed in an emergency power house at a different location on the site. Three of the four generators in the main power house will typically be run according to demand, with the fourth on standby.

Heating is the largest energy requirement for the operation of the stations, as shown in Table 2.1. Water jackets on the engines provide heat recovery from the diesel engine cooling water and exhausts. Additional heat production is by oil fired burners. Heating services are typically reticulated around the station on a services 'ring main' as hot water providing heat to the buildings via a system of heat exchangers.

Table 2.1: Australian Antarctic Stations Energy Production and Consumption, 1992.

January to December 1992	Casey	Mawson	Davis	Macquarie
*SAB used in generators (litres)	585,359	630,255	526,527	193,180
Generators Electrical Production (kWh)	1,993,075	2,200,685	1,756,302	587,675
Average Electrical Load (kW)	227	251	200	67
*Maximum Peak Load (kW)	310	350	315	91
Generators Heat Recovery (kWh)	1,835,374	1,976,144	1,650,908	605,709
*SAB used in Power House Boilers (litres)	93,761	N/A	133,212	2,219
Boilers Thermal Production (kWh)	1,073,725	N/A	1,044,204	17,394
Total Energy Production (kWh)	4,902,174	N/A	4,451,414	1,210,778

*Data Source: Australian Antarctic Division, Engineering Section.

Water is produced typically by two methods in Antarctica; desalination and melting ice or snow. The desalination process consumes a lot of energy and is no longer used at any of the Australian stations. Casey and Mawson use various heat exchangers to melt ice in melt lakes, while Davis melts snow that has been collected. The power requirement for the melt lakes are between 10 to 20 kW while melting of snow requires around 27 kW (Wilson pers. comms., 1993).

The fuel almost exclusively used by the stations is Special Antarctic Blend (SAB) diesel which has been chosen primarily for its cold temperature performance. The characteristics of SAB are:

Density at 15°C	0.805 kg/litre
Flashpoint	64 °C minimum
Pour Point	-36 °C
Sulphur Content	0.05 % wt
Colour	Pale Straw
Lower Heating Value (LHV)	35,274 kJ/litre

Data Source: Mobil Oil Australia

2.3.1. Energy Production

Comprehensive energy audits have not been undertaken by the Antarctic Division over the life of the stations in Antarctica. Prior to the rebuilding program energy audits were considered to be of low priority. The comprehensive Station Rebuilding Program undertaken has introduced anomalies in the use of power, due to construction practices, which would not be representative of the power use at the stations in the longer term.

The completion of the rebuilding program and the initiation of a conservation program initiated by the Antarctic Division is expected to stabilise the load and possibly reduce it. Current indications tend to support this. Fuel consumption from the first half of 1992 to the first half of 1993 has shown a decrease of: Casey down 13%; Davis down 2%; and Mawson down 1%.

The total energy production for the Australian Antarctic Stations is not represented in Table 2.1. Some boiler consumption has not been taken into account as boilers are used in other locations. Calculations are based on the Lower Heating Value (LHV) of SAB diesel and 32 % heat recovery from the engines; an 80 % efficiency for the boilers; and 35 % fuel/electrical efficiency.

2.3.2. Fuel Storage

Fuel storage is a significant capital cost for the Antarctic program. The total storage capacity of each of the three continental stations is 1,060,000 litres. This is the total stored in the fuel farms and the settling and bowser tanks. Each station has eleven 90,000 litre tanks, a 35,000 litre settling tank and a 35,000 litre tank for refuelling. The fuel farms occupy surface areas of (Ratcliffe pers. comm., 1993):

Mawson	new lower fuel farm 640 m^2
	new upper fuel farm 640 m^2
Davis	new fuel farm 780 m^2
Casey	lower fuel farm 640 m^2
	upper fuel farm 405 m^2

Fuel storage supplies are of critical importance in the provision of power to the stations. Two years supply of fuel is stored as a safety margin in case the stations cannot be resupplied in a particular summer season.

2.3.3. Emissions

The combustion of fossil fuels is the single largest local contributor to Antarctic produced airborne pollution. The pollution consists of gaseous and Dry Particulate Matters (DPM). A pollution estimate of exhaust emission rates can be made for the power house engines based on the assumption that the engines are all Caterpillar 3306 units producing an average electrical power of 75 kW. In practice there are a variety of engine loads and exhaust emission rates but the calculation of emissions based on this assumption is of the right order of accuracy. The results are summarised in Table 2.2.

Pollution present in the Antarctic environment is not all locally produced. There is significant gaseous transport of global pollution which tends to give an homogenous concentration around the globe. A recent model for the southern regions (Law *et al*. 1992) estimates that the time needed to reach 67% of final uniform concentration at latitude 70°S at a level of 850 hPa (□1500m) is about:

> 220 to 227 days for gases originating from the northern mid latitudes (44-54°N);
> 65 to 85 days from the tropics (5°S-5°N); and
> 2 days from the southern mid latitudes (44-54°S).

The model suggests that gaseous emissions originating in Australia reach the stations rapidly and that within a year any emission on the globe has been widely distributed.

The per capita figures of gaseous pollution give a different view. The annual generators CO_2 production of 78 tons per person at the stations is 22 times the world CO_2 production of 3.6 tons per person (World Resources Institute 1992).

The Dry Particulate Matter (DPM) pollution has a more significant local impact. A study by SCAR (1989) estimates the amount of particulate emissions produced annually in the Antarctic Treaty Area to be around 300 tons, of which less than 200 tons are produced on or adjacent to land. A significant proportion of this is most likely blown out to sea away from the stations on the prevailing winds. Here it is expected to have less impact than on the biota and wildlife breeding grounds surrounding the stations.

Table 2.2: Estimated Annual Emissions from Generators at four Australian Stations (Guichard & Steel 1993).

Period: January to December 1992		Total 4 Stations	Per Capita
Total Station occupancy	(persons-days)	52 148	366
Average Occupancy	(persons)	142	1
Winter Population	(persons)	92	0.65
Generators SAB Consumption	(litres)	1 935 321	13 583
Corresponding Engine Hours	[at 22 l/hr]	87 969	617
Emissions (kg) of:	**assuming a rate of:**		
Carbon Dioxide - CO_2	126.496 kg/h	11 127 744	78 100
Nitrogen - N_2	723.538 kg/h	63 649 013	446 720
Oxygen - O_2	82.143 kg/h	7 226 049	50 716
Water - H_2O	50.054 kg/h	4 403 207	30 904
Carbon Monoxide - CO	0.726 kg/h	63 866	448
Nitrogen Monoxide - NO	1.418 kg/h	124 740	875
Other Nitrogen Oxides - NO_x	2.166 kg/h	190 541	1 337
Hydrocarbons - HC	0.068 kg/h	5 982	42
Sulphur Dioxide - SO_2	0.161 kg/h	14 163	99
Dry Particulate Matters - DPM	0.092 kg/h	8 093	57

Data Source: Australian Antarctic Division

2.3.4. Logistical Program

The logistical supply of the Australian research stations to date has been performed by sea. The operational tasks of vessels for logistical support are:

transport of station personnel;
transport of station supplies and construction material;
transport of vehicles and equipment for field programs;
transport of fuels; and
helicopter platform operations.

The two vessels currently chartered make a total of eight or nine voyages to the continent in the summer season. The approximate cargo capacities for the vessels as summarised by the AAD are:

Icebird	5000 m^3 dry cargo
	950 m^3 SAB fuel cargo
	97 passengers
Aurora Australis	1650 m^3 dry cargo
	1000 m^3 SAB fuel cargo
	109 passengers

The logistical program also involves an environmental cost. The polar environment and its ecosystems are very fragile. Fuel spillage is potentially catastrophic. The damage that can be caused to the ecosystem has already been demonstrated by the *Bahia Paraiso* grounding in the Antarctic Peninsula and the *Exxon Valdez* incident in Alaska which impacted significantly on the surrounding environment.

Fuel spillage can occur either by leakage from ships, in ship-to-shore pumping operations, or when stored at the stations. As the stations are typically located in high biologically active areas great care has to be taken with operations involving fuel. This has become a priority requirement identified at an international level. SCALOP in 1990 established a subgroup on Oil Spill Prevention and Response to develop procedures/guidelines on oil spill contingency planning, fuel oil transfer at stations and bases, and design of fuel oil storage facilities for stations and bases. In addition, it has developed a series of recommendations on oil spill prevention and response (Roberts 1992).

2.3.5. Maintenance/Replacement Program

The diesel engines require a diesel mechanic to be on hand at the stations at all times in case of mechanical problems. The engines are replaced by brand new engines (cost □ $A 30,000) after 30,000 hours of operation (Sheers pers. comms., 1993). The corresponding engine hours of operation for all four stations means that approximately three engines are replaced each year. This represents a cost of $A 90,000 /year for engines only.

This involves the complete removal of the old engine and shipping back to Hobart. The rationale for this procedure includes the advantages that can be taken of the continuous improvements being made in engine design, especially in efficiency, and improving the reliability (Sheers pers. comms., 1993).

2.3.6. Financial Costs

The annual fuel supply for the four Australian stations costs around $A 1 million to purchase in Hobart and represents about 10 % of the total volume of cargo shipped south. Ten percent of the total shipping cost (excluding pure marine science cruises) is approximately $A 2 million, so on the basis of average shipping costs the cost of SAB upon delivery in Antarctica is tripled.

A detailed cost analysis undertaken in 1991 by the Engineering Section of the Australian Antarctic Division used the conservative estimate of 5 % of the shipping cost dedicated to fuel. This gave a final cost of $A 0.68 per electric kWh produced at the stations. This is about 7 times the commercial price of domestic electricity in Tasmania, and 14 times the off-peak price. The fuel itself represented 55 % of the electricity cost and equipment depreciation and maintenance represented 45 %. Such figures are a good example of the high cost of the current energy supply.

2.4. Antarctic Division Actions

The Engineering Section of the Antarctic Division has always looked at methods to improve the efficiencies of the current system. This has often involved improving the power distribution network, methods to stabilise power consumption, and taking advantage of engine performance improvements. Strategies to reduce emissions have focused on methods to reduce exhaust gas emissions and the use of lower polluting fuels.

Local Monitoring and Control Systems (LMCS) have been installed at the stations and are intended to be developed as a tool to provide data for more detailed analysis of the current system. These improvements will assist in reducing the environmental impact in Antarctica.

Conservation strategies have been implemented which have focused primarily on practices performed by station personnel. These practices, as successful as they may be, are not the focus of this project. Design practices for buildings have also been cited as areas of improving energy consumption efficiencies. Again this is beyond the scope of this project.

The introduction of alternative fuels to SAB has been discussed as a short term solution to the reduction of pollution in the Antarctic environment.

The French have been investigating the use of kerosene type fuels to power the planned French-Italian inland station at Dôme C in the Australian Antarctic Territory (IFRTP 1992). Sulphur Free JP8 (SFJP8) is a kerosene type fuel whose combustion is characterised by very low sulphur emissions.

SFJP8 possesses all the desired characteristics of an Antarctic fuel such as high heating value, satisfactorily high flash point, high viscosity and useability in many of the existing Antarctic facilities.

SFJP8 characteristics:

Density at 15°C	0.807 kg/litre
Flashpoint	61°C
Freeze Point	-54°C
Sulphur Content	< 0.01 % wt
Lower Heating Value (LHV)	42,800 kJ/litre

Data Source: Shell Oil Company, Houston, Texas August 9 1991.

The availability of SFJP8 is increasingly widespread. The use of SFJP8 can address the problem of reducing the amount of gaseous pollution emitted into the Antarctic environment, but the high cost of transportation and purchase will still remain.

Chapter 3

Alternative Energy

3. 1. Renewable Energy

Antarctica is a continent of harsh environmental conditions which have long been recognised as a potential source of renewable energy. The extreme conditions test the performance and survival of conventionally designed renewable energy equipment.

A study of environmental conditions experienced at the French Station of Dumont d'Urville (66°40'S, 140°01'E) constitutes a first crude estimation of potential renewable energies whose process can be applied to a more extended and detailed analysis. The following meteorological analysis is based on a set of meteorological data for Dumont d'Urville for the period 1 January, 1986 to 31 December, 1989. The analysis is based on averages over 10 days. The complete standard meteorological data set (data every 3 hours since the establishment of each station) from all Australian and French stations has been requested but has not arrived.

Some specific measurements dedicated to the assessment of the renewable energy potential will commence in the 1993/94 summer season at Casey, Davis and Dumont d'Urville. Specific parameters will be measured and linked to the standard meteorological measurements. With this data a detailed analysis can be performed for each station and specifications for equipment can be established.

The data set from Dumont d'Urville consists of measurements of: global solar radiation on a horizontal plane from 0 to 24 hours; wind speed at 10m high averaged over 10 minutes every 3 hours; and spot temperature every 3 hours. Data was processed to give averages over the standard decade. A decade corresponds to the days 1-10, 11-20, and 21-end of the month, of each month. A 'Typical Year' can then be defined as the average of each decade over the four year period of the data set. The meteorological parameters are illustrated in Figure 3.1.

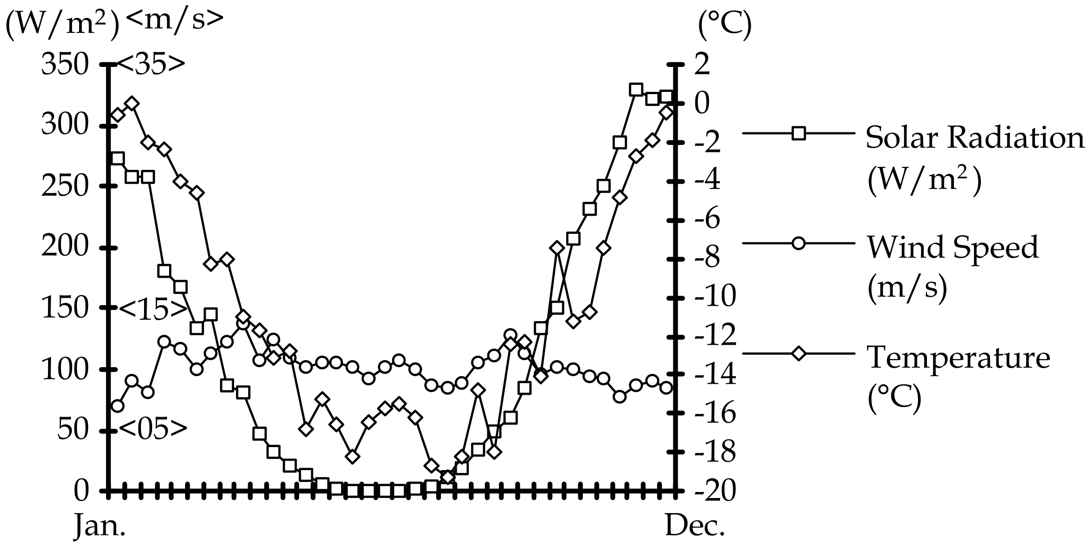


Figure 3.1: Meteorological Parameters during a "Typical Year" at Dumont d'Urville.

Data Source: Meteo France

The environmental conditions indicate the potential of wind energy as a renewable energy source as it remains relatively constant over the year. Solar radiation is extremely variable and minimal in the winter months.

Wind generators and solar panels have been used in Antarctica to support remote area equipment such as automatic weather stations and communication repeater sites. Small scale applications have been successful but this does not necessarily mean that the concept can be translated into large scale systems supplying the electrical demand for a permanent Antarctic Station.

The energy captured by renewable energy systems can be calculated using known equipment efficiencies and meteorological data on the conditions under which they will be installed. The following case study will illustrate the potential of three feasible renewable energy systems.

3.1.1. Wind Kinetic Energy

The difference in velocity between air in motion and a structure fixed to the ground, like a wind turbine , can be used to produce electrical energy. The kinetic energy content of 1 m^3 of air (j/m^3 or Pa) relative to an arbitrary "o" reference state is calculated by (Le Goff *et al*. 1993):

$$E_{(kinetic)} = 0.5\rho\,|u^2 - u_o^2| \qquad (1)$$

where ρ = density of the air (kg/m^3)

□ 1.3 kg/m^3 @ 990 hPa and -10°C

u = wind speed (m/s)

Multiplying the kinetic energy content of 1 m^3 of air by the wind speed, the amount of energy passing in one second through 1 m^2 of vertical cross-section can be obtained (Guichard & Steel 1993).

A realistic efficiency for a basic, reliable two bladed horizontal axis turbine is 25%. This is the proportion of the wind kinetic power that will be transformed by the turbine into electrical power.

Wind turbines in coastal Antarctica have often failed due to the extreme wind and icing conditions. The exception has been some small scale wind turbines that have been used for field installations charging batteries for scientific and communications equipment. Wind turbine technology is improving and there have been some recent successful demonstrations of larger wind turbines.

At Heard Island, the Australian Antarctic Division tested a 7m diameter two bladed horizontal axis turbine Vergnet-Aérowatt UM 70X for 3 months in 1992-93. The unit operated in extremely high and variable wind conditions producing an average 62.2 kWh per day over a three month period. The average output over its time of actual operation was 6.1 kW (Vrana 1993). The unit is rated at 12 kW at 12 m/s, has a swept area of 38.5 m^2, and a wind survival rating of 110 m/s. This would make it suitable for conditions in East Antarctica where outdoor structures are typically designed to withstand winds of 90 m/s.

The French have carried out tests on a 10m diameter vertical axis Darrieus rotor in the sub-Antarctic at New Amsterdam Island in 1986-88. The VAWT D10-2 turbine is rated 30 kW at 13.5 m/s, and has a swept area of 67.7 m^2. High winds led to failure though it generally operated well producing up to 400 kWh per day for wind speeds ranging from 12 to 35 m/s (Perroud *et al.* 1991).

At the German Georg Von Neumayer Station a 10 m diameter H rotor turbine is in its second year of continuous operation. The turbine has a permanent magnet rather than a mechanical transmission and is rated 20 kW at 9 m/s, with a swept area of 56 m^2. The unit has a survival wind speed of 68 m/s and a minimum operating temperature of -55°C (Heidelberg *et al.* 1990).

3.1.2. Solar Radiation Energy

Photovoltaic (PV) panels transform solar radiation into direct current with a typical efficiency of 10%. The technology is well developed and reliable. Improvements are continually being made and efficiencies are expected to reach 20%. Antarctic operators have used photovoltaic panels in conjunction with battery storage systems to power remote weather stations and radio repeaters.

Photovoltaics are finding further applications as PV-Hydrogen systems. Here the electricity generated by the photovoltaic is used directly to generate hydrogen by electrolysis techniques. A pilot plant to test and demonstrate PV-Hydrogen systems has been under construction by a consortium in northern Bavaria, Germany. The plant estimates an annual production of 500 MWh by conversion of hydrogen to electricity via fuel cell technology (Solar-Wasserstoff-Bayern Gmbh pers. comm., 1993).

3.1.3. Wind Thermal Energy

The temperature gradient that typically exists between sea water and air provides another potential source of renewable energy. Thermo-mechanical machines convert the thermal difference to mechanical power which in turn is converted to electrical power via an alternator.

Preliminary studies have been performed at the Laboratoire des Sciences du Génie Chimique (LSGC) on the potential to recover the energy in the thermal gradient between the cold Antarctic winds and the warmer Antarctic waters.

LSGC should provide a first reliable and detailed assessment of the attainable efficiencies in 1994. A crude estimation based on the LSGC preliminary work has been proposed by Guichard & Steel (1993):

$$ØTM = ØCarnot. \; ØReal. \; ØUsable \qquad (2)$$

where;

ØCarnot is the "limit" Carnot efficiency of the machine cycle.
= (□T-□Tusable/2)/T_o

ØReal is the proportion of ØCarnot practically attainable in the machine and is of the order of 25%.

ØUsable is the proportion of temperature drop □T usable of the air when passing through the exchanger. This also is of the order of 25%.

Assuming an efficiency of 80% for the alternator the final Thermal to Electric efficiency of the machine is;

ØTE = 0.05ØCarnot (3)

Thermo-mechanical devices are still in the development stage for polar applications. The Institut Français pour la Recherche et la Technologie Polaires will assist the LSGC/CNRS in the installation of the condenser or 'cold captor' which is the key component of the system in January 1994. This will enable a more detailed assessment of the technology and its potential.

3.1.4 Recoverable Electrical Power

The seasonal variation of recoverable electrical power for the three renewable energy systems is illustrated in Figure 3.2.

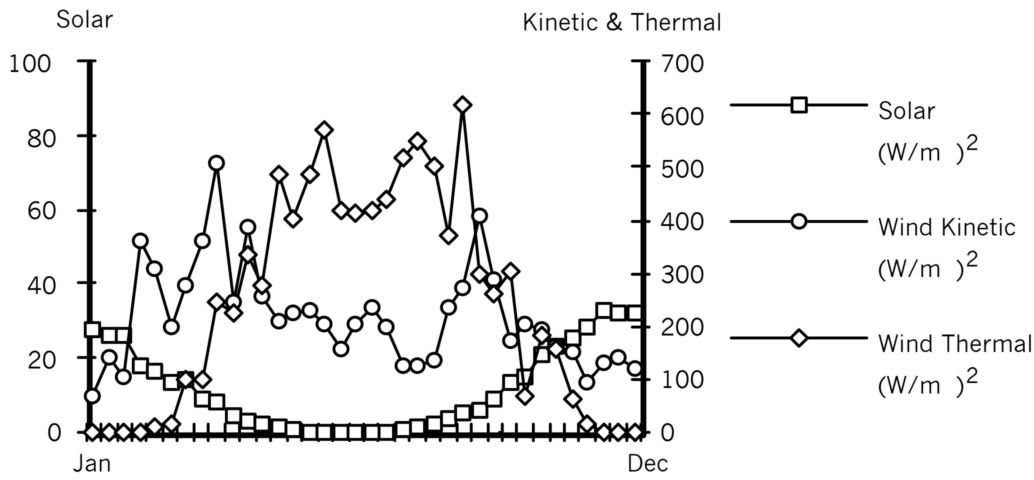


Figure 3.2: Estimated Variation of Recoverable Electrical Power for a 'Typical Year' at Dumont d'Urville.

Data Source: Meteo France

The graph indicates that a wind turbine generation facility would be best suited for yearly electrical power generation at Dumont d'Urville. The reason is the recoverable power is relatively constant over the year. A photovoltaic power plant would be suited only to the summer months due to the minimal available power for the remainder of the year. Electrical production by thermomechanical machines indicates similar characteristics. High recoverable power in the winter months falling to a limited potential during summer.

The estimated average, maximum, and minimum potential recoverable electrical power for the three renewable energies of the case study are listed in Table 3.1. This further demonstrates the suitability of a wind turbine facility over that of a photovoltaic or thermomechanical machine power plant.

Table 3.1: Estimated Average, Maximum and Minimum Recoverable Electrical Power for 'Typical Year' at Dumont d'Urville.

	Yearly Average	Maximum Decade	Minimum Decade
Solar (W/m^2)	11.7	32.9 (Dec 1-10)	<2.0 (May 1 - Aug 20)
Wind Kinetic (W/m^2)	181.4	422.4 (Mar 21-31)	56.9 (Jan 1-10)
Wind Thermal (W/m^2)	246.1	616.9 (Sep 1-10)	<2.0 (Dec 1 - Feb 10)

Data Source: Meteo France

The problem with most renewable energy systems is that the production of power is variable. Production of power is dependent on the environmental conditions and does not always match the energy load requirements of a station. An energy storage medium is required to store excess energy that can later be used when the load demands. An energy storage medium for Antarctica should be consistent with the objectives of environmental management. Hydrogen can be produced simply by electrolysis from water and it has inherently benign environmental characteristics.

3.2. Hydrogen

Hydrogen is the most plentiful element in the universe, making up about three quarters of the matter. All the stars and many of the planets essentially consist of hydrogen. On Earth, free hydrogen is scarce: the atmosphere contains trace amounts (0.07%), and it is usually found in small proportions mixed with natural gas in crustal reservoirs (Veziroglu & Barbir 1993).

Usually hydrogen bonds with two other elements. When bonded with carbon it yields fossil fuels; but with oxygen it yields water, H_2O. It is in the chemical combination with oxygen in which hydrogen is most abundantly found. In this form hydrogen is not a primary source of energy. It is an intermediary form or an 'energy carrier' requiring energy input to produce it from water. Conversion to energy can be achieved by various means when needed.

Hydrogen is also environmentally compatible when consumed. The combustion product of hydrogen in the presence of air (which contains 78 % nitrogen) is simply water vapour and small amounts of NO_2 . Hydrogen is also highly versatile as it can be converted to energy by:

flame combustion;
conversion directly to steam;
conversion to heat through catalytic combustion;
acting as a heat source and/or heat sink through chemical reactions; and
conversion directly to electricity through electrochemical processes, -i.e, fuel cells (Veziroglu & Barbir 1992).

Hydrogen has long been recognised as the 'fuel for the future' (Veziroglu & Barbir 1992). Ever since an English aristocrat named Henry Cavendish discovered what he called 'inflammable air' in 1766, scientists have been exploring the potential of hydrogen. The large scale use of hydrogen has not occurred primarily due to actual and perceived handling, storage and safety problems. The availability and social acceptance of fossil fuels in the past has also hindered dedicated efforts to develop and switch to an alternate fuel such as hydrogen.

3.2.1 Safety

The fire hazard characteristics of hydrogen compared to methane (composing 94.4 % by volume of natural gas) are illustrated in Table 3.2.

Table 3.2 : Properties of Hydrogen Compared to Methane.

Property	Hydrogen (H_2)	Methane (CH_4)
Molecular weight	2.02	16.04
Density of gas (kg/m^3)	0.082	0.656
Diffusion coefficient in air (cm^2/s)	0.712	0.16
Flammability Limits (Volume % in air)	4 - 75	5 - 15
Autoignition Temperature (°C)	400	537
Minimum Ignition Energy in Air (J)	[a] 2×10^{-5}	[b] 33
Quenching Distance (mm)	[a] 0.6	[b] 1.9
Flame Velocity (cm/sec)	[c] 264.8	[d] 33.8
Lower Heating Value (MJ/kg)	119.81	50.00
Higher Heating Value (MJ/kg)	141.85	55.54

All volumes, densities and calorific values are at 298.15 K (25°C) and 101.325 kPa (1.013 bar)

[a] Stoichiometric Fuel-Air Mixture: 29.50 Vol. % Fuel

[b] Stoichiometric Fuel-Air Mixture: 9.47 Vol. % Fuel

[c] Vol. % Fuel ~ 50

[d] Vol. % Fuel 9.96

Data Source: Fossil Fuel Combustion: A Source Book
Energy Managers Handbook

Hydrogen leaks are over rapidly and have no long term liabilities (Winter 1991). The high diffusivity in air of hydrogen results in a rapid dynamic lift in predominantly a vertical direction, with only limited horizontal spreading. Hydrogen has a wide ignition range, low ignition temperature and low minimum ignition energy which makes the fuel less safe as it increases the limits in which a fire could commence.

A measure of the safe use of hydrogen has been demonstrated in established facilities worldwide. This includes over 750 km of pipelines transporting gaseous hydrogen for commercial use (Hoenigmann 1992). Hydrogen has been used safely for various applications in industries such as; medicine, electronics, meteorology and increasingly by power utilities.

A further measure of a fuel's safety is its environmental safety. In addition to the toxicity of a fuel's combustion the fuel itself can be toxic. The toxicity increases as the carbon to hydrogen ratio increases. Hydrogen and its main combustion product, water or water vapour, are not toxic (Veziroglu & Barbir 1992).

With improved handling techniques hydrogen is demonstrably safe. The major obstacle for the widespread use of hydrogen is economic. Hydrogen produced using clean and renewable energy sources is generally more expensive than existing gaseous and liquid fossil fuels.

3.2.2. Hydrogen Production

Since hydrogen does not occur naturally in any quantity, it must be produced from other energy sources. Hydrogen was first produced by electrolysis of water in 1800 (Energy, Mines and Resources Canada 1986). Today, hydrogen is mainly produced by steam reforming of fossil fuels and coal gasification techniques. These methods represent the most cost effective way to produce hydrogen where the fossil fuels are readily available and there is a cheap electricity supply. This is not the case for Antarctica.

Electrolysis is the process of electrical splitting of the water molecule into hydrogen and oxygen. An electrolysis unit typically consists of a cathode, anode, diaphragm and electrolytic solution. The cathode is usually of iron construction and the anode of either nickel or nickel-plated iron.

An electric current is passed between the two electrodes which are immersed in an electrolytic solution. The electrolytic solution usually consists of 20 to 30 % potassium hydroxide dissolved with pure water. This increases the conductivity of the solution.

Hydrogen is produced at the cathode and oxygen at the anode. The two gases are isolated by a diaphragm which separates the two electrodes. The quantities of each gas that is produced depend on the size of the electric current between the two electrodes and the temperature of the electrolytic solution.

Currently there are two main types of electrolysers used throughout the world. A unipolar or 'tank' design and the bipolar or 'filter press' electrolyser (Energy, Mines and Resources Canada 1986). The distinguishing

factor between the two designs is the way the individual cells are assembled and the method of electrode polarisation.
In unipolar electrolysers, the electrodes are alternately suspended vertically and parallel to each other in a tank containing the electrolyte. The advantages of this design are that there are few and inexpensive parts needed and individual cells can be shut down for repair and replacement simply by short-circuiting two adjacent cells while the rest of the cell series continues making hydrogen. The main disadvantage is the inability to handle very high current densities and to operate at high temperatures. Their efficiency is therefore low.

The bipolar electrolyser incorporates a sandwich construction of electrode plates, separator materials and gasket insulators. One side of the electrode plate acts as an anode in one cell and the other side of the plate acts as the cathode of the next cell (hence, the term bipolar). The cells are connected in series. The main advantages of this design are that it can operate at high current densities, temperatures, and pressures, and requires less floor space than the unipolar electrolyser. The disadvantage is that it requires refined manufacturing processes in order to maintain close tolerances, and consequently is inherently more expensive. The other main disadvantage of bipolar units is the greater difficulty in cell maintenance: if one cell component fails, the entire stack has to be dismantled and removed from service for repair.

3.2.3. Hydrogen Storage

Hydrogen utilisation is being hindered by lack of good storage facilities. William Hoagland, manager of the US Department of Energy's hydrogen program said 'We're realising that without good storage technology, hydrogen's uses are limited' (Skerrett 1993b).

<u>Compressed Gas</u>

Storage as compressed gas is the simplest and cheapest commercially available technique for hydrogen. The containment vessels are heavy and bulky. The percentage of hydrogen per volume is low compared to other storage techniques as shown in Table 3.3. The size and capacity of the storage vessel is a function of the storage pressure.
Hydrogen stored at a typical pressure of 13.7 MPa (136 times standard atmospheric pressure) and its steel container together weigh about 30 times

more than an equivalent amount of gasoline; 99 per cent of the weight is in the container. The same container takes up about 24 times more space than a container holding the equivalent amount of gasoline (Energy, Mines and Resources Canada 1986).

Liquid Hydrogen

A storage method that improves the density of hydrogen is conversion to a liquid state. Hydrogen exists in a liquid form in the temperature range -259 to -253°C. Liquid hydrogen was first produced by Sir James Dewar, a British scientist, in 1896.

Equipment required to convert and maintain hydrogen in its liquid form requires a large energy input and complicated, expensive containment vessels. Liquefying hydrogen costs four times as much as producing an equivalent amount of gasoline (Skerrett 1993b). This factor alone makes liquid hydrogen storage for the Antarctic stations impractical.

Metal Hydrides

A technology that is attracting an increasing amount of research is the storage of hydrogen by metal hydride techniques. Metal hydrides are specially formulated alloys 'that soak up hydrogen much like a sponge absorbs water' (Kloeppel & Rogerson 1991). The alloys react chemically with hydrogen (sharing electrons) to form a loosely bonded compound which looks like a white powder. The application of a small amount of heat is enough to release the hydrogen from their loose bonds.

The desirable features of a metal hydride include the ability to store vast amounts of hydrogen at low charging pressures, fast release of the gas at low operating temperatures, light weight and reasonable cost (Kloeppel & Rogerson 1991). Existing hydrides require trade-offs between these parameters.

Hydride materials can hold more atomic hydrogen than an equivalent liquid or compressed gas storage vessel, as shown in Table 3.3. The Florida Solar Energy Centre at Cape Canaveral are investigating exclusively magnesium hydrides (MgH_2) that can hold almost 8 per cent hydrogen by weight. A quart jar of the grey powdery hydride holds as much hydrogen as a quart jar of liquefied gas. Unfortunately, the hydride weighs about eight times more than liquefied hydrogen. It is believed that by doping magnesium with nickel or other metals, or alloying it with aluminium, may lower the weight and operating temperatures to practical limits (Skerrett 1993b).

Refrigerated Activated Carbon

Another alternative solid-storage approach is to use super activated carbon. A material similar to the highly porous activated carbon used in water filters, which can hold hydrogen at sub zero temperatures. The colder the carbon, the less heat that's needed to disturb the weak forces holding the carbon and hydrogen together. This system offers an extraordinary surface area potentially available to absorb hydrogen.

The carbon storage system can be contained in pressurised canisters chilled to -120°C. Tiny temperature and pressure swings are used to pull the hydrogen away from the carbon. The size required can be illustrated by an estimation by Jim Schwarz, director of the Laboratory for Advanced Storage Systems for Hydrogen at Syracuse University New York, who predicts that 'a carbon-storage system for a city bus with a 300 mile range would weigh about 850 pounds, only 200 pounds more than a full gasoline tank' (Skerrett 1993b).

Table 3.3: Comparison of some Hydrogen Storage Techniques.

	Wt % H_2	Relative Weight	Volumetric Storage H_2 kg/l	Relative Volume Storage
[1]Gaseous H_2	100	1	0.082×10^{-3}	1.0
[2]Gaseous H_2	100	1	0.0283	1.0
Liquid H_2	100	1	0.07	1.0
Hydrides				
MgH_2	7.6	13	0.132	0.53
TiH_2	4.0	25	0.187	0.37
VH_2	3.8	26	0.234	0.30
Fe Ti H_2	1.9	53	0.123	0.57

1. pressure at 101.325 kPa (1 atm)
2. pressure at 35 MPa (345.4 atm)

Data Source: Hopkins 1984

There are potentially many options for storing hydrogen. Although much of the focus is being directed towards light, compact, inexpensive and safe systems applicable for transportation uses these can be applied to larger electrical utility storage systems. The main factors that determine the appropriate option to be pursued for Antarctica are low cost, high capacity, low energy input, and a high degree of safety.

At this stage the most promising application are the hydride technologies, though the expensive nature and further commercial development required will prolong the adoption of these technologies for Antarctic implementation. The compressed gas storage method represents the most economical and practical short term solution for the storage of hydrogen at the Antarctic Stations.

3.4 Fuel Cell: A Clean Power Generation Option

3.4.1 History

The fuel cell was invented by Sir William Grove over one hundred and fifty years ago. It is characterised by low emissions and high efficiencies. It remained undeveloped until the advent of the space program where the US National Aeronautics and Space Administration (NASA) chose the technology to supply on-board electric power units for the Apollo and Gemini space vehicles. Today, fuel cells are used on the space shuttle and are poised for large scale commercial use as a result of intensive research and capital investment (Kuehn 1993).

Concern for the environment has revitalised interest within the general community, and within government utilities as they have realised the potential of fuel cells as an alternative clean power generation option. Several major equipment companies have installed production facilities and 'more than $US 200 million is being spent annually to develop and commercialise fuel cells worldwide' (Hirschenhofer 1992).

3.4.2. Theory

A fuel cell is an electrochemical device consisting of anode, cathode and electrolyte. Unlike a battery were the chemical energy is stored within the cell, the fuel cell has the fuel and oxidant supplied from outside the cell. A fuel cell can continue to operate as long as fuel and oxidant are supplied and products are removed, or at least until the electrodes fail because of mechanical or chemical degradation. So in simplistic terms a fuel cell can be thought of as a primary battery in which the fuel and oxidiser are stored external to the unit and are fed to it as needed (Noyes 1977). Fuel cells are energy conversion devices whereas batteries are essentially storage devices.

The principle operation of a fuel cell is illustrated in Figure 3.3. On shorting the cell through the external load fuel oxidises at the anode (negative electrode) producing hydrogen ions (H^+) and electrons. The fuel is oxidised with the aid of a catalyst such as platinum. The electrons flow through the external load, doing work, and reduce the oxygen at the cathode (positive electrode) where they chemically react with the hydrogen ions and the oxygen to form water. The ionic flow within the electrolyte balances the charge flow within the external circuit. The product of this complete reaction is water, electric current and heat.

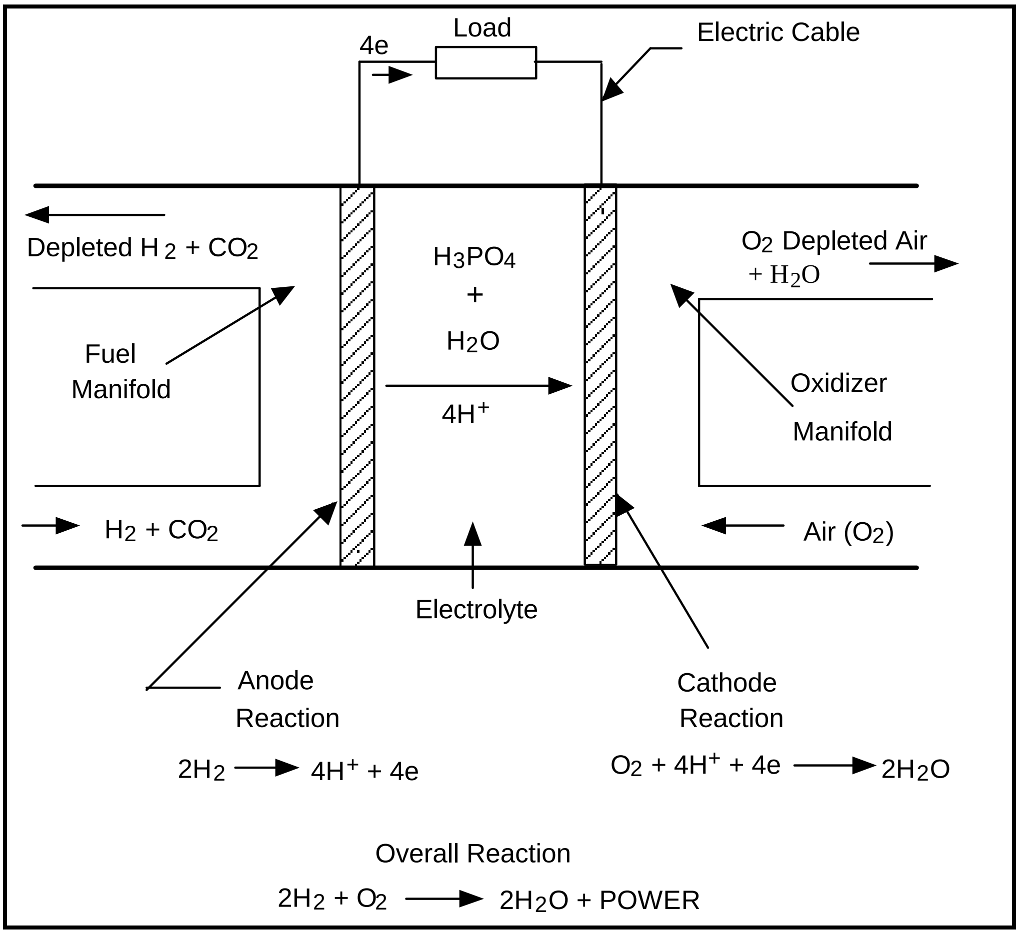


Figure 3.3: Principle of operation of a Phosphoric Acid Fuel Cell.

The open circuit or reversible voltage (E_{ocv}) of the cell is given by:

$$E_{ocv} = -\Delta G/nF \tag{4}$$

where:

□G is the free energy of the fuel oxidation reaction;
n is the number of electrons transferred in the fuel oxidation reaction; and
F is the Faraday Constant.

The voltage of a single cell under load conditions is in the vicinity of 0.6 to 1.0 V. Current densities are in the range of 100 to 500 mA/cm^2 (Badwal *et al.* 1991). Connecting a number cells in series through an interconnect material with high electric conductivity to form a fuel cell stack or module increases the current and thus the power produced by the unit.

3.4.3. Fuel Cell Types

The type of fuel cell is most typically identified by the type of electrolyte used. At present there are several different fuel cells: alkaline; phosphoric acid; molten carbonate; solid oxide; polymer electrolyte; and proton exchange membrane. Each type of fuel cell has different operating characteristics and efficiencies. The three holding the most near-term commercial promise are: phosphoric acid, molten carbonate, and solid oxide (Kuehn 1993).

Phosphoric Acid Fuel Cell (PAFC) - First Generation
The phosphoric acid fuel cell is by far the most tested and evaluated system. In this fuel cell, the phosphoric acid electrolyte (H^+ conductor) is held in a porous silicon carbide/teflon matrix between two graphite electrodes loaded with platinum. Like the Alkaline Fuel Cell (AFC) and the Proton Exchange Membrane Fuel Cell (PEMFC), PAFC operates only on hydrogen fuel. However, despite the use of platinum catalyst electrodes it can tolerate much higher levels of CO because of the higher cell operating temperature. For fuels such as methanol and natural gas, an external reformer and water gas shift reactor are required (to convert CO to CO_2 and hydrogen).

Operating Temperature	190-215°C
Fuel used	H_2
Fuel /Electric Efficiency	40%

Characteristic Equation

$$\text{Anode: } 2H_2 \dashrightarrow 4H^+ + 4e \quad (5)$$

$$\text{Cathode } O_2 + 4H^+ + 4e \dashrightarrow 2H_2O \quad (6)$$

Molten Carbonate Fuel Cell (MCFC) - Second Generation

The second generation fuel cell utilises a mixture of lithium and potassium carbonates as the solid electrolyte (CO_3^{2-} being the charge carriers). The electrolyte is held in porous ceramic tiles made from $LiAlO_2$ between two porous electrodes (anode: Ni/Cr alloy, cathode: Li doped NiO). The MCFC suffers from serious materials corrosion problems caused by the molten electrolyte and cell performance degradation.

The operating temperature of MCFC is lower than the minimum reforming temperature for methane (800°C), a suitable catalytic electrode is required to achieve internal fuel reforming. The stability of a catalytic electrode material in cell operating environments is still an obstacle. The electrolyte is consumed in the anode cell reaction and in order to preserve electrolyte, CO_2 has to be cycled from anode to the cathode compartment Badwal *et al.* 1991).

Operating Temperature	650°C
Fuel Used	H_2, CO, CH_4, CH_3OH
Fuel /Electric Efficiency	55%

Characteristic Equation

Anode: $CO_3^{2-} + H_2 \dashrightarrow CO_2 + H_2O + 2e$ (7)

Cathode $CO_2 + 1/2O_2 + 2e \dashrightarrow CO_3^{2-}$ (8)

Solid Oxide Fuel Cell (SOFC) - Third Generation

The solid oxide fuel cell (SOFC) is an all ceramic device. It operates at temperatures around 900 - 1000°C which allows for internal reforming of natural gas and produces high grade heat. The electrolyte is yttria-zirconia which is an oxygen-ion conductor. The anode is nickel/zirconia cermet and cathode is Sr doped $LaMnO_3$. Three basic designs currently under development are: tubular design (Westinghouse), monolithic (Allied Signal) and planar.

Operating Temperature	900 - 1000°C
Fuel Used	H_2, CO, CH_4, CH_3OH
Fuel /Electric Efficiency	60%

Characteristic Equation

Anode: $H^2 + O^{2-} \dashrightarrow H_2O + 2e$ (9)

Cathode $O_2 + 4e \dashrightarrow 2O^{2-}$ (10)

High temperature fuel cells (MCFC and SOFC) are fuel flexible and can use hydrogen as well as gaseous (at operating temperature) carbon fuels such as natural gas, coal gas, methanol and liquid hydrocarbons.

3.4.4. Fuel Cell Power Plant

A fuel cell power plant, as illustrated in Figure 3.4, comprises four main components: (1) the fuel processor (reformer, coal gasifier) and fuel and air delivery system; (2) the fuel cell stack; (3) the power conditioner; and (4) the waste heat recovery system.

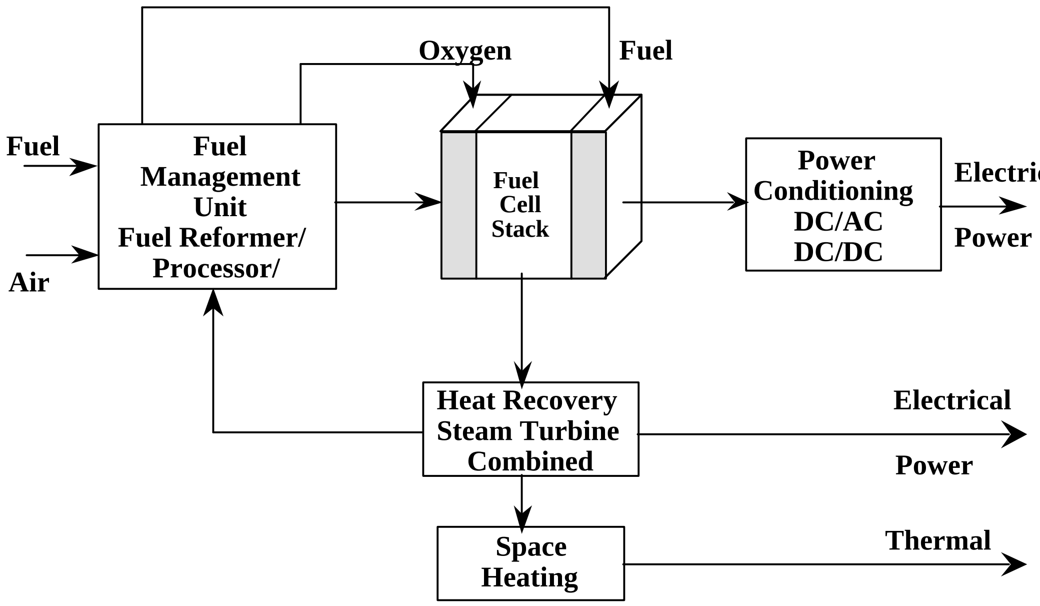


Figure 3.4: Fuel Cell Power Plant.

The fuel processor's primary duty is to convert a hydrocarbon-rich fuel into hydrogen if a pure source of hydrogen is unavailable. The fuel processor must also remove compounds such as sulfur that can poison the catalysts in the cells.

The fuel cell stack encompasses equipment necessary to feed or remove reactants from the cells, maintain cell stack conditions, manage the heat rejected by the stack, and the electric circuit.

3.4.6. Fuel Cell Advantages

Fuel cell technology is attractive for several compelling reasons. Foremost among them is the fact that fuel cells are a very clean source of power. The US Energy Research Corporation estimate that fuel cell power plants emit one-third less carbon dioxide than conventional power plants and only very small amounts of nitrogen and sulfur oxides (Kuehn 1993).

The major difference between a fuel cell and a thermal power plant is that in a fuel cell chemical energy of the fuel is converted directly to electric power without intermediate conversion to heat. The efficiency of a coal fired power plant is typically in the range 30 - 35%. In a combined cycle gas turbine system running on natural gas the maximum efficiency is in the range of 45 - 50%. The current diesel generator sets of the Australian Antarctic Research Stations have a fuel/electric+thermal efficiency of 67 % (Ratcliffe pers. comms., 1993). The Solid Oxide Fuel Cell has a fuel/electric efficiency of 60% and can be increased to 75 - 80% by the recovery of high quality heat (Badwal *et al.* 1991).

Fuel cells have the versatility to operate on a number of different fuels and some estimate fuel consumption to be one-third less than comparable generation sources. Fuel cell power plants are also compact and can be sited near the load centres. Multi-megawatt units can fit in the space of two tennis courts and are compatible to modular expansion (Kuehn 1993).

Fuel cell power systems demonstrate excellent part load and load following (30% - 130%) behaviour. Only fuel cells deliver almost constant efficiency over such a wide range of part load operation. Moreover, fuel cells have a good capability for fast response to changing load requirements. For instance, for a 200 kW PAFC system the response time in the range 50 - 200 kW is 15 seconds for 20%/min load change (Badwal *et al.* 1991).

Of most significance is the fact that fuel cell power plants are proving to be safe and reliable. In a paper titled "Fuel Cell Demonstrations Worldwide" presented at the 1992 Fuel Cell seminar, authors Edward A. Gillis (EPRI), Takeshi Sugimoto (New Energy and Industrial technology Development Organisation), and Lars A Sjummesson (Swedish Research company Sydkraft) outlined current demonstration projects around the world. According to the authors, more than one hundred demonstration projects are scheduled for the next two years in Europe, North America, and Japan (Kuehn 1993).

The future challenge of the fuel cell technology is gaining commercial acceptance. J. A. Serfass of the Fuel Cell Commercialisation Group has recognised that 'this challenge is complicated by economic, technical and external uncertainties. To lower costs substantial production volumes with significant investment in manufacturing facilities are required. Investment like that is dependent on the suppliers overall confidence of the market: yet buyers acceptance requires an adequate demonstration of the technology and assurance that the lower costs can be reached' (Kuehn 1993).

Chapter 4

Alternative Energy Options

A long standing misconception has been that the energy demands of an Antarctic Research Station could be met by a small renewable energy system. This is not the case. The following analysis of some alternative energy systems will demonstrate the magnitude required to meet the energy demands of an Australian Antarctic Research Station.

This study does not represent a comprehensive analysis of the wind energy, hydrogen, and fuel cell industry. The limitation has been the scarcity of specific performance data in this field of developing technologies.

The response of companies and research institutions contacted through the course of the study elicited enthusiasm and support for the project. The fuel cell manufacture ONSI Corporation of Connecticut USA (Whitaker pers. comms., 1993) expressed interest in 'installing units in Antarctica, to prove the product's versatility.' The Electrolyser Corporation of Toronto Canada (Stuart pers. comms., 1993) also expressed keen interest in not only providing hydrogen generator equipment but in collaborating with the development of new units. Special interest is in photovoltaic and wind turbine powered electrolyser units for outdoor unattended operation.

4.1 MCFC Unit

The US National Science Foundation is funding research to demonstrate the Molten Carbonate Fuel Cell (MCFC), or Direct Fuel Cell (DFC) as they are becoming increasingly known, to power the permanent and temporary scientific research stations of the US Antarctic program. Arctic Energies Limited (AEL) are performing the research under the objectives of the NSF and in collaboration with the US Department of Energy (DOE), Electric Power Research Institute (EPRI), and the Energy Research Corporation (ERC).

The MCFC is an internal thermo-chemical reformation unit operating at 650°C which is a sufficiently high temperature to permit diesel or SFJP8 fuel to be reformed internally within the stack. No external or 'indirect' reformer is required. This improves conversion efficiency, power system compactness and reliability.

A limiting factor for the MCFC is that it can tolerate fuels of sulfur content no greater than one or two parts per million before catalytic decomposition of the cell occurs. For this reason there is a shift to sulfur free fuels such as SFJP8.

The Energy Research Corporation are developing the 50 kW fuel stacks to be assembled into systems for use in polar conditions. The modular design permits rapid 'change-out', replacement, and easy system expansion.

The energy performance of a 50 kW MCFC and a MCFC power plant scaled to meet the energy demands of the station at Casey in 1992 is shown in Table 4.1. The fuel savings are relative to the fuel consumed by the existing diesel generator sets for the same power plant size.

Table 4.1: Estimated Energy Performance of Molten Carbonate Fuel Cell.

Molten Carbonate Fuel Cell		
SFJP8 Fuel Consumption		0.223 litres/kWh
Thermal Energy Recovered		3.56 kWh/litre
Power Plant	50 kW	Casey Electrical Demand
Electrical Production (kWh)	438,300	1,993,075
Fuel Consumption (litres/Year)	97,701	444,456
Thermal Energy Recovered (kWh)	347,815	1,582,263
[a] **Fuel Saved (litres)**	**26,063**	**119,615**

[a] Refer Appendix A

Data Source: Lisle, Jr. 1992

Australian Antarctic Division 1993

A MCFC of the type being investigated by AEL could realise significant savings in fuel if either power plant configuration is installed. The added benefit of the environmentally benign operation of the fuel cell is presently unable to be quantified. Data on the emissions per litre of fuel is unavailable, but an indication of the environmental performance of an MCFC can be seen by studies concluded by AEL for the US Antarctic Station at McMurdo :

The first output product is water, produced at about one m^3 per m^3 of fuel consumed. This electrochemical method of fresh water production is totally benign.

Nitrogen is passed through the system without change and there is virtually no environmental impact. Small quantities of nitrogen dioxide are produced. The present diesel electric generators produce 350,000 kg per year at McMurdo station alone, while the MCFC modules would produce less than 90 kg per year if used for all services (electricity, potable water, space heating, hydrogen and dry ice production).

Hydrogen is left over in the anode exhaust in a five percent concentration. The major portion, 95 per cent, is used in the primary process of making electricity and water. The five percent hydrogen can be provided as an output, it can be recirculated to the anode input or it can be burned ie. oxidised directly to water vapour.

Traces of carbon ash, particulate matter and carbon monoxide gases are produced by MCFC's in quantities too small to measure. Nitrogen dioxide production is orders of magnitude lower than Carnot cycle (Diesel and gasoline) devices. These particulate and gases have traditionally been associated with Carnot cycle systems such as diesel electric generators which produce them in significant and troublesome quantities (Lisle, Jr. 1992).

Commercial Status

The Energy Research Corporation has established a pilot production facility in Danbury Connecticut USA. The pilot production facility is designed to produce multi-megawatt output at cost approaching $US 1,500 per kW. As firm orders are developed a more automated assembly system will be designed and built which will lower the cost to approximately $US 300 per kW. The orders for MCFC stacks from ERC stands at 63 MW. The orders are contingent on ERC meeting cost and performance targets (Lisle, Jr. 1992).

4.2 ONSI PC-25 Power Plant

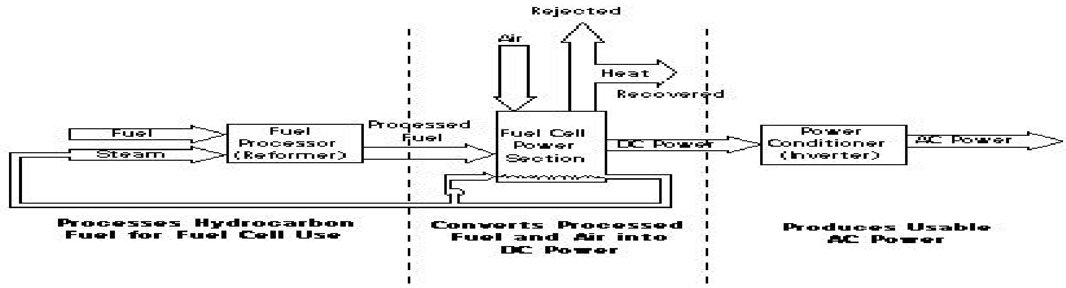
The PC-25 is a packaged, self contained fuel cell power plant that is in full commercial production at the ONSI Corporation manufacturing facility in Middletown, Connecticut. The PC-25 is a 200 kW phosphoric acid fuel cell (PAFC) developed by the International Fuel Cell Corporation (IFC), of which ONSI is a subsidiary. The technology used by IFC was developed with support from The Gas Research Institute (GRI), the US Department of Energy (DOE), and the Electric Power Research Institute (EPRI).

The unit is available as a grid-independent power plant, which can be paralleled with up to five other units to serve a common load, or as a grid-connected power plant which operates in parallel with the grid. The grid-connected power plant includes protection features to ensure proper operation with the grid and can provide emergency power to critical loads in the event of a grid outage.

The PC25 operates unattended and automatically on response to load demand for the grid-independent version or at a set power level selected by the operator for the grid-connected version. An all digital control system facilitates storing power plant component history and detailed information is available on the status of individual components. Remote monitoring capabilities are provided through a customer supplied modem. Remote monitoring permits degradation of the performance of some components to be observed before deterioration causes a power plant shutdown. It can also be used to diagnose problems before service personnel are dispatched.

The fuel cell power plant produces no sulfur dioxide or particulates. Emissions of nitrogen oxides, carbon monoxide and total hydrocarbons are negligible and carbon dioxide emissions are one-half the level of conventional plants. The power plant is very quiet with an estimated sound level of 60 dB at 30 feet from the power plant.

The PC 25 has been designed to consume pipeline natural gas as the fuel. The external fuel processor reforms the natural gas into hydrogen suitable for use by the PAFC. The power conditioning section and heat recovery are also contained within the unit, as schematically illustrated in Figure 4.1. Fredrick Whitaker, Vice President Marketing ONSI Corporation (pers. comms., 1993), has advised that 'if an uncontaminated source of relatively pure hydrogen is available, simple modifications can be made to have the unit run directly. These modifications will also reduce installed cost.'



Ref: ONSI Corporation 1993

Figure 4.1: ONSI Fuel Cell Power Plant Schematic.

The efficiency of the PC-25 operating on natural gas is:

Electrical Efficiency 40 %; and

Overall Energy Efficiency 85 %.

The efficiency of the PC-25 operating on hydrogen is currently unavailable.

Commercial Status

ONSI has manufactured and delivered 56 PC-25 fuel cell power plants to customers worldwide. Commissioning and operation has involved 22 of these units which have demonstrated 100,000 hours of uninterrupted operation (ONSI Corporation 1993).

4.3 Ceramic Fuel Cells Ltd SOFC unit

The all ceramic Solid Oxide Fuel Cell (SOFC) is being developed by a new company called Ceramic Fuel Cells Ltd. An Australian consortium backed by BHP, CSIRO, Pacific Power, the Energy Research and Development Corporation, the State Electricity Commission of Victoria and the Strategic Research Foundation intend to take the SOFC design to commercial stage by investing around $A 6 million over five years (Kannegieter 1992).

Commercialisation of the technology to date has not been achieved. Consequently, performance data is currently unavailable. The operating performance and efficiencies expected from SOFC designs in the near future merit continued monitoring of this technology. The Australian Antarctic Division have indicated interest in Ceramic Fuel Cells Ltd on grounds that it is state-of-the-art technology and is in support of an Australian based program.

The following analysis gives an indication of the quantity of hydrogen that would be used by a SOFC. A conservative estimate of the efficiency of the SOFC has been made based on expected performance (Badwal *et al.* 1991). The efficiencies based on the LHV of hydrogen are: 59 % Fuel/Electric; and 30 % Fuel/Thermal.

The energy performance of a 50 kW SOFC and a SOFC power plant scaled to meet the energy demands of the station at Casey in 1992 is shown in Table 4.2.

Table 4.2: Estimated Energy Performance of Solid Oxide Fuel Cell.

Solid Oxide Fuel Cell	
Hydrogen Fuel Consumption (101.325 kPa)	0.621 m^3/kWh
Thermal Energy Recovered	0.819 kWh/m^3

Power Plant	50 kW	Casey Electrical Demand
Electrical Production (kWh)	438,300	1,993,075
Fuel Consumption (m^3/Year)	272,184	1,237,700
Thermal Energy Recovered (kWh/year)	222,919	1,013,676

Hydrogen at 25°C and 101.325 kPa

Data Source: Australian Antarctic Division 1993

A SOFC power plant of either configuration would require a significant storage facility for the hydrogen.

The size of facilities required to store this quantity of hydrogen as a pressurised gas of 35 MPa is:

50 kW Power Plant 787,972 litres;

Power Plant sized to meet Electrical Demand of
Casey (1992) 2,934,592 litres.

The potential of metal hydrides as an alternative storage medium for hydrogen will reduce the size of the facilities. Storage by VH_2 (Vanadium Hydride) would involve the following facilities:

50 kW Power Plant 95,297 litres;
Power Plant sized to meet Electrical Demand of
Casey (1992) 354,910 litres.

The cost, weight, and losses associated with storage facilities of this size are still unknown.

On site hydrogen production would reduce the size of the storage facilities as a whole years supply of hydrogen would not necessarily need to be stored.

4.4 Wind Farm

To demonstrate the size of a wind farm required to support the Antarctic Station at Casey the Vergnet wind generator technical characteristics provided by the manufacturer are used. Vergnet wind generators are a realistic case study as the Vergnet UM 70-X wind generator has been successfully tested at Heard Island. The study shown in Table 4.3 estimates the size of wind farms for both the UM 70-X and the UM 100-N, of which the later has yet to be tested in Antarctic conditions.

Analysis of the monthly production by a wind turbine facility comprising 84 UM 70-X wind generators provide the following excess electrical production and additional electrical production required. The data set consists of monthly mean wind speed and average electrical load for the Australian Station at Casey.

The variable electrical production available from a wind farm is illustrated in Table 4.4 for months of maximum and minimum mean wind speed.

Table 4.3: Estimated size of Wind Farm.

Casey 1992		
Average Electrical Load (kW)		227
Annual Mean Wind Speed (m/s)		5.8
Product	Vergnet UM 70-X	Vergnet UM 100-N
Rated Wind Speed (m/s)	12	10
Critical Wind Speed (m/s)	110	70
Blade Swept Area (m^2)	38.5	78.5
Electrical Production @ 5.8 m/s (kW)	2.7	4.69
Required Number of Wind Generators	**84**	**49**
Blade Swept Area of Wind Farm (m^2)	3,234	3,846

Data Source: Vergnet 1993
Australian Antarctic Division 1993
ANARE News No. 69-73

The high mean wind speed in November would produce surplus electrical energy over that required by the station. The low mean wind speed in September would require the wind farm to be supported by an alternate power plant generating 145 kW in order to meet the station average load.

Table 4.4: Estimated Maximum and Minimum Electrical Production by a Wind Farm.

Casey 1992	November	September
Average Electrical Load (kW)	241	215
Mean Wind Speed (m/s)	9.4	4.1
Vergnet UM 70-X		
Wind Generator Farm Total Production (kW)	542	70
	Surplus: 301 (kW)	**Deficit: 145 (kW)**

Data Source: Vergnet 1993
Australian Antarctic Division 1993
ANARE News No. 69-73

4.5 Electrolyser Corporation

The Electrolyser Corporation based in Toronto Canada have been manufacturing and supplying electrolysis equipment which has operated for over 40 years (350,000 hours) with minimal but regular maintenance (Stuart pers. comm., 1993).

Electrolyser Corporation hydrogen generator equipment is already installed (indoor) at some of the Australian Antarctic Stations in support of the meteorological program. The electrolytic hydrogen generator is a four component system comprising a DC power supply, the electrolysis cell, deionised water system and the compressor and storage vessel. The hydrogen generator is powered from the station AC power supply through an AC/DC converter.

The Electrolyser units currently in operation have poor efficiencies, approximately 45 % AC power to the Higher Heating Value (HHV) of hydrogen. This is because of the rectifier unit converting station grid AC to DC, and the use of older electrolysis cells.

The current Electrolyser units typically have a 67 % efficiency (DC power to LHV of hydrogen) and require a DC input of ~4.08 kWh (25°C, 101.325 kPa) for every m^3 of hydrogen produced. The LHV and HHV of hydrogen are respectively 2.73 and 3.23 kWh per m^3 at 25°C and 101.325 kPa. Production is proportional to power input with systems operating from under 1 kW to many MW.

Electrolyser Corporation has been developing Photo-Voltaic (PV) Hydrogen generators for meteorological stations in mild climates for the last four years. Recently they have been developing these systems for 'essentially' out-of-door unattended operation to -40°C. This application to polar conditions is also about to include hydrogen generator systems coupled to wind turbines.

Testing of PV-Hydrogen units has demonstrated a system efficiency around 7% (Solar energy to LHV of H_2). The system is composed of:

1) PV arrays transforming solar radiation into DC power with about 10 % efficiency; and
2) Unipolar Electrolyser units with about 67 % efficiency of DC power to LHV of hydrogen.

Hydrogen production is essentially proportional to plain of array radiation. Using modern Siemens single crystal technology the 7% sunlight to hydrogen conversion efficiency is achievable in climates from -25°C to +30°C.

The wind powered hydrogen production system under development would be composed of:

1) a reliable horizontal axis two bladed wind turbine producing standard 380/415 V three phases AC power with an expected efficiency of 25 % wind kinetic energy into AC power;
2) a transformer rectifier AC/DC unit with an efficiency of about 90 % AC to DC; and
3) a unipolar Electrolyser unit.

The expected overall efficiency of the system is then around 15 % wind kinetic energy into LHV of hydrogen.

Upgrading the units already installed at the stations and powering them with renewable energy systems could be a first step towards the demonstration of Hydrogen energy systems.

4.6 Hydrogen - Diesel Combustion

Hydrogen has the versatility to be used in a number of ways to produce energy. Hydrogen can be used for a part diesel oil substitution in a compression ignition (CI) engine without major engine modifications. A hydrogen-diesel mix is necessary as the neat use of hydrogen poses a number of practical problems. Hydrogen has a very low cetane rating. The very high flame velocity of hydrogen results in a rapid rate of pressure rise during combustion and rough running of the engine, often referred to as engine knock. Its high self-ignition temperature makes it very difficult to ignite by compression alone in a conventional diesel engine.

A study conducted by Mathur *et al* (1992) detailed the operation of a small end-utility CI engine generator set as a dual fuel engine with hydrogen-air mixture induction during suction and injection of a pilot diesel charge in the conventional manner to trigger combustion. The flexibility of an easy switch back to diesel fuel operation is retained by this arrangement.

The study reports on hydrogen substitution in varying proportions to arrive at the optimum proportion of full load energy substitution by hydrogen. To control the onset of engine knock diluents such as helium, nitrogen, and water were employed individually in different proportions to arrive at their optimum proportions that permit high knock limited power output along with maximum hydrogen energy substitution.

The conclusions of the study as summarised by Mathur *et al* are as follows:

(1) Hydrogen can be advantageously used as a supplementary fuel from both the point of view of conservation of diesel oil and elimination of exhaust pollutants such as carbon monoxide, hydrocarbons, and sulphur compounds found in diesel exhaust.

(2) Addition of diluents improves the knock-limited engine operation, thereby increasing the optimum hydrogen energy substitution percentage.

(3) Nitrogen is the best diluent from an engine performance point of view, while from the standpoint of emission levels, water appears better than a nitrogen diluent.

(4) However, various considerations such as cost, ready-availability and ease of storage and handling favour water over nitrogen as a diluent.

(5) Water injection in as small a proportion as 2460 ppm can be profitably employed to achieve around 66% hydrogen energy substitution along with a smooth knock free engine operation and drastic reduction of exhaust smoke and NO_x emissions.

4.7. Catalytic Combustion

In the presence of some catalysts such as platinum, rhodium, and palladium, hydrogen will combine with oxygen without a flame (pure oxygen or oxygen from air), producing water vapour and heat. There is little or no NO_X production. Temperatures can be controlled by adjusting the hydrogen flow. The overall equation for catalytic combustion is:

$$H_2 + 1/2O_2 + \text{catalyst} \dashrightarrow H_2O + \text{Heat} \quad (11)$$

The catalytic combustion of hydrogen is more efficient than that of flame combustion. In some applications, eg. for space heating, catalytic combustion can be up to 99% efficient, since all the heat of the catalytic reaction remains inside the heated space; there are no exhaust gases (Veziroglu & Barbir 1992).

4.8. Overall System Design

The following analysis illustrates the overall size and efficiency of a dedicated wind energy, hydrogen production, and fuel cell system. The design involves the Solid Oxide Fuel Cell, Electrolyser hydrogen generator, and the Vergnet UM 70-X. The calculations are for the environmental conditions and electrical demands of Casey in 1992. Results are summarised in Table 4.5.

Table 4.5: Overall Estimated System Design Size and Efficiency.

Characteristics		
SOFC hydrogen consumption	0.621 m^3/kWh	
Electrolyser hydrogen production	4.08 kWh/m^3	
VH_2 Storage	0.234 kg/litre	
Casey annual mean wind speed	5.8 m/s	
Vergnet UM 70-X electrical production	2.43 kW DC	
Power Plant	50 kW	Casey Electrical Demand
Electrical Production (kWh)	438,300	1,993,075
SOFC Hydrogen Consumption (m^3/year)	272,184	1,237,700
Required Electrolyser Electrical Input (kWh)	1,110,511	5,049,816
Required VH_2 Storage (litres)	95,297	354,910
Required Number of Wind Generators	52	237
Overall System Efficiency	**39.5**	

Hydrogen at 25°C and 101.325 kPa

Data Source: Australian Antarctic Division 1993
Badwal *et al.* 1993
Electrolyser 1993
Hopkins 1984
ANARE News No. 69-73
Vergnet 1993

Preliminary calculations for an alternative energy system to support only the electrical demands of either of the two power plants demonstrates the significant size and low overall efficiency of the system. This suggests that alternative options for the use of the alternative energy technologies should be considered. Utilising the energy produced by the wind farm directly by the station load would reduce the size of the overall system and increase the efficiency. Exact figures would need to be calculated on a more complete data set detailing environmental conditions and station load.

The overall efficiency is calculated from point of electrical generation by the wind generators to the point of electrical production by the Solid Oxide Fuel Cell. The overall efficiency of the system does compare well with the 35 % fuel to electric efficiency of the current diesel generator sets.

The alternative energy components outlined can be utilised in a number of configurations as illustrated in Figure 4.2. The schematic illustrates the possible options for using fuel cells, hydrogen and renewable energies. Incorporating these components into an optimal alternative energy system requires design within the specific parameters of Antarctic Stations.

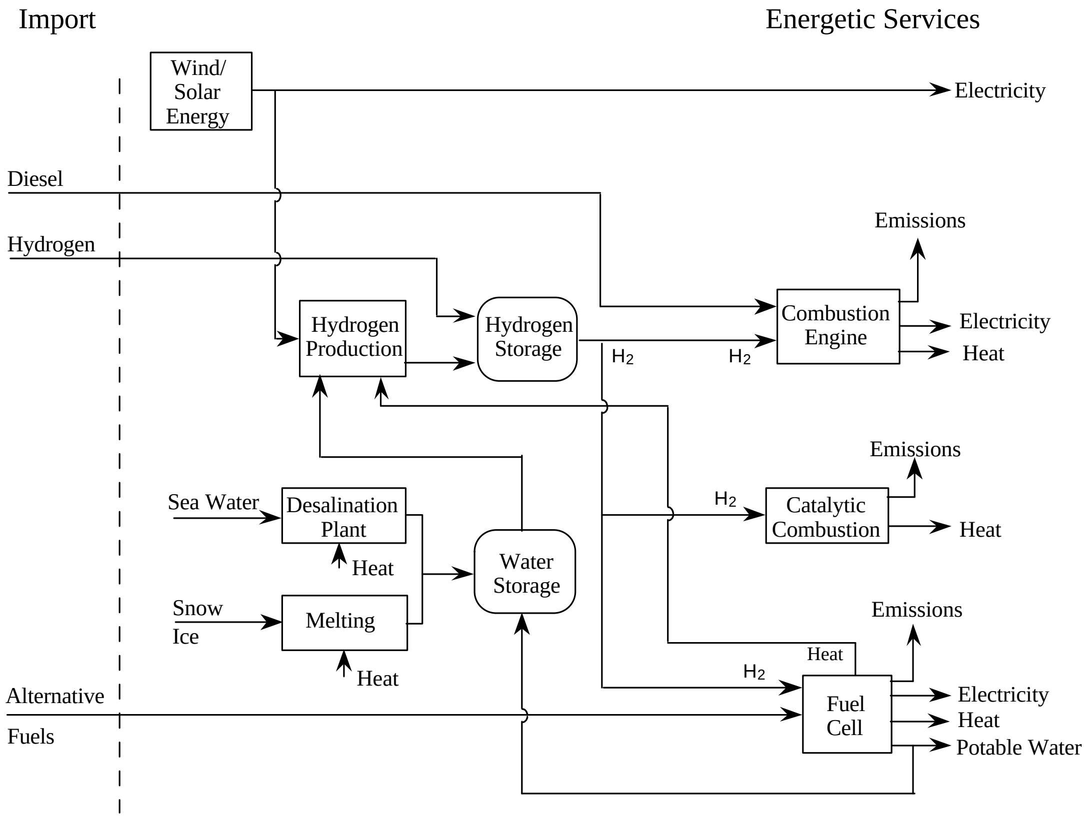


Figure 4.2: Alternative Energy Options for Antarctic Stations.

Chapter 5

Stages of Implementation

Due to practical and financial constraints, an alternative energy system should be implemented in stages. This would also enable the project to be modified over time to take advantage of technological developments.

The introduction of alternative energy systems to Antarctica needs to be initially undertaken on an experimental basis. The harsh environmental conditions of Antarctica and the specific design parameters of an Antarctic Research Station energy system requires demonstration of performance and suitability of an alternative energy system.

5.1: Plan A: Introducing Internal Fuel Reforming Fuel Cells

The introduction of fuel cell technology as the first stage in the implementation strategy is justified on the grounds that it would require minimal additional infrastructure. A pilot fuel cell power plant connected to the station electrical power grid will be able to support the current energy production system. The modular expansion capabilities of fuel cell power plants are well suited to increasing the system once its performance and suitability has been demonstrated and to follow evolutions in station energy demand.

The Molten Carbonate Fuel Cell (MCFC) that is being investigated by Arctic Energies Limited (AEL) would be well suited to this implementation plan. The consumption of SFJP8 fuel, as previously detailed, by the Molten Carbonate Fuel Cell unit does not immediately address the objective of reducing the volume of fossil fuel used in Antarctica. The fuel cell does reduce the amount of pollution caused by existing energy production practices.

AEL has estimated that air pollution emissions for MCFC units supplying electricity, water and heating for the US McMurdo Station, using the same quantity of fuel used in a year, would contribute only 90 kg of NO_2. Other pollutants such as SO_2 are negligible and CO can be processed into dry ice.

This is compared to estimated air pollution emission per year at McMurdo from a NSF/DPP Draft Supplemental Environmental Impact Statement (SEIS) of March 12, 1991 of which some significant pollutants are (Lisle, Jr. 1992):

SO_2	27,600 kg
NO_2	363,000 kg
CO	80,300 kg

Note: these estimates are totals for Diesel Generator Sets, Boilers and Furnaces.

There are two ways to proceed in implementing a MCFC unit. Firstly, negotiating for a cost sharing arrangement at the development stage of the fuel cell program. Secondly, waiting for the commercial availability of MCFC units and purchasing a unit when the technology is tried, tested, and reliable.

It is recommended that taking advantage of the high international exposure that Antarctic activities receives could be mutually beneficial to all parties involved in the implementation of a MCFC unit. The financial commitment for the Antarctic Division by taking this approach would be minimised as costs would be shared between manufacturer and customer.

5.1.1. AEL MCFC Unit

<u>Assumptions</u>

Commercial Development of unit.
Provision for supply of SFJP8 kerosene type fuel.

<u>Strategy</u>

Negotiations can proceed to obtain a unit from the Energy Research Corporation (ERC). The supply and storage of an appropriate quantity of SFJP8 fuel.

<u>Logistical Program</u>

Unit can be transported with the current shipping program and installation and commissioning is believed to be possible within a summer season.

Advantages

Reduction of fossil fuel consumption.
Reduction of airborne pollutants.
Reduction of noise pollution.
Small units to be assessed to support small field camp installations.

Limitations

Does not totally achieve stated objectives of environmental management.
MCFC technology not well suited to be upgraded to use hydrogen as a fuel.

Possible Alternatives
An alternative fuel cell type that would suit this implementation strategy are the Solid Oxide Fuel Cells (SOFC). The high operating temperatures of SOFCs can internally reform diesel or kerosene type fuels like SFJP8. The problem is that the third generation SOFC type design is very much in its development stage.

5.2. Plan B: Introducing Wind Energy

The size of a Wind Farm required to support the total energy demands of an Antarctic Station is initially prohibitively large. Similarly the size of a Wind Farm dedicated to the production of hydrogen for use by a fuel cell power plant is also prohibitively large. Consequently the introduction of wind turbine electrical generators would initially be best utilised as a grid connected facility supporting an alternate energy system.

Introducing wind turbine electrical generation systems are contingent on the demonstration of the equipment's survival in the harsh Antarctic environment. This will be validated through a testing program currently conducted by the Australian Antarctic program and other Antarctic Treaty Nations.

The continued assessment of wind turbine manufacturers is required to determine potential units for Antarctic Stations. Larger wind turbines of capacities greater than 50 kW would be well suited to supporting an alternative energy system for Antarctic Stations. This would reduce the number of wind turbines required and possibly reduce the environmental impact created by the introduction of wind turbines. The larger wind turbines will require further development as present indications are the larger the wind turbine, the lower the survival wind speed.

Potential Manufacturers

Northern Power Systems (Moretown, Vt USA) have reliable 3 kW units which have been operating successfully since 1985 on Black Island, McMurdo Sound. They intend to develop medium sized (100 kW) turbines for operation in extreme cold environments, but not extreme winds. The principle markets for the turbine are to be Alaska, northern Canada, the Scandinavian countries, northern Russia, Siberia and the continent of Antarctica (Coleman & Barlowe 1993). This doesn't include yet the East Antarctic coast nor the Sub-Antarctic Islands. The design specifications include:

> Extreme wind speeds: Class I (70 m/s extreme gust);
> Temperature Range: 60 °F to -100°F; (convert to C)
> One year maintenance interval; and
> No crane service required for maintenance or erection.

The development of a direct drive 100 kW wind turbine generator is a crucial step 'as traditional gear box wind turbine generator designs are not appropriate for extreme cold environments due to lubrication and fatigue limitations' (Coleman & Barlowe 1993).

Vergnet (Orléans, France) recently acquired Aérowatt which produced the UM 70-X successfully tested at Heard Island in 1992/93. Aérowatt originated from a group of people who successfully designed wind turbines used on top of the Greenland Ice Cap (Station Centrale) in the sixties by Expéditions Polaires Françaises. Vergnet continues to improve the Aérowatt machines and develops new ones.

Their wind turbines, currently in the range 1 - 12 kW, are designed for unattended operation in extreme conditions: high winds, corrosive environments. The 'N' and 'X' ranges of machines have rated survival wind speeds of respectively 70 m/s (252 km/h) and 110 m/s (396 km/h). To the best of our knowledge, this gives the Vergnet 'X' machines the highest survival wind speed ever obtained.

The UM 70-X exists in both 6 and 12 kW versions and produces standard 380/415 V, 50 Hz, 3 phases AC power. Larger units are about to enter production (25 kW, 10m diameter) or are in the development stage (30 kW, 14m diameter), but will be in the 'N' range of survival wind speed.

Strategy

Continue to assess wind turbine manufacturers.

Establish co-operative agreement with a manufacturer to test suitable wind turbines on the Antarctic Continent.

Establish wind turbine pilot plant facility. Electrical production to be connected to station electrical grid.

Determination of wind turbine pilot plant capacity and performance. Upgrade system to further support current energy system and in readiness for the introduction of hydrogen generation equipment.

Infrastructure

Wind turbine and power conditioning equipment.

Installation and commissioning equipment.

Advantages

Reduction of fossil fuel consumption at the stations.

Reduction of airborne pollution produced at the stations.

Reduction of infrastructure and logistical program supporting the supply and storage of fossil fuels.

Plan B is not dependent on the implementation of other systems.

Limitations

Technical problems associated with operation of wind turbines in extreme wind speeds and cold environments need to be solved.

Environmental impact required to be evaluated.

Possible Alternatives

Solar panels to support wind turbine generator facility in the generation of power in the summer months.

Thermo-mechanical machine developments to be monitored and assessed following the conclusion of testing program at Dumont d'Urville.

Pilot facilities to be assessed for summer field camp energy system.

5.3. Plan C: Introducing Hydrogen

The introduction of hydrogen to replace, or reduce the use of diesel fuel will involve large capital investment. Introducing hydrogen as the main 'energy carrier' for the Antarctic stations will require the introduction of:

1. Hydrogen production facilities;
2. Hydrogen storage facilities; and
3. Alternative electrical generation facilities.

For these reasons alone the large scale introduction of hydrogen is a long term solution to the reduction of fossil fuels used on the Antarctic Continent.

Hydrogen could be utilised at the Antarctic stations by fuel cell power plants, hydrogen-diesel substitution in diesel generator sets, and by catalytic burners. The benefit of using hydrogen in a fuel cell power plant and catalytic burners outweighs the advantages of diesel hydrogen substitution. This is primarily on the grounds of the improved efficiencies of fuel cells and catalytic burners and the greater reduction in emissions possible by these options.

Hydrogen would be best utilised in support a wind electrical generation system. The electrical load of an Antarctic Station can be met by the electrical production from a Wind Farm when environmental conditions permit. During periods of excess electrical production by the Wind Farm hydrogen can be produced by the electrolysis of water and then stored. The hydrogen can later be used by a Fuel Cell power plant during periods of low electrical production by the Wind Farm to supply the energy demands of the Station. This would complete a sustainable alternative energy system.

Potential Manufacturer

The Electrolyser Corporation have demonstrated the reliability and performance of their hydrogen generator products. Electrolyser have supplied small hydrogen generator units to the Australian Antarctic Program and have expressed interest in supplying larger systems.

Systems can be designed according to customer requirements. They can range in size from under 1 kW to many MW systems. The systems can be designed in conjunction with wind turbine or photo-voltaic systems supplying the energy input.

Strategy

Establish wind turbine facility, as of Plan B.

Obtain mid-sized Solid Oxide Fuel Cell (~200 kW) which can support station energy demand.
Obtain hydrogen generator equipment and storage facilities.

Infrastructure

Wind turbine facilities.
Electrolysis unit.
Fuel Cell unit.
Hydrogen storage facility.
Pipeline gaseous hydrogen transport facilities.

Advantages

Achieve objectives of significant reduction of the use of fossil fuels.
Reduction of airborne pollution produced at the stations.
Reduction of infrastructure and logistical program supporting the supply and storage of fossil fuels.

Limitations

Significant capital investment.
Significant infrastructure.

Possible Alternatives

Type of electrolysis equipment available.
Use of MCFC or other fuel cell using hydrogen as fuel.
Development of improved hydrogen storage techniques; metal hydrides, refrigerated activated carbon.
Hydrogen used in catalytic burners for thermal needs only.

5.4. Summary

The significant capital expenditure required to introduce hydrogen as an energy carrier will limit its short term implementation. The introduction of wind electrical generation and fuel cell power plants can reduce the consumption of fossil fuels at the stations.

The wind turbine alternative has greater potential as it can be used as a step to a larger renewable energy system. The use of a SFJP8 internal reforming Molten Carbonate Fuel Cell would demonstrate the performance and advantages of a fuel cell power plant. This would then need to be upgraded to an Solid Oxide Fuel Cell power plant as the program moves to a renewable energy system using hydrogen.

Chapter 6

Conclusions and Recommendations

6.1 Conclusion

The operational and policy objectives of the Australian Antarctic program support the investigation of alternative energy systems as a means to reduce the consumption of fossil fuels at the Antarctic Research Stations. The opportunity exists to invest in a renewable energy system that can provide higher performance efficiencies and significantly improved environmental operation.

A renewable energy system comprising of wind turbines, hydrogen production by electrolysis, and fuel cell power plants are a feasible alternative for use at the Antarctic Research Stations.

The study concluded that the most promising option for the alternative energy system would be to centre energy production around a wind turbine electrical generation system. Periods of excess electrical production by the wind farm can be used for the production of hydrogen by the electrolysis of water. The hydrogen can be stored and later used by a fuel cell power plant to produce energy during periods of low electrical production by the wind farm.

The alternative option to use an internal reforming fuel cell, such as a Molten Carbonate Fuel Cell operating on SFJP8 fuel, can be viewed as a short term solution. The benefit in the reduction of gaseous pollution to the Antarctic environment and the small reduction in the quantity of fossil fuels used by this system should be considered in assessing its implementation.

Due to practical and financial constraints, an alternative energy system should be able to be implemented in stages. This will also enable the project to be modified over time to take advantage of technological developments.

The implementation is contingent on further development and testing of equipment comprising the alternative energy system. Support will need to be sought in the collaboration with manufacturers willing to demonstrate their products in the harsh environmental conditions of Antarctica.

6.2 Recommendations

1. Continue the program of obtaining specific data sets on the environmental conditions at the Australian and French Antarctic Stations so a detailed renewable energy potential analysis can be performed.

2. Continue to obtain energy production and consumption data so a complete energy audit can be performed for the Australian and French Antarctic Stations.

3. Continue to assess performance data and commercial availability of the alternative energy system based on information obtained from industrial groups and research institutions.

4. Establish equipment specifications based on renewable energy potential and energy audit studies.

5. Complete a design of a wind turbine, hydrogen, and fuel cell power plant system for the supply of energy to the Australian and French Antarctic Research Stations.

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Appendix A

Some Fuel Cell Sizing Calculations.

Table A.1: Molten Carbonate Fuel Cell (MCFC) Power Plant Performance Compared to Diesel Generator Sets.

	Diesel Generators	MCFC
Fuel Type	SAB	SFJP8
LHV of Fuel (kWh/litre)	9.798	11.89
Electrical Production (kWh/litre)	3.413	4.482
Thermal Energy Recovered (kWh/litre)	3.135	3.56
50 kW Power Plant		
Electrical Production (kWh/year)	438,300	438,300
Fuel Consumed (litres/year)	128,413	97,701
Thermal Energy Recovered (kWh/year)	403,088	347,815
Power Plant sized to meet Total Electrical Demand of Casey in 1992		
Electrical Production (kWh/year)	1,993,075	1,993,075
Fuel Consumed (litres/year)	585,359	444,456
Thermal Energy Recovered (kWh/year)	1,835,374	1,582,263

50 kW Power Plant
MCFC power plant requires additional thermal energy production of 55,273 kWh to match thermal production by Diesel Generator power plant. Assuming Boiler efficiency of 80 % (Australian Antarctic Divsion 1993) consuming SFJP8.

Boiler fuel consumption to match thermal energy deficit. = 4,649 litres

Total fuel consumption by MCFC power plant and Boilers to match energy production of Diesel Generator power plant. =102,350 litres

Fuel saving by combined MCFC and Boiler power plant. = 26,063 litres

Power Plant sized to meet Total Electrical Demand of Casey in 1992
MCFC power plant requires additional thermal energy production of 253,110 kWh to match thermal production by Diesel Generator power plant. Assuming Boiler efficiency of 80 % (Australian Antarctic Divsion 1993) consuming SFJP8.

Boiler fuel consumption to match thermal energy deficit. = 21,288 litres

Total fuel consumption by MCFC power plant and Boilers to match energy production of Diesel Generator power plant. = 465,744 litres

Fuel saving by combined MCFC and Boiler power plant. = 119,615 litres

Appendix B

Alternative Energy Options for Antarctic Stations

Presented at
Solar 93 Conference
December 1993
Fremantle, Perth

Alternative Energy Options for Antarctic Stations

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Abstract
The purpose of this paper is to describe the unique problems of designing an alternative energy system for the Australian and French Antarctic research stations and the possible options that can be pursued to obtain a clean, efficient, safe and reliable energy system. The adoption of the alternative systems will rely on the further technological and commercial development of equipment and the collaboration of industry.

Résumé
Le présent article expose les problèmes particuliers liés à l'élaboration de nouveaux systèmes énergétiques pour les stations scientifiques Françaises et Australiennes de l'Antarctique. Diverses options visant à l'obtention de systèmes non polluants, à bon rendement, sûrs et fiables sont détaillées. Nous verrons que leur adoption dépend de développements technologiques en cours et de l'engagement de programmes de coopération avec les fabriquants d'équipements.

Table of Contents

1. Introduction

Research stations in the Antarctic have special needs for efficient, reliable, safe and environmentally friendly power systems to provide electricity, heat and potable water. The energy demands are dominated by the requirement for heating followed by the production of electricity, with water production, generally by desalination or ice melting, also requiring significant energy input.

The combustion of fossil fuels in powerhouses is the single largest local contributor to Antarctic produced airborne pollution.

Reducing the use of fossil fuels is important as it has the potential to:

- promote the protection of the Antarctic environment;
- reduce the cost of Antarctic research;
- alleviate the demand on the logistical support program, for fuel transport and handling; and
- enhance the credibility of Australia's and France's prominent positions in the international effort to reduce environmental impacts in Antarctica.

2. Current Station Energy Systems

Since the 1950s and 60s when the research stations were being developed, most energy demands were met by diesel generators and oil fired boilers. At the time, these methods were the most convenient, established and reliable means to support the needs of the stations where safety was, and still is, of highest priority.

The generator sets typically consist of 125 kVA alternators driven by diesel engines, with water jackets providing additional heat recovery from cooling water and exhausts. The fuel almost exclusively used by the stations is Special Antarctic Blend (SAB) diesel which has been chosen primarily for its cold temperature performance. The characteristics of SAB as tested by Mobil Oil, Hobart are:

Lower Heating Value: 35,274 kJ/litre (LHV)
Density @ 15°C : 0.805 kg/litre
Sulphur Content : 0.05 %wt

As an example, the fuel consumption by the Australian Antarctic and Sub-Antarctic stations, with the corresponding electrical and thermal production is represented in Table 1.

Table 1: Australian Antarctic Stations Energy Production and Consumption, 1992:

January to December 1992	Casey	Mawson	Davis	Macquarie
Total SAB used in powerhouse (l)	679,120	643,032	659,739	195,399
Average Electrical Load (kW)	227	251	200	67
Generators Electrical Production (kWh)	1,993,075	2,200,685	1,756,302	587,675
Total Thermal Production (kWh)	2,909,099	2,076,298	2,695,112	623,103
Total Energy Production (kWh)	4,902,174	4,276,983	4,451,414	1,210,778
Station Population (average)	32.9	43.2	44.8	21.6
Energy use per capita (kWh/person/day)	408	271	272	99

Data Source: Australian Antarctic Division, Engineering Section.

The remoteness of the Antarctic continent requires a major logistical program for the provision of SAB diesel and support of the research stations. The seasonal window for logistical operations is limited to the summer months and the fuel pumping program is both difficult and time consuming. Some conservative estimates put the cost of SAB at the point of use in Antarctica at double the purchase price in Hobart. Other estimates go further. The Australian Antarctic Division calculated the cost of electricity to be as high as 14 times that in Hobart. In addition to the financial cost there is a significant environmental cost. The transport of fuel by sea involves the risk of spillage. The potential for significant ecological damage to the fragile polar environment by such an event has been demonstrated by the *Bahia Paraiso* grounding in the Antarctic Peninsula and the *Exxon Valdez* incident in Alaska.

3. Alternative Energy Opportunities

The environmental and scientific values of Antarctica have recently received more attention, with the recognition of the importance of the interactions of the polar regions with the global environment. Increasing emphasis is being placed by the nations active in Antarctica on environmental management. These nations recently adopted a Protocol on Environmental Protection to the Antarctic Treaty, and through the Council of Managers of National Antarctic Programs have identified various practical initiatives, including the application of alternative energy, to implement the principles of the Protocol.

The main constraints in the implementation of alternative energy systems in Antarctica are:

- The remoteness of the stations and the logistical problems in supplying and storing fuel;
- The harsh environmental conditions imposing restrictions on traditional

renewable energies, such as wind and solar;

- Strict environmental protocols that need to be adhered to in the construction of any structures; and
- The difficulty in obtaining outside support and assistance, especially in the winter months.

With these constraints in mind, it became apparent that a wind energy hydrogen fuel cell system offered promising possibilities for an efficient, reliable, safe and environmentally clean system.

Due to practical and financial constraints, a sustainable energy system should be able to be implemented in stages. This will also enable the project to be modified over time to take advantage of technological developments.

3.1. Renewable Energies

Antarctica is a continent of harsh environmental conditions which test the performance and survival of conventionally designed equipment. The critical conditions influencing the design of renewable systems are:

Maximum Wind Speed 90 m/sec
Minimum Temperature -40 °C

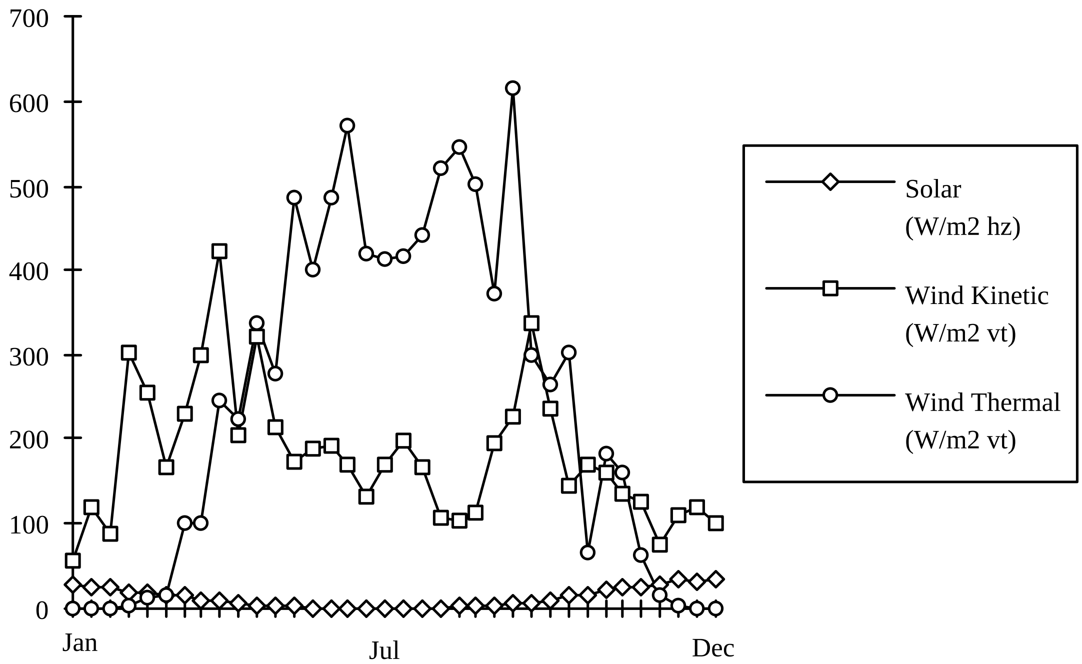

Fig. 1: An Estimate of Recoverable Energy at Dumont d'Urville.
Data Source: Le Goff, H., Laboratoire des Sciences du Génie Chimique

Min. daily Solar Irradiance 0 W/m^2 (by clear sky)

An example of energy recoverable by Solar Cells, Wind Turbines and Thermo-Mechanical machines at the French station of Dumont d'Urville is summarised in Fig. 1 (Guichard & Steel,1993). The global solar radiation was measured on a horizontal plane, at ground level, from 0 to 24 hours; wind speed at 10m high averaged over 10 minutes every 3 hours; and spot temperatures every 3 hours.

Thermal wind energy has the greatest abundance with a yearly average of 246 W/m^2 vt (vertical crossection). Wind kinetic energy is less abundant but more constant over the year (181 W/m^2 vt) and solar energy an average of 11.7 W/m^2 hz (horizontal panel). This has influenced the adoption of a renewable energy component based upon wind energy recovery. Solar energy is only practical in the summer months, as the irradiance in the winter months is as low as 0.1 W/m^2.

Electricity production by thermo-mechanical machines operate on the cooling power of the wind, the temperature T of which is lower than the temperature T_o of a reference medium, the sea for example. Thermo-mechanical machines have some potential and are actively being developed with the support of the French Polar Institute. A prototype is scheduled to be installed at Dumont d'Urville in the 1993/94 summer season.

3.2. Hydrogen as an Energy Carrier

In Antarctica energy storage systems are required so that energy is available at all times. Hydrogen is increasingly being accepted as a practical alternative fuel and is potentially well suited to the needs of the Antarctic. The advantages of hydrogen are:

- versatility in energy production method;
- negligible polluting emissions; and
- can be locally produced by the electrolysis of water.

The storage system represents the greatest problem for the large scale introduction of hydrogen as part of a sustainable energy system. The conventional methods of liquefying or compressing hydrogen require substantial energy input and heavy bulky storage cylinders. Though they are commercially available technologies there is increasing interest in the developing technologies of metal hydride and refrigerated activated carbon. These storage methods offer increased safety and may also be cheaper.

The safe use of hydrogen has been demonstrated in established facilities world wide and now includes over 750km of commercial gaseous hydrogen transport pipeline (Hoenigmann, 1992).

3.3. Fuel Cell Power Systems

The conceptually simple and environmentally attractive fuel cell offers a solution to the production of electricity in a compact, quiet, highly efficient, and exceptionally clean manner. The electrochemical reaction driving the fuel cell occurs between hydrogen and oxygen in a device consisting of an anode, cathode and electrode. Fuel cells operating on alternate fuels to hydrogen require the fuel to be reformed into hydrogen. This can be achieved in an external reformer or can be internally reformed in the higher temperature operating fuel cells. The co-generation capabilities of fuel cells to produce thermal energy and potable water can assist in meeting the demands of the research stations.

4. System Options

A comprehensive assessment of products is being carried out. To initiate the project, a testing program involving small pilot plants is desirable. The modular expansion capabilities of the components would better enable the system to gradually be expanded.

4.1. Introducing a Fuel Cell Unit

An internal reforming fuel cell unit can be introduced as a singular component connected to the station electrical grid. This will reduce the electrical load on the diesel generator sets and also assist in the production of heating and water for the station.

The US National Science Foundation is funding research to demonstrate the Molten Carbonate Fuel Cell (MCFC), or Direct Fuel Cell (DFC) as they are becoming increasingly known, to power the permanent and temporary scientific research stations of the US Antarctic program using diesel or sulfur free JP8 (SFJP8) fuel.

The DFC is a internal thermo-chemical reformation unit operating at 650°C which is sufficiently high to permit diesel or SFJP8 fuel to be reformed internally within the stack. The SFJP8 fuel has all the desired characteristics such as high heating value, satisfactorily high flash point, high viscosity and useability in many of the existing Antarctic facilities.

Lower Heating Value: 42,800 kJ/litre (LHV)
Density @15°C: 0.775 to 0.840 kg/litre
Sulphur Content: < 1ppm

The DFC unit can be assembled in 50 kW modules. A pilot facility of this size would have characteristics as calculated in Table 2.

Introducing a fuel cell unit using diesel as a fuel enables the unit to be installed and tested without the need for any additional infrastructure. This will reduce the capital cost and allow a suitable demonstration of the fuel cell technology.

Technological development is continuing with other internal reforming fuel cells. The CSIRO Division of Materials Science and Technology in Melbourne is actively investigating the Solid Oxide Fuel Cell (SOFC) which with its high operating temperature (900-1000°C) will have the capability to reform a variety of fuels. The availability of either test or commercial units is believed to be some time off, though the potential of the SOFC units is encouraging and warrants monitoring.

The internally reforming fuel cells would be ideally suited to the implementation of the program. Initially operating on the current fuels used in Antarctica they can be modified to operate directly on hydrogen, bypassing the reforming process, when the hydrogen system is developed.

4.2. Introducing Renewable Energy

Wind generators have been tried in Antarctica but have often failed due primarily to the extreme wind and icing conditions. A recent successful demonstration of a wind turbine was made on the sub-antarctic Heard Island. It is planned to continue a more ambitious testing program on the Antarctic continent with advanced wind turbines.

4.3. Introducing Hydrogen

It is not practicle to import hydrogen to Antarctica because of the special transport facilities required. It would be very expensive to modify existing vessels and would disrupt much of the shipping program at a time when there is a wish to further dedicate the vessels to scientific programs rather than logistical supply.

The meteorological program conducted at some of the research stations currently uses locally produced hydrogen for the meteorological balloon filling program. This is achieved by small electrolytic hydrogen generators made by the Electrolyser Corporation, with power to the unit supplied by the station electrical grid. The hydrogen is stored in a compressed gas storage vessel. Large scale electrolysis of water is viewed as the best option for hydrogen generation.

Hydrogen produced on site will need to be stored. Preliminary storage would involve compressed gas methods limiting the size of the system. The developing metal hydride and refrigerated activated carbon technologies need to be investigated to establish whether the compressed gas storage can be superseded.

Hydrogen can be used in two ways. Firstly, as an additive to diesel fuel in the current generator sets. This requires minimal modifications and improves the emission characteristics of the generator sets through the reduction of pollutants such as carbon monoxide, hydrocarbons, and sulphur compounds, and also reduces the consumption of diesel fuel.

Tests have been performed to establish optimum levels for the addition of hydrogen and other diluents to improve performance and the reduction of engine knock, which is a characteristic associated with the neat use of hydrogen. Water injection, in as small a proportion as 2460 ppm, can be profitably employed to achieve around 66% hydrogen energy substitution along with a smooth knock free engine operation and drastic reduction of exhaust smoke and NO_x emissions (Mathur and others 1992, p369-374).

Secondly, hydrogen can be used as a fuel for the commercially available Phosphoric Acid Fuel Cell (PAFC) developed by the ONSI Corporation. A suitable unit for Antarctic applications is the PC 25, being a packaged, self contained fuel cell power plant. The PC 25 is a 200 kW unit that is manufactured for use with pipeline natural gas. The unit can be simply modified to operate on an uncontaminated source of relatively pure hydrogen.

5. System Objectives

A complete renewable energy system is illustrated in Figure 2.

Table 2: Energy Generation Characteristics with respect to fuel quantity consumed.

Unit Type	Fuel Type & LHV (kWh/kg)	Electrical Production (kWh/kg)	Thermal Production (kWh/kg)	Total Energy Production (kWh/kg)	Total Energy Production (kWh/litre)	Energetic Efficiency (%)
1.Diesel Generator	SAB 12.17	4.24	3.90	8.14	6.55	66.88
2. DFC	SFJP8 14.82	5.55	3.10	8.65	6.94	58.36
3. PAFC	Natural Gas 13.25	5.09	6.34	11.43	0.00834 (@STP)	86.26

Data Source: 1. Australian Antarctic Division., Engineering Section.
2. Arctic Energies Limited., "Engineering Research on Fuel Cells for Antarctic Energy Production and Conservation as well as Potable Water Treatment and Delivery." Prepared for the Division of Polar Programs, National Science Foundation, 1991
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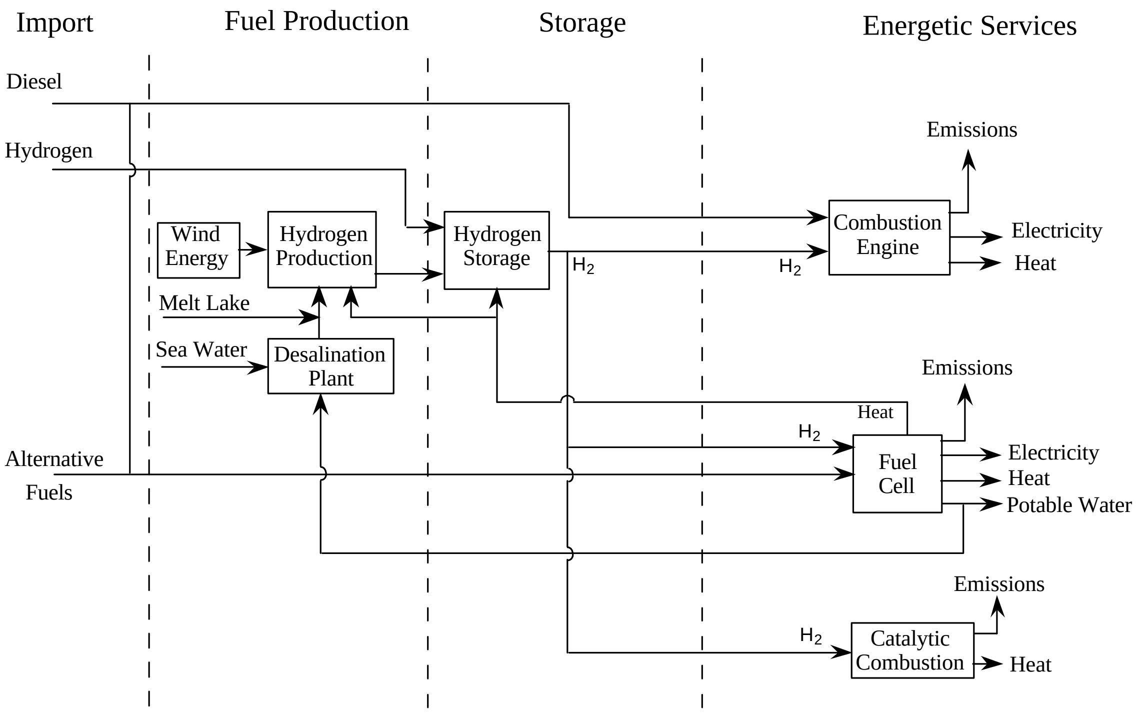

Fig. 2: Alternative Energy System Schematic.

6. Opportunities for Collaboration

The high international profile of activities conducted in Antarctica provide the opportunity for industries involved in clean, efficient, alternate energies to demonstrate their products and to obtain substantial international recognition. In addition, the Australian and French Antarctic research stations offer an established test-bed facility with monitoring capabilities to demonstrate advanced Remote Area Power Systems.

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Appendix C

Alternative Energy Systems for Antarctic Stations: Investing for the Future.

Presented at
IDEAA 2 Conference
24 - 27 October 1993
Montreal, Canada

ALTERNATIVE ENERGY SYSTEMS FOR ANTARCTIC STATIONS: INVESTING FOR THE FUTURE.

by
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Reference:
Guichard, A. and Steel, J. (1993) Alternative Energy Systems for Antarctic Stations: Investing for the Future. In: Growth and Environment: Challenging Extreme Frontiers, Proceedings of the Second International Design for Extreme Environments Assembly, 24-27 October 1993, 347-363. Published by the Centre for Northern Studies, McGill University, Montréal, Québec.

ABSTRACT

A French-Australian co-operative research project focused on energy systems at Antarctic research stations has been initiated. Its aims are to investigate the current energy requirements of the Australian and French stations and to conduct a feasibility study on the use of alternative energy systems. This is designed to reduce the quantity of fuel used and the impact on the environment.

This paper outlines the various issues addressed, presents the first options identified and provides a basis for identifying directions for future work.

Keywords: energy, Antarctic, renewable, environment.

RESUME

Un programme de recherche Franco-Australien sur les systèmes énergétiques des stations scientifiques Antarctiques a été initié. Ses objectifs sont de mener une investigation des besoins en énergie des stations Australiennes et Francaises, et d'étudier les possibilités d'utilisation de nouveaux systèmes énergétiques. Le but final du projet est de réduire les quantités de fuel utilisées et l'impact des stations sur l'environnement.

Cette communication expose les problèmes rencontrés, présente les premières options identifiées et fournit une base de reflexion pour identifier les orientations à donner aux recherches à venir.

Mots clés: énergie, Antarctique, renouvelable, environnement.

CONTENTS SUMMARY

PAPER

1. Introduction.

The harsh coast of East Antarctica lies around 3000 km south of Australia across the Southern Ocean. It was first reached in January 1840 by French navigator Jules Dumont d'Urville sailing from Hobart, Tasmania, on board *l'Astrolabe* and *la Zélée*. The ice cliffs occasionally give way to small rocky outcrops which are the favourable locations for both animal breeding grounds and human settlements. These remote sites experience high katabatic winds (up to 326 km/h recorded, average over 2 minutes, Dumont d'Urville, January 1972) and are further isolated in winter when the continent is surrounded by hundreds of kilometres of sea-ice.

The settlements are scientific stations operated by national organizations. Australia and France currently run four permanent stations on this coast: Mawson (67°36'S, 62°52'E), Davis (68°36'S, 77°58'E), Casey (66°18'S, 110°32'E) and Dumont d'Urville (66°40'S, 140°01'E), plus four others scattered in the Indian and Southern Oceans on the Sub-Antarctic islands of Crozet (Alfred-Faure, 46°26'S, 51°52'E), Kerguelen (Port-aux-Français, 49°21'S, 70°12'E), Nouvelle-Amsterdam (Martin-de Vivies, 37°50'S, 77°34'E) and Macquarie (54°30'S, 158°57'E). These eight stations are at present serviced by a total of four ships: *L'Astrolabe*, the *Aurora Australis*, the *Icebird* and the *Marion Dufresne*. The first three are ice strenghtened vessels.

Access to the Antarctic coastal stations is limited to the summer months. They remain totally isolated for the winter months when sea-ice fills the surrounding waters. Sub-Antarctic islands can receive limited supply voyages in winter. The stations typically house 15 to 35 expeditioners throughout winter, up to 100 in summer, and while some minor use is made of solar and wind energy for powering equipment in the field, they rely almost entirely for electricity and heating on conventional, mid-sized, diesel generator sets and oil fired boilers.

This approach has been dictated by the primary need for practicality and a very high degree of reliability. Intensive research demands a constant power supply and serious system failures can rapidly jeopardize the safety of expeditioners. At the time when most stations were established (the 1950s and 60s), investigations and trials showed that conventional generator sets and boilers were the only satisfactory, practical answer to the provision of energy.

Energy costs are high and exhaust gas emissions from stations are the most significant source of air pollution in the near pristine conditions of Antarctica. The possibility of oil spills also threatens the polar environment and fragile ecosystems. Technologies related to cleaner energy production, to renewable energies and to energy storage are rapidly evolving and new, realistic possibilities of alternative energy systems for Antarctic stations now arise.

France and Australia are leading Antarctic Treaty nations and have recently been successful with a joint policy initiative which resulted in agreement to a Protocol on Environmental Protection to the Antarctic Treaty (the Madrid Protocol). As part of the program to translate the environmental policy into action, a joint project has been initiated involving the Antarctic operating agencies and research institutions in France and Australia. The immediate objective of the project is to investigate the current energy requirements of the Australian and French Antarctic research stations and to conduct a feasibility study on the use of alternative energy systems designed to reduce the quantity of fuel used and the impact on the environment.

The main partners of this program are the French Institute for Polar Research and Technology (IFRTP), the Australian Antarctic Division (AAD), the Laboratoire des Sciences du Génie Chimique (LSGC/CNRS) and the Institute of Antarctic and Southern Ocean Studies (IASOS) at the University of Tasmania.

The long term objectives are to make Antarctic stations independent or near independent of fossil fuels and to minimize their impact on the environment. This would directly improve the quality of support to Antarctic research and would provide a significant contribution towards the ongoing international efforts to enhance the protection of the Antarctic environment.

2. Current Systems.

All source data used to describe and analyse the current systems has been obtained from operators of the stations through the Engineering Section of the Australian Antarctic Division and the Service Technique de l'Institut Français pour la Recherche et la Technologie Polaires which have both been of great assistance.

2.1. System Overview.

The main component of the energy system of a typical station is a central powerhouse comprising two to four diesel engines driving three phases alternators of 100 to 125 kVA capacity. Heat is recovered from cooling water jackets, and sometimes from exhausts. Additional thermal needs are fulfilled by boilers. Both engines and boilers are fueled with Special Antarctic Blend (SAB) diesel fuel shipped in by polar supply vessels and stored on the station in bulk storage tanks. Fuel farms can usually store enough SAB for the station to operate normally a whole year plus 'survive' an additional winter in case fuel cannot be delivered in the next summer season. Full storage capacity can be up to 1 060 000 litres at a single station with the tanks covering an area up to 1280 m^2 (Mawson).

The SAB fuel used is, like normal Diesel, registered as Flammable Liquid Class C and dangerous Good Class 3.3. The main difference lies in a much lower pour point. Some of its characteristics of interest are :

Density @15°C :	0.805 kg/litre
Flashpoint :	64 °C minimum
Pour Point :	-36 °C
Sulphur Content :	0.1 % wt max.
Lower Heat Value :	35 274 kJ/litre (or 9.8 kWh/litre)
Purchase Price :	≈ $A 0.38 (bulk, in Hobart)

When freshwater has to be produced from seawater, heat recovered from the engines is directly used in the powerhouse to desalinate seawater (e.g. Dumont d'Urville) and individual boilers provide heating to the buildings. In other cases, the recovered heat is reticulated through hot water mains around the station to feed heating systems through various exchangers, to melt ice (e.g. Casey and Mawson) or to melt snow (e.g. Davis). Boilers are also used to maintain the temperature of the reticulated hot water if needed.

Dumont d'Urville produces its freshwater through the highly energy intensive desalination process. This requires all the heat recovery from the engines plus 46 kW from boilers, that is

113 kW or 45% of the station's average power. Melting ice at Casey and Mawson requires 10 to 20 kW while melting snow at Davis uses around 27 kW.

The three Australian Antarctic coastal stations are mostly equipped with in-line six cylinder Caterpillar 3306 marine engines which drive 125 kVA alternators. The engines cost around $A 35,000 each and are replaced after 35,000 hours. This allows advantage to be taken of the continuous improvements being made in engine design, especially in efficiency. Each generator set usually generates an average electrical power of 75 kW. Using the Lower Heat Value (LHV) of SAB fuel, the efficiencies of electrical production and heat recovery are respectively around 35 and 32%, giving a combined efficiency of 67%. Dumont d'Urville has 30 year old generators which have corresponding efficiencies of 31, 30 and 61%. Boilers typically have a higher efficiency approaching 80 %. Thus, the higher the proportion of thermal energy demand, the better the overall efficiency. This is well illustrated by the fact that Dumont d'Urville has roughly the same overall fuel conversion efficiency as Casey and Davis. Table 1 gives some energy figures for three stations.

Station	**Casey**	**Dumont d'Urville**	**Davis**
Position	66°18'S 110°32'E	66°40'S 140°01'E	68°36'S 77°58'E
Year (winter population)	1992 (17)	1992 (35)	1992 (30)
SAB used in generators (litres)	585 359	200 000	526 527
Electrical Production (kWh)	1 993 075	613 200	1 756 302
Generators Heat Recovery (kWh)	1 835 374	588 000	1 650 908
Boilers Production (kWh)	1 073 725	980 000	1 044 204
Total Energy production (kWh)	4 902 174	2 181 200	4 451 414
SAB consumed in gen. & boilers (litres)	722 337	325 000	659 739
Overall efficiency (%)	69%	68%	69%
Average Electrical Load (kW)	227 (41%)	70 (28%)	200 (39%)
Average Thermal Load (kW)	331 (59%)	179 (72%)	307 (61%)
Average Total Load (kW)	558 (100%)	249 (100%)	507 (100%)

Table 1: Some Energy Figures for Casey, Dumont d'Urville and Davis Stations
(Data Source: AAD and IFRTP)

Energy needs throughout the year are influenced by two main factors: the level of activity on the station, which is highest in summer, and the thermal and lighting needs which are highest in winter. The latter factor leads to a maximum requirement in winter. Figure 1 illustrates energy production at Davis from January to December 1992. The high thermal energy production from boilers for November and December is an artefact. The original data used is not the amount of fuel actually consumed but the amount transferred from the main fuel farm to the tanks feeding the boilers. Sometimes, large amounts are transferred to provide for the busy months to come.

The most recently rebuilt stations have larger buildings and high standard sophisticated mechanical services characterised by higher component efficiency, but their complexity and extent result in higher total energy demands. Dumont d'Urville, rebuilt in the sixties, consumed in 1992 around 325 000 litres of SAB for a winter population of 35 expeditioners while Casey, rebuilt in the eighties, needed 722 000 litres for 17 persons in very similar climatic conditions. This shows that approximately 4.5 times the fuel per capita was required at Casey than at Dumont d'Urville.

Between the first half of 1992 and the first half of 1993, SAB consumption at Casey dropped about 12% due to the ongoing tuning of the new system. However, the energy demand will remain large. Casey offers high levels of comfort but this requires high standards which may be inappropriate for the Antarctic situation when the expressed aim is efficiency and minimal environmental impact.

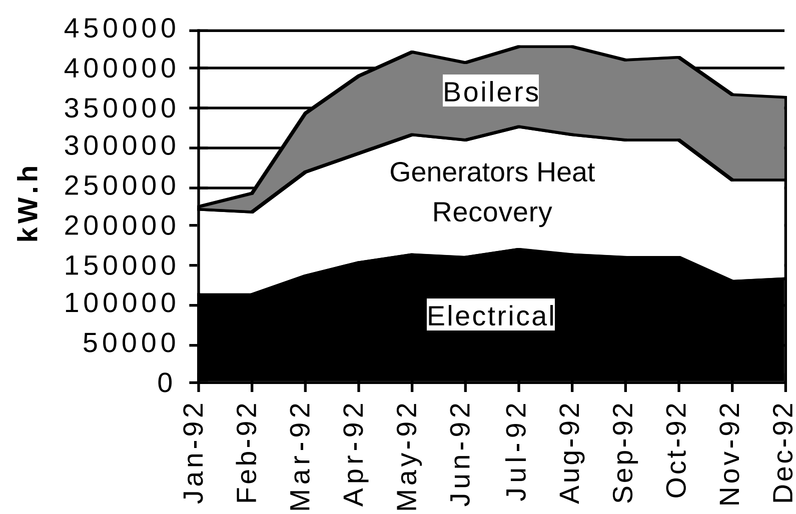

Fig. 1: 1992 Seasonal Variation of the Monthly Energy Production at Davis Station.
(Data source: AAD)

2.2. Financial Costs.

The annual fuel supply for the four Australian stations costs around $A 1 million to purchase in Hobart and represents about 10 % of the total volume of cargo shipped south. Ten percent of the total shipping cost (excluding pure marine science cruises) is approximately $A 2 million, so on the basis of average shipping costs, the cost of SAB upon delivery in Antarctica is tripled.

Allocating a share of the shipping costs is not quite so simple. In addition to the cargo, each voyage delivers and retrieves expeditioners necessary to the accomplishment of the various scientific programs and sometimes performs en-route marine science activities. Even allocating 5 % of the shipping cost to fuel transportation still doubles the initial purchase price.

A detailed cost analysis undertaken in 1991 by the Engineering Section of the Australian Antarctic Division used this conservative estimate of 5 % of the shipping cost dedicated to fuel. This gave a final cost of $A 0.68 per electric kWh produced at the stations. This is about 7 times the commercial price of domestic electricity in Tasmania, and 14 times the off-peak price. The fuel itself represented 55 % of the electricity cost and equipment depreciation and maintenance represented 45 %. Such figures are a good example of the high cost of the current energy supply.

The rebuilding of the Australian Antarctic stations is almost complete and the amount of dry cargo to be transported south is expected to be reduced. However the volume of fuel needed will be similar. This will increase the share of the total charter costs attributable to fuel transport.

2.3. Environmental Aspects.

The polar environment and its ecosystems are known to be very fragile. In addition, most stations are located in especially rich biological areas. Great care is needed in conducting operations.

2.3.1. Fuel Spills.

There is a clear distinction between routine operational pollution and accident hazards. The most likely and probably most damaging of such hazards is a fuel spill. It can either originate from a ship grounding or sinking, from transfer problems when pumping from ship to shore or simply leakage from a tank at a fuel farm. High priority is given to the prevention of such incidents and spills have so far been restricted to small quantities. Operations can unfortunately have to take place in difficult conditions, thus increasing the risks. The Exxon Valdez incident in Alaska has demonstrated the extent of possible impacts on a fragile polar environment, but it must be noted that the impact of the light volatile SAB diesel fuel would be far less serious than for heavy Bunker Fuel Oil (0.971 kg/litre @15°C) usually involved in tanker spills.

2.3.2. Atmospheric Emissions.

The second problem is due to the atmospheric emissions inherent to the operation of engines and boilers. They consist of gases and Dry Particulate Matters (DPM). To get an idea of the emissions generated by Antarctic stations, we can conduct a crude estimation of the contribution of the powerhouse engines. These calculations are based on the 1992 electrical production of the four Australian Stations, assuming that it has been entirely generated by 3306-DIT engines, each producing an average electrical power of 75 kW. In practice, there are a variety of engines load conditions and exhaust emission rates, but the order of magnitude of the calculation is correct. The results are summarised in Table 2.

Period: January to December 1992		Total 4 Stations	Per Capita
Total Station occupancy	(persons-days)	52 148	366
Average Occupancy	(persons)	142	1
Winter Population	(persons)	92	0.65
Generators SAB Consumption	(litres)	1 935 321	13 583
Corresponding Engine Hours	[at 22 l/hr]	87 969	617
Emissions (kg) of:	assuming a rate of:		
Carbon Dioxide - CO_2	126.496 kg/h	11 127 744	78 100
Nitrogen - N_2	723.538 kg/h	63 649 013	446 720
Oxygen - O_2	82.143 kg/h	7 226 049	50 716
Water - H_2O	50.054 kg/h	4 403 207	30 904
Carbon Monoxide - CO	0.726 kg/h	63 866	448
Nitrogen Monoxide - NO	1.418 kg/h	124 740	875
Other Nitrogen Oxides - NOx	2.166 kg/h	190 541	1 337
Hydrocarbons - HC	0.068 kg/h	5 982	42
Sulphur Dioxide - SO_2	0.161 kg/h	14 163	99
Dry Particulate Matters - DPM	0.092 kg/h	8 093	57

Table 2: Estimated Annual Emissions from Generators at four Australian Stations.
(Data source: AAD)

• Gaseous Emissions.

For reference, the annual production of CO_2 from fuels and cement is around 18 billion tonnes worldwide and 5 billion in the US (World Resources Institute, 1992). The 11 128 tonnes produced at the station represent then 0.62 Millionth of the worldwide emissions.

Any passive gas released in the atmosphere is mixed and tends to give an homogeneous concentration around the globe. One of the latest models for the southern regions (Law et al., 1992) estimates that the time needed to reach 67% of this final uniform concentration at the latitude 70°S at a level of 850 hPa (≈1500m) is about:

•220 to 227 days for gases originating from the northern midlatitudes (44-54°N);
•65 to 85 days from the tropics (5°S-5°N);
•2 days from the southern midlatitudes (44-54°S).

It can be seen that gaseous emissions originating in Australia reach the stations extremely quickly and that within a year any emission on the globe has been widely spread. In absolute terms, the stations are very minor contributors of the pollution affecting the atmosphere immediately above them.

Per capita figures give a completely different view. Annual CO_2 production by powerhouses at the Australian stations is about 78 tons per person. The total CO_2 figures for the world and the US are 3.6 and 20 tons per person, that is about 22 and 4 times less.

• Particulate Matters.

Particulate Matters are much heavier than gases and an important proportion will deposit on the surface. While gaseous emissions are more associated with global pollution, Particulate Matters are associated with local pollution. Composition varies with the fuel used, and it has to be noted that the powerhouses do not produce lead particules as SAB is lead free. The prevailing winds probably blow most of the particulates out to sea where their impact is expected to be much lower than on the breeding grounds surrounding the stations. The real impact will be difficult to assess, especially with the lack of detailed base line studies.

Table 2 gives an annual particulates amount of 8 tonnes for the generators of the four Australian stations. A study by SCAR (1989) estimates the amount of particulate emissions produced annually in the Antarctic Treaty Area to be around 300 tons, of which less than 200 tons are produced on or adjacent to land. This is compared with the 10 000 to 15 000 tons produced by an industrialised city of about 4 millions people (e.g. Sydney). Once again, per capita figures give a different view. The city emits 2.5 to 3.75 kg per person while the Antarctic stations powerhouses produce 57 kg per person, 15 to 13 times more.

3. Renewable Energy Potential.

The examples given in this chapter are based on a set of standard meteorological data from Dumont d'Urville for the period 1 January 1986 to 31 December 1989. The original measures are: global solar radiation on an horizontal plane from 0 to 24h; wind speed at 10 m high averaged over 10 minutes every 3 hours; and spot temperature every 3 hours.

Data was processed to give averages over the standard "decades" used in meteorology (3 decades per month, corresponding to the days 1-10, 11-20 and 21-end of the month). For each of the 36 decades of the year a data point is obtained representing an average over the four corresponding decades of the four year period. We will consider the three data sets obtained (Solar Radiation on an horizontal plane, Wind Speed, Temperature) to define a "Typical Year" for which we will assess the renewable energy potential. Parameters of this Typical year are illustrated by Figure 2 and some characteristics are summarized in Table 3.

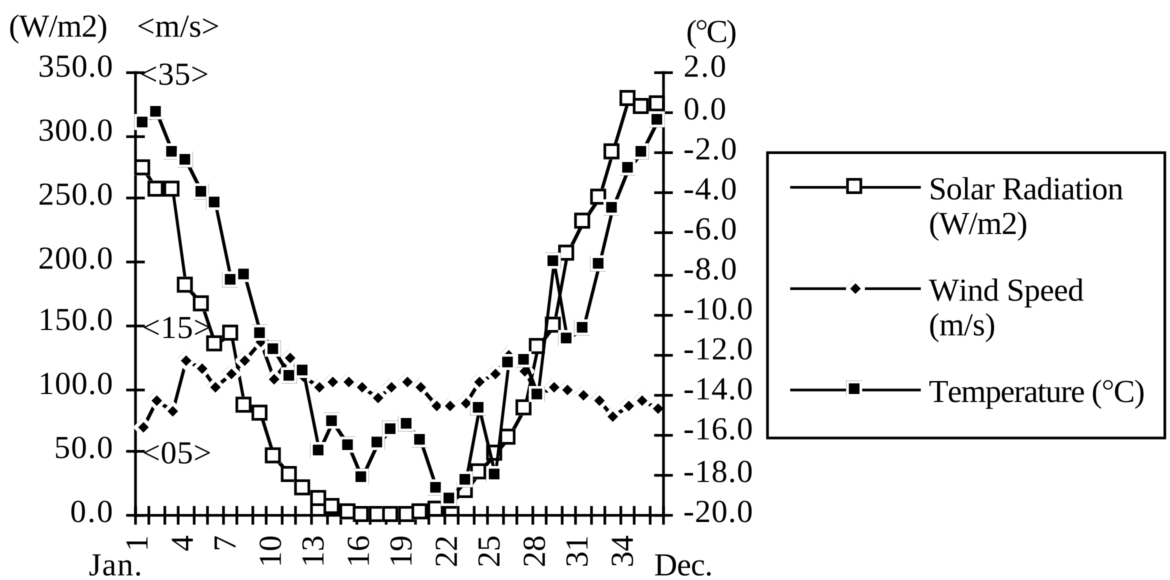

Figure 2: Meteorological Parameters during a "Typical Year" at Dumont d'Urville.
(Based on 1986-89 data)

	Yearly Average	Highest Decade	Lowest decade
Solar (W/m2)	117	329.1 (dec 1-10)	0.6 (jun 11-30)
Wind (m/s)	10.2	13.8 (mar21-31)	7.1 (jan 1-10)
Temp. (°C)	-10.7	0.0 (jan 11-20)	-19.2 (jul 21-31)

Table 3 (left):
Extremes and Averages of Typical Year.

3.1. Solar Radiation.

High latitudes are characterized by high seasonal variations in solar radiation. This makes solar energy inadequate to year round operations but can make it useful for particular summer applications. PhotoVoltaic (PV) panels typically transform solar radiations into direct current with an efficiency of 10%.

Figure 3 shows the seasonal variation of the energy recoverable from an horizontal photovoltaics array at Dumont d'Urville during our Typical Year, assuming a 10% efficiency. The peak power over a decade is 32.9 W/m^2 (December 21-31) while the yearly average is 11.7 W/m^2. It is interesting to note that over the best three summer months (November to January), the average recoverable power is 28.2 W/m^2.

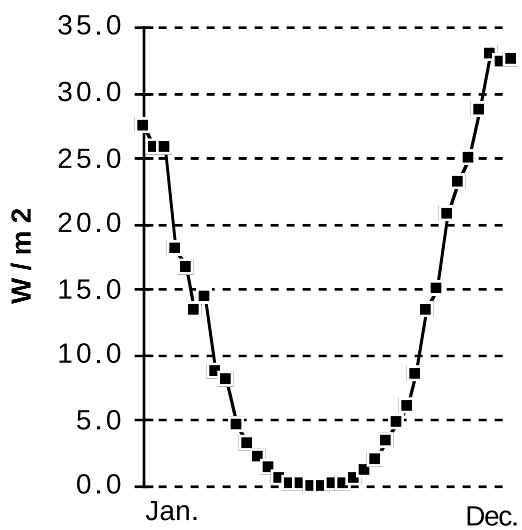

Figure 3:
Seasonal variation of the power recoverable from an horizontal PV array.

3.2. Wind Speed and Temperature.

The Energy content E of 1 m^3 of air (in J/m^3 or Pa) relative to an arbitrary "o" reference state is (Le Goff et al., 1993):

$$\mathbf{E} =$$

$$|\mathbf{P}-\mathbf{P_o}| \quad \text{(I). Atm. Pressure Energy}$$

$$+ \; \mathbf{0.5}\,\rho\,|\mathbf{u^2} - \mathbf{u_o^2}| \quad \text{(II). Kinetic Energy}$$

$$+ \; \mathbf{C_p}\,\rho\,|\mathbf{T}-\mathbf{T_o}| \quad \text{(III). Thermal Energy}$$

$$+ \; \mathbf{L_{lv}}\,|\mathbf{C}-\mathbf{C_o}| \quad \text{(IV). Drying Energy}$$

Where:
P= atmospheric pressure (Pa) (≈990 hPa along East Antarctic coast)
ρ= density of the air (kg/m^3) (≈1.3 kg/m^3 at 990hPa and -10°C)
u= wind speed (m/s)
Cp= specific heat capacity (≈1003 J/kg/K)
T= temperature (°C or K)
C= concentration of vapour (kg/m^3)
L_{lv}= latent heat of vaporisation of water (≈2470 kJ/kg at 20°C)

The gradients corresponding to each of these four energy components can be either time or space related depending on the choice of the reference state, but time gradients are not very practical to work with. Out of the four space gradients, two can be both consistent and practically recoverable: the speed gradient (ΔV between the air in motion and a fixed structure) and the temperature gradient (ΔT between the cold air and the 'warm' seawater). At Dumont d'Urville, like at the three other Antarctic coastal stations, the seawater is at a fairly constant temperature of about To= -1.8°C, close to its freezing point.

For our Typical Year, the two corresponding energy components (II-kinetic) & (III-thermal) are calculated for 1m^3 of air. By multiplying them by the wind speed, we obtained the amount of energy passing in one second through 1m^2 of vertical wind cross-section. The resulting unit is then (W per m^2 of vertical wind cross-section), noted (W/m^2 vt), relatively consistent with the unit used for solar energy (W per m^2 of horizontal surface or W/m^2 hz). The kinetic and thermal wind power, along with the solar power, are illustrated by Figure 4 and Table 4.

	Yearly Average	Highest Decade	Lowest decade
Solar	117	329.1 (dec 1-10)	0.6 (jun 11-30)
Wind Kinetic	726	1690 (mar21-31)	228 (jan 1-10)
Wind Thermal	121 072	236 324 (sept 1-10)	0 (dec21-jan20)

Table 4 (left):
Wind and Solar Power (W/m^2),
Extremes and Averages of Typical Year at Dumont d'Urville.
(Based on 1986-89 data)

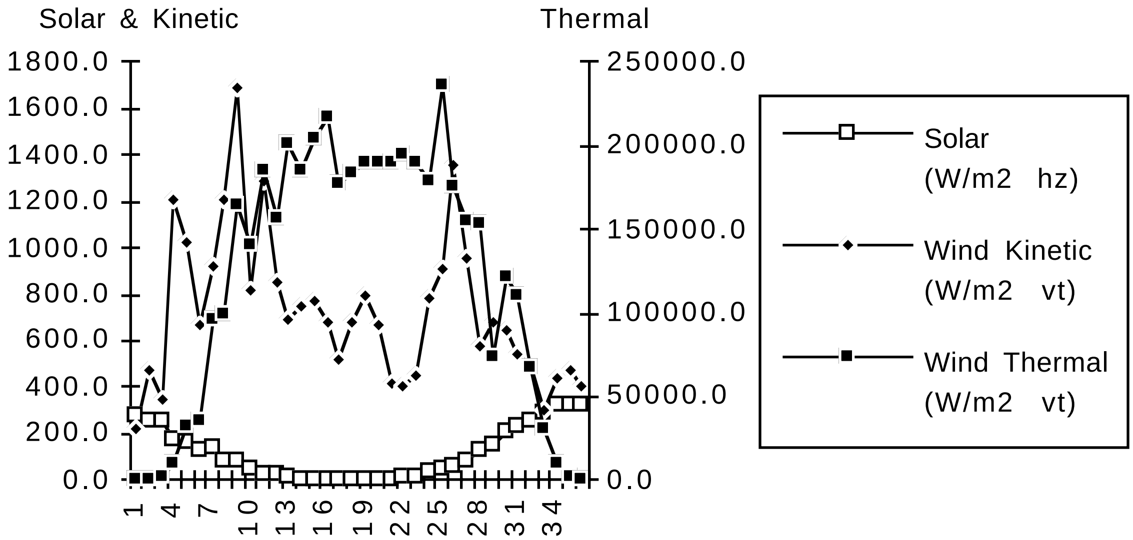

Figure 4: Typical seasonal variation of Wind Kinetic, Wind Thermal & Solar Power (Dumont d'Urville, based on 1986-89 data)

The speed gradient can be used to drive a wind turbine. A realistic efficiency for a basic and reliable two bladed horizontal axis turbine producing electricity is:
ØWindTurbine= 25%.
This is the proportion of the wind kinetic power which will be transformed by the turbine into electrical power.

Le Goff et al. (1993) detailed the process of recovering the wind thermal power with the help of thermo-mechanical machines for electricity production or multistage absorption heat pumps for space heating. We will base our calculations on the first type of machines for proper comparisons with photovoltaics and wind turbines which provide electrical outputs. It has to be noted that heat pumps would produce heat with better efficiencies and should be well suited to space heating in the stations as their production capabilities would be coupled with the heating demands.

The thermo-mechanical machines are inspired from OTEC (Ocean Thermal Energy Conversion) machines. Their efficiency in converting Thermal to Mechanical power is:

ØTM= ØCarnot.ØReal.ØUsable

where:

ØCarnot is the "limit" Carnot efficiency of the machine cycle.
ØReal is the proportion of ØCarnot practically attainable in the machine.
ØUsable is the proportion of temperature gradient usable, that is the temperature drop ΔTusable of the air when passing through the exchanger.

With temperatures given in °Kelvin, the Carnot efficiency of the cycle is:

(ΔT-ΔTusable/2)/To

Values put forward for ØReal and ØUsable are of the order of 25%. They have to be confirmed and refined by proper in-situ trials of prototypes. A typical efficiency for an alternator converting Mechanical power into Electrical Power is ØME= 80%. Then the final Thermal to Electricity efficiency ØTE is:

ØTE= ØTM.ØME

which should be in the order of:

ØTE= 0.05 ØCarnot

The electrical power recoverable throughout the Typical Year from both the wind kinetic and thermal energies have been calculated for such efficiencies. The results are illustrated by Figure 5 and Table 5.

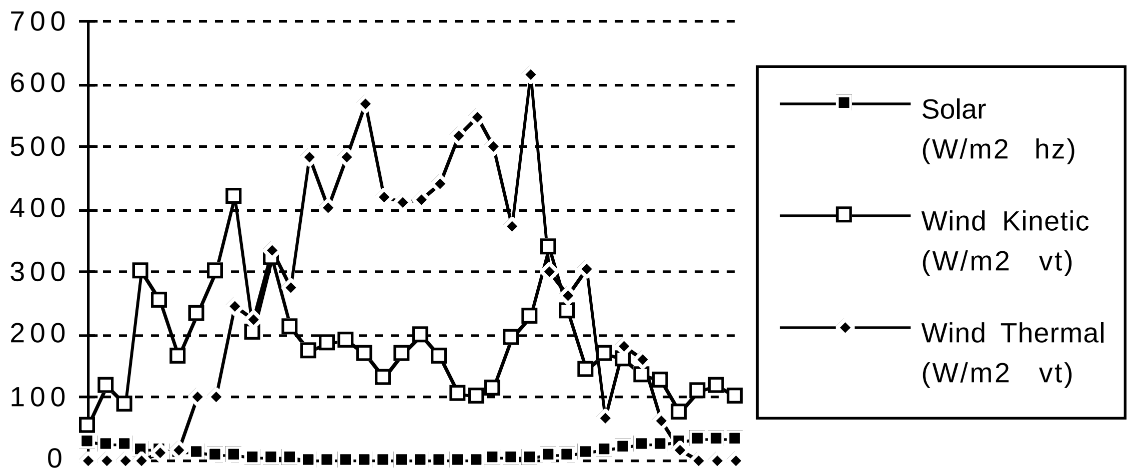

Figure 5: Typical seasonal variation of Recoverable Electrical Power.
(Dumont d'Urville, based on 1986-89 data)

	Yearly Average	Highest Decade	Lowest decades
Solar	11.7	32.9 dec 1-10	< 2.0 may1-aug20
Wind Kinetic	181.4	422.4 mar21-31	56.9 jan 1-10
Wind Thermal	246.1	616.9 sep 1-10	< 2.0 dec1-feb10

Table 5 (left):
Recoverable Electrical Power (W/m^2),
Extremes and Averages of Typical Year.
(Dumont d'Urville, based on 1986-89 data)

3.3. Recovering the Energy.

*Solar Panels

Photovoltaics work well in cold temperatures and are reliable technology. However, the low concentration of solar radiation (see Figure 5) requires large surface areas of panel arrays which are susceptible to damage in high winds. The other disadvantage is having virtually no production during the long winter darkness. Their use is therefore generally restricted to summer field camps with installed capacities ranging from twenty to a several hundred watts, sometimes coupled with small wind turbines.

For example, 60 to 90 w solar panels units successfully power radio repeaters linking Mawson to the Prince Charles Mountains, Davis to the Vestfold Hills and Casey to Law Dome. Near Dumont d'Urville, a 2 kW unit will, from 1994, provide power to an isolated accommodation-workshop shelter for lighting, cooking, radio transmission and gas-boiler control.

Photovoltaic panels typically transform solar radiation into direct current with an efficiency of 10% and cost of the order of $A 1,000 per m^2 (or $A 10 per rated watt, the ratings being generally based on a solar radiation of 1 kW/m^2).

*Wind Turbines

Small-scale wind generators were used and tested in the Antarctic as early as the first post-war expeditions of the 1950s. High failure rates due to both low temperatures and high powerful gusty winds, energy storage problems and the continuing need for complete back-up systems led to their withdrawal, with the exception of a few small field installations for charging batteries for scientific and communications equipment.

Most of the recent developments in wind turbine technology have been concentrated on large machines for industrial windfarms but small and medium size machines have found a niche and their technology is rapidly improving. Suppliers offer reliable (in most conditions) machines generating direct current rated up to a few kilowatts or grid-compatible alternating current from a few kilowatts to 50-60 kW. A survey is being carried out of such wind generators available on the world market. Their suitability for Antarctic conditions (very high, gusty winds with snow and ice particles and low temperatures) will be assessed. So far, most trials have not involved the manufacturers. The best way of achieving a reliable effective wind turbine for such conditions is by cooperation programs with selected manufacturers.

In recent times, tests on larger types of wind generators have been carried out by the French on a vertical axis Darrieus rotor in the sub-Antarctic at New Amsterdam Island (1986-88), by the Germans on a vertical axis H rotor in the Antarctic at Georg Von Neumayer Station (1991 to date) , and by the Australians on a horizontal axis turbine in the sub-Antarctic at Heard Island (1992-93).

At New Amsterdam Island, the 10 m diameter Darrieus rotor VAWT D10-2 (67.7 m^2 swept area, rated 30 kW at 13.5 m/s) was designed and constructed by the Centre d'Etudes Nucléaires de Grenoble which installed and monitored it in collaboration with the technical services group of the station. It showed good capabilities with daily energy production of 400 kWh recorded for wind speeds ranging from 12 to 25 m/s. High winds led to failures but there is still potential for improvements (Perroud et al., 1991).

At Georg Von Neumayer Station, the 10 m diameter H rotor (56 m^2 swept area, rated 20 kW from 9 m/s) has been developed as a joint project between the Alfred-Wegener-Institute, Germanisher Lloyd, Hochschulke Bremerhaven and Heidelberg Motor. It is characterized by simplicity (permanent magnet, no mechanical transmission). It has a survival wind speed of 68 m/s and a minimum operating temperature of -55°C. In its second year of operation, it is running continuously without interruptions and breakdowns and produces roughly 5% to 15% of the energy requirement of the station (Heidelberg et al., 1990; and Kohnen, pers. com., 1993).

At Heard Island, the 7 m diameter two bladed horizontal axis turbine Vergnet-Aérowatt UM 70X (38.5 m^2 swept area, rated 12 kW at 12 m/s) showed good performance in extremely variable, high, gusty winds. The unit operated over a three months period during which it produced an average of 62.2 kWh per day. Over the time of actual operation, the average output was 6.1 kW (Vrana, in preparation). This unit has a rated survival wind speed of 110 m/s which should make it worthwhile testing in the East Antarctic coastal stations where any outdoor structure has to be designed to withstand winds of 90 m/s.

*ThermoMechanical Machines and Heat Pumps

Preliminary studies have been performed by Laboratoire des Sciences du Génie Chimique (LSGC) in France on the exploitation by such machines of thermal gradients between the wind and Antarctic/Arctic waters (Le Goff et al., 1992, 1993). As seen in section 3.2, calculations indicate that if good overall practical efficiencies can be obtained, this method could provide, for the same cross section of wind used, more energy than rotating machines which exploit the kinetic energy of the wind. The potential for energy production is less constant throughout the year than from wind kinetics, but has the advantage of providing most energy in winter when heating requirements are greatest. The strong point is that this method involves far lighter and more reliable machines as no moving parts are exposed.

The first step towards proper assessment and development of such machines will be taken in January 1993 with the installation at Dumont d'Urville of the key component of the concept: the condenser or 'cold' captor. The experiment will be conducted in association by LSGC/CNRS and the technical services of IFRTP with direct funding and logistical support from IFRTP.

4. Possible Evolutions.

4.1. Short Term: Improvements.

Improving the current systems is the first logical step. It is, and has always been, one of the main preoccupations of the engineering staff running the stations. Power distribution networks at the stations are being tuned to progressively optimise and stabilise power needs. Incremental efficiency improvements have allowed effective increases in research activities and comfort with minimal power supply increases.

With the increasing capabilities of sensors, monitoring and control systems, computing systems and communications, new possibilities arise for detailed analysis and control of energy fluxes and consumption patterns. A first step has been taken with the installation, during the rebuilding of Casey, Davis and Mawson, of a Local Monitoring and Control System (LMCS) and some preliminary energy audit studies have been undertaken (Hall 1992). The Australian Antarctic Division (AAD) intends to develop the LMCS as a tool to provide data for more detailed analyses in order to identify areas where further efficiencies can be obtained with the current system of power production and distribution.

Devices such as electric lamps, pumps, transceivers and computers are regularly upgraded to more energy efficient products as technology advances. This is mostly carried out when new equipment is installed or devices are replaced on a routine basis.

While efficiencies are increased, work is done on lowering polluting emissions. Most improvements in this area are linked to engine technology and occur as engines are replaced or upgraded. Work on fuel composition and exhaust gas treatment could also lower atmospheric pollution, but further improvements can only have a marginal effect on emission levels compared to the introduction of alternative fuels or radically new systems. The Antarctic station operators will continue to take advantage of advances in this field while current technology is in use.

4.2. Medium Term: Introduction of New Fuels or Technologies.

• Introducing New Fuels.

The introduction of new fuels can address the pollution problem but can not solve the problems of purchasing the fuel and transporting it at high cost to the stations.

Preliminary investigations have been carried out by IFRTP on the use of power kerosene, as an alternative to diesel oil, to power the planned French–Italian inland station at Dôme C in the Australian Antarctic Territory (IFRTP 1992). Kerosene combustion is characterized by very low sulfur emissions. The use of kerosene will be monitored by IFRTP when Dôme C Station is operational.

The use in large quantities of fuels such as natural gas, liquid petroleum gas (LPG) and hydrogen has not yet been seriously considered for Antarctica because of assumed handling and storage difficulties. The technical and practical aspects of using alternative fuels are under review to assess their practicality and potential environmental impacts when used in conventional combustion engines, in catalytic combustion and in fuel cells.

• Introducing Renewable Energy as 'Fuel and Pollution Saver'.

This approach consists of using wind turbines, thermomechanical machines, heat pumps or photovoltaics to supplement the current systems. It will directly save fuel and reduce emissions.

The main disadvantage is that this does not eliminate the need for the entire current system. But such an option is ideally suited to the experimental phases of renewable energy systems.

• Introducing Fuel Cells.

The conceptually simple and environmentally attractive fuel cell offers a solution to the production of electricity in a compact, quiet, highly efficient, and exceptionally clean manner. The electrochemical reaction driving the fuel cell occurs between hydrogen and oxygen in a device consisting of an anode, cathode and electrode. Fuel cells operating on alternate fuels to hydrogen require the fuel to be reformed into hydrogen. This can be achieved in an external reformer or can be internally reformed in the higher temperature operating fuel cells. The co-generation capabilities of fuel cells to produce thermal energy and potable water can assist in meeting the energy demands of the Antarctic stations (Steel and Guichard, 1993).

The US National Science Foundation is funding research to demonstrate the Molten Carbonate Fuel Cell (MCFC), or Direct Fuel Cell (DFC) as they are becoming increasingly known, to power the permanent and temporary scientific research stations of the US Antarctic program using diesel or sulfur free JP8 (SFJP8) fuel. The DFC is a internal thermo-chemical reformation unit operating at 650°C which is sufficiently high to permit diesel or SFJP8 fuel to be reformed internally within the stack.

Introducing a fuel cell unit using diesel as a fuel enables the unit to be installed and tested without the need for any additional infrastructure. This will reduce the capital cost and allow a suitable demonstration of the fuel cell technology.

Technological development is continuing with other internal reforming fuel cells. The CSIRO Division of Materials Science and Technology in Melbourne is actively investigating the Solid Oxide Fuel Cell (SOFC) which with its high operating temperature (900-1000°C) will have the capability to reform a variety of fuels. The availability of either test or commercial units is believed to be some time off, though the potential of the SOFC units is encouraging and warrants monitoring.

Internally reforming fuel cells initially operating on the current fuels used in Antarctica can be modified to operate directly on hydrogen, bypassing the reforming process, with higher efficiencies and lower emissions. The next ideal step would then be to feed the fuel cells with hydrogen produced on site with the help of renewable energy.

4.3 Long Term: A Sustainable Station.

The ideal long term solution would be to achieve a sustainable station making use of the locally available renewable energy potential (see section 2). In addition to being clean, this eliminates the need for non-renewable fossil fuels and the difficulties and cost of transportation to Antarctica.

The first problem is the practicality and reliability of the various machines to be used to recover the renewable energy. Once this overcome, the biggest restriction on the viability of renewable energy systems is the necessity for large buffer storage capacity to match the irregular energy supply with the demand.

The most common types of storage are hydraulic storage, largely unsuitable for this situation (due to freezing of water in the Antarctic and environmental concerns in the Sub-Antarctic), and batteries which become decreasingly practical as the amount of stored energy required increases. However, intensive research work is under way around the world on battery storage systems, particularly by car makers in relation to electric vehicles.

Two other types of storage are being extensively investigated: hydrogen production and thermochemical separation of chemical components. The latter type complements the heat pumps and is being studied in connection with those machines at LSGC. At IASOS an investigation has commenced of all aspects of hydrogen production, handling, storage and utilization. This includes electrolytic plants, cryogenic and compressed gas storage and distribution, combustion engines, catalytic combustion and fuel cells.

Electrolytic plants produce hydrogen from water and electricity through a clean process. This is proven and reliable technology. Some units from The Electrolyser Corporation have operated for over 40 years with minimal but regular maintenance (every 10 to 20 years, some part replacements; minor part replacement more often but very inexpensive). Their recent PhotoVoltaics-Hydrogen unit commercially available has already operated for 900 days with 100% reliability -Out of doors- in a temperature regime of -25 to +25°C. Research targets for systems with fuel cells will include 18 months unattended operation at temperatures to -50°C (The Electrolyser Corporation, pers. communications, 1993).

The Hydrogen option is very versatile as the produced and stored hydrogen can be reconverted through various clean and efficient processes into electricity and heat (fuel cells), heat (catalytic burners) and mechanical work (combustion engines) to fulfill all station energy needs.

5. Conclusions.

The provision of energy to Antarctic stations is costly, difficult logistically and has significant environmental impacts. This makes any improvement of energy systems at the stations far more cost-effective than for most other places on earth.

Improving the energy systems is, and has always been, an everyday job for the technical staff of the agencies operating the stations. This staff has valuable experience and great motivation to pursue the development and implementation of new solutions.

The French and Australian Antarctic and Sub-Antarctic stations with their extreme conditions and comprehensive facilities offer valuable sites to develop and test advanced energy systems. In addition, the high international profile of activities conducted in Antarctica would allow successful systems to obtain substantial international recognition.

Researching and implementing clean and efficient alternative energy systems in Antarctica could have an invaluable role in perfecting and demonstrating promising systems to be used around the world.

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