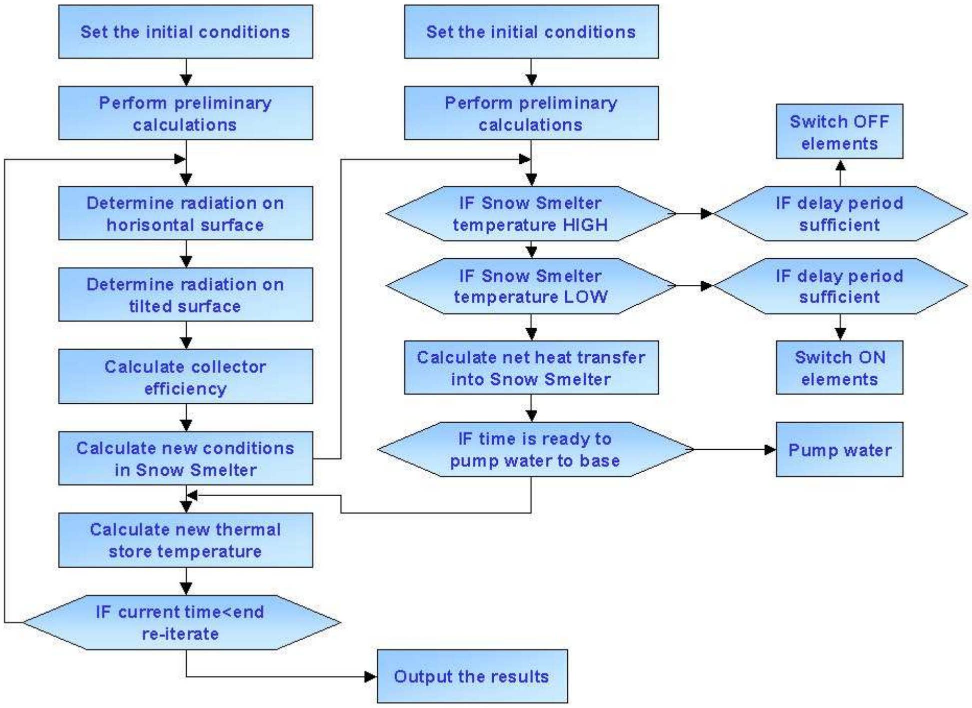

Figure 4.12: Basic logic behind snow smelter simulation programme

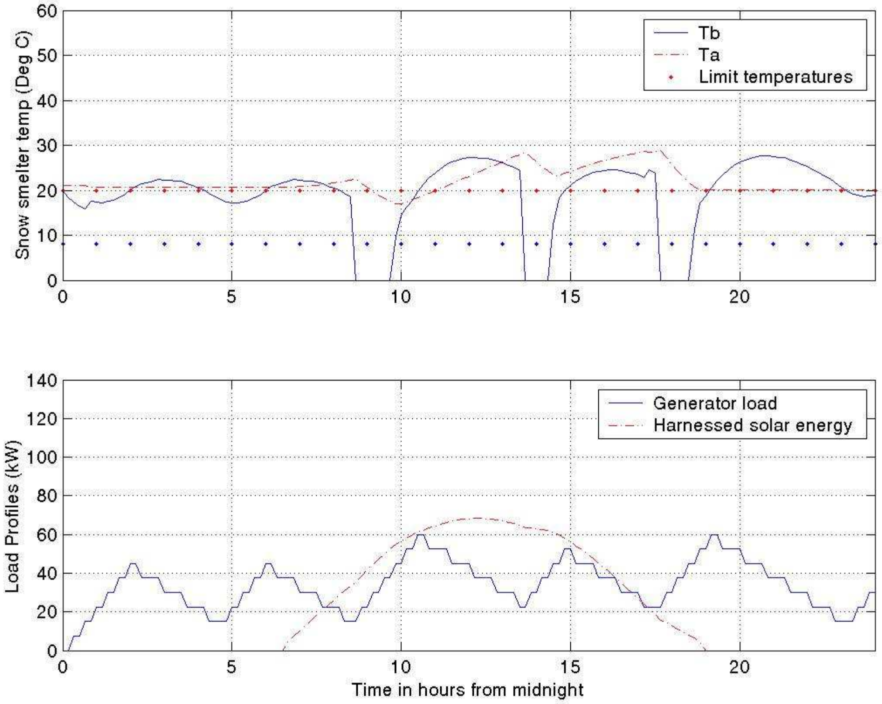

Figure 4.13: Sample results from snow smelter simulation programme

Table 4.8: Estimated daily load for snow smelter with and without Bt collector system

ESTIMATED DAILY GENERATOR LOAD FROM SNOW SMELTER (kWh/day)																		
Collector Size	**NONE (0 PANELS)**						**MEDIUM (24 PANELS)**						**LARGE (72 PANELS)**					
Tresponse (min)	*30*	*10*	*30*	*10*	*30*	*10*	*30*	*10*	*30*	*10*	*30*	*10*	*30*	*10*	*30*	*10*	*30*	*10*
Tmax (°C)	*30*	*30*	*20*	*20*	*10*	*10*	*30*	*30*	*20*	*20*	*10*	*10*	*30*	*30*	*20*	*20*	*10*	*10*
January	1715	1578	1485	1313	1318	1069	1628	1428	1388	1153	1209	891	1464	1294	1129	906	916	554
February	1715	1578	1485	1313	1318	1069	1655	1479	1415	1204	1249	951	1533	1361	1267	1205	1003	686
March	1315	1157	1115	865	663	569	1280	1106	856	759	530	429	1135	1041	682	657	250	296
April	1315	1157	1115	865	663	569	1303	1140	939	770	530	447	1195	1097	853	714	374	337
May	1315	1157	1115	865	663	569	1315	1157	1115	865	663	569	1315	1157	1115	865	663	569
June	1315	1157	1115	865	663	569	1315	1157	1115	865	663	569	1315	1157	1115	865	663	569
July	1315	1157	1115	865	663	569	1315	1157	1115	865	663	569	1315	1157	1115	865	663	569
August	1315	1157	1115	865	663	569	1315	1157	1115	865	663	569	1315	1157	1115	865	663	569
September	1315	1157	1115	865	663	569	1303	1140	939	770	530	447	1195	1097	853	714	374	337
October	1315	1157	1115	865	663	569	1280	1106	856	759	530	429	1135	1041	682	657	250	296
November	1315	1157	1115	865	663	569	1024	1003	677	623	354	281	788	769	380	359	77	32
December	1315	1157	1115	865	663	569	987	956	595	574	296	260	683	610	283	250	28	15

Table 4.9: Energy savings generated at snow smelter from Bt collector system

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 (°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*

The following points should be noted concerning tables 4.8 and 4.9. In these tables *Tmax* is the temperature at which the heating elements in the storage tank of the snow smelter are switched off (i.e. the design temperature of water in the snow smelter). The value *Tresponse* is the enforced delay time programmed into the PLC between switching heating elements off (one at a time and only after *Tmax* is reached) in minutes. The standard design values for these parameters are; *Tmax* = 30ºC and *Tresponse* = 30 minutes. Furthermore, the savings listed in table 4.9 have all been calculated with respect to each corresponding "No-Collector" column in table 4.8. In other words, savings indicate the effect of the collector system only, and not the savings achieved due to any adjustments of the snow smelter PLC logic.

The data shown in the tables above are for the Solahart Bt-Collector. The Thermomax vacuum-tube collectors slightly outperformed the Bt collectors on a cost basis (refer to appendix D.7 and table D.6), however the Bt-Collector was preferred due to its availability in South Africa. The Bt's reliability (Solahart has proven this technology in cold weather on a number of occasions), and ruggedness also played a role in selecting this device.

Because snow has a latency period while melting during which the addition of energy does not raise the temperature it is unlikely that a solar thermal collector system will be able to remove the peaks from the load profile. All heating elements in the snow smelter will switch on during filling, even if only for a short period, due to the sudden drop in water temperature. Of course the addition of solar energy would reduce the total load on the generators. Hence, only total daily energy consumption is reduced, and not the peak or maximum demands. In addition it should be noted that the simulation programme used to estimate the savings in table 4.9 could not account for local heating phenomenon around the elements that play an important role in calculating the actual, as opposed to theoretical energy consumption of the snow smelter. For instance, the fluid around the heating elements might measure 30 ºC (as well as around the PLC temperature sensor), while much of the rest of the snow smelter is still filled with snow.

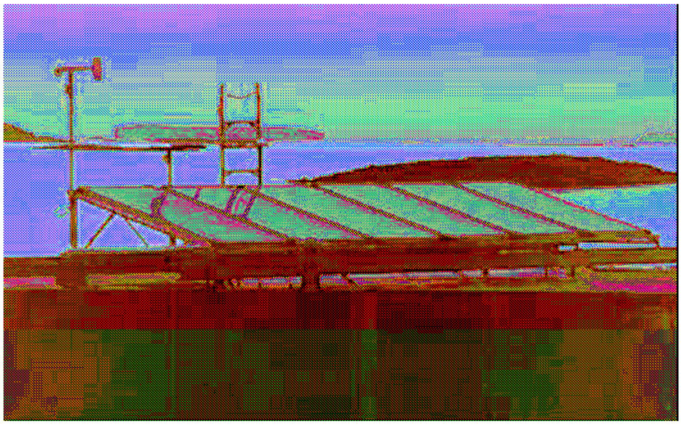

Figure 4.14: The Solahart PowerPack system installed at the Davis Station (Solahart, 2005)

4.4 Summary

In this chapter approximations of potential energy savings have been made using the expected amounts of insolation (studied in chapter 2), the nature of energy loads at SANAE IV (investigated in chapter 3) and estimates of solar energy system characteristics (calculated in chapter 4) as shown in figure 4.1. These approximations of energy savings pertain particularly to application at the station's electrical mini-grid and snow smelter as described above. It was found that photovoltaic and solar thermal collectors both present good opportunities for utilising solar energy at SANAE IV.

Notably, commissioning a PV system for use with the SANAE IV electrical mini-grid could be accomplished without utilising expensive storage equipment. The relatively large base demand of the station (60 kW) would allow a substantial system to be designed around feeding energy directly into the electrical mini-grid, which, in view of the economic results obtained in chapter 5, is very expedient.

It was found from the methodology suggested by RETScreen that mono-crystalline modules could capture solar radiation at an average efficiency of approximately 14 % (from collector to energy consumer), while it was noted from the AAD that installing tracking mechanisms is not advisable. Annual power generation savings from tilted collectors could therefore potentially reach 200 kWh/m^2.year (calculated using the information in tables 4.6 and 2.3).

Although used less readily in Antarctica than devices such as wind turbines and PV panels, solar thermal collectors presented a unique opportunity for application at SANAE IV's snow smelter. Known characteristics of three flat-plate products were used in a snow smelter simulation programme, and results from each were tabulated and compared in table 4.9 and appendix D.7. It is likely that more than 420 kWh/m^2.year could be available in thermal energy from such a system, and that further energy savings from the snow smelter could be realised by adjusting the PLC logic of this device (i.e. the set-point temperatures and pre-set delays).

Chapter 5 – Economic Analysis

5.1 Introduction

To a large extent the economic evaluation of the suggested solar thermal and PV systems is the main criteria upon which the feasibility of utilising solar energy at SANAE IV will be determined. Therefore the effect of less tangible system changes, such as those in pollution and emissions, must also be included in the study to properly account for all costs and savings in monetary terms. These *externalities* have previously been investigated and quantified for conditions similar to those at SANAE IV in research projects such as the one by Isherwood et al. (1999), and form part of this analysis.

The basic methodology of the ensuing economic evaluation is presented in the report created by the South African Department of Environmental Affairs and Tourism entitled "*Cost Benefit Analysis*" (DEAT, 2005). The report stipulates the manner in which projects that fall under the administration of DEAT should be evaluated, and as a result the ensuing economic analysis has been constructed largely from the information provided in this document. However, a number of quantitative values used in the investigation have also been obtained from other resources. Two particularly relevant publications in this regard were the articles entitled "*Towards New Energy Systems for Antarctic Stations*" authored by Guichard (1994) and the "*Technical and Economic Evaluation of the Utilisation of Wind Energy at the SANAE IV Base in Antarctica*" authored by Teetz (2002).

Significant difficulties were encountered in forecasting fuel prices for the future, and as a result a sensitivity analysis was conducted using low, medium and high price projections at the end of this chapter. In this regard information provided by Helm (2005) in "*The Assessment: The New Energy Paradigm*" and by the International Energy Agency (IEA) proved to be particularly helpful resources.

In the ensuing economic feasibility study of chapter 5 a short summary of all the project costs involved are first provided in sections 5.2 to 5.7. Following this results for the solar PV system and solar thermal systems are calculated in sections 5.8.1 and 5.8.2 respectively and lastly table 5.8 provides estimates of the financial feasibility criteria employing assumptions other than those used up to that point. Sample calculations have been presented in Appendix E.

5.2 Basic Investment Costs

The basic investment costs of the proposed energy system include all the expenditures that are required to commission the project, excluding the ancillary costs listed in section 5.3. These costs are varied and numerous, and can be categorised as follows (Teetz, 2002):

1. Feasibility study
    a. Site investigation
    b. Solar energy resource assessment
2. Development
    a. Permits and approval
    b. Project management
3. Engineering
    a. Design of solar energy system
    b. Mechanical design
    c. Electrical design
4. Renewable energy equipment
    a. Solar thermal collector and/or PV modules
    b. Spare parts and special tools
    c. Control system
    d. Transportation
5. Balance of plant
    a. Transport by ship
    b. Transport from ship to base
    c. Solar energy system foundations
    d. Solar energy system erection
    e. Electrical connection
    f. Commissioning of system
6. Miscellaneous
    a. Training
    b. Contingencies

5.3 Investment Costs of Supplementary Infrastructure and Electrical Connections to SANAE IV's Electrical Grid

The investment costs of supplementary infrastructure and electrical connections are sometimes less obvious than the basic investment costs listed in section 5.1, however, no less important. They include (Teetz, 2002):

1. Cost of access roads
2. Cost of cables, poles, transformers, etc.
3. Testing costs
    a. System testing under normal conditions
    b. System testing in Antarctic conditions
    c. Electrical grid connection testing at SANAE IV
    d. Complete system testing

In the ensuing investigation the costs mentioned above in sections 5.2 and 5.3 (viz. basic investment costs, and the investment costs of supplementary infrastructure and electrical connections to SANAE IV's electrical mini-grid) will be grouped together under the term *capital investment*. This capital investment represents the entire cost required to commission the proposed energy system at SANAE IV, and does not include recurring costs that will be incurred cyclically due to maintenance and other expenditures. These recurring costs are listed below in section 5.4.

5.4 Annual Recurring Costs and Savings

The implementation of any renewable energy system at SANAE IV will result in a number of costs and savings occurring cyclically throughout the lifetime of the project. By considering the magnitude of these cyclic costs and savings along with the capital investment, the feasibility of the project can be determined. These recurring costs (or savings) may or may not exceed the initial capital investment depending on their amounts and temporal nature (i.e. at what time during the lifetime of the system they occur), and which for the purposes of this investigation include (Teetz, 2002):

1. Energy system operation and maintenance costs

2. Labour costs
3. Interest on capital investment
4. Fuel savings due to reduction in diesel consumption
5. Operation and maintenance savings due reduction in generator use
6. Labour savings due to reduced generator usage

The installation of a solar energy system will therefore result in an increase of capital, maintenance and labour costs, yet also in a reduction in fuel consumption and external penalties. This relationship can be expressed as:

$$LCC = C_{pw} + M_{pw} + L_{pw} + F_{pw} + X_{pw} \tag{5.1}$$

Where the lifecycle cost (LCC) is the present worth (PW) sum of capital (C), maintenance (M), labour (L), fuel (F) and external (X) expenses. The present worth of each annual cost is calculated by multiplying a future sum of money by a Present Worth Factor (PWF):

$$PWF(i,n) = \frac{1}{(1+i)^n} \tag{5.2}$$

Where the present worth factor ($PWF(i,n)$) is a function of the relevant interest rate (i) and number of years between the present and expected future date of cash flow (n). Sample calculations of the economic evaluation have been provided in appendix E.

5.5 Economic Viability Criteria Necessary to Evaluate Investments for Solar Energy Systems

The methods used in this thesis to investigate the economic feasibility are presented in a document entitled "*Cost Benefit Analysis*" (DEAT, 2005) that, *"…aim*[s] *…to provide general information on techniques, tools and processes for environmental assessment and management"*. They include calculating:

1. Net present value (NPV),
2. Internal Rate of Return (IRR),

3. Benefit-Cost Ratio (BC Ratio) and
4. Cost of Energy Production (R/kWh)

5.6 Externalities

Externalities refer to those factors that lie beyond the immediate system costs under consideration (i.e. the costs mentioned in sections 5.2, 5.3 and 5.4) yet which still have a significant impact on the decision making process. In this instance the relevant externalities concern the environment, or in other words, the cost to the environment of the current energy generation methods. Reducing the operating intensity of energy generation methods becomes immediately beneficial to the environment if it is possible to assuage emissions, waste or the risk of oil spills. These are assigned a monetary value and accounted for in the economic analysis.

In table 5.1 the estimated air pollutants that are emitted into the atmosphere by the diesel-electric generators at SANAE IV each year are presented.

Table 5.1: Total annual emissions from generators (Taylor et al., 2002)

	VOC	CO	NO_x	SO_2	CO_2	PM
Lower Estimate (tons)	0.341	0.533	13.451	0.076	744	0.198
Upper Estimate (tons)	0.546	0.853	13.451	0.076	744	0.317

The Rand values of these emissions have been estimated (adapted with 1 % per annum compound increase from Teetz, 2002) and are presented in table 5.2.

Table 5.2: Cost of pollutants (Teetz, 2002)

POLLUTANT	COST (R/kg)	AMOUNT PRODUCED (LOWER LIMIT, TONS)	AMOUNT PRODUCED (UPPER LIMIT, TONS)	COST
VOC	41.59	0.34	0.55	R 22 709.92
CO	41.59	0.53	0.85	R 35 479.04
NO_X	25.40	13.45	13.45	R 341 613.97
SO_2	62.76	0.08	0.08	R 4 769.43
CO_2	0.20	744.00	744.00	R 145 643.35
PM	36.62	0.20	0.32	R 11 607.56
			TOTAL COST:	*R 561 823.26*

According to table 5.2 a maximum saving of approximately R 560 000 in externalities currently exists at SANAE IV (which translates into a value of 1.88 R/L or 0.30 US$/L) if the total savings is divided by the annual fuel consumption of the generators (297 872 L). Note, however, that the expected fuel savings of the suggested solar system would not entirely eliminate the use of fuel at the station, and therefore the actual savings would in reality be significantly less than the total of R 560 000.

Teetz (2002) also provided a second estimate of the cost of externalities by assigning a Rand value to each litre of fuel consumed as suggested by El-Kordy et al. (2001). This value of 0.87 US$/L (adapted with 3 % per annum compound increase from Teetz, 2002) also accounts for the impact of fuel spills, yet is 290 % higher than the estimate derived from table 5.2.

The following relevant points should be noted in this regard. The cost to the environment of cleaning spills and waste are significantly higher than the cost of air pollutants alone. In the case of SANAE IV shipping and storage add considerably to non-emission type environmental costs since snow has to be collected from the station and transported back to South Africa. These costs should therefore be included in the economic assessment and support the use of the value suggested by El-Kordy above. Furthermore, a case in point concerns the snow smelter at SANAE IV that may in the future experience water contamination problems due to the melting of contaminated snow. Fuel spills are immediately frozen in the snow, however, warmer weather tends to melt the top layer of this snow allowing the fuel to seep down towards the snow smelter that lies at a lower elevation. To correct this problem would require re-locating the snow smelter entirely. The second value suggested by El-Kordy et al. and used by Teetz (2002) in his investigation at the South African station will therefore also be used here.

5.7 Diesel Fuel Price

Three estimates of diesel point-of-use costs are presented in table 5.3 for comparison. As a rule of thumb the purchase price of fuel in the country of origin can be tripled to obtain a rough estimate of final costs (Guichard, 1996), however, the extensive study undertaken by the AAD in 1991 (Steel, 1993) suggests a factor of 3.70 and is most probably the more accurate estimate. For the purposes of this study a factor of 3 will be applied since it coincides with the results obtained by Teetz (2002) which considered factors specific to the conditions at SANAE IV. It is also slightly more conservative than the value suggested by the AAD. Since the current purchase price of SAB Diesel in South Africa for DEAT is 5.36 R/L the point-of-use cost will therefore be 16.08 R/L in the ensuing investigation.

Table 5.3: Diesel costs for use in Antarctica

	TEETZ[Δ] (RAND/L)	GUICHARD[Ŧ] (AUD/L)	STEEL[Ψ] (AUD/kWh)	GUICHARD[Å] (US$/kWh)
Purchase cost	1.932	± 0.33	± 0.10	0.0275
Final cost	5.847	± 1.00	± 0.37	0.0785
Factor	*3.026*	*±3.00*	*±3.70*	*2.8545*

[Δ]Teetz (2002); [Ŧ]Guichard (1996); [Ψ]Steel (1993); [Å]Guichard (1994)

5.8 Economic Assessment

The economic assessment of the solar energy systems at South Africa's SANAE IV station has been undertaken in two parts. In the first part the economic feasibility of installing a PV system is investigated in detail, followed in the second part by an identical consideration of the suggested flat-plate solar thermal system. Unless otherwise stated the methods employed consider the time value of money by using a hurdle rate of 8 % as suggested by DEAT (2005) (also referred to as the Minimum Attractive Rate of Return [MARR]), and are presented in real terms (i.e. not actual or nominal values). The fuel-price escalation rate used in the investigation was assumed to be 5 %, and all other assumptions have been listed in tables 5.4 and 5.6.

5.8.1 Photovoltaic Energy System Assessment

The financial assessment of the proposed PV system at SANAE IV is presented below. All assumptions have been listed in table 5.4, and as mentioned above the investigation utilises the following tools to determine feasibility:

1. Net Present Value,
2. Internal Rate of Return,
3. Benefit Cost Ratio and
4. Cost of energy produced.

Table 5.4: Essential data and system characteristics of PV System

Solar Energy Characteristics and Data:		
Total Number of Panels (Dependent on inverter size)	572.00	No.
Solar System Efficiency	13.00	%
Panel Watts Peak (SANYO HIT 63S1)	63.00	Wp
Total Available Titled Insolation	1 430.80	kWh/m^2.year
Area per panel	0.47	m^2
Annual solar system operating hours	8 640.00	hr
Expected design life of solar system	25	years
Solar panels unit purchase price	-R 35.00	R/Wp
Solar panels total purchase price	-R 1 261 260.00	Rand
Auxiliary equipment (Trace Engineering 2x20 kW PV-series inverter)	-R 214 782.08	Rand
Installation cost (cables, module support frames, infrastructure)	-R 147 604.21	Rand
Transportation cost	-R 29 520.84	Rand
Estimated annual maintenance & operation cost	-R 73 802.10	Rand
Estimated annual labour cost	-R 1 000.00	Rand
Solar system energy penetration factor	100.00	%
Complete solar system cost	-R 1 653 167.13	Rand
Annual power production	48 795.63	kWh
Installed area	265.98	m^2
Installed Watts (peak)	36	kWp
Fuel saved annually due to solar system energy capture	9 958.29	L
Diesel Generator Characteristics and Data:		
Diesel purchase price	-5.36	Rand/L
Diesel point-of-use price for SANAE IV	-16.08	Rand/L
Estimated annual maintenance & operation cost	-30000.00	Rand
Estimated annual labour cost	-20000.00	Rand
Annual power production	1 061 971	kWh
Annual power generation hours	11304.00	hr
Estimated diesel generator efficiency (considering summer HVAC conditions)[ϕ]	50.00	%
Fuel energy density	9.80	kWh/L
Annual generator diesel consumption	297 872	L
Estimated saving in L and M due to reduced operating time	0.00	%
Economic Data:		
Value of Externalities (on every litre of fuel saved)	5.32	R/L
Interest rate on lent capital	10.00	%
Estimated maintenance and labour cost escalation per year	1.00	%
Estimated fuel cost escalation	5.00	%
General inflation rate (August 2005)	3.50	%
Crude Oil Price (US$/barrel)	61.00	US$/barrel
Exchange rate (R to US$)	6.46	Rand/US$
Estimated escalation rate of external costs	1.00	%
MARR (hurdle rate)	8.00	%

[ϕ] During summer there is a net *heat gain* in SANAE IV. Waste-heat is therefore not completely utilised.

NET PRESENT VALUE (NPV)

In figure 5.1 the NPV of all the costs incurred by the diesel-only and hybrid-PV systems are illustrated throughout the expected 25-year project lifetime. The results have been calculated using equation 5.1 excluding externalities for the moment. It is evident for the hybrid system that until the 21st year total costs remain greater than those of a diesel only system (i.e. no breakeven point is reached through the mitigation of fuel consumption), and that only after such a time net profits are made. Note that, as stated above, the time value of money in this figure has been accounted for by using a hurdle rate of 8 % meaning that these investments must be able to outperform the equivalent profits that could be obtained from an alternative investment (at a bank for instance) with an interest rate of that amount.

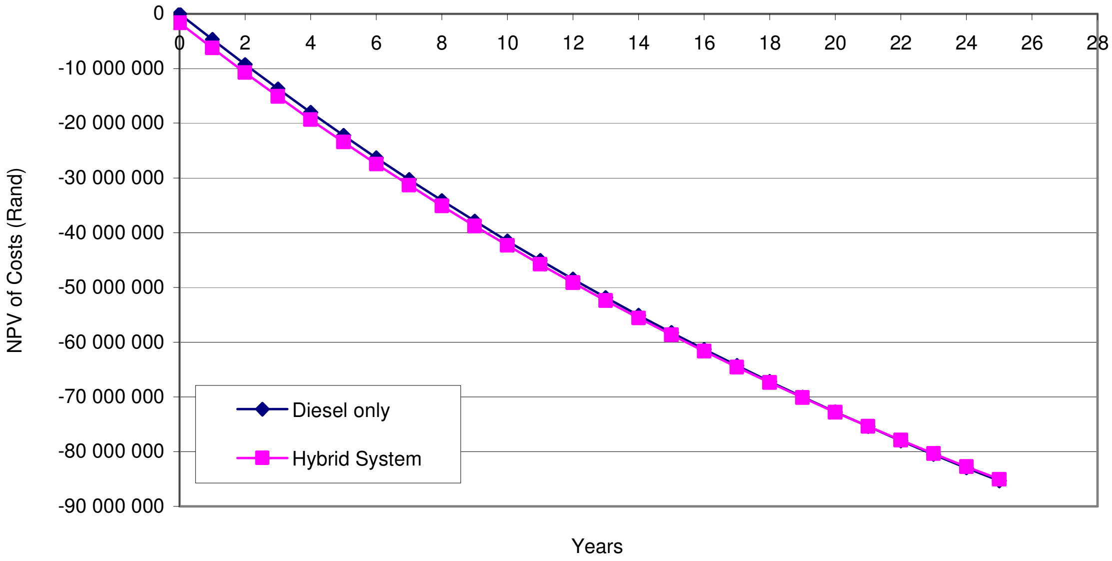

Figure 5.1: NPV of costs incurred during expected project lifetime

In figure 5.2 expected payback periods for the system at different interest rates (viz. 8 % and 0 %) with and without externalities (see section 5.6) are shown. From the figure it is evident that regardless of the hurdle rate or environmental costs the PV system will struggle to rapidly recover investment costs sunk into the project assuming that an eighteen to twenty-four month payback is optimal. Nonetheless, even under the most stringent assumptions (viz. 8 % hurdle rate and excluding externalities) costs can be recovered within the lifetime of the system, and with increasing promise as emphasis is placed on more desirable funding methods and external costs.

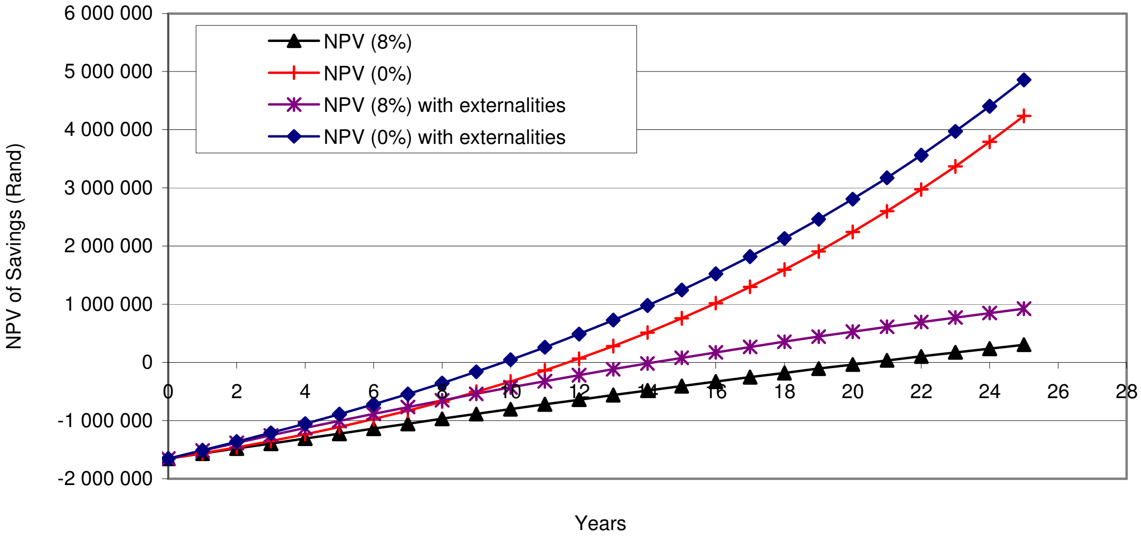

Figure 5.2: NPV of the difference between the costs of the two alternatives

A comparison of initial capital investment and the consequent net savings is given in figure 5.3. From the figure it is evident that an initial capital investment of R 1 900 000 will result in a breakeven point after approximately 25 years. Capital outlay should therefore be less than approximately this amount to make a profit within the system lifetime utilising an 8 % interest rate criteria (without externalities) and the assumptions listed in table 5.4.

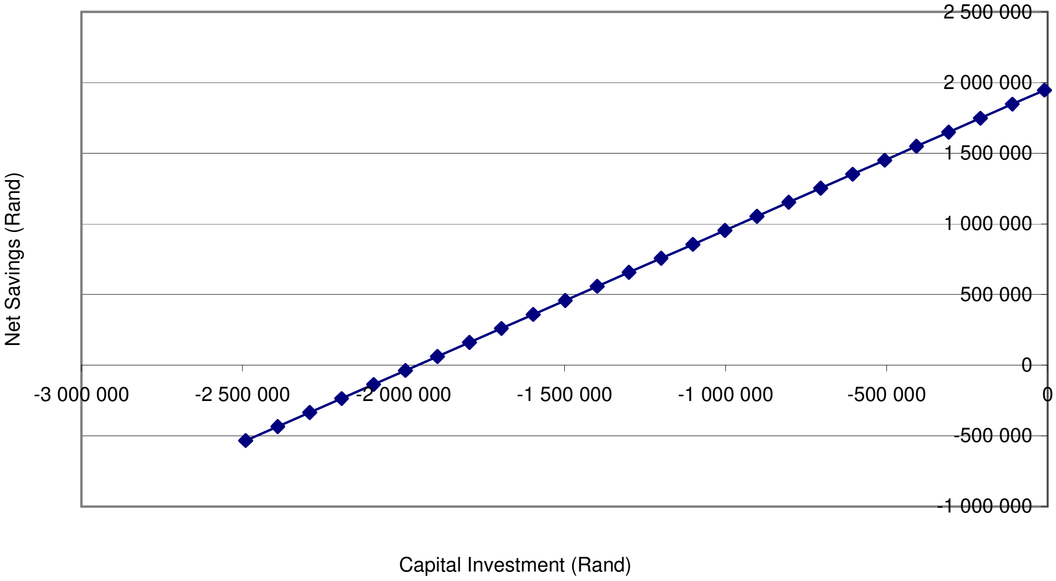

Figure 5.3: NPV after 25 years at various initial capital investments (8 % MARR)

INTERNAL RATE OF RETURN (IRR)

The IRR method (otherwise known as the profitability index or discounted cash flow method) is defined as that method which, *"…solves for the interest rate that equates the equivalent worth of an investment's cash inflows (receipts or savings) to the equivalent worth of cash outflows"* (Sullivan et al., 2003). Consequently the breakeven interest rate, or that interest rate which will result in a zero net profit over the lifetime of the investment, is determined. If this rate of return calculated is higher than a company's minimum attractive rate from alternative investments, it stands to reason that the investment is desirable.

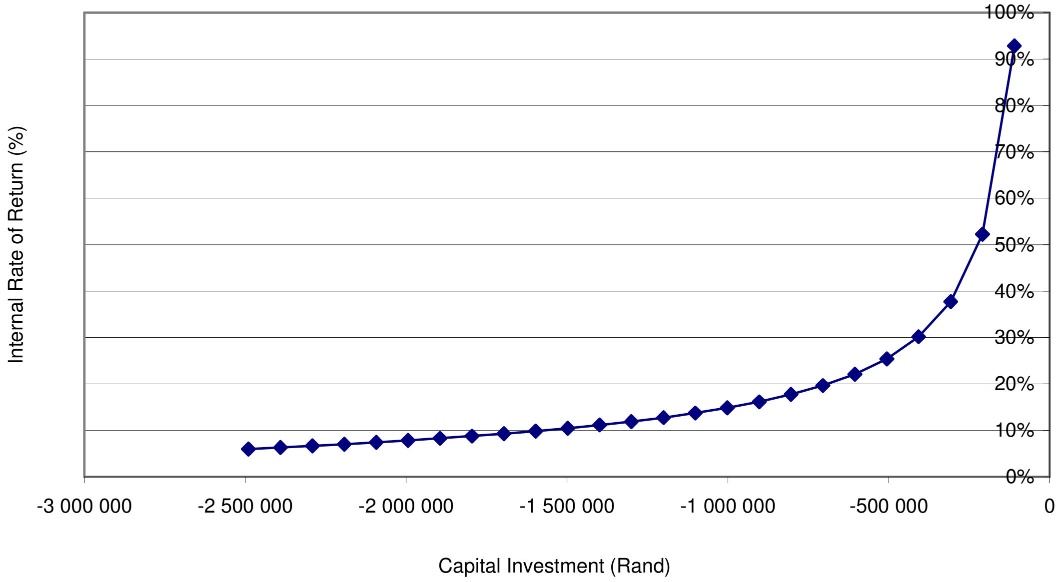

Figure 5.4: IRR at various initial capital investments

From figure 5.4 an IRR of 9.52 % was calculated, compared to the Minimum Attractive Rate of Return that was set at 8 %. The Net Annual Worth and Present Values are listed in table 5.5 (again at an 8 % hurdle rate) and should be compared to figure 5.2 for a comparison of possible NPVs using alternative assumptions.

Table 5.5: PV System results after 25 years

CRITERIA	AMOUNT
NPV (R)	302 915
IRR (%)	9.52
NAW (R)	26 907

BENEFIT COST RATIO (BC RATIO)

A BC Analysis is useful for estimating the relative worth of savings against costs. In this investigation (where a value of unity suggests that savings are equal in magnitude to costs) a value greater than unity indicates that potential revenues generated by an investment exceed the associated costs, and indicates a desirable alternative to the current method of investment.

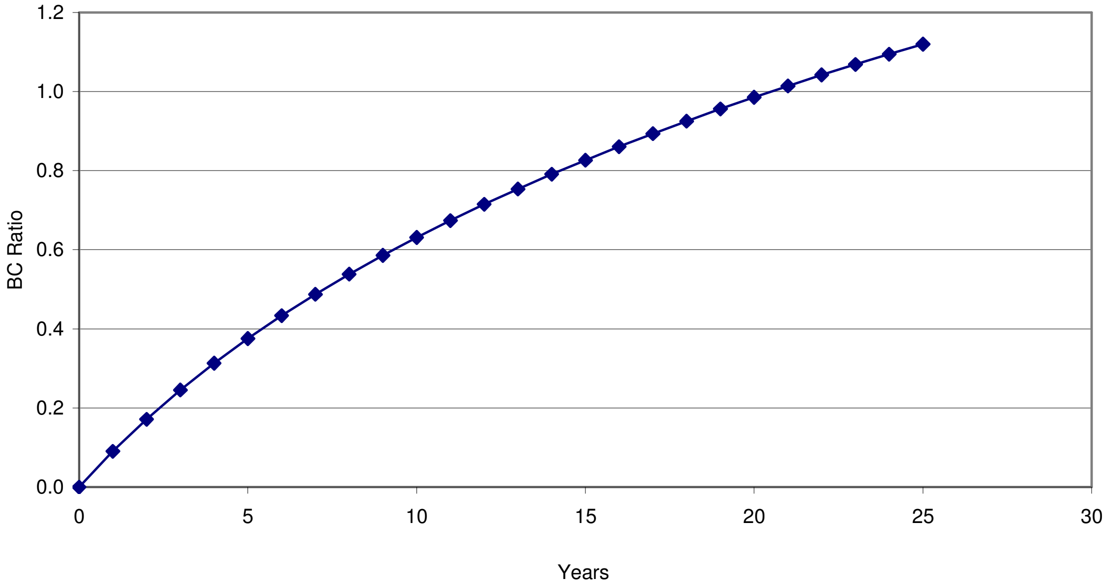

Figure 5.5: BC Ratio over lifespan of project

The suggested PV system is able to recover the costs after a period of 21 years (at an 8 % hurdle rate and without the inclusion of externalities in the system savings) as was also found in figures 5.1 and 5.2. The trend also illustrates that a longer system lifetime equates to greater potential benefits derived from the investment, albeit with a smaller differential gain after each year.

Referring to figure 5.6 it is again evident that the breakeven point should occur for an initial capital outlay of R 1 900 000 or less, a value that corresponds with information given by figures 5.3 and 5.4. Note that revenues are markedly increased with a reduction in initial capital investment and an extension of the project lifetime. For the suggested PV system an estimated capital investment of R 1 653 167 will be required (as stated in table 5.4).

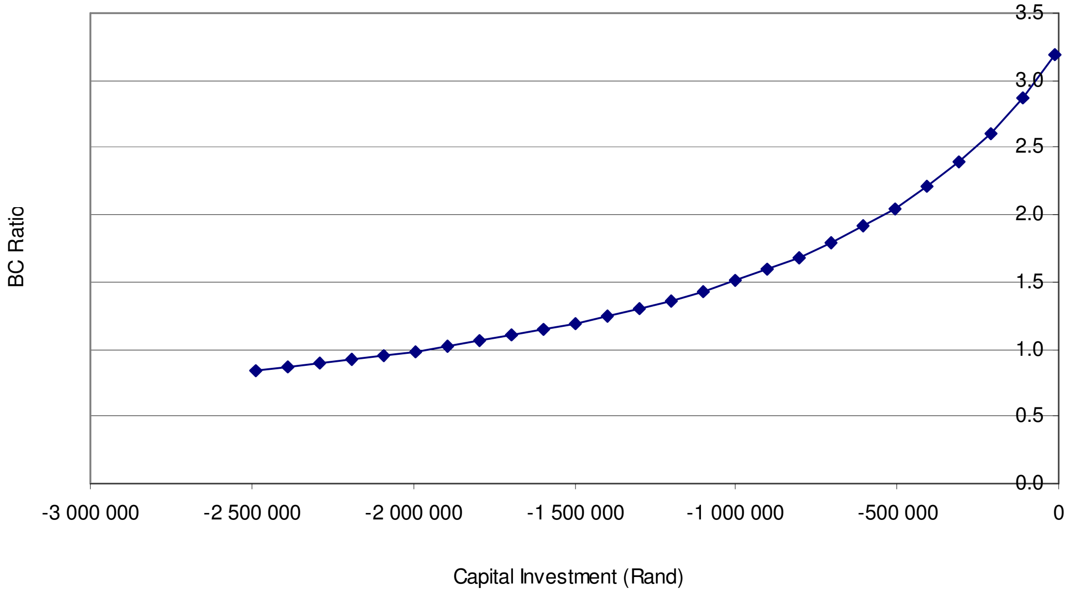

Figure 5.6: BC Ratio at various capital investments

COST OF ENERGY GENERATION (R/kWh)

The cost of energy generation at SANAE IV for hybrid and diesel-only systems has been calculated by summing the project expenses (given in equation 5.1 but excluding externalities) over the expected 25 year lifetime and dividing by energy consumption over the same period (approximately 1 062 MWh annually). Therefore, and referring to figure 5.7, it is evident that diesel-only system energy costs amount to roughly 3.21 R/kWh (since the associated capital investment costs are zero) and that diesel-PV systems could generate energy at a cost of 3.20 R/kWh.

Standard off-peak domestic rates of electrical energy in South Africa are currently approximately 0.30 R/kWh, and therefore almost 11 times cheaper than the estimated current diesel-only cost of energy generated at SANAE IV. This is a value that correlates reasonably well with the reference by Steel (1993) to the detailed cost analysis completed by the Energy Section of the AAD in 1991. Results from this investigation showed that the final cost of energy consumption in Antarctica amounted to approximately 7 times the domestic price of electricity in Tasmania, and 14 times the off-peak charge. In this investigation carried out by the AAD the cost of the fuel itself represented approximately 55 % of this final value, while equipment depreciation and maintenance represented the other 45 %.

From figure 5.7 the minimum attractive PV-system capital investment associated with this diesel-only-system energy cost is again estimated at approximately R 1 900 000, while the actual investment of the PV system, as mentioned above, is in the order of R 1 653 167. This capital investment corresponds with an energy production price of approximately 3.20 R/kWh, and represents a reduction in fuel generation costs of less than 1 %. Teetz (2002) estimated that wind generation would be able to reduce fuel generation costs in the order of 20 %.

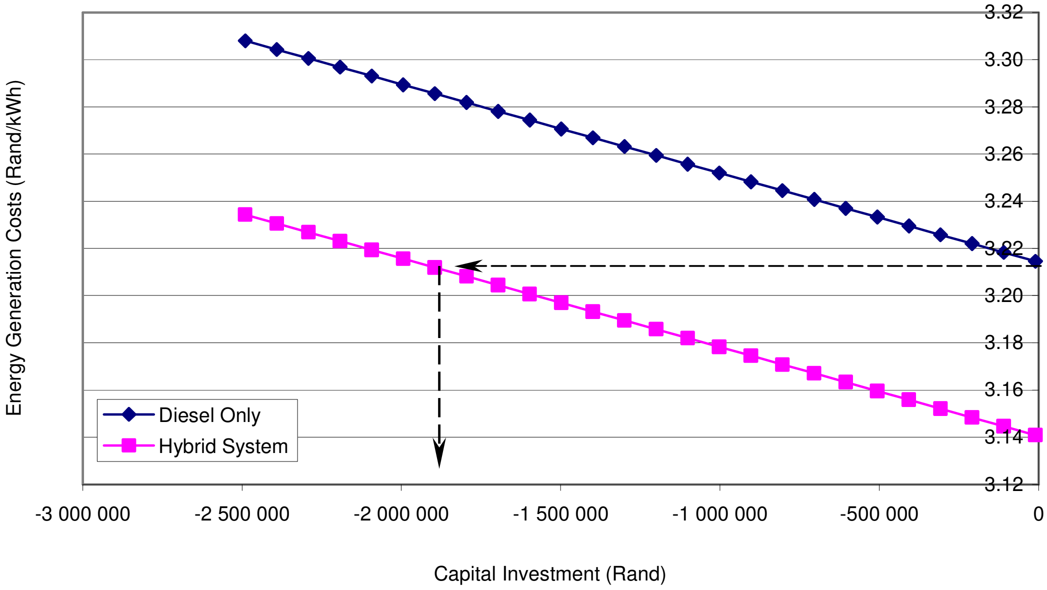

Figure 5.7: Energy generation costs of diesel only and hybrid systems

5.8.2 Solar Thermal Energy System Assessment

The suggested solar thermal system described here shows more potential for financial and energy savings than the photovoltaic collectors assessed above. Assumptions have been tabulated in table 5.6 and illustrations of the costs are provided as before. Estimated fuel savings have again been calculated based on a generator efficiency of 50 % (refer to table 5.4) since waste-heat recovery is relatively insignificant during the summer period owing to the high inside station temperatures. Even though the Domestic Hot Water System utilises a small portion of the waste heat during the summer months the suggested percentage is still conservative.

Table 5.6: Essential data and system characteristics of solar thermal system

Solar Energy Characteristics and Data:		
Number of panels (either 24 or 72)	72	No.
Tmax (stable smelter temperature)	20	°C
Tresponse (for switching elements off)	10	min
Total available titled insolation on non-tracking surface	1 430.80	kWh/m^2.year
Area per panel	1.98	m^2
Expected design life of solar system	25	years
Solar panels unit purchase price	-R 7 000.00	R/Panel
Solar panels total purchase price	-R 504 000.00	Rand
Cost of Accessories (Thermal Energy Store, pumps, controller & pump room)	-R 170 000.00	Rand
Installation cost	-R 134 800.00	Rand
Transportation cost	-R 33 700.00	Rand
Estimated annual maintenance & operation cost	-R 33 700.00	Rand
Estimated annual labour cost	-R 5 000.00	Rand
Solar system energy penetration factor	100.00	%
Complete solar system cost	-R 881 200.00	Rand
Annual power production	60 000	kWh
Installed area	142.56	m^2
Fuel saved annually due to solar system energy capture	12 244.90	L
Estimated Annual System Efficiency	29.42	%
Diesel Generator Characteristics and Data:		
Diesel purchase price	-5.36	Rand/L
Diesel point-of-use price for SANAE IV	-16.08	Rand/L
Estimated annual maintenance & operation cost	-30 000.00	Rand
Estimated annual labour cost	-20 000.00	Rand
Annual power production	1 061 971	kWh
Annual power generation hours	11 304.00	hr
Estimated diesel generator efficiency (considering summer HVAC conditions)[ϕ]	50.00	%
Fuel energy density	9.80	kWh/L
Annual generator diesel consumption	297 872	L
Estimated saving in L and M due to reduced operating time	0.00	%
Economic Data:		
Value of Externalities (on every litre of fuel saved)	5.32	R/L
Interest rate on lent capital	10.00	%
Estimated maintenance and labour cost escalation per year	1.00	%
Estimated fuel cost escalation	5.00	%
General inflation rate (August 2005)	3.50	%
Crude Oil Price (US$/barrel)	61.00	US$/barrel
Exchange rate (R to US$)	6.46	Rand/US$
Estimated escalation rate of external costs	1.00	%
MARR (hurdle rate)	8.00	%

[ϕ] During summer there is a net *heat gain* in SANAE IV. Waste-heat is therefore not completely utilised.

NET PRESENT VALUE (NPV)

In figure 5.8, as in figure 5.2, the expected payback periods for the solar system at different interest rates and with externalities (see section 5.6) are shown. Costs are recovered within 6 years from the initial investment, and the system worth at the end of the project duration under the assumptions listed in table 5.6 is estimated at R 2 148 811 (with an initial investment of R 881 200).

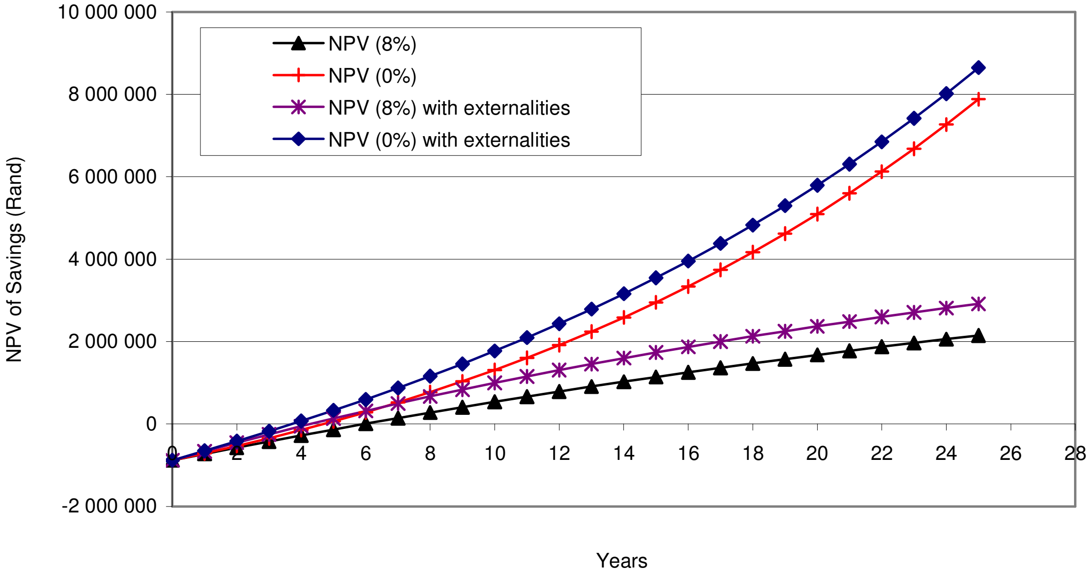

Figure 5.8: NPV of the difference between the costs of the two alternatives

Thus the economic characteristics of the solar thermal system described here show potential for breakeven on the short to medium term of the project. This is unlike the photovoltaic system that was not able to recover the costs as rapidly, and contrary to the expectations of the discussion in section 4.3. Mainly this is because the snow smelter presents the unique opportunity to utilise solar thermal energy at reasonably low process temperatures, during the summer, with relative ease of installation.

Note that the solar thermal system currently under investigation is large (72 collector panels), however it should be remembered that these collectors are modular and that any smaller combination is possible. Savings generated in these instances will not be of the same magnitude as those presented above yet breakeven periods will still take place in the same amount of time.

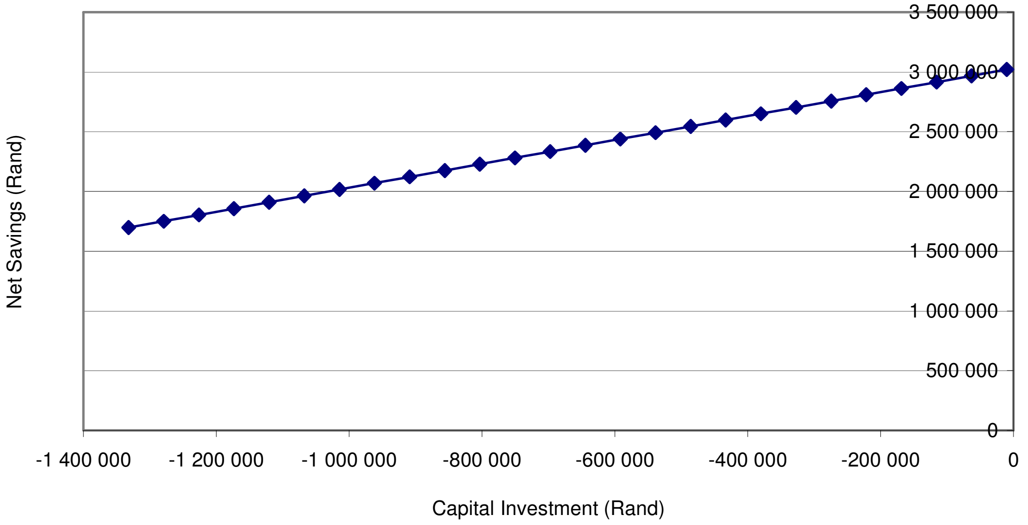

Figure 5.9: NPV after 25 years at various initial capital investments (8 % MARR)

INTERNAL RATE OF RETURN (IRR)

The IRR of the suggested solar thermal system shown in figure 5.10 has been calculated as 24 % (from an initial investment of R 881 200), while smaller systems show slightly lower yet still consistently large rates of around 15 % (as compared to the MARR of 8 %). Refer to table 5.7 for estimates of the expected NAW and NPV of the system after 25 years and to figure 5.8 for estimates of the NPV using different assumptions.

Table 5.7: Solar thermal system results after 25 years

CRITERIA	AMOUNT
NPV (R)	2 148 811
IRR (%)	24.47
NAW (R)	190 873

BENEFIT COST RATIO (BC RATIO) AND COST OF ENERGY GENERATION (R/kWh)

Following figure 5.10 (which illustrates the IRR) graphs of BC Ratio and cost of energy generation are illustrated in figures 5.11 and 5.12 below. The results correlate well with those discussed so far, and show that a thermal collector system used to supplement the energy demand of the snow smelter has the ability to recover the cost of the initial investment well within the lifetime of the project. A breakeven point is expected on the short to medium term, as well as under various adverse conditions (such as low fuel price escalation rates, high initial investment costs, high labour expenses, etc.). The cost of energy generation in this instance has been calculated at 3.13 R/kWh, as opposed to the 3.20 R/kWh of the PV system in section 5.8.1, and is approximately 3 % cheaper than the cost of 3.21 R/kWh for diesel-only power generation.

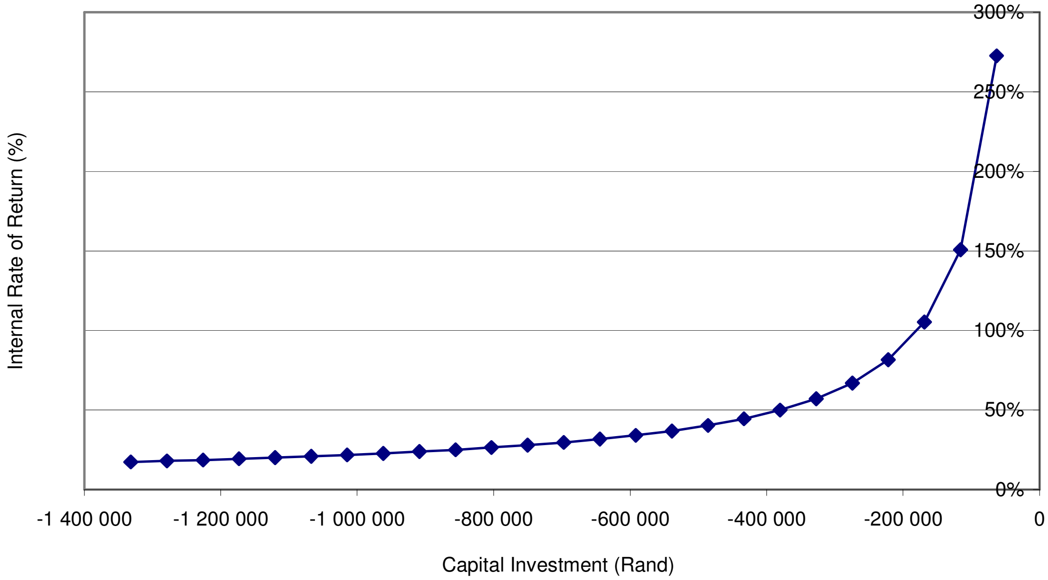

Figure 5.10: IRR at various initial capital investments

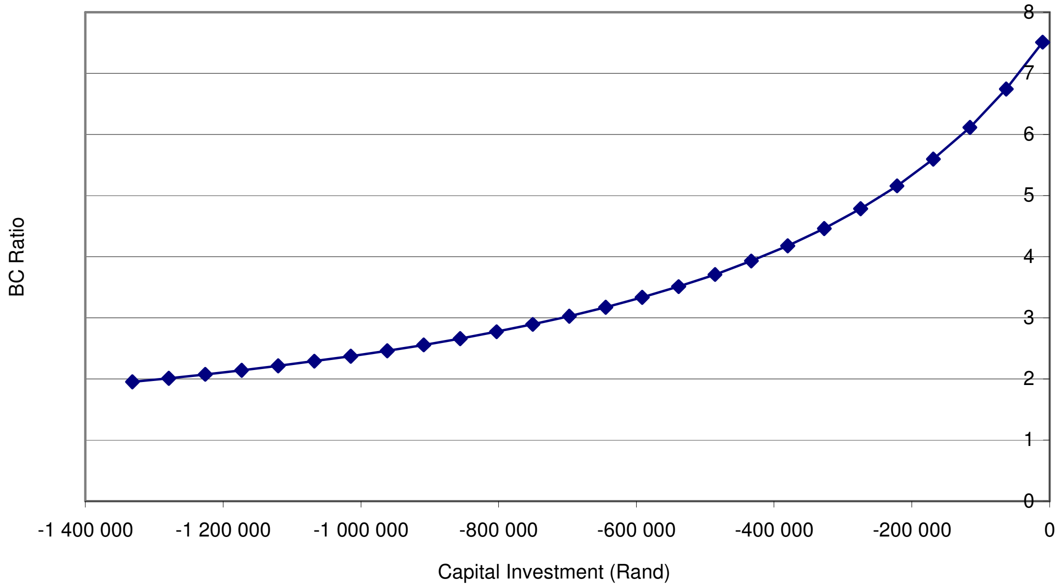

Figure 5.11: BC Ratio at various capital investments

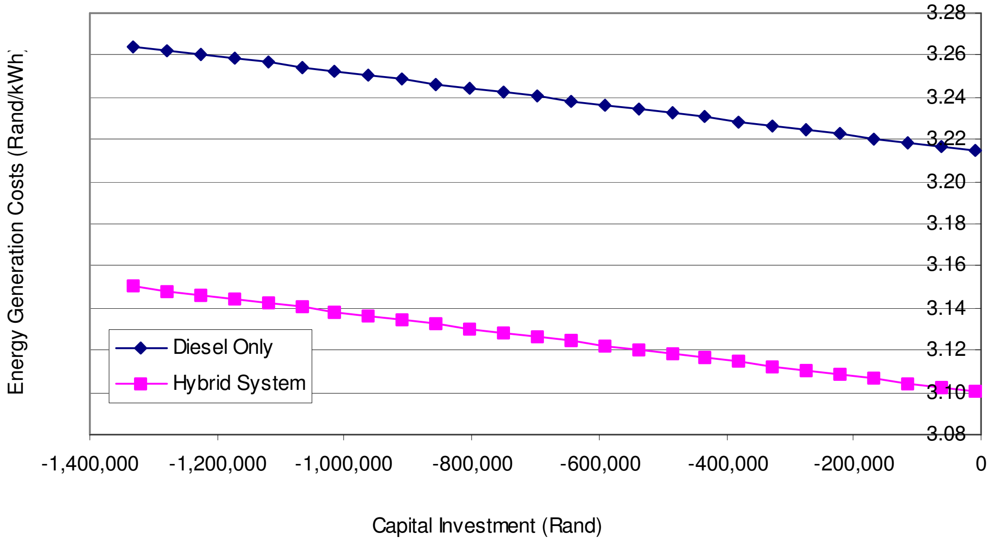

Figure 5.12: Energy generation costs of diesel only and hybrid systems

5.8.3 Economic Performance Criteria at Various Financial Conditions

Due to the difficulties involved with predicting criteria such as future fuel price escalation rates and a fair MARR, the performance of the PV and solar thermal systems under various economic conditions have been presented in table 5.8. These values serve as an indication of how sensitive the systems' financial criteria are to change, showing that although the solar thermal system is a relatively low risk investment the success of the PV systems depends on the realisation of expected future scenarios. Any significantly unfavourable economic conditions would result in a net financial loss related to the installation of a PV system.

Table 5.8: 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
BC (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
BC (after 25 years)	2.00	1.50	1.20	4.75	3.50	2.75

5.9 Summary

It is evident from chapter 5 that with proper implementation the suggested solar energy systems should be capable of recovering their initial capital investment within the project lifetime. Therefore these systems represent not only economically feasible investments, but also good opportunities for improving living conditions at SANAE IV during the summer as discussed in chapter 3.

The average cost of generating electricity after commissioning a solar thermal system with a 143 m^2 collector field (assuming a real hurdle rate of 8 % and fuel price escalation rate of 5 %) would be approximately 3.13 Rand/kWh, as opposed to the 3.21 Rand/kWh of the current diesel-only system. Annual fuel savings associated with such a system were calculated as 12 245 litres. The project would arrive at a breakeven point after approximately 6 years, and represent a NPV of 2 148 811 Rand after 25 years. By further considering environmental factors such as the cost of removing soiled snow from Antarctica and diesel fuel emissions the magnitude of the net present savings would increase by approximately 500 000 Rand.

The 40 kW photovoltaic system that was investigated was only able to fully recover the initial costs after 21 years. It is expected that installing such a system would equate to a NPV of 302 915 Rand at the end of the 25 year system lifetime, saving 9 958 litres of diesel annually in the process and generating energy at a cost of 3.20 Rand/kWh. It should be noted, however, that under more ideal conditions (i.e. less attractive alternative investment opportunities, higher fuel price escalation rates and a stronger emphasis on environmental concerns) investment into a photovoltaic system could potentially breakeven after approximately 10-15 years, while simultaneously significantly improving base operation.

The opportunity to install a solar energy system at SANAE IV therefore warrants action. There is potential not only to generate savings over the operational lifetime but also to preserve the environment in accordance with the desires of the Antarctic Treaty. It is firmly believed that with careful planning and implementation such a project can and should be successfully undertaken.

Chapter 6 – Conclusion

At the start of this project four 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). These questions have been addressed in chapters 2 through to 5, and the necessary information obtained from each. Results were compared with information contained in relevant sources and where applicable with data measured during the 2004/2005 takeover at SANAE IV, as detailed in sections 2.3.1 and 3.2. Various financial outcomes resulting from different economic scenarios were also considered. At the close of this study it is therefore possible to summarise the information obtained, draw important conclusions and suggest a future course of action.

As described in chapter 2, 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 with other locations on Earth. The insolation is characterised by significant seasonal fluctuations and comprised large components of diffuse radiation. Except for clear-sky days when tilted surfaces may be exposed to radiation of up to 1 300 W/m^2, the diffuse component contributes to an estimated 1.74 kWh/m^2.day, or approximately 60 % of the annual average global insolation. In comparison to other resources these estimates of radiation at SANAE IV are very similar to the conditions at its closest neighbour, the German Neumeyer station, as shown in figure 2.12. The required collector tilt angles were also found to be relatively high, starting at 50° in the peak of summer and increasing to 90° in the winter. This makes it difficult to design small and compact collector fields since, due to the high tilt angles, it is not possible to place collectors directly behind each other.

After investigating the energy consumption of SANAE IV (chapter 3) the station's electrical mini-grid and snow smelter were highlighted as favourable electrical and thermal loads respectively for the application of solar energy systems. It was evident that, due to the difficulties synonymous with generating electricity during the summer takeover period, supplementing these systems with solar energy would prove to be particularly beneficial for the station. During this time the generators are prone to overheating, even disrupting normal grid operation, and there is a restricted supply of fresh water from the snow smelter to the base. These loads therefore present opportunities for a twofold gain by implementing a solar energy system; firstly, by