TECHNICAL AND ECONOMIC EVALUATION OF THE UTILISATION OF SOLAR ENERGY AT THE SANAE IV BASE IN ANTARCTICA

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4 INTRODUCTION

The objectives for this research project were described in the SACAR 1 project proposal of 2003. In the proposal it was stated that,

"A significant component of supplies taken annually to the base [SANAE IV] *is the fuel for the diesel generators. Currently crude oil prices are experiencing a 20-year high price level. Adding the logistics involved in conveying the fuel to the base, the energy costs of operating the base are therefore high.*

World wide significant development in solar energy takes place. Eskom has recently completed the prefeasibility study for a solar thermal power station in the Northern Cape. The relevance of this to SANAE is that solar energy for heat and power generation technology is developing at an associated high rate and reached a level of maturity in certain methodologies. It seems therefore an appropriate moment in time to investigate the technical and economic feasibility of installing solar collectors at SANAE IV. This is the purpose of this study.

Climatic concerns relating to the impact of CO2 production from hydrocarbon combustion is increasing. An environmental research station would be the ideal candidate to demonstrate responsible employment of renewable energy technology."

In 1991 during the XIth Antarctic Treaty Special Consultative Meeting (ATSCM) a decision was made to adopt the Madrid Protocol to the Antarctic Treaty. Essentially this protocol states that signatories to the Treaty are *"…convinced of the need to enhance the protection of the Antarctic environment and dependent and associated ecosystems"* (Madrid Protocol, 1991). Furthermore it is stated in the Protocol that, *"The Parties commit themselves to the comprehensive protection of the Antarctic environment and dependent and associated ecosystems and hereby designate Antarctica as a natural reserve, devoted to peace and science."* And so it was established during this XIth ATSCM that *"…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* [should be investigated]" (Steel, 1993, emphasis added).

Thus, projected against the background of potential benefits to the entire SANAP programme, the suggestions of the XIth ATSCM stated above embody the aims of this project. That is; to investigate the feasibility, and sensibility, of harnessing solar energy incident at SANAE IV in an endeavour to reduce financial and environmental costs while carrying out operations in a responsible manner. This is by no means a novel idea, and America, Australia, Japan, Spain and Sweden have all installed solar energy systems at their bases, while Australia, Germany and Sweden are further investigating the possibility of installing hybrid solar and wind-powered hydrogen fuel cell systems. Note that Teetz (2002) has already investigated the feasibility of installing a wind turbine at SANAE IV and concluded that it would be very advantageous to do so, thus it now remains only to arrange the proper funding for purchasing and installing the appropriate machinery. Currently America, Argentina, Australia, Germany, India, Japan, Spain and Sweden are all currently utilising wind energy. In fact, the Australian Mawson base set itself and achieved the target of generating an unprecedented 80 % of its energy demand from wind power. Many countries have realised the advantages of running effectively, and efficiently, not only in these remote locations, but also back home.

4.1 History of the Project

Prior to this investigation four projects focusing on the improvement of the SANAE IV energy systems had already been undertaken from the Department of Mechanical Engineering at the University of Stellenbosch. These projects, completed by Teetz (2000 and 2002), Cencelli (2002) and Taylor et al. (2002) went about investigating: the heating and ventilation system of the base, the feasibility of utilizing wind energy at South Africa's Antarctic station, an energy audit of SANAE IV and the impact of the diesel engines on the Antarctic environment respectively. From each of these previous studies valuable information regarding the energy consumption and system operation of the base was obtained for the current project, and thus, in many ways, this study should be viewed as a continuation of their work.

Yet research on the use of solar energy in Antarctica has been undertaken internationally for some time already in an attempt to increase the energy autonomy of stations, reduce operating costs, and protect the environment. Thus, this project has also drawn from past international studies that focus on the application of solar energy in Antarctica. In this regard useful data was obtained from the Australian Antarctic Division (AAD) whom have not only been involved in researching the feasibility of utilizing solar energy in Antarctica since 1993, but are also responsible for installing the only solar thermal device currently operational on the continent (at the Australian Davis Station). An investigation carried out at the Swedish WASA station (Henryson et al., 2004) also provided useful information.

All of these endeavours are encouraged by the terms of the Protocol on Environmental Protection to the Antarctic Treaty (the Madrid Protocol, 1991). For this reason the Council of Managers of National Antarctica Programs (COMNAP) also supports this work, and helps to disseminate information regarding renewable resources to other countries via its website and during meetings. The Council encourages countries to implement wind and solar energy systems in order to reduce the impact of the relevant Antarctic Programmes. Thus, although this field of study has been well researched to date by a number of organisations, it appears to be increasing in significance and relevance into the future.

4.2 Objectives of the Project

This project aimed, very simply, to evaluate the technical and economic feasibility of utilising solar energy at SANAE IV. In order to complete this four focus-questions were asked that together provided an answer to the feasibility of utilising this resource at South Africa's Antarctic station (please refer to KEY QUESTIONS in section 5 below). Ultimately these questions investigated: how much solar energy is available for use at SANAE IV (both quantitively and on a temporal scale), how much energy the base consumes (in what types and at what times), what devices could be utilized to harness the solar energy, and finally an estimate of how much the system would cost. Accordingly, the project was divided into the following chapters:

- Chapter 1 – Introduction
- Chapter 2 – Available Solar Energy at SANAE IV in Antarctica
- Chapter 3 – SANAE IV Energy Demand
- Chapter 4 – Energy Capturing Solutions
- Chapter 5 – Economic Analysis
- Chapter 6 – Conclusion

4.3 Financial Support

This project was funded for the first twelve months by the South African Department of Environmental Affairs and Tourism (DEAT), while the second twelve months was sponsored by a constituent of the Department of Science and Technology (DST), namely the National Research Foundation (NRF). The total funding for this project amounted to R30 000 for the first year, and R40 000 for the second year. The researcher, who made the field trip to the SANAE IV base from December 2004 to February 2005, was equipped with clothes and provided with subsistence by the Directorate for the Antarctic and Islands, while the University of Stellenbosch funded all the instrumentation and equipment required (including pyranometers, data loggers, cables, computer, shade ring and tools).

5 KEY QUESTIONS

As discussed in section 4.2 above the four key questions to this project were:

I. How much solar energy is available for use at SANAE IV, both quantitively and on a temporal scale?

II. How much energy the base consumes, in what types, at what times and in what amounts?

III. What devices could be used to harness solar energy at SANAE IV?

IV. What the expected payback periods, internal rates of return, and benefit/cost ratios of the suggested courses of action are?

6 SUMMARY OF FINDINGS

6.1 Available Solar Energy at SANAE IV in Antarctica

The solar radiation levels at SANAE IV were investigated using four different methods. These methods were namely: a study of NASA's global Solar Radiation and Surface Energy (SSE) dataset for the location of SANAE IV, investigation of radiation data recorded by the author during the 2004/2005 takeover expedition, consideration of various theoretical approaches to define available solar at a given location, and an investigation of data from surrounding and other research stations (viz. Neumeyer, WASA and Dumont d'Urville). The results of this investigation included the information shown in figures 1 and 2, and table 1 below.

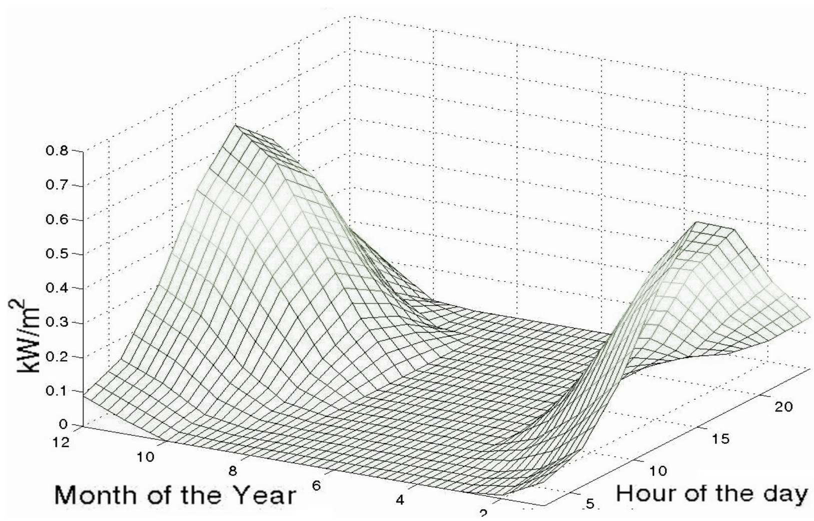

Figure 1: SSE Dataset values for the location of SANAE IV

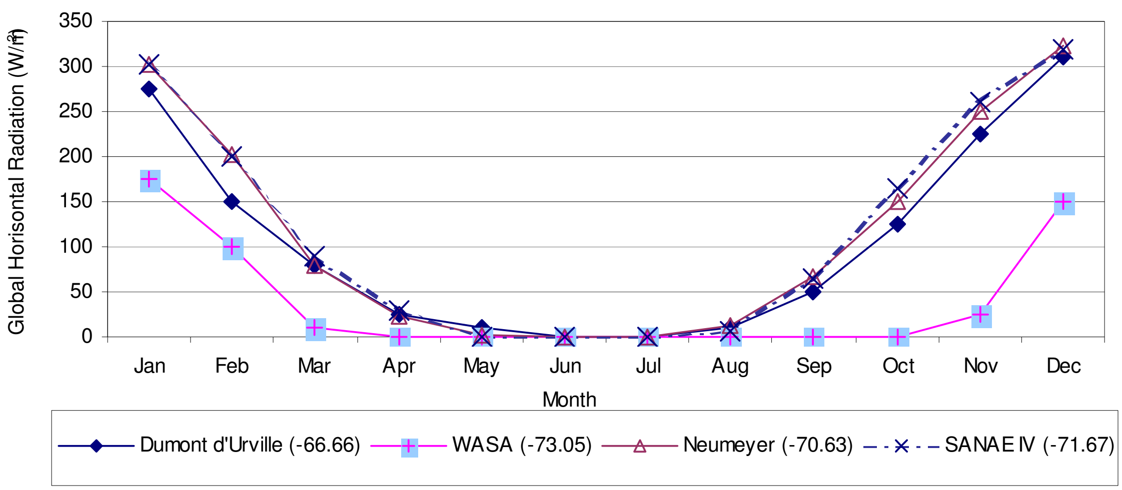

Figure 2: The estimated average insolation rates at SANAE IV compared to other Antarctic stations

Once insolation rates had been established for a horisontal surface the calculation of available radiation on tilted surfaces was investigated utilizing the Perez et al. (1988) model. This model accounts for horizon brightening, reflected components of radiation (from the snow for instance) and circumsolar radiation. The results (including the established values of global horisontal radiation) are given in the table below.

Table 1: Expected values of radiation at SANAE IV at horisontal and optimally tilted orientations

MONTH	GLOBAL HORISONTAL INSOLATION (kWh/m^2.day)	HORISONTAL BEAM INSOLATION (kWh/m^2.day)	OPTIMUM GLOBAL TILT (°)	OPTIMUM BEAM TILT (°)	GLOBAL TILTED INSOLATION (kWh/m^2.day)	TITLED BEAM INSOLATION (kWh/m^2.day)	AVERAGE TEMP (°C)
January	7.26	2.92	52	39	8.05	3.54	-6.6
February	4.78	1.88	63	53	6.11	2.99	-10.3
March	2.13	0.74	74	68	3.51	1.99	-14.9
April	0.72	0.26	84	83	2.54	2.12	-18.2
May	0.01	0.01	90	90	0.01	0.00	-19.5
June	0.00	0.00	00	00	0.00	0.00	-20.1
July	0.00	0.00	00	00	0.00	0.00	-23.1
August	0.17	0.06	88	87	1.24	1.13	-22.9
September	1.53	0.59	78	75	3.23	2.21	-22.9
October	3.93	1.49	69	68	6.86	3.78	-18.2
November	6.23	2.47	52	44	7.14	3.18	-12.8
December	7.63	3.09	48	35	8.30	3.55	-7.1
Average	*2.87*	*1.13*	*70*	*64*	*3.92*	*2.04*	*-16.4*

The estimated values of radiation on tilted surfaces from table 1 were also compared to measured data, and although only a small set of measurements was available from the 2004/2005 takeover expedition results showed good correlations. An example of these results for a clear-sky day at SANAE IV is given in the following figure.

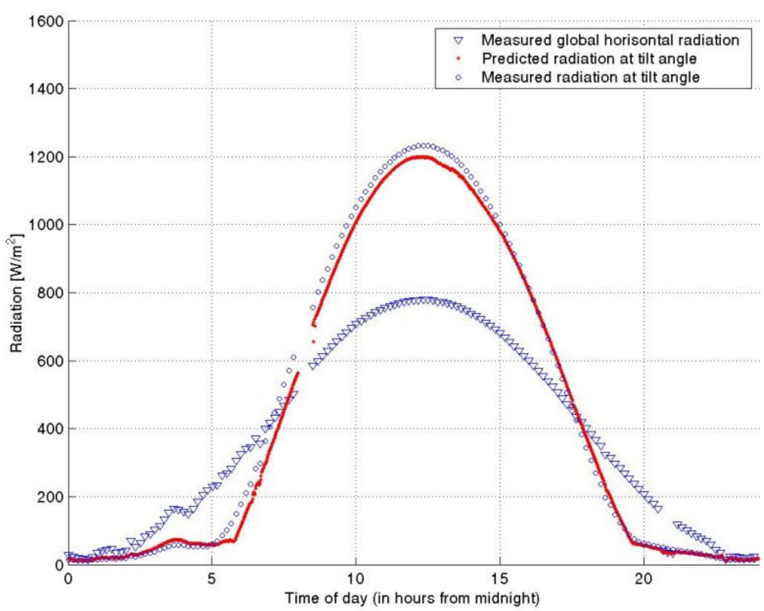

Figure 3: Predicted and measured values of radiation on tilted surfaces

6.2 SANAE IV Energy Demand

Annual diesel demand at SANAE IV amounts to approximately 346 594 litres, of which 297 244 litres is used by the generators for creating electricity and the remainder is used for refuelling the fleet of diesel-powered vehicles. Small amounts of petrol and jet-fuel are also required at the station to power Skidoos and aircraft respectively, a demand that totals in the region of 5 % of the overall fuel consumption at the station with diesel making up the difference. On average the base consumes 2856 kWh each day (a value that will be shown to have a fair amount of activity related and seasonal dependence) with estimated maximum and minimum values of 5160 kWh and 1440 kWh respectively. Collected data are shown in figure 4 and table 2 below.

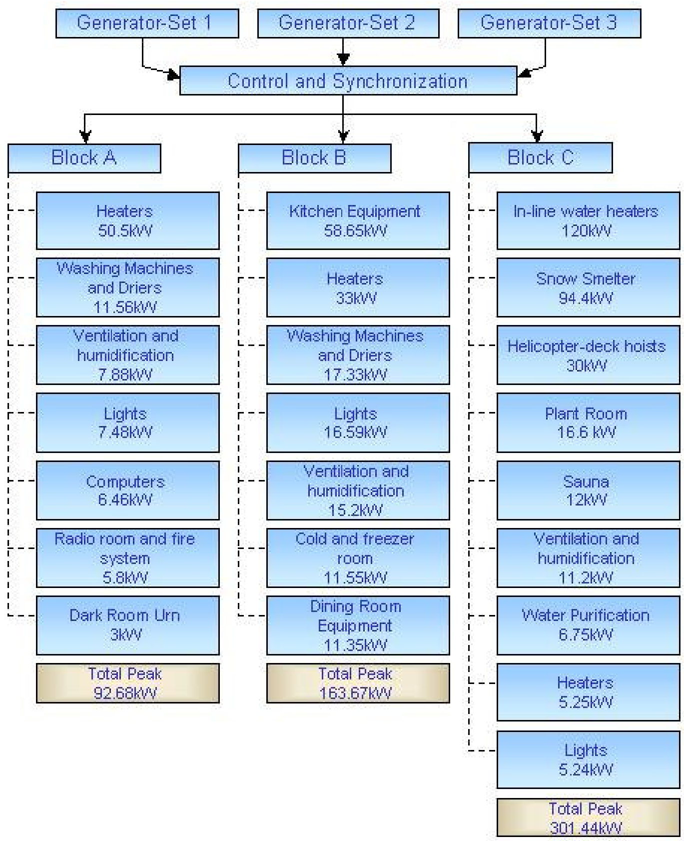

Figure 4: Peak power demand breakdown of all electrical energy consumers

Table 2: Electricity consumption data, 2005

PARAMETER	TOTAL
Five-Year Average Annual Electricity Consumption (kWh)	1 061 971
Expected Maximum Daily Electricity Consumption (kWh)$^{\Psi}$	5 160
Expected Minimum Daily Electricity Consumption (kWh)$^{\Psi}$	1 440
Average Daily Electricity Consumption (kWh)	2 910
Average Daily Electricity Load (kW)	121.2

$^{\Psi}$Taken from Teetz (2002)

A load profile was created from measurements of electrical consumption at the base to determine the match between available solar energy and the station's demand. Due to the high variability of energy consumption it was necessary to construct the curve shown in figure 5. This base load curve represents historical minima, or loads that should always be exceeded. It is evident, therefore that the rate of energy consumption is in the order of 60 kW.

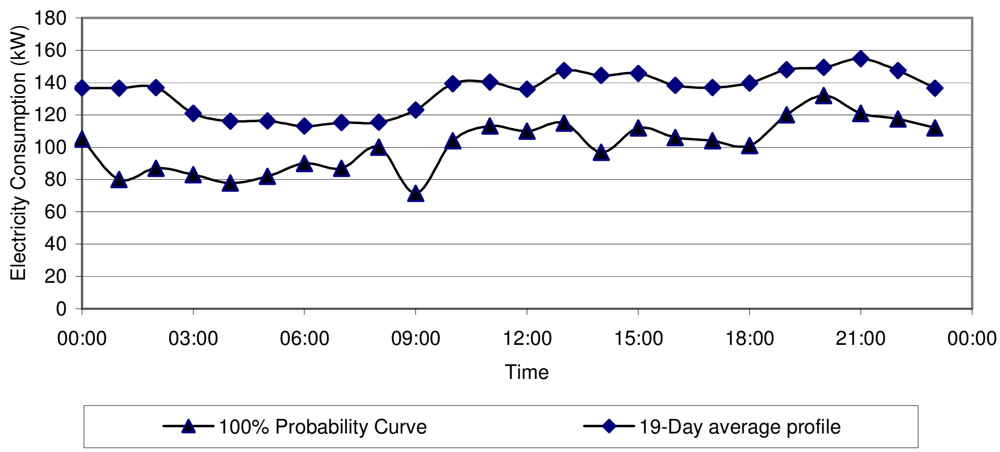

Figure 5: Minimum electrical loads expected at SANAE IV

A useful correlation relating the station's electrical energy production to the generator's diesel fuel consumption was also refined, and is given in equation 4.1.

$$PP = 3.5652 \cdot FC - 2.5683 \qquad \textit{6.1}$$

In this equation PP is the base's electrical production in kWh, FC is the generator diesel consumption in litres and the regression coefficient for the equation is 0.99.

Mainly this section of the project investigated the operational condition of all the energy systems currently being utilized at SANAE IV, specifying the amounts of energy as well as the type of energy (viz. electrical or thermal) required by each system. Suggestions for possible improvements to some of these systems were also made and will be discussed here briefly (refer to section 8.2 in this document). Notably, difficulties with PLC control (c.f. section 3.2.5 [Olivier, 2005]) and plant room temperatures (c.f. section 3.2.4 [Olivier, 2005]) during the summer takeover period, as well as thermal heat losses from the station to the environment (c.f. end of section 3.3 [Olivier, 2005]) were discussed. Most importantly, however, from this investigation of the current station energy demand two loads most suited to solar energy applications were identified, those being the snow smelter, and the stations electrical mini-grid.

It is suggested that an effort is made to implement the changes discussed above before undertaking to install a solar or other renewable energy device. The large amounts of capital and effort that will go into commissioning a renewable energy system at SANAE IV could best be justified if firstly, the station is not wasting or poorly utilising energy, and secondly, all of the most significant shortcomings have been addressed (Pareto's Principle).

6.3 Energy Capturing Solutions

In any solar energy system commissioned at SANAE IV the energy received from the sun will ultimately undergo a number of processes before it is finally utilised. Figure 6 below illustrates some of these stages, and was used as a starting point to study the individual characteristics of these stages. Referring to figure 6, the available solar insolation was estimated in chapter 2 [Olivier, 2005], and the energy demand of South Africa's base was studied in chapter 3 [Olivier, 2005], thus it remained in the current section (chapter 4 [Olivier, 2005]) only to investigate the characteristics of the individual solar energy devices.

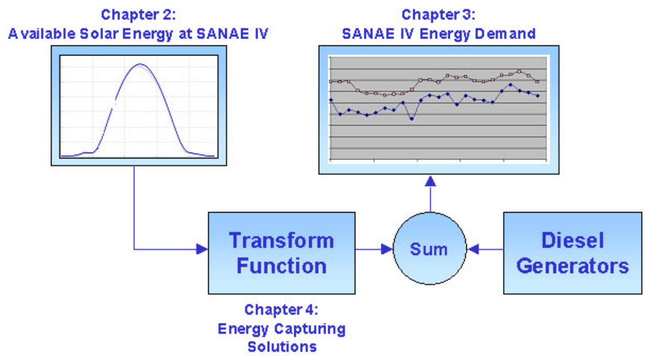

Figure 6: SANAE IV solar energy system

The two solar-energy capturing devices investigated for use at SANAE IV were photovoltaic panels and solar thermal collectors. In the instance of photovoltaic devices the methodology presented by RETScreen was used as the benchmark of further investigation since apart from the quality of the organisations supporting and developing the RETScreen tool there is also useful software available from this organisation for investigating the feasibility of renewable energy projects. Thus, the annual averages of the expected amounts of energy that could be captured with solar electric devices were estimated and are presented here in table 3.

Table 3: Expected efficiencies and daily energy capture from different PV technologies

			MONO-CRYSTALLINE		POLY-CRYSTALLINE		THIN FILM	
	Average Temp (°C)	***kWh/m² Available***	*Average Efficiency*	*kWh/m² Captured*	*Average Efficiency*	*kWh/m² Captured*	*Average Efficiency*	*kWh/m² Captured*
January	*-6.60*	*8.05*	13.81	1.11	11.51	0.93	5.99	0.48
February	*-10.30*	*6.11*	14.01	0.86	11.68	0.71	6.07	0.37
March	*-14.90*	*3.51*	14.26	0.50	11.88	0.42	6.18	0.22
April	*-18.20*	*2.54*	14.43	0.37	12.03	0.31	6.25	0.16
May	*-19.50*	*0.01*	14.50	0.00	12.09	0.00	6.29	0.00
June	*-20.10*	*0.00*	14.54	0.00	12.11	0.00	6.30	0.00
July	*-23.10*	*0.00*	14.70	0.00	12.25	0.00	6.37	0.00
August	*-22.90*	*1.24*	14.69	0.18	12.24	0.15	6.36	0.08
September	*-22.90*	*3.23*	14.69	0.47	12.24	0.40	6.36	0.21
October	*-18.20*	*6.86*	14.43	0.99	12.03	0.83	6.25	0.43
November	*-12.80*	*7.14*	14.14	1.01	11.79	0.84	6.13	0.44
December	*-7.10*	*8.30*	13.84	1.15	11.53	0.96	6.00	0.50
Average	***-16.40***	***3.92***	***14.34***	***0.56***	***11.95***	***0.47***	***6.21***	***0.24***

It was reasoned that the most simple and convenient solar thermal solution for the case of SANAE IV was the flat plate solar collector. Such a collector will not only operate at lower process temperatures, but also be less susceptible to wind related efficiency losses or damage, utilise both the beam and diffuse components of radiation, allow for easier maintenance and is manufactured locally. This result seems to correlate well with the current research being carried out by the Australian Antarctic Division that have installed a flat plate collector in Antarctica (the only solar thermal device currently operational on the continent), and. found that for these devices optimally tilted as opposed to tracking panels are the most economical solution for harnessing solar energy in Antarctica (AAD, 2005).

Consequently, a simulation program was written to investigate the savings that could be expected from such a system taking into account varying solar insolation rates as well as the estimated temperatures inside the snow smelter which have a marked impact on the efficiencies of the flat plate solar collectors (since the solar collector's main task is to exchange heat with this system, and higher collector inlet temperatures lead to greater losses).

The results of the simulation are given below in table 4, and indicate expected electrical savings that could potentially be generated. These are achieved by adding a flat plate solar collector system in parallel with the snow smelter at SANAE IV, while simultaneously altering the smelter's response time (the compulsory delay time between switching the smelter's heating elements off) and maximum temperature (the temperature at which heating elements begin switching off).

Table 4: Savings generated at snow smelter from collector systems

DAILY SAVINGS (kWh)												
Collector Size	**MEDIUM (24 PANELS)**						**LARGE (72 PANELS)**					
Tresponse (min)	*30*	*10*	*30*	*10*	*30*	*10*	*30*	*10*	*30*	*10*	*30*	*10*
Tmax (Deg C)	*30*	*30*	*20*	*20*	*10*	*10*	*30*	*30*	*20*	*20*	*10*	*10*
January	87	150	97	160	109	178	251	284	356	407	402	515
February	60	99	70	109	69	118	182	217	218	108	315	383
March	35	51	259	106	133	140	180	116	433	208	413	273
April	12	17	176	95	133	122	120	60	262	151	289	232
May	0	0	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	0	0
September	12	17	176	95	133	122	180	116	433	208	413	273
October	35	51	259	106	133	140	120	60	262	151	289	232
November	291	154	438	242	309	288	527	388	735	506	586	537
December	328	201	520	291	367	309	632	547	832	615	635	554
Average	*72*	*62*	*166*	*100*	*116*	*118*	*183*	*149*	*294*	*196*	*279*	*250*

6.4 Economic Analysis

The economic evaluation of solar thermal and PV systems investigated here will largely determine the feasibility of utilising solar energy at South Africa's SANAE IV base in Antarctic. Of course, it remains essential to include the implications of less tangible criteria such as pollution and emissions, yet these have already been carefully studied and quantified in a number of similar research projects (such as Isherwood et al., 1999).

The basic methodology of the economic evaluation was taken from the report created by DEAT entitled "*Cost Benefit Analysis*" (DEAT, 2005) that stipulates the manner in which projects that fall under the umbrella of their administration should be undertaken. Consequently the ensuing economic analysis is grounded in the information provided by DEAT, and uses quantitative values that are taken from a number of other resources.

Significant difficulties were encountered in forecasting the fuel prices of the future, and consequently a sensitivity analysis was conducted using low, medium and high price projections. In this regard "*The Assessment: The New Energy Paradigm*" (Helm, 2005) and the International Energy Agency (IEA) proved to be particularly helpful resources in projecting the possible future scenarios.

Thus, the ensuing graphs illustrate the estimated Net Present Values (NPV's) of the suggested solar energy systems (for both photovoltaic and solar thermal devices in figure 7 and figure 8 respectively) at various hurdle rates (otherwise referred to as Minimum Attractive Rates of Return or MARR). Also note that in some instances the effect of externalities (that is, the environmental savings of the suggested system quantified in monetary values) on the NPV of the system costs are also included in the figures. According to the analysis protocol supplied by DEAT (2005) concerning the proper methodology for evaluating these systems the plot representing the NPV of the systems at an 8 % hurdle rate, including the effect of environmental savings is the strongest indication of expected payback periods. Note that all values are given in *real* terms relative to 2005 Rand values.

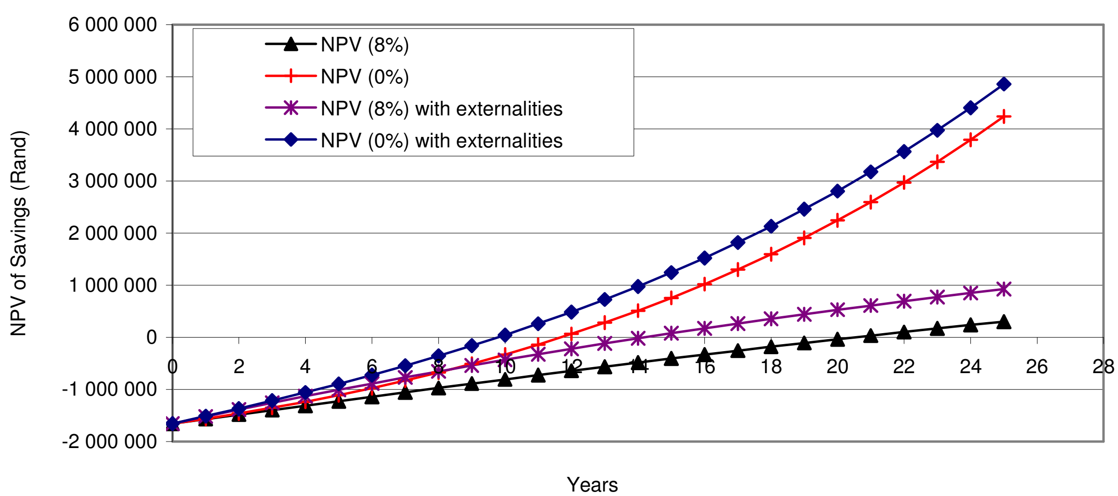

Figure 7: NPV of the difference between the costs of the two alternatives (diesel only and hybrid diesel/photovoltaic)

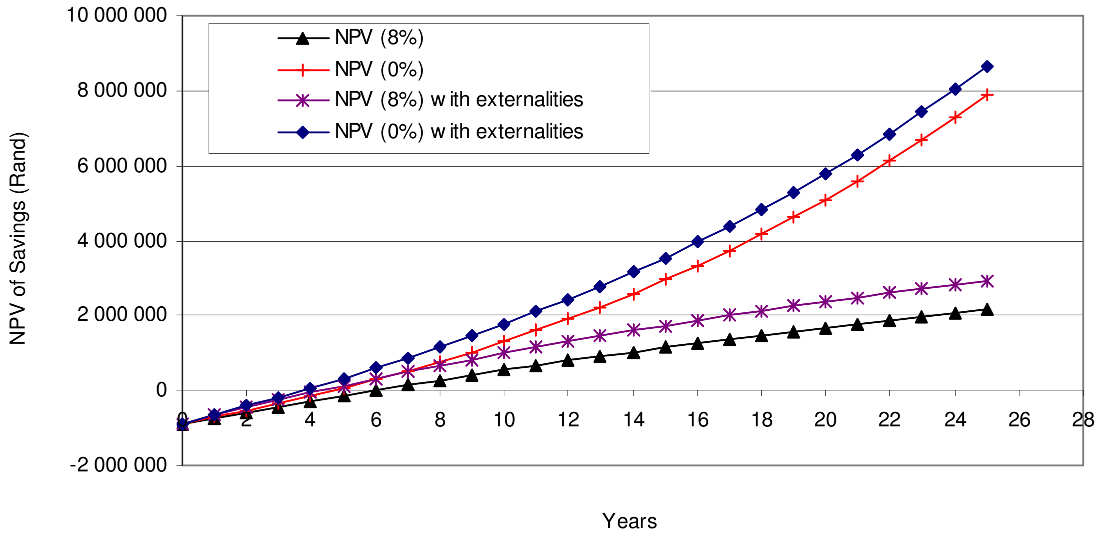

Figure 8: NPV of the difference between the costs of the two alternatives (diesel only and hybrid diesel/solar-thermal)

Due to the difficulty of predicting criteria such as fuel price escalation rates and fair MARR's the performances of the PV and solar thermal systems under various conditions have been given in table 5. These values serve as an indication of the systems' financial resilience, and should be used to judge the risk involved with each financial opportunity. Included in this table are Internal Rates of Return (IRR), Net Annual Worth (NAW) and Benefit/Cost Ratios (B/C Ratios).

Table 5: Financial outcomes under various economic conditions

	SOLAR PHOTOVOLTAIC			SOLAR THERMAL		
MARR				*8%*		
Fuel Price Escalation	*7 %*	*5 %*	*3 %*	*7 %*	*5 %*	*3 %*
Breakeven period (years)	16	21	n/a	6	6	7
IRR (%)	12	10	7	27	24	22
NAW (Rand after 25 years)	91 037	26 907	-21 335	269 729	190 873	131 554
NPV (Rand after 25 years)	1 024 882	302 915	-240 183	3 036 554	2 148 811	1 481 007
B/C (after 25 years)	1.40	1.10	0.90	3.25	2.50	2.00
MARR				*4 %*		
Fuel Price Escalation	*7 %*	*5 %*	*3 %*	*7 %*	*5 %*	*3 %*
Breakeven period (years)	13	15	18	5	5	6
IRR (%)	12	10	7	27	25	22
NAW (Rand after 25 years)	170 969	91 622	33 498	330 651	233 083	161 614
NPV (Rand after 25 years)	2 956 406	1 584 322	579 252	5 717 633	4 030 493	2 794 640
B/C (after 25 years)	2.00	1.50	1.20	4.75	3.50	2.75

7 CONCLUSION

At the start of this project five questions were posed that together would determine the technical and economic feasibility of utilising solar energy at South Africa's SANAE IV station in Antarctica (refer to chapter 1 [Olivier, 2005]). Subsequently these questions have been addressed in their respective chapters and the necessary information obtained from each. Results have been compared to relevant sources (and where applicable also to measured data obtained during the 2004/2005 takeover at SANAE IV), and various financial outcomes have been considered resulting from different economic scenarios. At the conclusion to this analysis it is therefore possible to present an answer that collates the information obtained, and suggests a future course of action regarding the installation of solar energy devices.

From chapter 2 [Olivier, 2005] the annual-average global horizontal insolation at SANAE IV was found to be relatively low (2.87 kWh/m^2.day, or 10.33 MJ/m^2) compared to other locations around the globe. It was also characterised by large seasonal fluctuations and large components of diffuse radiation. Except for clear-sky days when tilted surfaces may be exposed to radiation of up to 1300 W/m^2, diffuse radiation contributed to an estimated 1.74 kWh/m^2.day (or approximately 60 %) of the annual average global radiation. Nonetheless, estimates of radiation at SANAE IV during the year lie very close to the conditions at its closest neighbour, the German Neumeyer station. The required collector tilt angles are also relatively high, starting at 50° in the peak of summer and increasing to 90° in the winter, making it difficult to design small and compact collector fields. Due to the high tilt angles it is not possible to place collectors directly behind each other.

From investigating the energy consumption of SANAE IV in chapter 3 [Olivier, 2005] the station's electrical mini-grid and snow smelter were highlighted as favourable electrical and thermal loads for the application of renewable energy systems. In the context of the difficulties synonymous with generating electricity during the summer takeover period these systems would be particularly advantageous. During this time the generators are prone to overheating, even disrupting normal grid operation, and there is a restricted supply of fresh water to the base from the snow smelter. These loads present opportunities to gain doubly by implementing a solar energy system. Firstly, by generating financial savings, but secondly, by releasing some of the pressure placed on the station's energy systems during the summer months.

It was calculated that under ideal assumptions the snow smelter would consume approximately 820 kWh each day during the takeover period (when base population totals approximately 80 people) while creating fresh water. However, as shown later if heat losses and the snow smelter PLC logic are accounted for the actual value is more than double this amount. The consequent load on the generators required for the snow smelter is therefore on average in the order of 34 to 68 kW, with peaks that could reach up to 94 kW during the day.

The electrical mini-grid is characterised by large daily demand fluctuations making it unreasonable to use an average daily load profile as a method of approximating demand during the summer period. It is important to account for the high load-profile variability when matching a renewable energy system to the demand at the station. From this study the base load of SANAE IV was calculated as 60 kW, and thus, a PV system with a rated power smaller than this size was investigated (viz. a 40 kW system).

Emphasis is here again placed on the suggestion that was made in this chapter to improve the working computer simulation model of all the energy systems at the station. This would result in a number of benefits, but particularly it would help to better understand the effect that any suggested changes will have on the station by accounting for the complex interaction of all existing systems in a way that simple calculations cannot. Furthermore, it would also make the identification of savings opportunities at the station much easier.

In section 3.2.4 [Olivier, 2005] it was recommended that additional methods of supplying fresh air to the plant-room should be investigated. Any added contribution of fresh air to the room would noticeably improve the working conditions during the summer.

In chapter 4 [Olivier, 2005] the behaviour of the suggested PV and solar thermal collectors were investigated. Although the purchase of photovoltaic panels in South Africa poses no problems for the implementation of a solar energy system at SANAE IV it was more difficult to find suitable locally manufactured solar thermal devices. By far the least complicated of these thermal systems is the flat-plate collector, a choice supported by considering the low ambient temperatures, high fractions of diffuse radiation and the collector tracker device reliability for instance. On this basis a flat-plate solar collector was selected for further investigation and an economic analysis performed.

For the PV system some difficulty was encountered in establishing what type of inverter is most suitable for use at the base. Even though there are currently no acceptable products for purchase in South Africa oversees markets manufacture three-phase grid-tie inverters that automatically lock onto and feed into an existing grid. Since the generators at SANAE IV output electrical energy at three-phase, 380 VAC and 50 Hz there is no problem in obtaining an inverter that would supply electrical energy at these standard values.

Using this information it was established in chapter 5 [Olivier, 2005] that a 40 kW PV system could save as much as 10 000 litres of fuel annually, and that during the same amount of time a solar thermal system (with 72 collector panels) supplementing the snow smelter could save 12 245 litres of fuel. The solar thermal collector system has a lower capital expense, thus it is not surprising that of these two options this is also financially more secure. Maintenance and installation for such a system would be slightly more significant, yet still very possible within the scope of work completed by the summer takeover maintenance crew.

The payback period for the thermal collector system was estimated at 6 years under the standard investment assumptions, although under more favourable conditions (high fuel price escalation rates and a lower MARR) this amount of time could be reduced to a 5-year horizon. The system, which would realize an IRR of 25 %, and a NPV of R 2 148 811 after 25 years, is therefore an attractive investment. The PV system, on the other hand, would only be able to break even towards the end of the project lifetime, however, under the more ideal conditions of high fuel price escalation rates, lower MARRs, low attractiveness of other investment opportunities and a stronger emphasis on environmental considerations a breakeven point could potentially be realised within 13-16 years.

It should be noted, however, that a PV system is capable of reducing the size of peak electrical loads on the generators while a solar thermal device is only able to shorten the length of these peaks. Thus each system must be evaluated on its own merits, and presents its own unique benefits.

It is clear that there is ample scope for the utilisation of solar energy at South Africa's SANAE IV station in Antarctica. The suggested solar energy systems present good opportunities for reducing station load and improving living conditions during the summer, and with the proper implementation can recover their initial capital investment within the project lifetime (PV only towards the end of the project lifetime, and solar thermal more certainly within 6 years). Although these systems may seem large it should be remembered that they could be scaled to smaller versions of those suggested, and that under these conditions they would most likely recover their capital investment in an amount of time similar to that identified here.

It is recommended that an assessment of available funds be made within DEAT in order to establish what financial resources are available for the future implementation of a renewable energy system at SANAE IV. Once it has been established under what conditions these resources could be used (i.e. lending rates and available amount) a quick refinement of the above assessment may be performed in order to re-assess the economic implications of such a decision if necessary. Over and above the direct savings and improvements which could be made, the increased awareness of global environmental change and the effect of greenhouse gasses should lend itself towards a careful consideration of the benefits that renewable energy systems offer SANAE IV.

8 *DATA AND SAMPLE STORAGE*

All data and sample storage relevant to this report can be found in,

"Olivier, JR (2005), *Technical and Economic Evaluation of the Utilisation of Solar Energy at South Africa's SANAE IV Base in Antarctica*, MSc Thesis, Department of Mechanical Engineering, University of Stellenbosch"

Which presents in further detail the work performed in this project. Data from the above reference and relevant to this report has also been included below.

8.1 Predicted Available Average Radiation at SANAE IV

Estimated average global and diffuse horisontal radiation rates at SANAE IV (in W/m^2).

For January (where x is any number from 0 to 24):

$$G = -0.0003187 \cdot x^6 + 0.024072 \cdot x^5 - 0.64063 \cdot x^4 + 6.8013 \cdot x^3 - 22.662 \cdot x^2 + 33.863 \cdot x + 6.5175 \tag{8.1}$$

$$Gd = -0.0001608 \cdot x^6 + 0.012169 \cdot x^5 - 0.32434 \cdot x^4 + 3.4278 \cdot x^3 - 11.02 \cdot x^2 + 16.759 \cdot x + 11.998 \tag{8.2}$$

For February (where x is any number from 3.493 to 21.360):

$$G = -0.0012182 \cdot x^6 + 0.090864 \cdot x^5 - 2.5999 \cdot x^4 + 35.673 \cdot x^3 - 245.63 \cdot x^2 + 866.61 \cdot x - 1219.3 \tag{8.3}$$

$$Gd = -0.0007333 \cdot x^6 + 0.054576 \cdot x^5 - 1.5697 \cdot x^4 + 21.958 \cdot x^3 - 158.09 \cdot x^2 + 597.99 \cdot x - 899.57 \tag{8.4}$$

For March (where x is any number from 5.860 to 18.760):

$$G = -0.0025561 \cdot x^5 + 0.25082 \cdot x^4 - 8.521 \cdot x^3 + 114.08 \cdot x^2 - 640.82 \cdot x + 1230.9 \tag{8.5}$$

$$Gd = -0.0012648 \cdot x^5 + 0.10078 \cdot x^4 - 2.9637 \cdot x^3 + 36.676 \cdot x^2 - 163.52 \cdot x + 193.12 \tag{8.6}$$

For April (where x is any number from 8.193 to 16.193):

$$G = -0.0026532 \cdot x^5 + 0.2618 \cdot x^4 - 8.9646 \cdot x^3 + 132.14 \cdot x^2 - 826.19 \cdot x + 1748.4 \tag{8.7}$$

$$Gd = -0.0022056 \cdot x^5 + 0.10044 \cdot x^4 - 1.6247 \cdot x^3 + 5.1313 \cdot x^2 + 115.6 \cdot x - 768.2 \tag{8.8}$$

For May (where x is any number from 10.590 to 13.657):

$$G = -8.2884\cdot 10^{-14}x^4 + 4.0637\cdot 10^{-12}\cdot x^3 - 2.483\cdot x^2 + 60.204\cdot x - 359.08 \quad 8.9$$

$$Gd = -0.0020699\cdot x^4 + 0.1488\cdot x^3 - 5.3644\cdot x^2 + 79.098\cdot x - 386.72 \quad 8.10$$

For June and July (where x is any number from 11.999 to 12.001):

$$G = 0 \quad 8.11$$

$$Gd = 0 \quad 8.12$$

For August (where x is any number from 8.867 to 15.667):

$$G = 2.3785\cdot 10^{-15}\cdot x^4 - 1.5383\cdot 10^{-13}\cdot x^3 - 3.4373\cdot x^2 + 84.331\cdot x - 477.51 \quad 8.13$$

$$Gd = -0.063729\cdot x^4 + 3.1409\cdot x^3 - 59.386\cdot x^2 + 509.44\cdot x - 1643.5 \quad 8.14$$

For September (where x is any number from 6.5582 to 17.665):

$$G = -0.0014105\cdot x^5 + 0.26263\cdot x^4 - 10.501\cdot x^3 + 162.37\cdot x^2 - 1030.1\cdot x + 2269.8 \quad 8.15$$

$$Gd = 0.06291\cdot x^4 - 2.9828\cdot x^3 + 46.624\cdot x^2 - 265.9\cdot x + 465.31 \quad 8.16$$

For October (where x is any number from 4.005 to 20.100):

$$G = -0.0015866\cdot x^6 + 0.11482\cdot x^5 - 3.2308\cdot x^4 + 44.536\cdot x^3 - 317.69\cdot x^2 + 1181.3\cdot x - 1785.9 \quad 8.17$$

$$Gd = -0.0008765\cdot x^6 + 0.06435\cdot x^5 - 1.8296\cdot x^4 + 25.799\cdot x^3 - 191.5\cdot x^2 + 751.82\cdot x - 1194.3 \quad 8.18$$

For November (where x is any number from 0 to 24):

$$G = -0.00049941\cdot x^6 + 0.035343\cdot x^5 - 0.88544\cdot x^4 + 8.9745\cdot x^3 - 29.957\cdot x^2 + 39.632\cdot x + 4.4457 \quad 8.19$$

$$Gd = -0.00025896\cdot x^6 + 0.018308\cdot x^5 - 0.45638\cdot x^4 + 4.5441\cdot x^3 - 14.133\cdot x^2 + 17.913\cdot x + 7.9901 \quad 8.20$$

For December (where x is any number from 0 to 24):

$$G = -1.6487\cdot 10^{-8}\cdot x^{10} + 1.9982\cdot 10^{-6}\cdot x^9 - 9.8769\cdot 10^{-5}\cdot x^8 + 0.0025415\cdot x^7 - ....$$

$$....0.035956\cdot x^6 + 0.27337\cdot x^5 - 1.094\cdot x^4 + 3.0168\cdot x^3 - 4.9394\cdot x^2 + 25.783\cdot x + 29.969 \quad 8.21$$

$$Gd = -3.8755 \cdot 10^{-9} \cdot x^{10} + 5.001 \cdot 10^{-7} \cdot x^{9} - 2.5358 \cdot 10^{-5} \cdot x^{8} + 0.00063774 \cdot x^{7} - ....$$

$$....0.0080792 \cdot x^{6} + 0.043821 \cdot x^{5} - 0.049655 \cdot x^{4} + 0.21121 \cdot x^{3} - 1.6514 \cdot x^{2} + 16.667 \cdot x + 25.387 \qquad 8.22$$

8.2 SANAE IV Energy Demand

The Heating and Ventilation System (H&V System) is responsible for maintaining comfortable temperatures, humidity levels and good circulation of fresh air in the base. Currently this system does not re-cycle any component of the heated air but instead uses a 100 % fresh air content, which is an expensive practice yet often utilised in applications where health concerns are significant (e.g. in operating theatres at hospitals). There are three air-handling units (AHUs) in each block that receive heat from the FCU Water System and transfer this energy to fresh air blown in from outside. By varying the speed of the AHU-fans the temperature of this air can be controlled since the amount of energy passing from the FCU Water System into the air is thus regulated. The air can therefore be heated to the exact temperature required to offset heat losses from the base and by so doing a stable temperature is maintained.

Cencelli (2002) estimates that the amount of heat lost to the surroundings during summer and winter varies between 39 kW and 72 kW respectively, reaching up to 120 kW during very cold spells. This heat loss is due to the processes of conduction through walls, radiative heat transfer and leakage through poor seals or other openings. Fortunately many appliances in the base that make up part of the electrical load serve a double utility and provide much of the required heat themselves. The remainder, however, is replenished by heating outside air to the required temperature in the FCUs as explained above. With 100 % fresh air ventilation requirements and such low ambient temperatures in Antarctica this task is energy intensive.

A quick calculation to illustrate the energy required by the FCU System to replenish heat losses is given below. Here Q is the heat load that must be met by the H&V System and ΔT is the necessary temperature difference between supply duct (at temperature T) and room conditions (at temperature T_{inside}) to meet this load at the given mass flow-rate of the air.

$$\dot{Q} = \dot{m} \cdot C_p \cdot \Delta T \qquad 8.23$$

And,

$$T = \Delta T + T_{inside} \qquad 8.24$$

Where T is the temperature of the H&V supply air. Therefore,

$$T = \frac{\dot{Q}}{\dot{m} \times C_p} + T_{inside} \qquad 8.25$$

The air leaving the FCU and moving into the supply ducts must be heated from ambient to T. The amount of energy required to do this is consequently:

$$\dot{Q}_{FCU} = \dot{m} \times C_p \times (T - T_{ambient}) \qquad 8.26$$

But we have an equation for T, therefore,

$$\dot{Q}_{FCU} = \dot{m} \times C_p ((\frac{\dot{Q}}{\dot{m} \times C_p} + T_{inside}) - T_{ambient}) \qquad 8.27$$

Using equation C.5 and values for its variables from the report by Cencelli (given in table C.1) graphs have been created and plotted in figure C.1. From the figure it is clear that most intensive part of the current system is that portion of heating required to bring the cold outside air to room temperature (the y-intercept). Consider the plot of the required FCU thermal summer contribution with 15 % re-circulation (by mass) that has also been included in the figure. A 15 % re-circulation results in a 55 % FCU energy demand reduction. Moreover a direct link with mass flow-rate and energy requirements has been found (i.e. a 10 % reduction or increase in mass flow-rate results in a corresponding 10 % reduction or increase in FCU energy requirements).

Table 6: A-Block summer conditions suggested by Cencelli (2002)

PARAMETER	SUMMER	WINTER
Estimated heat loss from base due to conduction etc. (kW)	12.6	24.1
Mass flow-rate of air through FCUs (kg/s)	3.23	1.87
Specific heat capacity of air (J/kg.K)	1008	1008
Inside temperature (°C)	22	18
Ambient Temperature (°C)	-10	-55

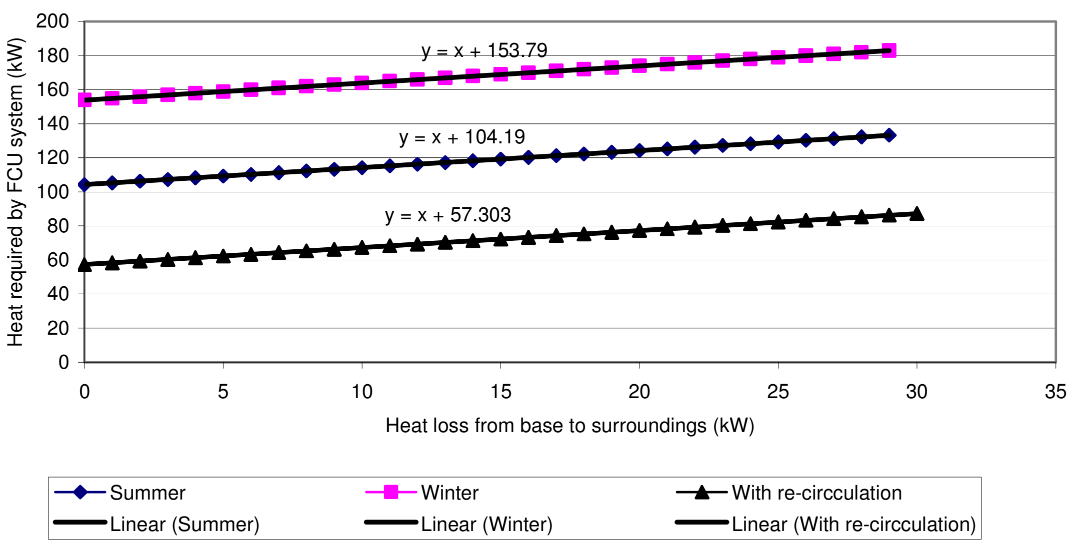

Figure 9: Contribution required by the FCUs to meet heat losses from the base

Although well suited to winter conditions the suggestion of implementing re-circulation is not practical for summer conditions. During the summertime it is necessary to use the H&V System as a method of removing heat from the station. Good flexibility can be achieved by running the current FCU-fans at a wider range of speeds in place of, as is currently the case (Cencelli, 2002), just two discreet settings. Also note that the FCU-Water System does not presently operate at its set-point temperatures and requires adjustment.

The above investigation was not meant as a comprehensive study, but rather as an introduction to the processes of the H&V System. This system is in fact very complex and changes to it should only be considered while simultaneously accounting for the resultant effects on other systems (like for instance the Primary Hot Water System). It is believed that updating the existing computer based simulation programme of SANAE IV (which is entirely separate from the station's actual control systems and simply models a number of cause and effect relationships at the base) could be very useful in investigating and improving the current performance of SANAE IV. An energy management and data capture system was once operational at the station, however, difficulties in maintaining the system's hardware have led to its decommissioning. In this instance the programme suggested and referred to is completely based in software. Utilisation of such a programme would mean, firstly, that the entire base operating system will become currently and technically documented and audited. Secondly, this exercise would result in the identification of all the best opportunities for improvements at the base, with a resultant quantification of return on investment. Thirdly, the performance of the base could be monitored constantly and potential problems would therefore be identified soon. It is the opinion of the author that together with the opportunity of ensuring that the base does not lose any heat unnecessarily to the surroundings (through unsealed openings and cracks particularly at the hangar doors, seals around windows and any unplugged cable outlets) such a simulation programme poses a significant opportunity to generate savings.

Also note that the relative humidity of the base has for a long time been unsatisfactory (Cencelli, 2002). Due to the extremely cold temperatures water vapour in Antarctica tends to freeze and settle out as snow leaving the air dry and uncomfortable. Although humidifiers are installed in all three blocks they exacerbate the problem of water shortages and are sometimes not used in the summer for this reason. However, contrary to the amounts of water they consume the 500 W of electrical energy they each require is not much. Consequently the best way to improve humidification is an indirect approach. If one could ensure a greater supply of water in the hangar then this system could be used more freely.

It is evident that the H&V System is 180 degrees "out of phase" with the availability of sunshine. During the summer there is ample heat available from the generators to keep the base warm (in fact it is necessary to cool the base) while conversely the winter periods are characterised by cold inside temperatures. With the obvious lack of sunshine during the winter periods it is evident that the Heating and Ventilation System is not an ideal application for the utilisation of solar energy.

9 LIST OF PROJECT PUBLICATIONS

- The current report to the South African Committee on Antarctic Research (SACAR)
- Article (completed as on 2006/02/01) still to be submitted to Solar Energy, a peer reviewed journal

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