Towards New Energy Systems for Antarctic Stations

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Abstract
Technologies for cleaner, renewable energy production and energy storage are rapidly evolving and new, realistic options for alternative energy systems for Antarctic stations can now be considered. This paper which originates from a co-ordinated French-Australian project presents a review of the main station energy supply issues and a schematic presentation of selected power generation technologies and system integration options. It provides an opportunity to refocus the orientation of the project and to motivate a move "towards new energy systems for Antarctic stations."

Keywords: Energy, Sustainable, Renewable, Environment, Antarctic, Wind Turbines, Hydrogen

Résumé
Vers de nouveaux systèmes énergétiques pour les stations antarctiques
De nouvelles alternatives énergétiques sont désormais réalistiquement envisageables pour les stations Antarctiques avec l'évolution rapide de certaines technologies de production énergétique moins, ou non polluantes, ou encore de stockage de l'énergie. Cet article issu d'un programme coordonné franco-australien présente une revue des principaux problèmes posés par la fourniture d'énergie aux stations ainsi que la présentation schématique d'une sélection de modes de production d'énergie et de possibilités d'intégration des systèmes. Il offre une opportunité de repenser l'orientation du projet et de motiver un mouvement "Vers de nouveaux systèmes énergétiques pour les stations antarctiques".

Mots Clés: Énergie, Durable, Renouvelable, Environnement, Antarctique, Aérogénérateurs, Hydrogène

1. Introduction

The "Classic" methods of providing energy from fossil fuels have allowed and supported most human advances and achievements from the Industrial Revolution to the exploration of the Antarctic continent and it's establishment as a unique scientific laboratory.

But these methods are associated with a large use of limited resources and substantial impacts on the biosphere. The need has now been identified for a new value system oriented towards the protection of the biosphere as well as the local environment and most activities have to be reviewed in the light of new priorities.

Antarctic activities are of special concern as they occur in pristine remote areas where ecosystems are particularly fragile and where supply operations remain difficult and hazardous.

A coordinated program was initiated in early 1993 in a joint French-Australian effort to prepare and initiate the move "Towards New Energy Systems for Antarctic Stations". The present paper finds most of its origins in various components of this program and the related publications and reports listed in the bibliography. Through a review of the main issues and a schematic presentation of selected power generation technologies and system integration options, it provides an opportunity to refocus the orientation of our project and could be the foundation for a wider coordinated effort with several Antarctic nations.

2. Basic Considerations

2.1 Energy Needs

We will focus on the main "static" energy needs of a station, normally satisfied through the provision of electrical power (for lights, telecommunications, electronic equipment, electric tools, electric heaters, pumps, water production...) and thermal power (space heating, water production...).

The energy need for water production varies greatly depending on the production method imposed by the site. The most demanding process is desalination, which can require an average power over 100 kW to produce some 5,000 litres a day at 25°C (Dumont d'Urville - evaporator - seawater at -1.8°C) while melting ice would require some 10 to 20 kW. New improved reverse osmosis systems could dramatically reduce the power required for desalination. The other energy needs vary with the station's size and design, the scientific equipment used and the meteorological conditions. The seasonal variations are influenced by two main factors: the level of activity on the station, reaching a maximum in summer, and the thermal and lighting needs which are at their greatest during winter. Total energy requirements are usually at a maximum during the long winter.

Typical average power requirements at current French and Australian Antarctic stations are in the range 70 to 250 kW electrical and 150 to 350 kW thermal. These needs are presently fulfilled almost exclusively through the combustion in generator sets and boilers of large quantities of fossil fuels, typically 350,000 to 800,000 litres of Diesel Fuel or Kerosene each year. Exhaust emissions contain the usual polluting gases and particulate matter.

2.2 Fuel Supply

Fuel has to be shipped to the stations long distances over the Southern Ocean, usually in special ice strenghtened multipurpose vessels. Fuel is then pumped to the shore and stored in large tanks or bladders. The few inland stations receive their fuel supply from the coast either by tracked vehicle convoys or special ski equipped aircraft. Depending on the transport method, the important factor can be either the weight or the volume of the fuel, if not both.

Fuel supply operations induce high costs, use up large logistic capabilities which could be more beneficial to other activities, and can present safety problems. Both supply operations and the storage of large quantities of fuel for long periods on the station produce the possibility of a damaging fuel spill.

2.3 Site Constraints

Many stations are located along the coast on small rocky outcrops which are the most favorable locations for both animal breeding grounds and human settlements. The cohabitation on limited space favours the use of the most compact energy systems, that is, fossil fuel powered systems, while making local exhaust pollution and fuel spill hazards particularly menacing.

2.4 Cost Considerations

The financial cost of energy supply to the stations is difficult to assess as most equipment, facilities and personnel are also involved in other activities. It means that cost comparisons are difficult to assess and financially based decisions are not necessarily relevant. We will only attempt to provide some orders of magnitude for the cost of primary power generation.

Costs will be expressed in U.S. Dollars (US$) on the basis of 1 US$ = 1.3 Australian Dollars (A$) = 5.3 French Francs (FRF). Because of the variety of parameter values that can be used (depending on the country, the invester status, etc...), Life Cycle Costing will be restricted here to a simple "stable value" case corresponding to Discount Rate = Inflation Rate = 0, but sufficient information should be given for further analysis with different values. The life cycle base will be 20 years, imposing an amortization on 20 years for equipment having longer life expectations. Costing results will be summarised in a recapitulative table.

3. Non Renewable Energy Production

3.1 Fuels

Fossil fuels widely used in the Antarctic for power generation are special "cold weather" blends of Diesel Fuel and Kerosene. Both are used in the same type of engines and boilers, although requiring different tuning.

We indicate in Table 1 the approximative energetic characteristics of the Special Antarctic Blend "SAB" Diesel Fuel used by the French and Australian expeditions out of Hobart, and the JP8 Kerosene used by the US Antarctic program. We added for comparison two cleaner fossil fuels, Liquid Petroleum Gas "LPG" and liquid Methane (Methane being the major component of Natural Gas), as well as "The" perfect clean (non fossil) fuel, Hydrogen, in liquid and gaseous forms.

The energy content used here and subsequently is the Lower Heating Value "LHV" (or Pouvoir Calorifique Inférieur "PCI") which corresponds to a combustion where the water produced is in vapour form. The energy unit used throughout this paper is for practical reasons the kiloWatt-hour "kWh", which is the energy generated over one hour by a power of 1 kW. We have then 1 kWh = 3,600 kJ = 3412 Btu.

The storage requirement factors indicate the proportions, respectively in volume and weight, of the total storage systems (fuel + containers) required to hold the same energy content, SAB being taken as reference (factors =1). For example, the weight factor = 3 for liquid hydrogen means that a cylinder containing 1,000 kWh worth of liquid hydrogen would be 3 times heavier than a tank containing 1,000 kWh worth of SAB. Those factors are indicative orders of magnitude only as they can vary significantly with the type and size of the storage units. This is particularly true for the metal hydride storage of gaseous hydrogen, where several different technologies are under development.

We can see from Table 1 that the cleaner the fuel, the higher the storage requirement. Independently from the purchase cost, clean fuels will be more difficult and expensive to store and transport. Hydrogen could probably only confirm its "perfect fuel" status if produced on-site.

Fuel	densi-ty	Lower Heating Value		Storage requirement factor	
lq=liquid gs=gas	Kg/l	kWh /litre	kWh /kg	volu-me	wei-ght
lq SAB	0.805	9.8	12.2	1	1
lq JP8	0.810	9.4	11.6	1.05	1.05
lq LPG	0.515	6.6	12.8		
lq Methane	0.420	5.9	13.9	6	2
lq Hydrogen	0.071	2.4	33.6	16	3
gs Hydrogen	0.017	0.6	33.6	35	10
gs Hydrogen (in Hydrides)				best: 2.3?	best: 5.3?

Table 1 :
Indicative characteristics of selected fuels.

3.2 Diesel/Kerosene Generator Sets

The arrangement where a diesel engine drives an alternator usually constitutes the backbone of a station's energy systems. It is a compact, reliable and mature technology. On a fuel LHV basis, a modern unit such as the Caterpillar 3306B Direct Injection with water cooled manifold has an electrical efficiency of 35% (AC Power output at the alternator) and a heat recovery efficiency of 32% (hot water around 70-80°C). In case of cogeneration (both electricity and heat recovered), the global efficiency is then 67% (this is synthetised on Figure 1.a). It means that for each litre of SAB with a LHV of 9.8 kWh/l, the generator set can produce 9.8x0.35=3.43 kWh of electrical energy and 9.8x0.32=3.14 kWh of heat, that is a total of 6.57 kWh.

Let us define for the generator sets (and all other power generation equipment) a Load Factor equal to the proportion of the total generation capacity effectively used. For example, a 100 kW generator used to produce an average 70 kW will have a load factor Lg=0.7 or 70%.

By combining various considerations and estimates about the generator sets of the Australian Stations (from Ref. 2 & 6), we find that:
- For reasonable load factors, the capital cost is negligible compared to the operating costs (fuel + maintenance):
Assuming for a 125 kW generator set a purchase cost of 5,400 US$ for the alternator (20 years life) and 27,000 US$ for the engine (4 years life, salvage value of 2,000 US$), we get a total capital cost over 20 years of 130,400 US$, that is 1,043 US$ per rated kW, or about 0.0060 US$ per rated kW and per hour. For a load factor Lg, the share of the capital cost in each kWh (electrical only!) produced is then (0.0060/Lg) US$, which is less than 0.01 US$ for load factors over 0.6 and even stays under 0.05 US$ for load factors as low as 0.12!
- The order of magnitude of the maintenance cost is some 0.25 US$ per electrical kWh produced;

If Pfuel is the cost of 1 kWh worth of fuel delivered at the station, then the order of magnitude of the financial cost of generating 1 kWh can be estimated for load factors over 0.6 at :
if electrical power only is recovered:
• Pel = 0.25 + Pfuel / 0.35
and for cogeneration:
• Pcog = 0.25 / (1+0.32/0.35) + Pfuel / 0.67 [i.e. Pel (0.35/0.67)]

An estimation for SAB delivered at the Australian stations (Ref. 2) gives Pfuel = 0.0785 US$/kWh (1 A$ = 0.77 US$ per litre). This estimation was based on a 0.62 US$/kg transport cost on a "share of cargo weight" basis, that is 0.50 US$/litre or 0.051 US$/kWh, and gives the order of magnitude:
• Pel = 0.47 US$ / kWh
• Pcog = 0.25 US$ / kWh
For comparison, the full domestic price of the electricity delivered by the Hydro Electric Commission in Tasmania is around 0.07 US$ / kWh.

And in terms of energy, the energetic costs (quantity of non renewable lower heating value sacrificed) are for each kWh produced:
• Eel = 1/0.35 = 2.86 kWh
• Ecog = 1/0.67 = 1.49 kWh

3.3 Diesel/Kerosene/Gas Boilers

These well known boilers that we find in many houses equipped with central heating are reliable, low maintenance, long life, efficient machines. They produce heat with an efficiency reaching 80% with good tuning. This is synthetised on Figure 1.b.

With a typical purchase cost of 70 US$ per rated kW, a life exceeding 20 years and little maintenance, a boiler offers a financial power generation cost that can be in general estimated as being the fuel cost, which gives :
• Pboil = Pfuel / 0.80
That is with Pfuel = 0.0785 US$/kWh for SAB an order of magnitude of:
• Pboil = 0.098 US$ / kWh
While the energetic cost is:
• Eboil = 1/0.80 = 1.25 kWh

3.4 Fuel Cells

The environmentally attractive Fuel Cell is an electrochemical device which efficiently recombines hydrogen and oxygen into water, releasing electrons (DC current) and heat with negligible polluting emissions. When a fossil fuel is used rather than pure hydrogen, the fuel is first reformed into a hydrogen rich gas which then feeds the cell itself.

Used by NASA aboard space vehicles as far back as the 1960s' Apollo program, fuel cells are now moving towards the large scale commercial production stage through intensive research and investment. Different types of fuel cells are under development, with different electrolytes and operating temperatures.

The only fully commercial unit is the PC25 from the Connecticut based company International Fuel Cells. It is a 200 kW (electrical) Phosphoric Acid Fuel Cell (PAFC) unit designed to operate on natural gas as primary fuel, easily modifiable for LPG or Methanol. The current model PC25C is a complete packaged power plant of some 3x3x5.5m and 18 tonnes which includes a Fuel Processor (natural gas into hydrogen rich gas + CO^2), a fuel cell stack (hydrogen + oxygen into DC power + Heat + water) and a power conditioner (DC to AC). If air rather than oxygen is used, the stack will produce small amounts of Nitrogen compounds (N_2O,NO_x, N_2). Direct use of hydrogen, for example produced on site from renewable energy systems, is possible by bypassing the reformer.

The fuel processor uses heat from the cell stack to reform the primary fuel, which means that efficient operation requires a good match between the respective fuel cell and reforming process operating temperatures. The PAFC operating temperature, around 200°C, is well matched with the reforming temperatures of fuels such as Natural Gas, LPG or Methanol, but not with the higher temperatures required to reform Diesel and Kerosene.

The Direct Fuel Cell (DFC) and Solid Oxide Fuel Cell (SOFC) with cell temperatures of 650°C or more would be better suited to the use of Diesel or Kerosene as primary fuel. The Energy Research Corporation (also in Connecticut), is expecting its first fully commercial DFC unit for 1998, but as a 2 MW unit operating on Natural Gas. The development of small (200 to 300 kW electric) packaged units running on Diesel or Kerosene is under consideration but hasn't yet gone much further than the drawing board. The Solid Oxide option currently appears very promising but is still at an early development stage. In Australia, Victorian based Ceramic Fuel Cells Pty Ltd (in which BHP and CSIRO are partners) is actively developing Solid Oxide Fuel Cell technology.

The commercial Natural Gas fueled PC25C can deliver 3 phases AC Power (400/230 Volts at 50 Hz or 480/277 Volts at 60 Hz) either Grid-Connected or Grid-Independent, and usable heat, either all around 60-74°C (140-165°F) or half around 60-74°C and half around 120°C (250°F).

About 60 PC25 units have been delivered so far and a cumulated total of more than 300,000 hours of operation have demonstrated some 95% availability and operational efficiencies of 40% (electric) and 45% (heat at 74°C) on a LHV basis, giving a global efficiency of 85% in cogeneration (this is synthetised on Figure 1.c). Energetic costs are then:
• Eel = 1/0.40 = 2.50 kWh if electrical power only is recovered;
• Ecog = 1/0.85 = 1.18 kWh for cogeneration.

Higher efficiencies could be reached when using pure hydrogen as primary fuel. Polluting emissions are negligible apart from CO^2 (which would disappear if hydrogen was used), and as an option, about 106 litres (400 gallons) of clean water could be produced each day at rated (200kW) power, although 25 out of these 200 kW would be lost in the condensing process.

The approximative capital cost of the PC25 has already decreased from 5,000 US$ / kW for the PC25B to 3,000 US$ / kW for the PC25C and the goal for the PC25D is 1,500 US$ / kW by 1998. The units require very low maintenance and when operating continuously at rated power the maintenance cost (including cells stack replacement every 5 years) is evaluated at 0.01 US$ / kWh electric. With the current capital cost of 3,000 US$ / kW spread over 20 years, the share of capital cost in each kWh electric produced by a unit used with a load factor Lf is around (0.0171 / Lf) US$. If Pgas is the cost of 1 kWh worth of Natural Gas, then we obtain per kWh produced a financial generation cost of:
• Pel = 0.0171 / Lf + Pgas / 0.40 + 0.01
• Pcog = 0.0171 / Lf / (1+0.45/0.40) + Pgas / 0.85 + 0.01

For a Natural Gas cost (in the US, by pipeline) of 2 to 4 US$ per 300 kWh or million Btu (0.00667 to 0.01333 US$/kWh), we find for Lf=1 (full potential use) and a realistic Lf=0.7 (use at 70%):
• Pel = 0.044 to 0.060 US$ / kWh for Lf=1, • Pel = 0.051 to 0.068 US$ / kWh for Lf=0.7
• Pcog = 0.035 to 0.043 US$ / kWh " • Pcog = 0.042 to 0.050 US$ / kWh "
which is certainly very competitive in the US conditions, but what kind of cost could we expect when using Natural Gas or LPG at the stations?

Lets try a simple estimate based on the transport of LPG in easy to handle standard ISO cylinder units having the overall dimensions of a 20 foot container (20x8x8.5 feet parallelepiped, overall volume of 38.5 m^3). Such cylinder units which cost some 51,000 US$ (270,000 FRF) weigh

8,500 kg and can hold 9,000 kg of LPG for a total weight of 17,500 kg. On a 20 year life cycle basis and assuming a one year turnover, the share of the cylinder capital cost on each shipment is 0.0221 US$/kWh. Standard purchase price of LPG is 0.0516 US$/kWh (3.5 FRF/kg).

Carrying 0.515 density LPG worth 12.8 kWh/kg in these cylinders means carrying a global shipment worth only 6.58 kWh/kg or 1.54 kWh/l. We used in section 3.2 a shipping cost estimate of 0.051 US$/kWh for SAB (12.2 kWh/kg) carried bulk in tanks included in the ship deadweight, established on a "share of cargo weight basis".

When keeping a weight basis for coherence, we obtain for LPG a shipping cost of 0.051x12.2/6.58 = 0.095 US$/kWh, which gives for LPG a final cost of

Pgas =0.0516+0.0221+0.095
=0.169 US$/kWh

Financial generation cost depend then mostly on the fuel cost and variation of the load factor in the 0.5-1.0 range has little effect. For a load factor Lf=1, the respective costs for electricity only and for cogeneration are:

• Pel = 0.0171 / Lf + Pgas / 0.40 + 0.01
= 0.450 US$/kWh

• Pcog = 0.217 US$/kWh

These costs are of the same order than those found for the diesel generator sets, but correspond to a much cleaner process.

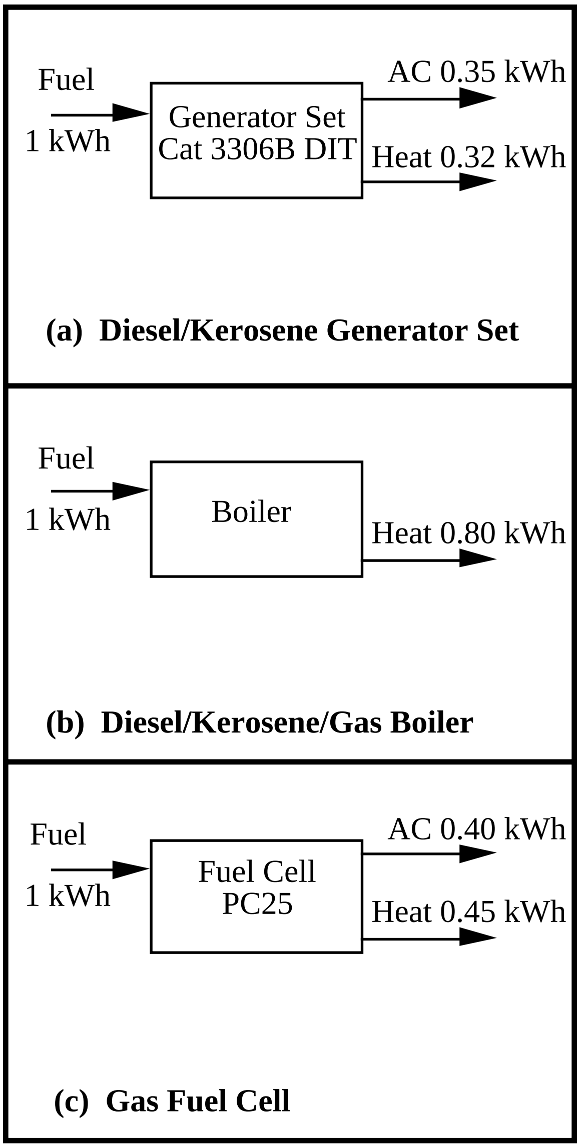


Figure 1 :
Schematic of Selected
Non Renewable Energy Production Methods

4. Renewable Energy Production

The use of wind and solar energy, and more generally of an array of renewable energy, is usually suggested as the "obvious" solution for Antarctic stations. But if the availability and diversity of renewable energy sources at the stations is promising, it can be confusing and requires extensive studies and comparisons to make the right choices.

One of the most important but difficult tasks is sizing the system to match resource abundance and variability against the desired usable power availability. To provide a simple example of resource potential, a basic estimate of the renewable energy potential at one station has been made by examining meteorological data from Dumont d'Urville over the period 1986 to 1989 (published in Ref. 2). This gives an idea of the orders of magnitude involved and illustrates seasonal variations.

The original data are averages over 10 days periods, or decades. The average and extremes of these decade radiation, wind speed and temperature values are shown in Table 2. Three power components have been estimated:

- Solar radiation vertical flux (W/m^2)
- Wind Kinetic horizontal flux (W/m^2)
- Wind Thermal horizontal flux available from the 'coldness' of the wind in relation to the 'warmth' of the sea (W/m^2)

The potential solar and wind power are shown in Table 3.

Solar power can be converted by current standard photovoltaic panels into electricity with an average efficiency of 10%. Wind kinetic power can be converted by wind turbines into electricity with 25% efficiency. Wind thermal power can be converted either into heat by a heat pump or into electricity by a thermomechanical machine driving an alternator. The recovery of this wind thermal power is only at its early development stage. The first machine components are being tested at Dumont d'Urville from January 1994. The latest estimation of expected efficiency for producing electricity is around 5% of the Carnot efficiency calculated on the total temperature difference between wind and seawater.

Taking these efficiencies into account, the estimated power recoverable is shown in Table 4 and Figure 2.

	Yearly Average	**Highest Decade**	**Lowest decades**
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 2 :
Solar Radiation, Wind Speed, Temperature Extremes and Averages, Dumont d'Urville.
(Based on 1986-89 data)

	Yearly Average	**Highest Decade**	**Lowest decades**
Solar	117	329.1 dec 1-10	0.6 jun 11-30
Wind Kinetic	726	1690 mar 21-31	228 jan 1-10
Wind Thermal	121 072	236 324 sept 1-10	0 dec21-jan20

Table 3 :
Potential Wind and Solar Power (W/m^2)
Extremes and Averages, 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 mar 21-31	56.9 jan 1-10
Wind Thermal	246.1	616.9 sep 1-10	< 2.0 dec 1-feb 10

Table 4 :
Recoverable Electrical Power (W/m^2)
Extremes and Averages, Dumont d'Urville.
(Based on 1986-89 data)

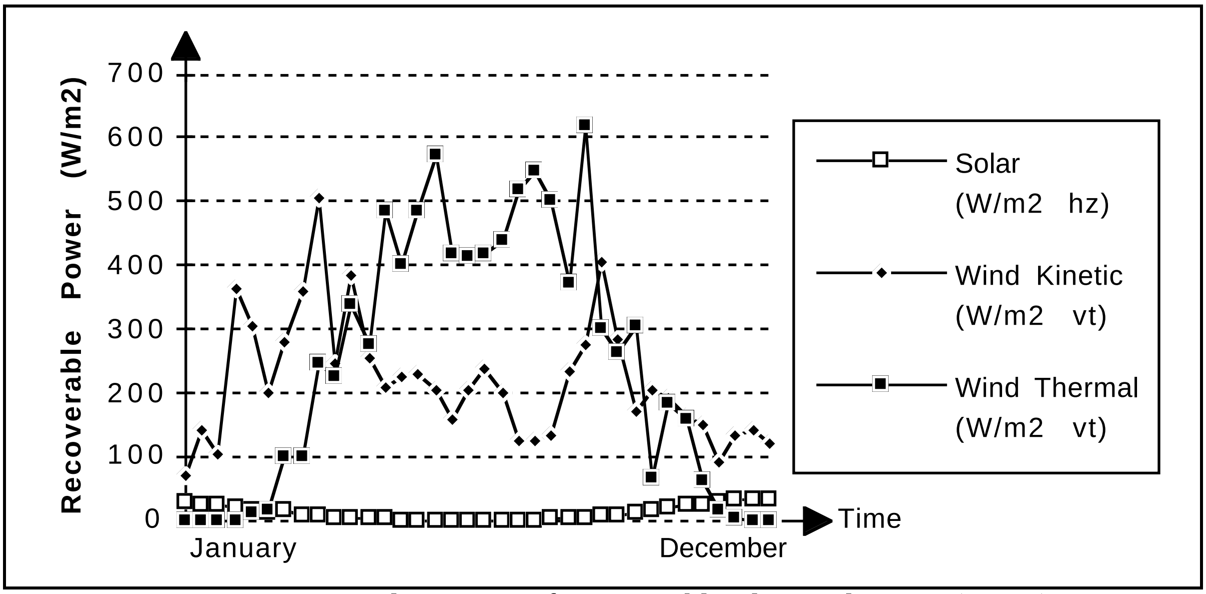


Figure 2 : Seasonal variation of Recoverable Electrical Power (W/m^2).
(Dumont d'Urville, based on 1986-89 data)

To put this into practical perspective, in order to meet the typical annual average of 70 to 250 kW (electrical power only) required by the existing stations, it would require something of the order of :

- 6000 to 21,400 m^2 of photovoltaic panels,
  i.e. an area the size of 23 to 82 tennis courts, or
- 385 to 1380 m^2 of wind turbine swept area, i.e.
  10 to 36 turbines with 7m diameter blades, or
- 285 to 1015 m^2 of condenser banks,
  i.e. a 3m high wall 95 to 340m long.

Those simple calculations, summarised in Table 5 only provide an order of magnitude for the size of energy captors. These results show that wind and solar energy cannot easily be the only answer to the provision of energy to the most energy demanding stations, but can certainly be of valuable assistance in well designed hybrid systems. Proper sizing of these systems will require elaborate simulations from specific meteorological data, precise equipment operating characteristics and stations power demand patterns. Collection and processing of this information is under way.

	Average Potential Power (W/m^2)	**Assumed Recovery Rate** (%)	**Average Recoverable Power** (W/m^2)	**Captor area needed to produce 70 to 250 kW**	
				(m^2)	Equivalent to:
Solar	117	10%	11.7	6,000 to 21,400	23 to 82 tennis courts in area
Wind Kinetic	726	25%	181.4	385 to 1,380	10 to 36 turbines 7m diameter blades
Wind Thermal	121,072	5% of Carnot Efficiency	246.1	285 to 1,015	3m high condenser bank 95 to 340m long

Table 5:
Size of Renewable Energy Systems to Produce Electrical Power at the Stations.
(Based on 1986-89 meteorological data from Dumont d'Urville station)

Now that we have an idea of the potential for renewable energy production, we need to look into the feasibility aspect of such production. We have done so for three major energy production machines: wind turbines, thermal machines and photovoltaics.

4.1 Wind Turbines

Consistent winds offer in most stations a high potential for wind power generation. This was recognised very early and wind generators were used and tested as early as the first post-war expeditions of the 1950s. High failure rates tended to discredit wind turbines and led to their withdrawal, with the exception of a few small field installations for charging batteries for scientific and communications equipment, and a few trials of prototypes. The success (non-failure) of small turbines where often due to basic oversizing, which is not a realistic solution for larger machines.

Since then, a couple of manufacturers have developed mature products designed for standalone operation in very difficult wind conditions, cold and/or corrosive environments. These high quality products have already proven their reliability and cost effectiveness in conditions nearly as difficult as the East Antarctic coastal stations and sub Antarctic islands.

The 3 kW Northern Power Systems HR3 turbines have successfully powered since 1985 the communications facility at Black Island near McMurdo. However, they remain small oversized machines with fairly little efficiency delivering Direct Current, well adapted to low power isolated systems, but not to station's energy requirements.

More versatile is the 1 to 25 kW range of variable pitch two bladed GEV turbines from Vergnet which deliver grid-compatible three phase AC power. Originating from the renowned Aérowatt machines, they are well designed for extreme wind conditions and to the best of our knowledge, offer the highest resistance to extreme winds in the medium power range together with high efficiency and low maintenance requirements. They have proved their effectiveness in difficult conditions, especially in the Indian Ocean where they have survived 90 m/s gusts at Tromelin, and in the Sub Antarctic at Heard Island.

A 10 kW / 7m diameter GEV 7.10 turbine on its 24m mast costs around 40 000 US$ (211 000 FRF) and should last at least 20 years. At Dumont d'Urville, with an average wind speed of about 10 m/s, the GEV 7.10 would deliver an average of some 7 kW in laminar winds, some 6 kW in real conditions (Load factor Lw=0.7, typical turbulence factor A=0.85). Other examples of approximative load factors for this turbine are: 0.15 at Davis, 0.20 at South Pole, 0.30 at McMurdo, 0.35 at Casey, 0.45 at Amsterdam Island, 0.50 at Macquarie, 0.65 at Kerguelen, 0.73 at Crozet and Mawson.

An accepted maintenance cost for these turbines is 2% of the initial capital cost every year. Over a 20 year lifetime, the estimated production cost of one kWh for the GEV 7.10 is then:

• Pwt= (0.0320 / Lw /A) US$/kWh

Which gives for the selected stations the following costs:
0.251 US$/kWh at Davis, 0.188 at South Pole, 0.125 at McMurdo, 0.108 at Casey,
0.0837 at Amsterdam Island, 0.0753 at Macquarie, 0.0579 at Kerguelen,
0.0538 at Dumont d'Urville, 0.0516 at Crozet and Mawson.

We can note that some of these costs are the lowest seen so far for primary energy generation at the stations. However, we must keep in mind that it doesn't include the energy storage systems that can be needed in some renewable energy system options (see section 5).

4.2 Thermal Machines

These most promising machines currently under development at the Laboratoire des Sciences du Génie Chimique in Nancy, France, as part of our French-Australian project, use the thermal gradient existing at coastal stations between the 'cold' wind and the 'warm' -1.8°C seawater (ref. 7 through to 13).

Preliminary results from the first experimental set-ups currently operated at Dumont d'Urville and in the Arctic at Krankel show that these machines could provide to the coastal stations, for the same cross-section of wind used, more energy than wind turbines. The potential for energy production is less constant throughout the year than for wind turbines, but has the advantage of providing most energy in winter when heating requirements are greatest, and doesn't involve exposed moving parts.

Both thermomechanical machines (producing mechanical work which can drive an alternator) and multistage heat pumps (producing heat) could exploit this thermal energy of the wind. It is too early to evaluate energy production costs, development could proceed in the next few years .

4.3 Photovoltaics

High latitudes are characterised by high seasonal variations in solar radiation. This makes solar energy inadequate for year round operations but can make it useful for particular summer applications. Solar radiation can be converted by current standard PhotoVoltaic (PV) panels into Direct Current (DC) with an efficiency of about 10%. PV work well in cold temperatures, are reliable, require minimal repair outlay and only negligible maintenance. But because of the low concentration of recoverable power (see Tables 3 to 5 and Figure 2), large panel areas are required, which encroach on the often limited space available. In a 'sustainable' point of view, it must also be noted that photovoltaics' manufacturing process is highly energy intensive, and for low load factors photovoltaics may produce in their entire life less energy than was required in their manufacturing process.

The cost of PV panels is of the order of 770 US$ (1000 A$) per m^2, that is 7,700 US$ per rated kW, the ratings being based on a solar radiation of 1 kW/m^2. But if the yearly average total global radiation on a horizontal surface in Alice Springs, Central Australia, is reaching about 0.250 kW/m^2 (load factor Lpv= 0.25), giving a cost of 31,000 US$ per generated kW, the Antarctic stations are more in the 0.100 kW/m^2 range(Lpv= 0.1), giving a cost of some 77,000 US$ per generated kW.

Repair and maintenance costs beeing assumed negligible, we find over a 20 year lifetime the following financial kWh cost (PV panels only, no mounting, primary DC power):

• Ppv= (7,700 US$ / 20 years / 365.25 days / 24 hours) / Lpv = 0.0439 / Lpv

Which gives for a horizontal panel at a typical Antarctic station (Lpv=0.1) :

• Ppv= 0.439 US$ / kWh

The amount of radiation received by a panel can be increased some 3 to 4 times by using tracking systems. Although the panel costs can be lowered to some 20,000 US$ per generated kW, and the primary generation cost to 0.11 US$/kWh (panels only, DC power), it introduces additional costs for the tracking system. More importantly, it generates maintenance and reliability problems as large panel areas are required and most stations experience high winds. For example, generating a yearly average of only 100 kW of DC power at Dumont d'Urville would require some 8,500 m^2 of horizontal panels (space problem) or some 2,500 m^2 of tracking panels in winds up to 90 m/s (additional reliability and cost problem for the tracking system). If a few low wind sites could offer lower costs for photovoltaics (little mounting problems) than for wind turbines (low potential), it often remains impractical for large scale systems.

Technological advances could however modify the photovoltaics potential. New production models are now appearing with efficiencies around 20% and further improvements are expected.

The most favorable locations for large scale PV use are the stations located on the Antarctic plateau, such as South Pole or Dôme C, where low winds, large spaces and little cloud cover prevail. Some interesting studies are under way on the use of PV panels at South Pole (Peeran, 1993) as well as solar thermal heating systems for summer buildings (Tobbiasson W., Ferraro J. , Davis L., pers. comm.).

Power Generation Costing Basis	**Power Type**	**Financial Cost** *US cents/kWh*	**Energetic Cost** *kWh*
Hydro Electricity, Tasmania, Domestic Commercial Price	AC	*7.*	*0.00*
Diesel Generator Sets, Australian Stations, Load Factor > 0.6 SAB Fuel at 0.0785 US$/kWh (0.77 US$/litre)	AC AC+heat	47. 25.	2.86 1.49
Diesel Fired Boilers, Australian Stations SAB Fuel at 0.0785 US$/kWh (0.77 US$/litre)	heat	9.8	1.25
PC25C Fuel Cell, in the US, Load Factor = 1 *Natural Gas at 2 US$ per million Btu (0.00667 US$/kWh)*	AC AC+heat	*4.4* *3.5*	*2.50* *1.18*
PC25C Fuel Cell, in the US, Load Factor = 1 *Natural Gas at 4 US$ per million Btu (0.01333 US$/kWh)*	AC AC+heat	*6.0* *4.3*	*2.50* *1.18*
PC25C Fuel Cell, Australian Stations, Load Factor = 1 LPG at 0.169 US$/kWh (2.163 US$/kg)	AC AC+heat	45.0 21.7	2.50 1.18
Wind Turbine GEV 7.10, Turbulence Factor A=0.85 Load Factor Lw = 0.15, Davis 0.20, South Pole 0.30, McMurdo 0.35, Casey 0.45, Amsterdam Island 0.50, Macquarie 0.65, Kerguelen 0.70, Dumont d'Urville 0.73, Crozet & Mawson	 AC AC AC AC AC AC AC AC AC	 25.1 18.8 12.5 10.8 8.37 7.53 5.79 5.38 5.16	 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
Photovoltaics, 10% efficiency, 770 US$/$m^2$, 0.1 kW/$m^2$ Radiation on an horizontal plane horizontal panel tracking panel	 DC DC	 43.9 11.0	 0.00 0.00

Table 6 :
Tentative Cost Estimates for Selected Energy Generation Methods.
(20 years life cycles, Discount Rate = Inflation Rate = 0)

5. Some System Options

Many system options exist. We will briefly describe a few basic options, from which many variations are possible. It is meant to provide ideas to help design systems for each particular case.

As photovoltaics seem to remain impractical for large scale systems, they wont be mentioned in the system options but can easily be inserted alongside the wind systems if required. We will only mention the type of Thermal Machines producing Heat, which seems particularly interesting because of the good match between production potential and heating needs. However, Thermomechanical machines can just be inserted in the system in place of the Wind Turbines.

5.1 Storage Considerations

The inconsistent nature of renewable energy resources imposes the use of buffer energy storage systems to achieve high penetration of the renewable systems. Hydraulic storage (i.e. using artificial water reservoirs) being not suited to the stations, only two realistic options remain, electrochemical batteries and hydrogen (H2).

Battery systems are reliable and proven technology, although the size and weight of battery banks make it become decreasingly practical as the amount of stored energy required increases. Batteries also have limited life expectancy and could have to be replaced every 5 to 10 years.

For AC power, systems are composed of a battery charger, a battery bank and an inverter, with a round trip efficiency around 50%. If DC systems have better efficiency, they are not practical for large scale applications and spread networks. A very good point of battery systems is that they are simple and modular, making small installations easy to set up.

A very promising option is to use hydrogen as storage medium: produce it from electricity and water by electrolysis, store it, then use it as needed. A system composed of Stuart Cells Electrolyser units, compressed hydrogen tanks and a PC25 Fuel Cell modified for H2 use can offer an AC round trip efficiency around 30%. The fuel cell generates heat as well, and in case of cogeneration, the global system efficiency is approaching 60%. The potential for large storage capacity is better than for batteries, and all system components are reliable and have long life expectancies.

More generally, the Hydrogen option is very powerful and versatile as the produced and stored stable hydrogen is a real fuel in itself. It can be reconverted through various <u>clean</u> and <u>efficient</u> processes not only into electricity and heat in fuel cells or modified fossil fuel type generator sets, but also into heat in catalytic burners and into mechanical work in combustion engines to fulfil <u>all</u> station energy needs.

Since the hydrogen filled dirigible *Hindenburg LZ-129* burst into flames (not exploded) on 6 May 1937 when landing at Lakehurst, New Jersey, killing 25 of the 97 people on board, hydrogen use has had the reputation of being unsafe. Although hydrogen remains a hazardous substance, its safe use is now being demonstrated in established facilities world wide, with over 750 km of commercial gaseous hydrogen transport pipelines operating on a routine basis.

Hydrogen is increasingly being accepted as a practical alternative fuel and current large scale projects include producing hydrogen in Québec with hydro-electricity from Baie James and shipping it to Europe (Euro-Québec Project). The Gouvernement du Québec and the Union Européenne are funding intensive research to develop a variety of hydrogen powered equipment, from home cooking stoves to motor vehicles to aircraft.

Electrolytic plants can produce hydrogen from water and electricity through a clean process. This is a proven and reliable technology, already used at some of the stations to provide hydrogen for the meteorological balloons. Some units from the Toronto based Electrolyser Corporation have operated worldwide for over 40 years with minimal but regular maintenance. Their recent Photovoltaics-Hydrogen unit commercially available has already operated out of doors for 1000 days in a temperature regime of -30 to +30°C. The manufacturer's research targets for systems with fuel cells include 18 months unattended operation at temperatures to -50°C.

5.2 Fossil Fueled Based Systems
with Renewable Supplement

(a) Gen.Set or Fuel Cell, and Boiler
+Wind and Thermal when available

In this most simple option, renewable energy is simply "injected into the grid" and only used as a fuel saver when available. The fossil fuel system has still to be sized to be capable of meeting all power demand, but no storage medium is required. The installation is very simple and the cost of renewable energy is limited to the primary energy production cost. This option is ideally suited to the experimentation phases of renewable power generation equipment. (see Figure 3.a)

(b) Generator Set or Fuel Cell, and Boiler
+Wind with partial battery storage
+Thermal when available

This option is basically an evolution of the previous one, where wind turbines still deliver most of their power directly to the grid and a battery system allows some regulation. The energy stored can be used to assist the fossil fueled system on times of peak power demand. This system can provide an effective tool for an efficient management of the load imposed to the base system, and can for example avoid the need for oversized generators in stations experiencing short duration high peak demands. (see Figure 3.b)

(c) Generator Set or Fuel Cell, and Boiler
+Wind with hydrogen production &storage
+Thermal when available

This third system uses a hydrogen production and storage system. Better suited to larger scale wind farms, it offers greater storage capacities and a long life stable storage medium. It doesn't offer the possibility of load management on the base system but allows large scale wind turbine installations (peak power greater than the minimum station's load) to use excess power to produce on site a real versatile fuel useable in many different ways. For example, a diesel engine (such as used in a generator set or in machinery and vehicles) can easily be modified to accept a diesel-hydrogen mixture containing anything from 0 to 95% of hydrogen. The hydrogen can be mixed with fossil fuels to lower the amount of fuel to be shipped and lower atmospheric pollution at the station. (see Figure 3.c)

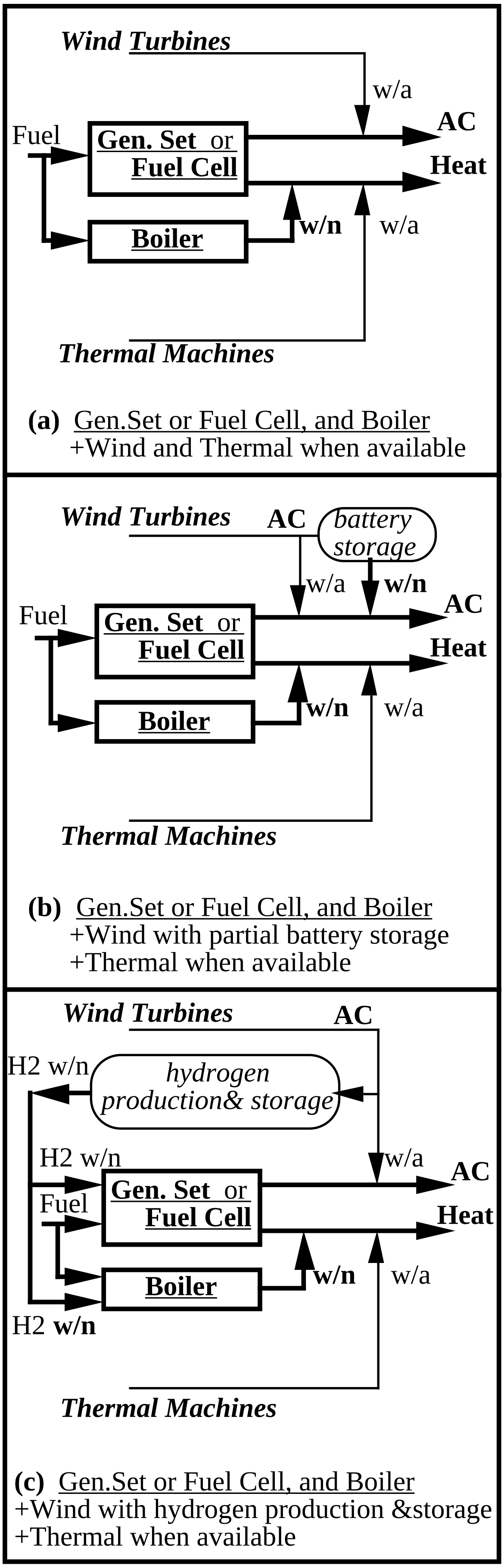


Figure 3:
Fossil Fuel Based System Options
with Renewable Supplement
(w/n = when needed, w/a = when available)

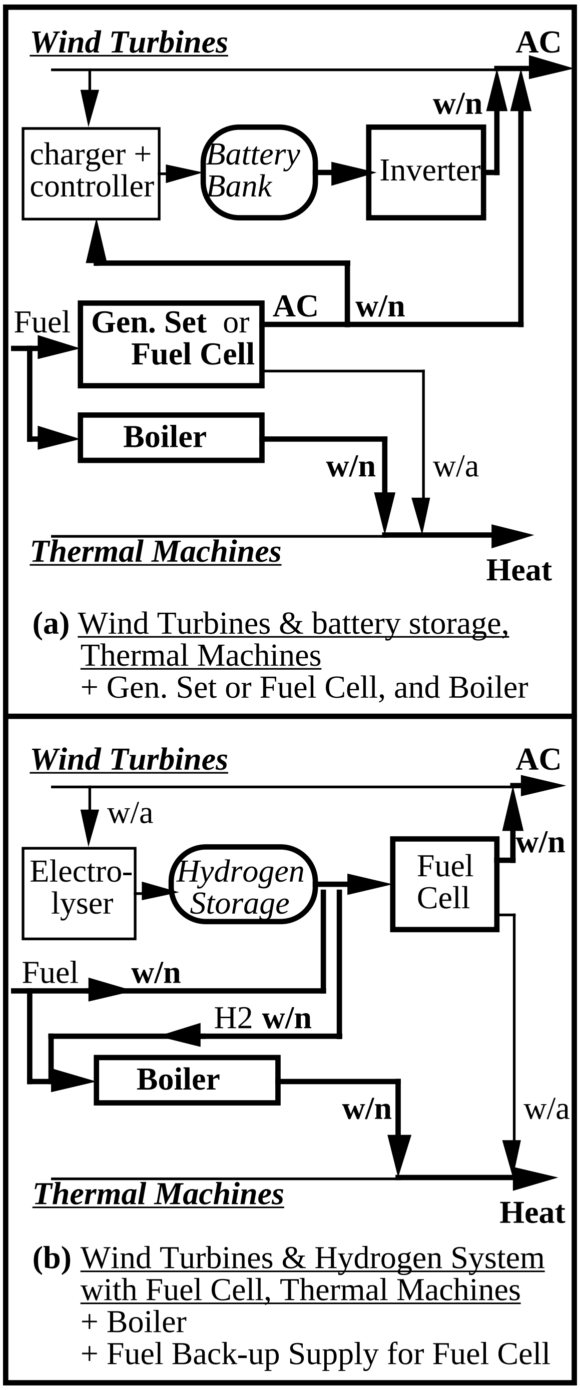
5.3 Renewable Based Systems
with Fossil Fueled Supplement/Back-Up

(a) Wind Turbines & Battery Storage, Thermal Machines
+ Gen. Set or Fuel Cell, and Boiler

This renewable system is based on wind turbines and thermal machines to provide respectively AC power and Heat. A battery storage system allows for normal regulation of AC power (matching the production with the demand) while a generator set or fuel cell is used for back-up in case of long periods of low winds. Thermal machines are sized to provide all the heat required in winter while boilers act as a back-up and can provide the base heating needs required in summer when thermal machines can't operate.

(b) Wind Turbines & Hydrogen System with Fuel Cell, Thermal Machines
+ Boiler
+ Fuel Back-Up Supply for Fuel Cell

This last option is the most advanced and probably the most satisfying. As a renewable system associated with hydrogen, it can provide hydrogen for use as a fuel to fulfill all other energy requirements at the stations with negligible pollution. For example, vehicles staying around the station could run on hydrogen. For emergency back-up, the fuel cell unit can be fed by fossil fuels.



(a) Wind Turbines & battery storage, Thermal Machines
+ Gen. Set or Fuel Cell, and Boiler

(b) Wind Turbines & Hydrogen System with Fuel Cell, Thermal Machines
+ Boiler
+ Fuel Back-up Supply for Fuel Cell

Figure 4:
Renewable Energy Based System Options
with Fossil Fueled Supplement/Back-Up
(w/n = when needed, w/a = when available)

6. Conclusions

A relatively interesting point is that most elements of the cost analysis made, especially for fossil fuel systems, can be easily disputed. It could then generate valuable debates and discussions, but more importantly, it shows that strict financial comparisons are generally made irrelevant by the uncertainties about cost elements. And cost estimates show quite well that renewable energy production costs can compete with classic production systems used. Then, because of all their advantages in terms of sustainability, pollution or logistics, renewable systems should be implemented as soon as their financial cost is realistically affordable: If we CAN do something 'clean and sustainable', we HAVE to do it.

One usual complaint about renewable energy systems at Antarctic stations is the unreliability of wind turbines (see section 4.1). But wind turbine technology has matured and reliable machines designed for difficult conditions are now available. We need now to properly assess the operational onsite behaviour of such machines which should reveal successful. Experimental programs have been initiated.

A second complaint is about the unrealistic size of the systems needed to provide all station's energy needs (see Table 5), which will limit the penetration of renewables in the existing stations. But why should we necessarily see renewable energy systems as being too 'weak' rather than find stations too "energy demanding"? The move towards new energy systems will have to go with a moderation of energy needs and a return to the "simple is beautiful" philosophy. This move will need a multidisciplinary approach, coordinated testing programs and long term studies.

This paper was certainly not designed to give definitive answers. We hope that the goal of providing basic reflection elements, iniating thoughts and creating new motivations will be somewhat achieved. If it provides for us an opportunity to refocus the orientation of the project, it could also be the foundation for a wider coordinated effort with several Antarctic nations.

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