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A "new" source of renewable energy: the coldness of the wind

Hervé Le Goff, Uli F. Hasert, Pierre Le Goff*

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Abstract — Until now the wind considered as an energy source has mainly been used for its propulsive power (sailing boats, wind mills) and its drying power (cereals, linen, etc.). The cooling power of a wind, which has a temperature T lower than the temperature T_0 of a reference medium (sea, river, waste fluid) has seldom been used. Analysing weather data for different sites, we show that the enthalpy and exergy fluxes available from these thermal dipoles, can largely exceed the pure kinetic energy of the strongest wind. As practical examples of systems able to use this "free wind exergy", we describe a thermo-mechanical machine for electricity production (inspired from OTEC: ocean thermal energy conversion) and an original multistage absorption heat pump for space heating. © 1999 Éditions scientifiques et médicales Elsevier SAS.

thermal machine / absorption heat pump / energy of wind / renewable energy / coldness of the wind

Nomenclature

C	water vapour concentration in the air	kg·m^{-3}
COP	coefficient of performance	
c_P	specific heat	J·kg^{-1}·K^{-1}
E	total specific energy	J·m^{-3}
Ex	specific exergy	J·m^{-3}
L_V	latent heat of vaporisation	J·kg^{-1}
P	pressure	Pa
Q	heat flux	J·m^{-3}
T	temperature	K
u	velocity	m·s^{-1}
W	mechanical specific energy	J·m^{-3}
$\dot{W}$	mechanical power per surface unit	W·m^{-2}

Greek symbols

ρ	density	kg·m^{-3}
η_c	Carnot efficiency	

Subscripts

A	absorber
D	boiler
E	evaporator
M	wind turbine
0	reference state
T	thermal machine

* Correspondence and reprints.

1. INTRODUCTION

The wind which blows on an obstacle applies to it a certain pressure and thus degrades by friction a part of its incident energy. This is how sailboats and windmills work. The wind, however, is usually colder or warmer and/or drier than the obstacle, which leads to the exchange of thermal energy between the wind and the obstacle.

In wintertime, one finds in the polar regions and even in northern parts of Europe, Canada or Siberia, regular powerful ($\gg$ 10 m·s^{-1}) and cold (–10 °C to –30 °C) winds, often loaded with particles of snow, whereas the earth's crust keeps, because of its thermal inertia, a temperature higher than 0 °C. Does there not lie in this temperature difference a powerful, inexhaustible source of energy ready to be used, in particular, for heating buildings and maintaining them at a temperature of 20 °C? Such a system is equivalent to a heat pump using the cold wind as cold source and for instance sea water as heat source.

2. THE ENERGY OF THE WIND

Air pressure, flow velocity, temperature and humidity are known to vary greatly from one point to another, and at every point as a function of time. In terms of energy, these fluctuations of P, u, T and C express the fluctuations of the energy content of each cubic meter of air. They constitute an intermediate state in the degradation process of incident solar energy absorbed on one face of the globe and finally dissipated by radiation towards space.

The fluctuations of the total energy E contained in one cubic meter of air are expressed approximately by 4 terms:

$$E = \underbrace{(P - P_0)}_{I} + \underbrace{\frac{1}{2}\rho(u^2 - u_0^2)}_{II} + \underbrace{c_p\,\rho\,(T - T_0)}_{III} + \underbrace{L_V\,(C - C_0)}_{IV} \quad (1)$$

In this P_0, u_0, T_0, C_0 are the values of P, u, T, C at an arbitrary reference state where the symbols have the following meaning: C is the concentration of water vapour in the air (in kg·m^{-3}), L_V is the latent heat of vaporisation of water (L_V = 2 470 kJ·kg^{-1} at 20 °C), the energy E is in J·m^{-3}, the pressure P is in Pascals. In what follows, we will take as a reference state: motionless air ($u_0 = 0$), at the mean annual atmospheric pressure of the location considered, saturated in humidity at the temperature under consideration.

The temperature T_0 can be chosen in several ways depending on the aim in mind. By taking T_0 to be the annual mean temperature of the location, previous studies have shown: (1) that the temporal variations of the terms III (thermal energy) and IV (drying energy) are 100 to 1 000 times greater than those of the term II (kinetic energy). Term I (the temporal variation of atmospheric pressure) is 10 to 50 times greater than that of the kinetic energy. However, in practice it is difficult to make use of temporal gradients of energy potentials and we seek rather to make use of spatial variations in the form of a thermal dipole.

Figure 1 compares, in logarithmic co-ordinates, kinetic drying and thermal energy of the wind in respect to a reference temperature of T_0 = 20 °C for Nancy in 1979. It is to be noted that this energy is, all year round, cooling energy, even in July when the average temperature is 17.5 °C, and thus less than the reference temperature. It appears that this cooling energy is about 200 times larger than the kinetic energy. But it is important to note that this ratio is largest in winter time. In January 1979, for example, the kinetic energy of the wind was 7.8 J·m^{-3} whereas its cooling energy was 29 000 J·m^{-3}, i.e. 3 700 times as much.

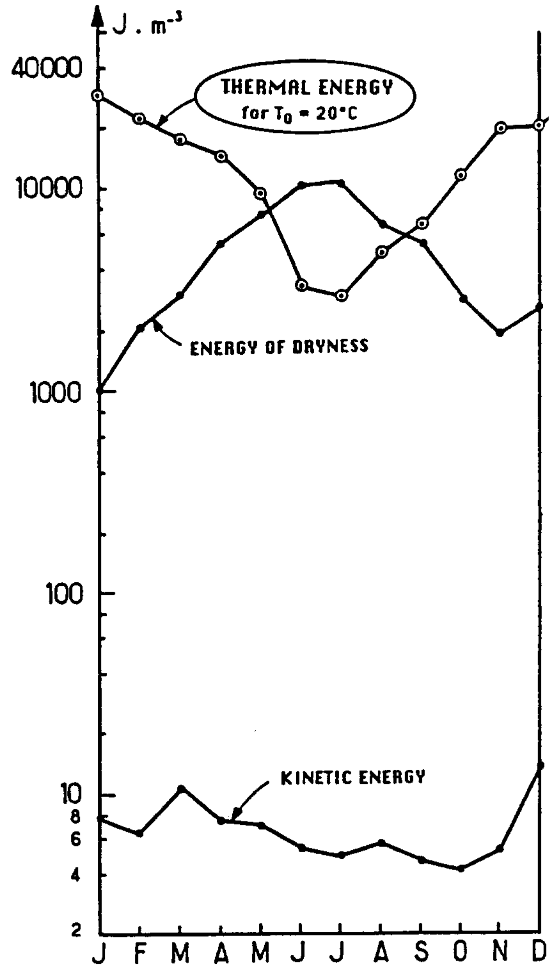

Figure 1. Comparison between the kinetic and thermal energies and the energy of dryness, with respect to a reference temperature of 20 °C.

3. HOW CAN WE USE THIS ENERGY?

3.1. To produce mechanical energy

A thermal dipole can be used in a thermodynamic machine to produce mechanical energy. Let us imagine (*figure 2a*) a thermomechanical machine working in a Rankine cycle using ammonia between a "hot" source of sea water at $T_h \cong 5$ °C and a "cold" wind at $T_c \cong 15$ °C (*figure 3*).

For a wind speed u = 10 m·s^{-1}, the useful power per m^2 of condenser would be:

$$\dot{W}_T \cong 1\,000 \text{ W·m}^{-2}$$

It may be noted that such a machine would be analogous to those proposed for exploiting the thermal

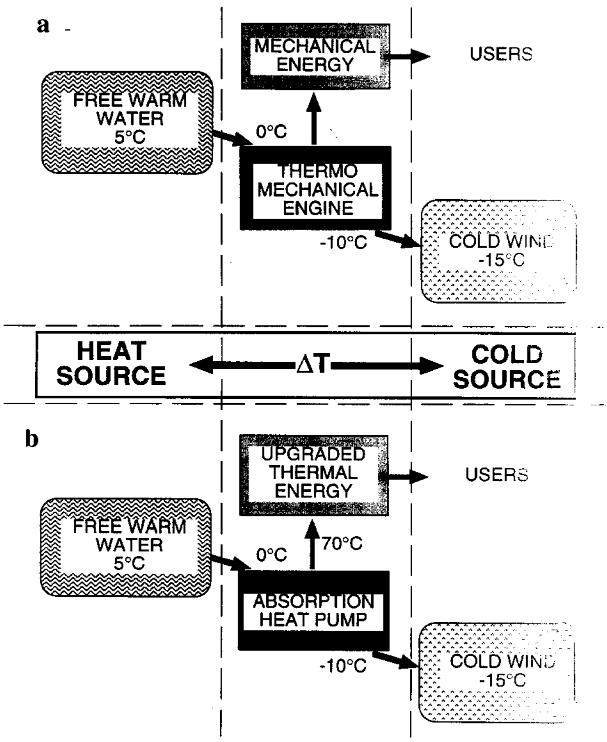

Figure 2. Principle of the systems using the wind coldness. **a.** Thermo-mechanical engine. **b.** Absorption heat pump.

energy of the tropical seas by making use of the difference in temperature between the surface waters (25–30 °C) and the depths ($\cong$ 5 °C) (OTEC machines). A comparison between the thermal energy of the sea and the cold winds energy is given in reference [1].

The cold wind absorbs heat from the condenser and is warmed up. The energy transferred is therefore:

$$E_T = \rho \, c_p \, \Delta T_F \cong 6\,800 \text{ J·m}^{-3}$$

of air.

The Carnot efficiency for the wind/sea water dipole is: $\eta_c = 6{,}3$ %. Therefore the corresponding thermal exergy is: $Ex_T = E_T \, \eta_c = 430$ J·m^{-3}.

Let us now suppose that the real efficiency of the cycle is a quarter of the Carnot efficiency. The mechanical energy available from the ammonia turbine would therefore be:

$$W_T \cong 100 \text{ J·m}^{-3}$$

Let us now compare these results with those of a conventional wind turbine. The kinetic energy of the wind is:

$$Ex_M = E_M = \frac{\rho \, u^2}{2} = 18 \text{ J·m}^{-3}$$

hence: $\dfrac{Ex_T}{Ex_M} = 24$.

The mechanical energy (pure exergy) is 24 times less than the thermal exergy of the wind.

A rustic and reliable windturbine designed for operating in polar conditions would have an efficiency of about 30 %. The mechanical power available from a 10 m·s^{-1} wind would therefore be:

$$\dot{W}_M \cong 55 \text{ W·m}^{-2}$$

of swept area.

This is 18 times less than that which could be provided by a thermal machine:

$$\frac{\dot{W}_T}{\dot{W}_M} = 18$$

This example illustrates two things:

– the very great potential of the thermal dipole examined here;

– the necessity of comparing the different contributions in equation (1) in terms of exergy rather than energy.

3.2. To produce useful heat

The thermodynamic machine shown in *figure 2b* works with the same dipole (sea water/cold wind) as above and here produces heat upgraded to a temperature of 70 °C for space heating.

Figure 4 shows a heat transformer using two sources at –15 °C and 5 °C, respectively.

The separator unit is composed of a 15-stage battery for separation-condensation. Each stage consists of a vertical tube with fins on the outside (*figure 5*). The film of the solution to be evaporated flows down the inside wall of the lower part of the tube which is maintained at a temperature of 0 °C by "warm" water (5 to 10 °C) circulating between the fins. The vapour condenses on the upper part which is maintained at –10 °C by the wind (supposed colder than –10 °C) circulating between the fins.

The separator is provided with a water-ammonia mixture containing 25 % ammonia. It produces an ammonia rich solution ($x = 0.5$) and an ammonia poor solution ($x = 0.10$).

The mixer is analogous to a one stage separator. It is made of an enclosure composed of two vertical walls which the two liquid films flow down:

– one is the rich solution which is evaporated at around 0 °C, heated by warm water of 5 to 10 °C;

– the other one is the poor solution which absorbs the ammonia enriched vapour; the absorption heat is extracted by an heat carrier fluid entering the system at about 40 °C, in order to be recirculated into the heating system of a building at 70 °C.

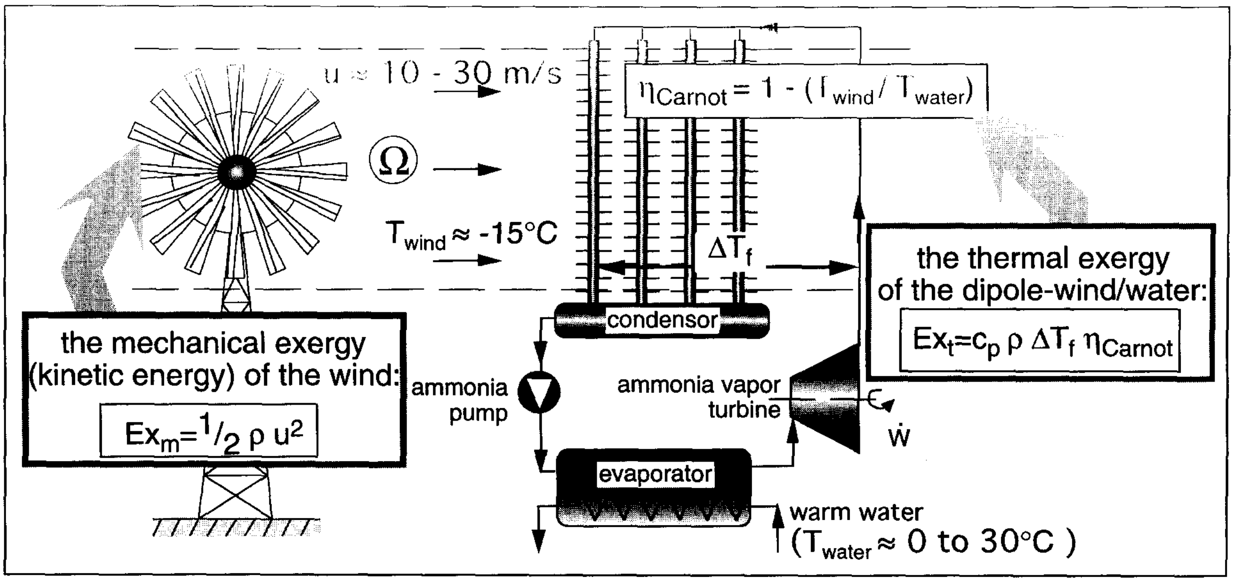

Figure 3. Windgenerator and Rankine cycle fror a polar wind application.

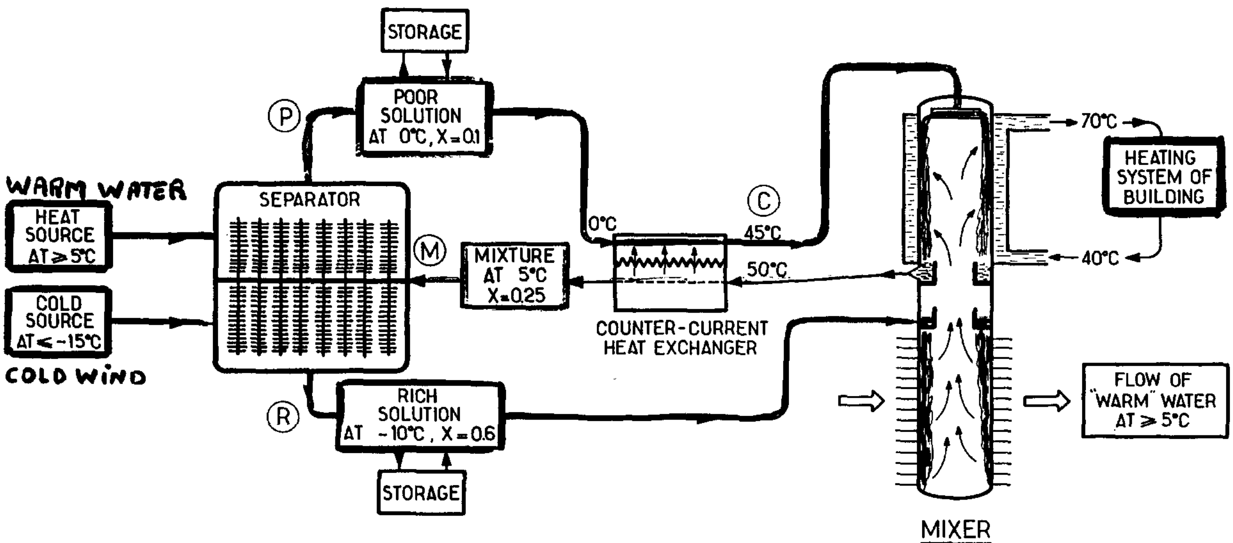

Figure 4. Multistage absorption heat pump.

Figure 6 shows the diagram $\log P$ versus $-1/T$ representing the 15 stages of separation, between 0 °C and −10 °C. Starting with the initial mixture (point M), 4 stages lead to point P (poor solution) and 10 stages lead to point R (rich solution). The mixing performed under a pressure of 1.5 bar leads to the points (A) at 75 °C and (B) at 50 °C.

Such a system produces a usable heat flux, Q_{A}, in the absorber starting from the free heat fluxes (Q_{E}) supplied for evaporation and Q_{D} supplied for desorption.

The coefficient of performance (COP) of this heat transformer given by the ratio:

$$COP = \frac{Q_{\mathrm{A}}}{Q_{\mathrm{E}} + Q_{\mathrm{D}}}$$

is very low, around 5 %.

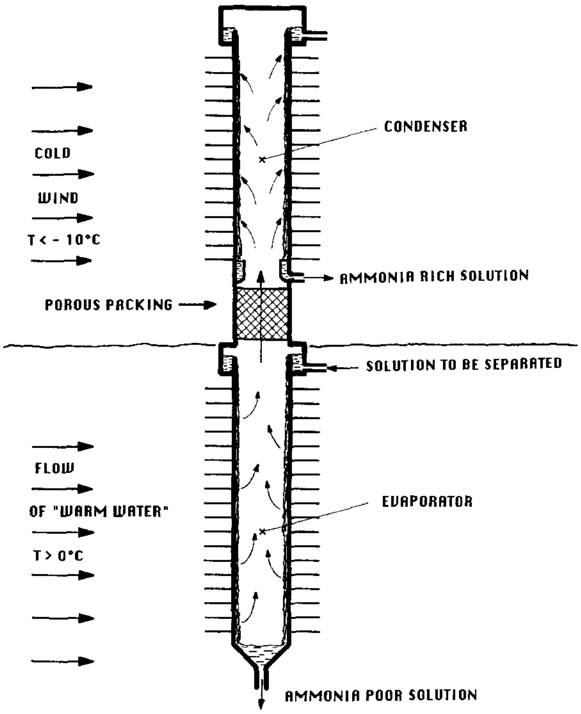

Figure 5. Evaporator–condenser in a single vertical tube.

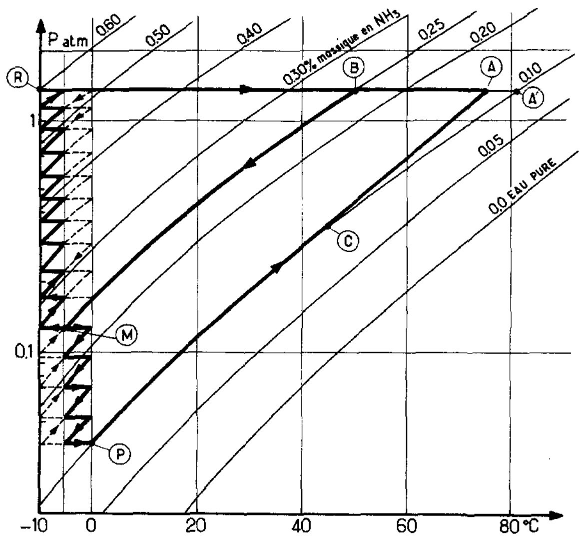

Figure 6. Production of heat at 70 °C using sources at −10 and 0 °C.

4. THREE EXAMPLES OF INSTALLATIONS FOR POLAR REGIONS

Let us consider two coastal sites on the Antarctic continent: Mawson and Halley Bay, for which the monthly weather data are available (*table*).

Figures 7 and *8* show the comparative monthly variations of thermal and mechanical exergy of the wind at Halley Bay and Mawson. In both cases, seawater is pumped from under the ice layer at about its freezing point (−1.8 °C).

– At Mawson, which is a very windy and not a very cold location, the mean annual thermal exergy is only twice as great as the mechanical exergy with a winter maximum (August) of up to a factor 4. In the two summer months there is no dipole.

– At Halley Bay, which is not very windy and much colder, the ratios are respectively:

$$\text{annual mean, } \frac{Ex_T}{Ex_M} = 22; \text{ max (August), } \frac{Ex_T}{Ex_M} = 40.$$

Let us finally consider the very special case of Deception Island in the South Shetland Islands (*figure 9*). The

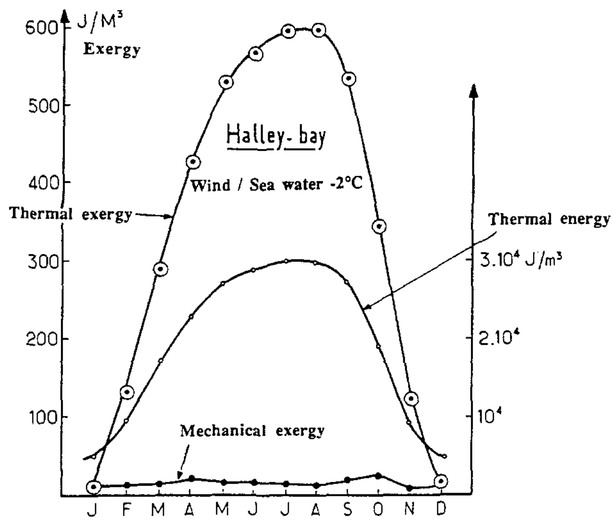

Figure 7. Comparison between thermal and mechanical exergies at Halley Bay, on the Antarctic Continent.

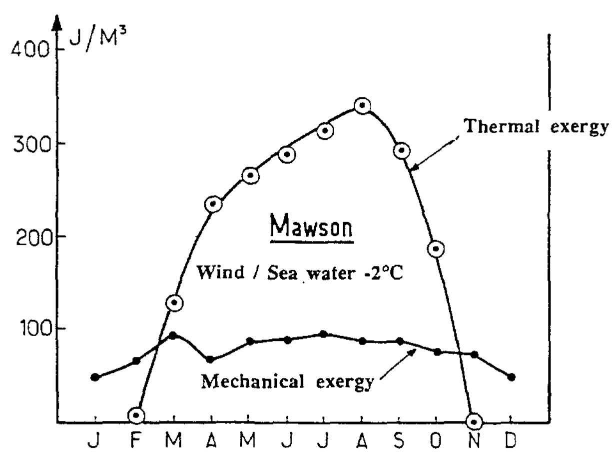

Figure 8. Comparison between thermal and mechanical exergies at Mawson, on the Antarctic Continent.

TABLE
Data for 3 polar regions.

Station	Position	Characteristics	Annual mean data		
			Wind		Sea
			Speed (knots)	Temperature (°C)	Temperature (°C)
Deception South Shetland Islands	62°56 S 60°37 W	Antarctic Ocean Islands	12	− 2	Geothermal 30 to 50
Mawson	67°36 S 62°52 W	Land coast of East Antarctica	21	−10.5	Subglacial −1
Halley Bay	75°35 S 26°46 W	Ice Shelf Weddell Sea	9	−18	Subglacial −2

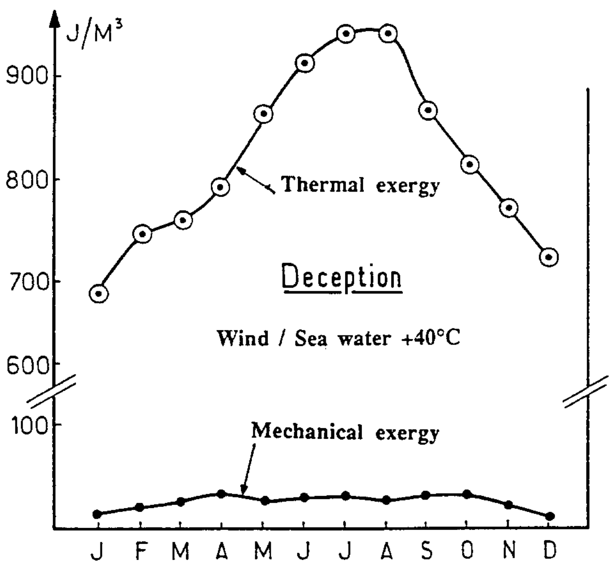

Figure 9. Comparison between thermal and mechanical exergies at Deception Island, in the South Shetland Islands.

site is moderately windy and not very cold (temperatures of the three summer months are positive). But Deception is a volcanic island where the main crater is invaded by the sea. Hence sea water heated by the upper layers of hot ashes on the beaches can reach temperatures of 40 to 50 °C. The wind/sea water dipole is shifted towards positive temperatures and has a very high exergetic content:

– annual mean, $\frac{Ex_T}{Ex_M} = 34$;

max (August), $\frac{Ex_T}{Ex_M} = 37$.

In this case the production of thermomechanical energy is extremely interesting ($\eta_c = 13\ \%$) and space heating could be provided almost directly by means of volcanic heat at 50 °C. The only restriction to such a project is precisely the volcanic nature of the island. The last large eruption in 1969 destroyed all the scientific installations on the island and there was a new increase of seismic activity in the summer of 1992... Nature always makes us pay for its generosity in one way or another!

5. TECHNICAL FEASABILITY

5.1. The sea water as the heat source

In polar conditions, as illustrated in the examples treated above, the main limitation is the absence, or the poor accessibility of a hot source. Russian scientists have shown that there is a high solar radiation available on the Antarctic Ice cap which increases with altitude and latitude. For example, at the South Pole, flat vertical solar panels could be used as evaporators in the thermodynamic cycles described above. However this direct solar radiation is obviously not available during the polar night, precisely when the needs of the bases, and the availability of the cold wind, are at a maximum.

The technological problems involved in pumping water close to its freezing point have been solved on polar ships by a slight heating of the inlet pipes. The energy thus used is minimal with respect to the overall heat balance in a sufficiently large system. This water will be cooled in passing through the primary circuit of the evaporator and will therefore freeze. This is not a problem if the ice is continually removed from the exchanger so as not to degrade the heat transfer kinetics nor affect the water flow. The technique involved is that used in industrial machines producing ice flakes where blades scrape the ice as it is formed from the heat exchange surfaces. In addition the latent heat of crystallisation of water (80 kcal·kg^{-1}) is 80 times greater than its sensible heat. Sea water at −2 °C is therefore quite a good heat source if it is reasonably close to the site where it is to be used (although the OTEC machines effectively in use pump their sea water from 1 000 m deep).

5.2. Exchangers for cold wind enthalpy

The technology involved is that of any atmospheric heat exchanger with bundles of finned tubes. This gives the advantages of simple construction, robustness in high winds, low sound nuisance which compares well with the problems involved with wind turbines. We have made a theoretical and experimental study to evaluate and maximise the heat transfer coefficients between a heated obstacle and a dry wind, or one loaded with snow or ice.

6. EXPERIMENTAL WORK IN ARCTIC AND ANTARCTIC SITES

6.1. The "cold wind fluxmeter"

An experimental device, called "cold wind fluxmeter", was designed and built at the LSGC in Nancy. *Figure 10* shows the fluxmeter (7).

The cold wind fluxmeter consists of two vertical, cylindrical, tubes: one smooth tube, with a well-known tube wind heat transfer and one tube with external, annular fins, for the testing of snow effects and to increase the heat transfer by increasing the effective surface area of the tube. The internal electrical resistance is generating the thermal gradient for heat flux transfer.

The surface and wind temperature and speed are measured and recorded continuously by an automatic data acquisition system. After some preliminary testing in the French Alps, the first fluxmeter was installed in the 1993 northern summer at the meteorological station of Krenkel, Franz Joseph Land, in the Russian Arctic, and the second in January 1994 at the French Antarctic Station Dumont d'Urville.

The meteorological characteristics of these two locations (Krenkel, Arctic, and Dumont d'Urville,

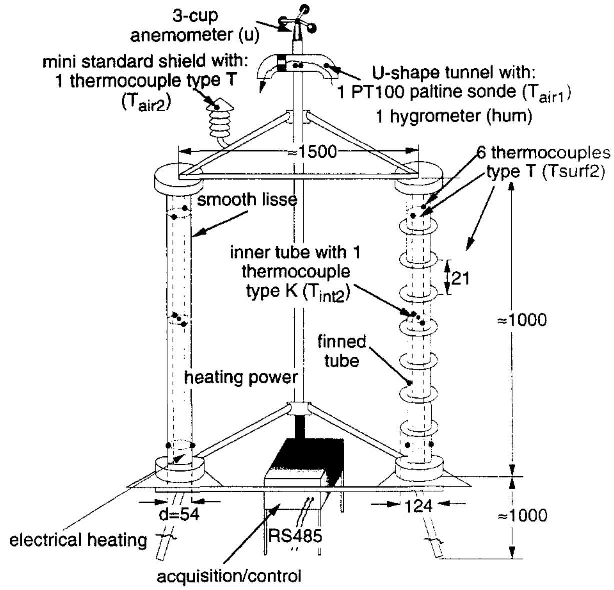

Figure 10. The first cold wind fluxmeter with a single tube.

Antarctic) are quite different. The average temperature at Krenkel during the 4.5 months of polar night is around −30 °C. At Dumont d'Urville there is no polar night and the temperatures are not as low, but there are very strong catabatic winds with recorded speeds up to 90 m·s^{-1}. The aggregation of results obtained at those two different locations improves the reliability of our conclusions and expands their scope.

The next step towards a real working unit was taken in January 1995 with the installation of a bundle of tubes as heat exchanger. It represented the real condenser planned for the final installation and will provide more detailed information on the wind refrigeration power practically recoverable.

6.2. Multidimensional weather data analysis and results

To compare the recoverable mechanical energy of kinetic wind energy to thermal wind energy and solar energy at the two test sites, we have made a multidimensional weather data analysis, with occurancy tables of speed/temperature for the wind. Represented in *figure 11* as an example of the 10 days period 10–20 March (decade 08) for Dumont d'Urville (8 measurements a day; 1985–1989). The corresponding analysis of the energy potential will show the influence of the characteristic value (s) by the localisation of their maxima (*figure 12*).

For a classical Rankine cycle we have calculated the net output for two different heat sources, seawater at ≅ −1,8 °C and waste water at 20 °C. On polar bases

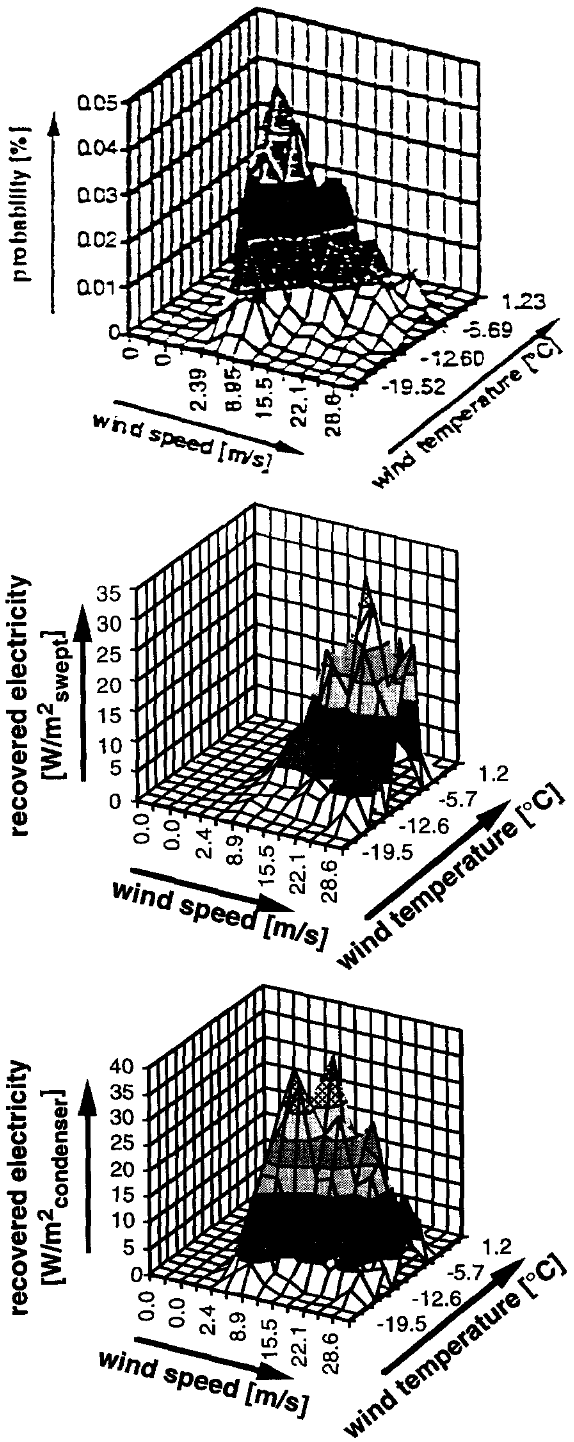

Figure 11. The second cold wind fluxmeter with a bundle of finned tubes. **a.** Occurancy of speed/temperature for wind (DDU in March). **b.** Occurancy and distribution of recovered electricity by a bi-pale, horizontal windgenerator (DDU in March). **c.** Occurancy and distribution of recovered electricity by a Rankine cycle using waste water at 20 °C (DDU in March).

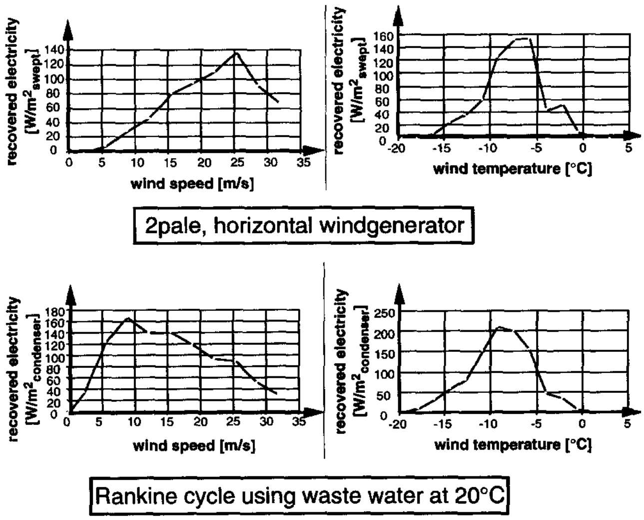

Figure 12. Distributions of recovered electricity.

waste water is mostly used to preheat in the drinking water production process. But waste water could be possibly found on industrial (polar) sites as in the large paper industries of Northern Canada, for example.

By integration of the distributions we obtain the mean decade values, as shown in *figure 13* for both test sites.

7. CONCLUSIONS

The provision of energy to polar stations using conventional fossil fuels is costly, difficult logistically and has significant environmental impacts. This makes any improvement of energy systems at the stations far more cost-effective than at 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.

Researching and implementing clean and efficient alternative energy systems in polar regions could have an invaluable role in perfecting and demonstrating promising systems to be used around the world. Among such systems, thermal machines could play an important and valuable role. And the thermal dipole of the cold polar wind and the "warm" sea water could bear more potential if using as heat source lake-water or waste water with temperatures higher than sea water. However the use of a waste water will mean that we have to give up our idea of the "real" renewable energy resource...

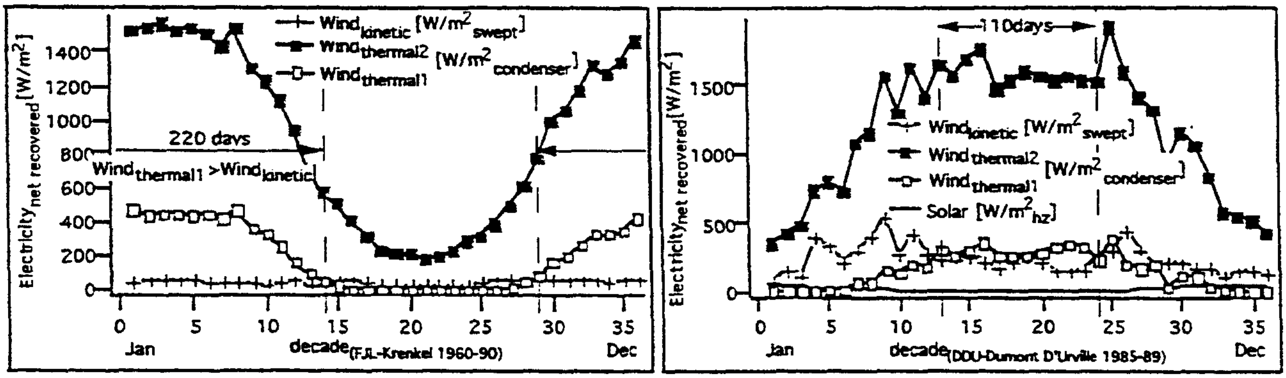

Figure 13. Recovered electricity for FJL and DDU.

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