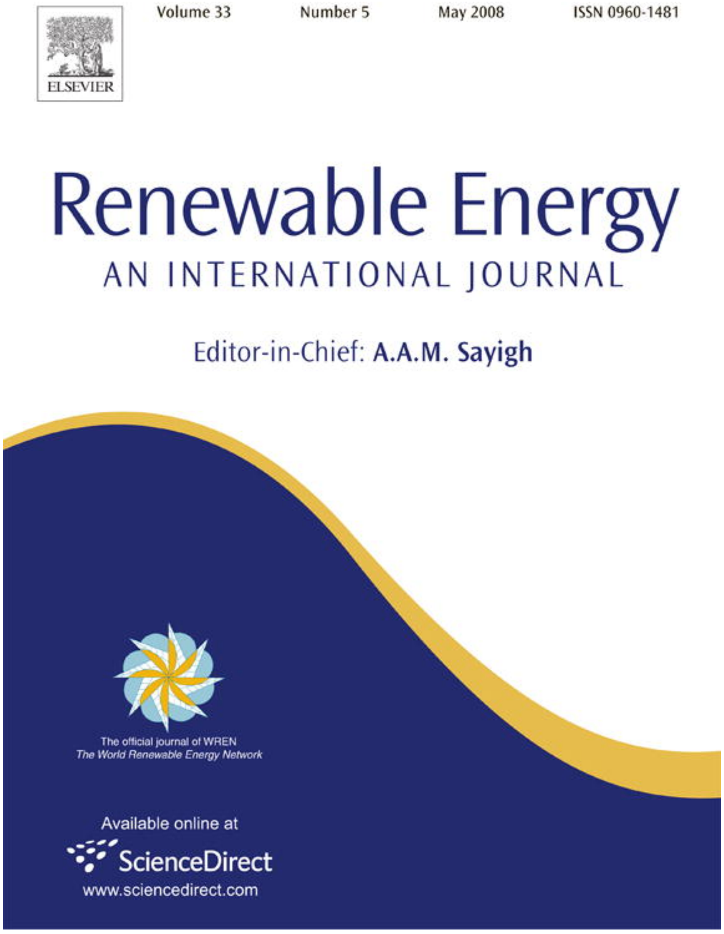

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Technical and economic evaluation of the utilization of solar energy at South Africa's SANAE IV base in Antarctica

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Abstract

The technical and economic feasibility of utilizing solar energy at South Africa's SANAE IV station in Antarctica was evaluated in order to estimate potential financial and external savings, and to alleviate the programme's dependence on the special blend of diesel shipped annually from Cape Town. The average global horizontal and tilted insolation rates at the base were studied, energy consumption data of the station was investigated, technical performance characteristics of devices for harnessing solar energy were assessed and an economic analysis was completed. It was shown that at SANAE IV flat-plate solar thermal collectors could potentially be used in conjunction with the snow smelter (a device that meets the station's fresh water demand) and that photovoltaic modules could feasibly be used to reduce the station's electrical demand. Flat-plate solar thermal collectors could collect solar energy at an average of 3.13 R/kWh (viz. 0.49 US$/kWh) from a suggested 143 m^2 array, while comparatively a 40 kWp photovoltaic system would be less economically sound and only able to pay back costs at the end of the system's expected 25-year lifetime, generating electricity at an estimated 3.20 R/kWh (annual electrical consumption at SANAE IV amounts to more than 1062 MWh). The total diesel savings of the solar thermal and photovoltaic systems were estimated at approximately 12 245 and 9958 l, respectively, which represent savings in externalities of R67 338 and R55 879 each.

Keywords: Solar energy; Antarctica; Feasibility study; SANAE IV; Technical analysis; Economic analysis

1. Introduction

A significant cost component of operating South Africa's Antarctic SANAE IV research station currently depends on the volatile price of oil. Each year the station's electrical consumption is generated from roughly 297 872 l of Special Antarctic Blend (SAB) diesel that can only be transported from Cape Town with considerable logistical and financial effort, resulting in an estimated point-of-use cost triple that of the purchase price. Growing concern about future oil security, a continued effort to improve the performance of the station with reduced financial commitment, but above all the Antarctic Treaty's 1959 mandate, re-emphasized through the Protocol on Environmental Protection of 1991, ratified in 1998 [1], to protect the unspoiled environment, motivate an investigation of utilizing solar energy at South Africa's SANAE IV station (70°40′ South and 2°49′ West). Taylor et al. [2] record the following emissions per annum from the station's three combined heat and power (CHP) diesel generator systems: volatile organic compounds 0.341 tonnes, carbon monoxide 0.533 tonnes, nitrous oxides 13.451 tonnes, sulphur dioxide 0.076 tonnes, carbon dioxide 744 tonnes and particulate matter 0.190 tonnes. In the light of the international treaty endeavour to minimize the environmental footprint of Antarctic activities, investigations into alternative energy supply options which would have the potential to reduce such emissions are decidedly warranted.

Thus, progress in the utilization of renewable energy resources on Antarctica has taken place. Fourteen stations are at present utilizing renewable energy on the continent, mainly wind, of which six bases employ solar energy systems [3]. Continued research pertaining to the Australian

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Nomenclature

B/C	benefit cost ratio
C	capital investment (R)
F	fuel costs (R)
i	interest rate (%)
IRR	internal rate of return (%)
$\mathrm{kW_p}$	kilowatt captured by a photovoltaic array at Standard Test Conditions (1000 $\mathrm{W/m^2}$ irradiation and a module temperature of 25°C) (kWp)
L	labour costs (R)
M	maintenance costs (R)
MARR	minimum attractive rate of return (%)
n	number of years (years)
NAW	net annual worth (R)
NPV	net present value (R)
PW	present worth (R)
PWF	present worth factor
Rand	Rand (South African currency abbreviated as R)
E	externalities (R)

Antarctic Division [4] has also shown that solar thermal devices can perform satisfactorily in these conditions, as is currently the case at the Australian Davis station, while large photovoltaic arrays have been installed at the American McMurdo and Japanese Syowa stations (323 and 236 $\mathrm{m^2}$, respectively).

This paper presents results from the study of factors relevant to the utilization of solar energy at SANAE IV. Global horizontal and tilted insolation rates at SANAE IV are calculated, the station's energy systems and annual average electrical consumption are analysed, performance estimates of photovoltaic and flat-plate solar thermal devices are given, and financial and external savings are established in the economic evaluation.

The *a priori* motivation to focus on solar energy exclusively stems further from the facts that while in the Antarctic summer the heating load at the base is at a minimum, this is well compensated for by the energy demand resulting from much higher occupancy during this time (e.g., water generation). Also, an earlier study by Teetz et al. [5] examined the feasibility for using wind energy at the base.

2. Analysis procedure

The investigation was undertaken by considering four criteria in turn, namely, availability, demand, devices and costs. That is, the availability of the solar energy resource at SANAE IV, total energy demand at the station, potential solutions to harnessing the solar energy in the given conditions, and the complete system lifecycle costs.

The results from each of these four criteria were used to establish and compare potential savings that could be generated for the programme, and the details of this investigation have been discussed here under the sections of solar radiation analysis, station energy demand analysis, device characteristics and energy production, and economic analysis, respectively.

Costs have been expressed in Rand values (South African currency) of December 2005, but can be converted to the equivalent American Dollar amounts of that time by multiplying with 0.158 (US$/ZAR). Furthermore, the economic analysis has been presented in *real* terms (that is as December 2005 Rands).

3. Complete data capture

During a field trip to SANAE IV (in the summer season of 2004/2005) the following data were acquired:

- Eighteen consecutive days of January radiation measurements obtained using two Kipp & Zonen CM5, and a Kipp & Zonen SP-Light pyranometer (which included measurements of global horizontal, horizontal diffuse global tilted radiation).
- Corresponding temperature measurements of the pyranometers, photovoltaic module and ambient conditions using T- and K-type thermocouples.
- Energy production data from a 5 W Liselo-Solar photovoltaic module.
- Historical data of electricity generation and the corresponding diesel consumption during 2000, 2001, 2002, 2003 and 2004.
- An investigation of the station's fresh water consumption and the production rates of the snow smelter (a device used to melt snow in order to create fresh water for the station).
- General information regarding all the power systems and power distribution was collected and compiled into an energy audit of the station.

4. Solar radiation analysis

A critical component of the feasibility study was an assessment of the solar radiation expected throughout the year at SANAE IV. Significantly, however, there was no historical data available for analysis from the station, except for measurements obtained during a field trip in January 2005 (detailed in the previous section and subsequently referred to in context). Not being able to use long-term averages to estimate insolation rates, a number of other sources were consulted. These included the Langley Research Center's of the National Aeronautic and Space Agency (NASA) Surface Meteorology and Solar Energy Dataset (SSE dataset), compiled from satellite data, ground-based comparisons and various correlations [6]. The dataset makes estimates of radiation values available for every location on Earth. Data recorded at the German Neumayer Station (70°39′S, 8°15′W), located approximately 300 km from SANAE IV and the South African station's closest neighbour, was also utilized [7]. Neumayer is a contributor to the Baseline Surface Radiation Network, and, consequently, values measured by this station will be deemed accurate. Cloud-cover data were consulted for comparative purposes, and methodologies presented by Duffie and Beckman [8] were used to approximate insolation on tilted surfaces from values of global horizontal radiation.

This investigation into available radiation established a number of important conditions. Firstly, as can be seen in Fig. 1, during January the values provided by the SSE dataset under-predict global horizontal levels of radiation measured at Neumayer. It is also evident that the suggested amount of diffuse radiation, calculated using the correlation devised by Erbs et al. [9], is underestimated.

Secondly, it was established that the measurements of solar radiation taken at SANAE IV and shown in Fig. 2 were obtained during a relatively cloudy period. The clearness index of the data was calculated as 51.2%, which is less than the long-term January average of Neumayer (viz. 63.7%). Yet, Neumayer is known to have on average greater amounts of cloud-cover than SANAE IV [7,10]. Consequently the SSE dataset values for global horizontal solar radiation at SANAE IV (which show an acceptable correlation with the values measured at the South African station during the above mentioned cloudy period) could be used only as a rough conservative estimate of the actual values at the South African station.

Upper limits of expected radiation at SANAE IV were established by investigating clear-sky conditions. It was found that the clear-sky models of the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) [11], as well as Hottel's model [12], both significantly under predicted measured values of radiation, and that the expected value of clear-sky January horizontal radiation is 9.1 kWh/m^2.

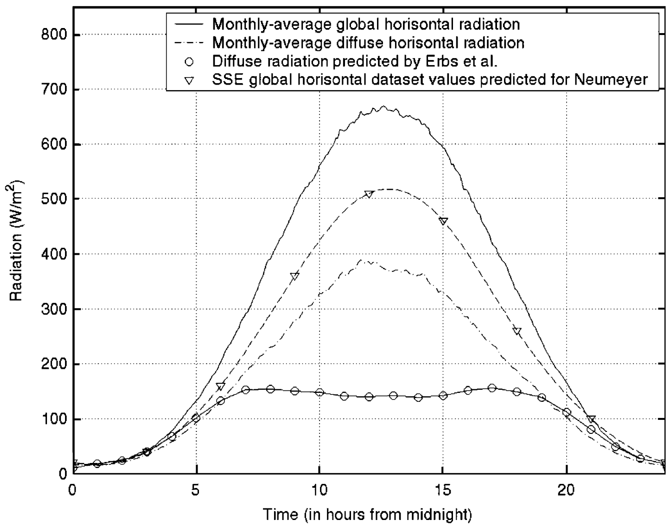


Fig. 1. Five-year average January daily radiation at Neumayer station (1994–1998) compared to SSE data.

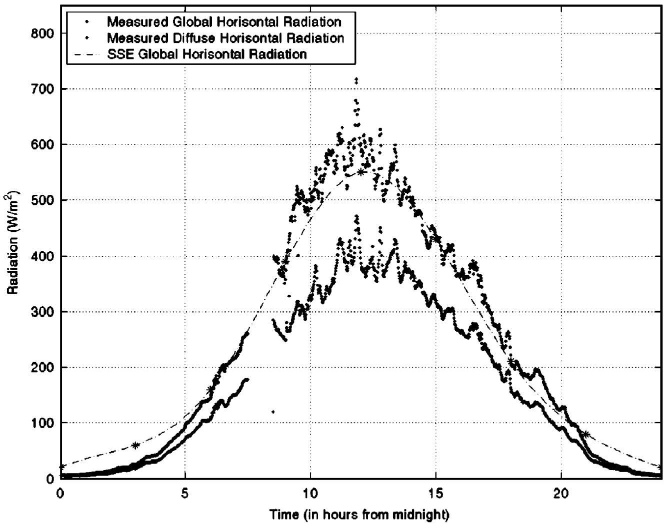


Fig. 2. Comparison of SANAE IV measured data with the SSE dataset.

Considering that the levels of solar radiation at Neumayer are higher than the SSE dataset values for SANAE IV, it is evident that the Neumayer measurements offer a more accurate estimate of the actual conditions at the South African station than those suggested by the dataset. As has been stated already cloud-cover levels at Neumayer are greater than those at SANAE IV (which is true throughout the year), and as such radiation measurements from Neumayer still offer a conservative estimate of the conditions at SANAE IV. These estimated and slightly adjusted values of global horizontal radiation at SANAE IV are shown in Fig. 3 alongside estimates of radiation at the French Dumont d'Urville [13], Swedish WASA [14] and German Neumayer [15] stations for comparison. Note that the value shown for SANAE IV during January is 20% lower than the clear-sky average (an absolute maximum), however, according to the SSE dataset [6] only two clear-sky days are expected in this month. Thus, although the suggested values are lower than the expected averages they must be significantly within 20% of the actual values. Seasonal variations of up to 17% are expected from long-term averages [6], thus, not only is the uncertainty in the amount of global horizontal radiation expected at SANAE IV deemed acceptable, the ensuing feasibility study is also desirably conservative.

Historical data of cloud-cover were not appropriate for calculating precise levels of solar radiation at SANAE IV according to Norris [16], whose research concluded that, "… *it is probably impossible to use cloud information to predict solar radiation*".

Estimates of radiation levels on tilted surfaces were derived using the correlation of Perez et al. [17] that accounts for horizon brightening and circumsolar radiation

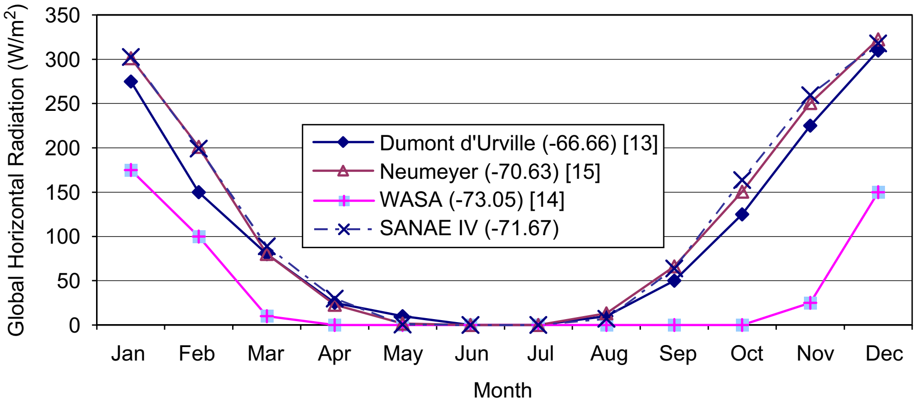


Fig. 3. Monthly average global horizontal radiation at four Antarctic stations.

Table 1
Expected average values of insolation at SANAE IV

Month	Global horizontal insolation (kWh/m^2 day)	Horizontal beam insolation (kWh/m^2 day)	Optimum global tilt (deg)	Optimum beam tilt (deg)	Global tilted insolation (kWh/m^2 day)	Titled beam insolation (kWh/m^2 day)	Average temperature (°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

and are provided in Table 1. The table also includes the calculated optimal tilt angles for collector surfaces throughout the year (of both global and beam radiation). A ground reflectivity of 0.7 was used [8], although Schmidt and Langlo [15] suggest a value of 0.84 for the German Neumayer station.

5. Station energy demand analysis

Annual diesel demand at SANAE IV amounts to approximately 347 222 l [2], of which 297 872 l is used by the diesel-electric generators for creating heat and electricity and the remainder is used for re-fuelling the fleet of diesel-powered vehicles. Relatively small amounts of petrol and jet-fuel are also required at the station to power Skidoos and aircraft, respectively, a demand that totals approximately 5% of the overall fuel consumption at the station with diesel making up the difference. Annual averages of station electrical energy consumption have been calculated at 2910 kWh/day (a value found to have a fair amount of activity related and seasonal dependence) with estimated maximum and minimum values of 5160 and 1440 kWh, respectively.

The station's summer base-load energy consumption (i.e., minimum values) was established as 60 kW, which is supplied by two ADE turbo-charged 442 T and one turbo-charged inter-cooled 442Ti diesel-electric generator CHP system. Heat is recovered from both the engines' cooling water loops and exhaust gas-to-water heat exchangers [18]. It is in this context that both solar thermal and electrical energy harvesting is investigated. The generators operate with an average electrical efficiency of 36.4%, thus 3.6 kWh of electrical energy is generated from every liter of diesel combusted (since the lower heating value of SAB diesel is 9.8 kWh/l). The electrical mini-grid is a three-phase, 380 VAC and 50 Hz system. Electrical and thermal power distributed from the CHP system of SANAE IV is shown in Fig. 4, and an illustration of the average annual diesel consumption in Fig. 5.

From an investigation of each of the energy consuming components shown in Fig. 4 it was determined that solar energy supplemented either to the SANAE IV electrical

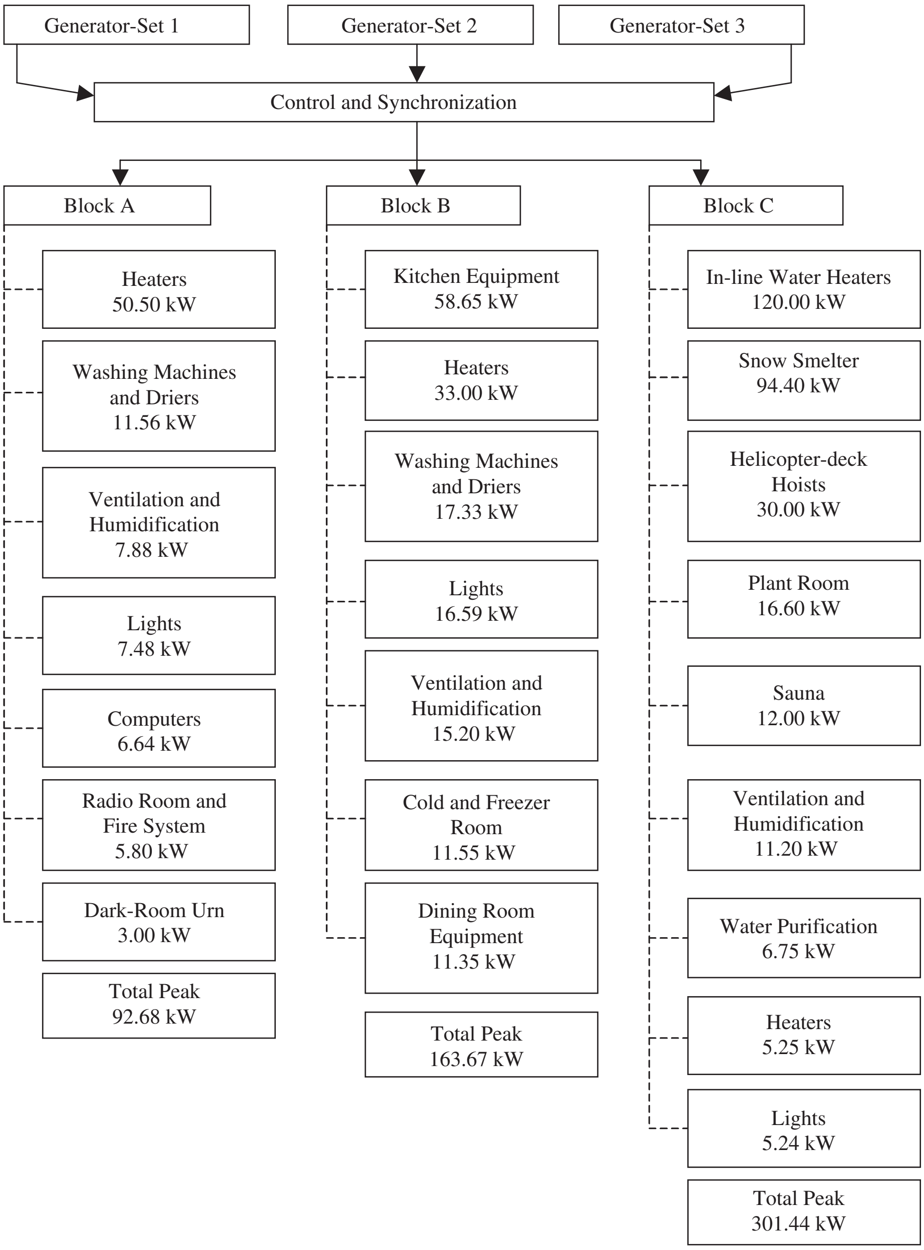
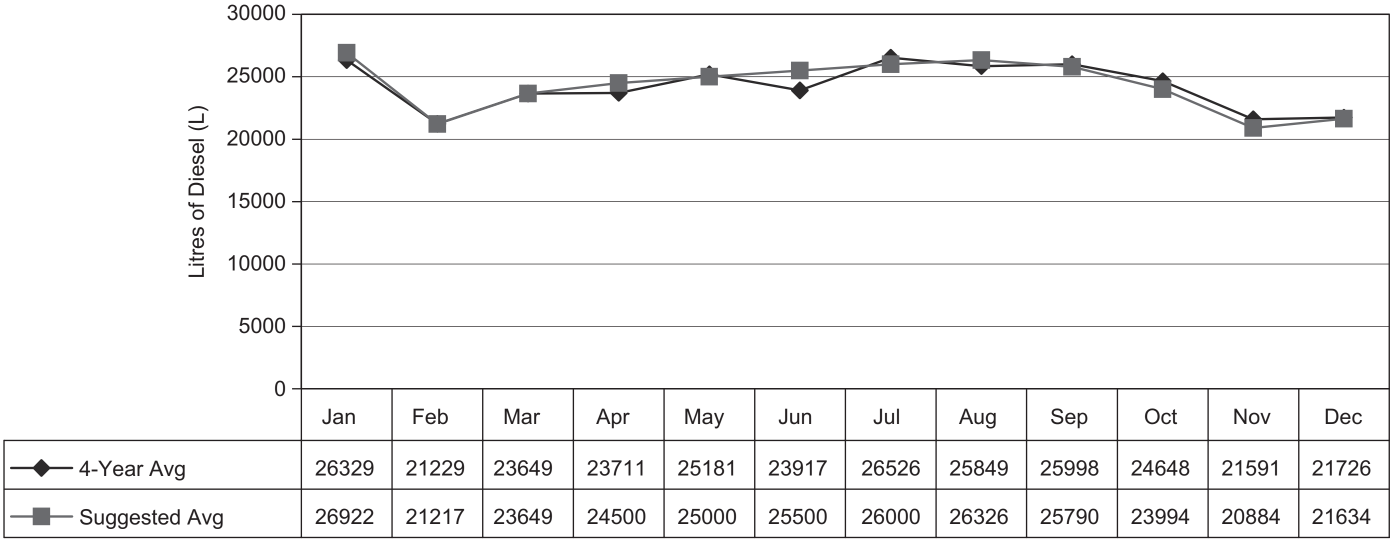


Fig. 4. Peak power demand breakdown of all energy consumers at SANAE IV (updated from [5]).

mini-grid or to the snow smelter (a device that meets the station's fresh water requirements by melting snow) would offer the greatest benefit to the station [18]. The snow smelter must supply large amounts of fresh water during the summer takeover season, a 6-week period during which the number of personnel resident at the station increases from approximately 10 to 80 people. The period is characterized by noticeable increased strain on the electrical generation system and as such load reductions present valuable opportunities for improving operation.

Average fresh water consumption rates were determined from measured data and literature [19] as 80 l per person per day for all activities at the station. The snow smelter is filled three times per day with snow, and the fluid is heated to 30 °C after each filling before the heating elements are switched off to stabilize the water at this temperature. Normally, however, due to the increased need for fresh water during the takeover, the water will be pumped at a temperature of about 10 °C.

Thus, the snow smelter represents an energy intensive process requiring a minimum of 819 kWh/day during the takeover season, or more than 25% of average daily takeover electricity consumption of 3096 kWh/day. This vitally important component of the station's operation presents a good match between the availability of solar energy and a need for greater energy supply. Conversely, it was found that the availability of solar energy and the need for space heating in the station, for instance, did not correlate well. In fact, the station required cooling during



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
◆ 4-Year Avg	26329	21229	23649	23711	25181	23917	26526	25849	25998	24648	21591	21726
■ Suggested Avg	26922	21217	23649	24500	25000	25500	26000	26326	25790	23994	20884	21634

Fig. 5. Seasonal variations of diesel consumption.

the summer months [20], while solar radiation levels during the winter were too low to justify supplementing the load with solar energy.

6. Device characteristics and energy production

Characteristics of photovoltaic and solar thermal collectors were investigated in order to establish which devices are best suited for the utilization of solar energy in Antarctica.

In order to assess efficiencies of photovoltaic systems the methodology presented by RETScreen [21] was implemented, resulting in an estimated overall system efficiency of 13% (from panel to power grid, including array and power conditioning losses). This figure represents a generic, crystalline baseline adopted: while making great strides in the development of thin film high-efficiency silicon-free materials [22], South Africa will only start manufacturing photo voltaic collectors shortly. Presently, all devices are imported, exposed to currency exchange fluctuations and variations in supply structures and thus subject to a high degree of uncertainty in the context of this study. Captured solar power is to be transferred from a suggested 40 kWp photovoltaic array to SANAE IV's mini-grid through a three-phase grid-tie inverter. Notice was also taken of research completed at the Australian Antarctic stations which established that, "… *despite the greater collection potential offered by tracking systems, an annually optimized fixed system is the best overall design option when operational costs are assessed on a per area basis*" [23]. What must be kept in mind here is that wind speeds exceeding 100 km/h for about 5% of the time [5] make the increased reliability of rigid systems much more attractive at sites of extreme remoteness.

Thus, the solar thermal collector was chosen based on a number of decisive factors. Low process temperatures, low ambient temperatures (resulting in large amounts of heat loss from collectors), the significant proportion of diffuse radiation compared to global radiation at SANAE IV (refer to Fig. 2), availability of products, and difficulty in installing or maintaining tracking systems support the choice of flat-plate collectors over concentrating devices. It is also a flat-plate solar collector system (currently the only solar thermal system operational in Antarctica) that is functional at the Australian Davis station, "… *supplying 100% of the hot water used for personal ablutions and laundry*" [4].

The potential yield of a flat-plate solar collector was investigated by running simulations of the Solahart Bt collector [24] to estimate potential yields. Fig. 6 represents a schematic of the array connection to the snow smelter (a split system) also illustrating the controller and pumps that facilitate the heat transfer from the energy store to the snow smelter by coordinating pumping intervals. The collector is designed with drain-back capabilities, implying that at times of low solar radiation no fluid is present in the collector preventing heat transfer from the snow smelter to the environment. Assumptions include: using estimated average monthly radiation profiles, assuming a fixed average daily production of fresh water and not accounting for the variation in demand and available solar energy, using fixed average monthly ambient temperatures, and estimating the overall heat transfer coefficients for the heat exchanger and for losses from the snow smelter as 1500 and 20 W/K m^2, respectively. The result is an estimated net annual collector efficiency of 29.3% (viz. an annual production of 60 000 kWh from a possible 204 604 kWh for a tilted array of 143 m^2).

7. Economic analysis

The basic methodology of the ensuing economic evaluation is detailed in a report created for the South African

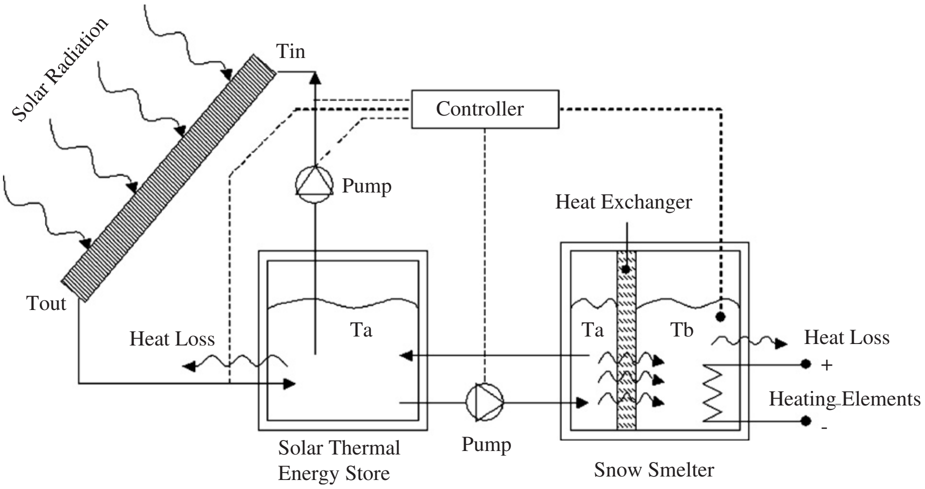


Fig. 6. Schematic of solar thermal collector connected to snow smelter.

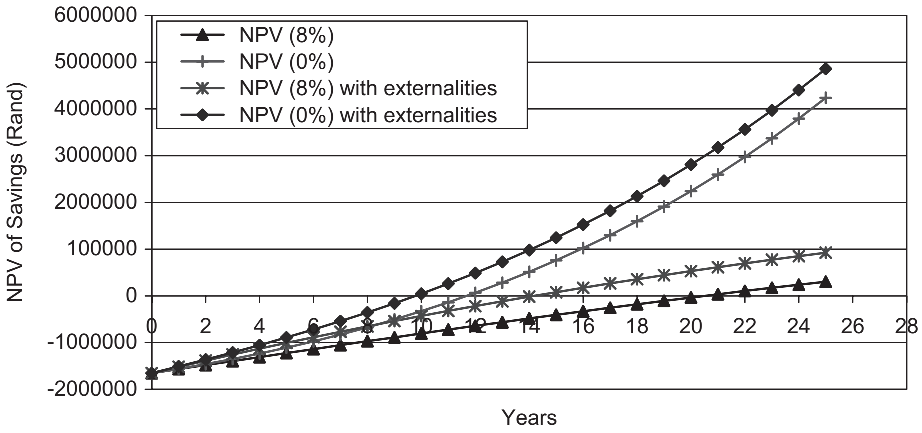


Fig. 7. NPV of savings generated by photovoltaic system (MARR 8% and 0%).

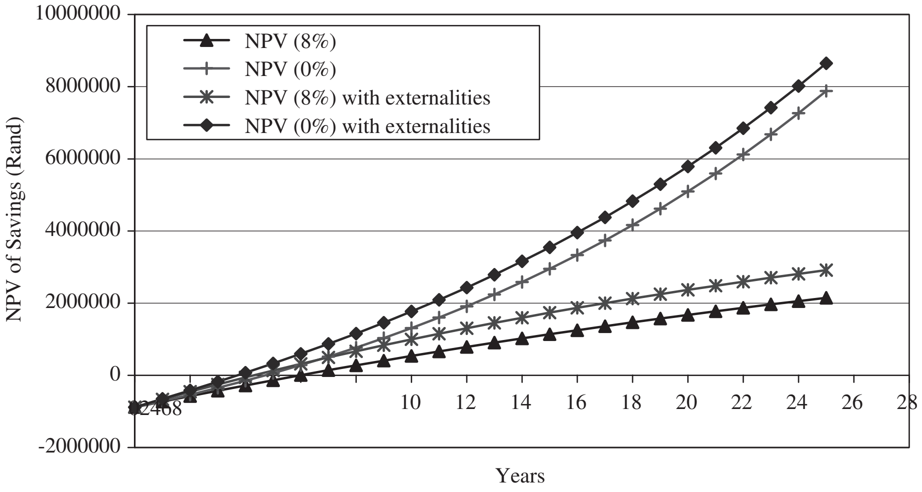


Fig. 8. NPV of savings generated by solar thermal system (MARR 8% and 0%).

Department of Environmental Affairs and Tourism entitled "*Cost Benefit Analysis*" [25]. The analysis assesses net present value (NPV), internal rates of return (IRR), net annual worth (NAW), benefit cost ratio (B/C ratio), payback periods and cost per kWh of energy produced in real monetary terms (i.e., relative to the Rand value in

December 2005). A standard minimum attractive rate of return (MARR, also referred to as a "hurdle rate") of 8% was used in the analysis.

The NPV is calculated from Eq. (1) by summing the initial capital expenditure (C), annual maintenance (M), annual labour (L), annual fuel (F) and annual external (E) costs over the 25-year lifetime of the project. External savings (or savings generated by reducing the programme's impact on the environment) have been taken from values suggested by Teetz et al. [5] as 5.61 R/l. The final purchase price of diesel included transport expenses to the station, and point-of-use costs were established as three times more expensive than the original purchase price of 5.36 R/l [5,13,26,27]. Fuel savings of the photovoltaic and flat-plate solar thermal systems amounted to 9958 and 12 244 l, respectively. Purchase prices of 35 R/Wp were used for the photovoltaic panels, while Solahart Bt flat-plate collectors can be purchased from R7000 per panel (of 1.98 m^2)

$$\mathrm{NPV} = \sum_{n=0}^{N} (C_n + M_n + L_n + F_n + E_n)\left(\frac{1}{(1+i)^n}\right). \tag{1}$$

Figs. 7 and 8 illustrate the results of installing the recommended photovoltaic or solar thermal systems, respectively (i.e., a hybrid solar–diesel system) at a MARR of 8% and fuel price escalation rate of 5%. The IRR shown in Table 2 is calculated by solving Eq. (3), where the present worth factor (PWF) is defined by Eq. (2). The PWF is a function of an interest rate (i), and time period in years (n):

$$\mathrm{PWF}(i,n) = \frac{1}{(1+i)^n}, \tag{2}$$

$$\sum_{k=0}^{N} (\mathrm{PWF}(\mathrm{IRR},k))\mathrm{Income}_k = \sum_{k=0}^{N} (\mathrm{PWF}(\mathrm{IRR},k))\mathrm{Expenses}_k. \tag{3}$$

B/C ratios given in Table 2 are established by calculating the value of B/C ratios from Eq. (4):

$$B/C = \frac{\sum_{k=0}^{N} (\mathrm{PWF}(\mathrm{MARR},k))\mathrm{Income}_k}{\sum_{k=0}^{N} (\mathrm{PWF}(\mathrm{MARR},k))\mathrm{Expenses}_k}. \tag{4}$$

Final energy generation costs for the diesel–photovoltaic and diesel–solar thermal hybrid systems were calculated as 3.20 and 3.13 R/kWh, respectively. They are calculated by solving

$$\mathrm{Cost} = \frac{\sum_{k=0}^{N} (\mathrm{PWF}(\mathrm{MARR},k))\mathrm{Expenses}_k}{\sum_{k=0}^{N} \text{Annual Energy Production}_k}. \tag{5}$$

The feasibility of the suggested solar system hinges largely on the economic benefits achievable by commissioning the recommended devices. In the light of difficult to establish criteria such as changing fuel purchase prices, the cost of transporting fuel to Antarctica, installation costs, annual maintenance costs and external savings, the results of this analysis are subject to change. Care has been taken, however, to establish how sensitive the suggested system is to this change (as is evident in Table 2), and to use conservative estimates where applicable.

8. Conclusion

The presented analysis procedure was found to be applicable for assessing the solar energy potential at SANAE IV in Antarctica. Although the decrease in fuel consumption from the suggested solar systems is small (viz. 3–4% of average annual diesel consumption), financial savings generated and electrical load reduction in the demanding summer takeover months justify effort expended. This is also true if external costs are considered. Thus, an annual diesel fuel saving of 3.5% translates to savings of approximately

Table 2
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

10 4251 diesel, 0.012 tonnes volatile organic compounds, 0.019 tonnes carbon monoxide, 0.471 tonnes nitrous oxides, 0.003 tonnes sulphur dioxides, 26 tonnes carbon dioxide and 0.007 tonnes particulate matter. While Teetz et al. [5] showed that wind energy could economically supply about 35% of the energy required at the base, a solar system will nevertheless make a worth while impact. The short payback period of the suggested flat-plate solar thermal system of 6 years validates this. The results therefore demonstrate that the proposed hybrid systems are technically feasible, as well as that utilizing solar energy at SANAE IV can be economically viable.

Acknowledgements

The authors would like to thank the South African Department of Environmental Affairs and Tourism, Subdirectorate Antarctica and Islands, for funding and logistical support, as well as the South African Department of Science and Technology, who through the South African National Research Foundation also contributed in funding.

Appendix A. Sample calculations of economic analysis for the photovoltaic system

A mathematical analysis subordinate to discussion of the economic evaluation above (in Section 7) has been included below. Table A1 provides a list of all annual costs, after which the relevant sample calculations are given.

A.1. Net present value

The NPV of cash flows has been calculated with the help of Eqs. (A.1) and (A.2). For example, the NPV of cash flows for the diesel-only system (excluding externalities) after the first year equals the total costs at the end of year 1 brought back by the PWF with an interest rate equal to the hurdle rate:

$$\mathrm{NPV} = \sum_{n=0}^{N} (C_n + M_n + L_n + F_n)\left(\frac{1}{(1+i)^n}\right), \tag{A.1}$$

$$\mathrm{NPV} = -5079770.85\left(\frac{1}{(1+0.08)^1}\right). \tag{A.2}$$

A.2. Internal rate of return

The IRR can easily be calculated with the help of Microsoft Excel's formulae function, however, by way of example the formula and sample calculation is given here. The IRR is that interest rate which solves Eq. (A.3). For example, the IRR in Table A2 at the end of year 6 is calculated from the column "Yearly cashflows" in the same table as

$$\sum_{k=0}^{N} (\mathrm{PWF}(\mathrm{IRR}, k))\mathrm{Income}_k = \sum_{k=0}^{N} (\mathrm{PWF}(\mathrm{IRR}, k))\mathrm{Expenses}_k, \tag{A.3}$$

which is solved by

$$\begin{aligned} 1653167.13\left[\frac{1}{(1+0.1983)^0}\right] &= 92585.66\left[\frac{1}{(1+0.1983)^1}\right] + 100236.95\left[\frac{1}{(1+0.1983)^2}\right] \\ &+ 108301.02\left[\frac{1}{(1+0.1983)^3}\right] + 116798.22\left[\frac{1}{(1+0.1983)^4}\right] \\ &+ 125752.34\left[\frac{1}{(1+0.1983)^5}\right] + 135184.67\left[\frac{1}{(1+0.1983)^6}\right]. \end{aligned} \tag{A.4}$$

A.3. Benefit cost ratio

The B/C ratio is easily calculated as the sum of the total benefits projected to the same point in time (in this instance the NPV) divided by the sum of the total costs. Therefore (excluding externalities)

$$B/C = \frac{\sum_{k=0}^{N} (\mathrm{PWF}(\mathrm{MARR}, k))\mathrm{Income}_k}{\sum_{k=0}^{N} (\mathrm{PWF}(\mathrm{MARR}, k))\mathrm{Expenses}_k}, \tag{A.5}$$

Table A1
List of annual system costs pertaining to Eq. (A.1)

Cost item	Diesel-only system (Rand)	Diesel−photovoltaic system (Rand)	Diesel−solar thermal system (Rand)
Initial capital expenditure (C)	0.00	−1 653 167.13	−881 200.00
Annual maintenance cost (M)	−30 000.00	−103 802.10	−63 700.00
Annual labor cost (L)	−20 000.00	−21 000.00	−25 000.00
Annual fuel cost (F)	−5 038 455.74	−4 870 319.96	−4 831 712.89
Annual external cost (E)	0.00	53 554.11	65 851.12

Table A2
Sample results for solar PV system (column A is for diesel-only and column B is for the hybrid system)

NPV		Yearly cashflows	Discounted payback	Simple payback	Externalities	NPV of externalities	Dscnted payback (with externalites)	Simple payback with externalities	IRR based on years	*B*/*C* ratio based on years
A	B									
0.00	−1 653 167.13	−1 653 167.13	−1 653 167.13	−1 653 167.13	0.00	0.00	−1 653 167.13	−1 653 167.13	#NUM!	0.00
−4 703 491.53	−6 270 931.19	92 585.66	−1 567 439.66	−1 560 581.47	53 554.11	49 587.14	−1 517 852.52	−1 510 994.33	#NUM!	0.09
−9 274 598.69	−10 756 101.32	100 236.95	−1 481 502.63	−1 460 344.51	54 089.65	95 960.30	−1 385 542.33	−1 364 384.21	#NUM!	0.17
−13 717 111.07	−15 112 640.86	108 301.02	−1 395 529.79	−1 352 043.49	54 630.55	139 327.79	−1 256 202.00	−1 212 715.70	#NUM!	0.25
−18 034 705.73	−19 344 384.89	116 798.82	−1 309 679.17	−1 235 244.67	55 176.86	179 884.43	−1 129 794.74	−1 055 360.24	#NUM!	0.31
−22 230 950.76	−23 455 045.00	125 752.34	−1 224 094.24	−1 109 492.33	55 728.62	217 812.39	−1 006 281.85	−891 679.94	#NUM!	0.38
−26 309 308.81	−27 448 213.78	135 184.67	−1 138 904.97	−974 307.66	56 285.91	253 282.06	−885 622.90	−721 025.60	−19.83%	0.43
−30 273 140.36	−31 327 369.17	145 120.06	−1 054 228.81	−829 187.60	56 848.77	286 452.77	−767 776.03	−542 734.83	−14.08%	0.49
−34 125 706.99	−35 095 878.62	155 583.98	−970 171.62	−673 603.63	57 417.26	317 473.53	−652 698.09	−356 130.09	−9.68%	0.54
−37 870 174.49	−38 757 003.05	166 603.18	−886 828.56	−507 000.45	57 991.43	346 483.68	−540 344.87	−160 516.77	−6.23%	0.59
−41 509 615.83	−42 313 900.65	178 205.73	−804 284.82	−328 794.71	58 571.34	373 613.55	−430 671.27	44 818.83	−3.50%	0.63
−45 047 014.07	−45 769 630.53	190 421.14	−722 616.46	−138 373.57	59 157.06	398 985.00	−323 631.46	260 611.42	−1.28%	0.67
−48 485 265.15	−49 127 156.17	203 280.37	−641 891.02	64 906.80	59 748.63	422 712.00	−219 179.03	487 618.80	0.53%	0.71
−51 827 180.59	−52 389 348.84	216 815.95	−562 168.25	281 722.75	60 346.11	444 901.14	−117 267.11	726 623.89	2.03%	0.75
−55 075 490.10	−55 558 990.74	231 062.02	−483 500.64	512 784.77	60 949.57	465 652.09	−17 848.54	978 436.86	3.28%	0.79
−58 232 844.06	−58 638 778.08	246 054.44	−405 934.01	758 839.21	61 559.07	485 058.08	79 124.07	1 243 897.29	4.34%	0.83
−61 301 816.00	−61 631 324.07	261 830.88	−329 508.08	1 020 670.09	62 174.66	503 206.27	173 698.19	1 523 876.36	5.25%	0.86
−64 284 904.89	−64 539 161.74	278 430.88	−254 256.86	1 299 100.96	62 796.41	520 178.19	265 921.34	1 819 279.15	6.02%	0.89
−67 184 537.45	−67 364 746.63	295 895.96	−180 209.18	1 594 996.92	63 424.37	536 050.08	355 840.90	2 131 047.00	6.69%	0.93
−70 003 070.35	−70 110 459.44	314 269.73	−107 389.09	1 909 266.65	64 058.62	550 893.23	443 504.14	2 460 159.89	7.26%	0.96
−72 742 792.27	−72 778 608.51	333 597.98	−35 816.24	2 242 864.63	64 699.20	564 774.33	528 958.09	2 807 638.97	7.77%	0.99
−75 405 926.01	−75 371 432.26	353 928.79	34 493.75	2 596 793.43	65 346.19	577 755.73	612 249.47	3 174 549.15	8.21%	1.01
−77 994 630.43	−77 891 101.49	375 312.65	103 528.95	2 972 106.08	65 999.66	589 895.74	693 424.68	3 562 001.82	8.60%	1.04
−80 511 002.42	−80 339 721.61	397 802.58	171 280.81	3 369 908.66	66 659.65	601 248.90	772 529.70	3 971 157.55	8.94%	1.07
−82 957 078.67	−82 719 334.81	421 454.25	237 743.86	3 791 362.90	67 326.25	611 866.20	849 610.06	4 403 229.10	9.25%	1.09
−85 334 837.55	−85 031 922.09	446 326.11	302 915.46	4 237 689.01	67 999.51	621 795.35	924 710.81	4 859 484.36	9.52%	1.12
R −85 334 837.55	R −85 031 922.09	R 302 915.46	R 302 915.46	R 4 237 689.01	R 621 795.35	R 621 795.35	R 924 710.81	R 4 859 484.36		

Table A3
Sample results for the solar PV system (column A is for diesel-only and column B is for the hybrid system)

	Capital investment		Fuel costs		Maintenance		Labor		Total	
	A	B	A	B	A	B	A	B	A	B
0	0.00	−1 653 167.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	−1 653 167.13
1	0.00	0.00	−5 029 270.85	−4 861 135.06	−30 300.00	−104 840.13	−20 200.00	−21 210.00	−5 079 770.85	−4 987 185.18
2	0.00	0.00	−5 280 734.39	−5 104 191.81	−30 603.00	−105 888.53	−20 402.00	−21 422.10	−5 331 739.39	−5 231 502.44
3	0.00	0.00	−5 544 771.11	−5 359 401.40	−30 909.03	−106 947.41	−20 606.02	−21 636.32	−5 596 286.16	−5 487 985.14
4	0.00	0.00	−5 822 009.67	−5 627 371.47	−31 218.12	−108 016.89	−20 812.08	−21 852.68	−5 874 039.87	−5 757 241.04
5	0.00	0.00	−6 113 110.15	−5 908 740.05	−31 530.30	−109 097.05	−21 020.20	−22 071.21	−6 165 660.65	−6 039 908.31
6	0.00	0.00	−6 418 765.66	−6 204 177.05	−31 845.60	−110 188.03	−21 230.40	−22 291.92	−6 471 841.66	−6 336 657.00
7	0.00	0.00	−6 739 703.94	−6 514 385.90	−32 164.06	−111 289.91	−21 442.71	−22 514.84	−6 793 310.71	−6 648 190.65
8	0.00	0.00	−7 076 689.14	−6 840 105.20	−32 485.70	−112 402.80	−21 657.13	−22 739.99	−7 130 831.97	−6 975 247.99
9	0.00	0.00	−7 430 523.59	−7 182 110.46	−32 810.56	−113 526.83	−21 873.71	−22 967.39	−7 485 207.86	−7 318 604.68
10	0.00	0.00	−7 802 049.77	−7 541 215.98	−33 138.66	−114 662.10	−22 092.44	−23 197.06	−7 857 280.88	−7 679 075.14
11	0.00	0.00	−8 192 152.26	−7 918 276.78	−33 470.05	−115 808.72	−22 313.37	−23 429.04	−8 247 935.68	−8 057 514.54
12	0.00	0.00	−8 601 759.87	−8 314 190.62	−33 804.75	−116 966.81	−22 536.50	−23 663.33	−8 658 101.13	−8 454 820.75
13	0.00	0.00	−9 031 847.87	−8 729 900.15	−34 142.80	−118 136.48	−22 761.87	−23 899.96	−9 088 752.53	−8 871 936.58
14	0.00	0.00	−9 483 440.26	−9 166 395.16	−34 484.23	−119 317.84	−22 989.48	−24 138.96	−9 540 913.97	−9 309 851.96
15	0.00	0.00	−9 957 612.27	−9 624 714.91	−34 829.07	−120 511.02	−23 219.38	−24 380.35	−10 015 660.72	−9 769 606.28
16	0.00	0.00	−10 455 492.89	−10 105 950.66	−35 177.36	−121 716.13	−23 451.57	−24 624.15	−10 514 121.82	−10 252 290.94
17	0.00	0.00	−10 978 267.53	−10 611 248.19	−35 529.13	−122 933.29	−23 686.09	−24 870.39	−11 037 482.75	−10 759 051.88
18	0.00	0.00	−11 527 180.91	−11 141 810.60	−35 884.42	−124 162.62	−23 922.95	−25 119.10	−11 586 988.28	−11 291 092.32
19	0.00	0.00	−12 103 539.95	−11 698 901.13	−36 243.27	−125 404.25	−24 162.18	−25 370.29	−12 163 945.40	−11 849 675.67
20	0.00	0.00	−12 708 716.95	−12 283 846.19	−36 605.70	−126 658.29	−24 403.80	−25 623.99	−12 769 726.45	−12 436 128.47
21	0.00	0.00	−13 344 152.80	−12 898 038.50	−36 971.76	−127 924.88	−24 647.84	−25 880.23	−13 405 772.40	−13 051 843.60
22	0.00	0.00	−14 011 360.44	−13 542 940.42	−37 341.48	−129 204.13	−24 894.32	−26 139.03	−14 073 596.23	−13 698 283.58
23	0.00	0.00	−14 711 928.46	−14 220 087.44	−37 714.89	−130 496.17	−25 143.26	−26 400.42	−14 774 786.61	−14 376 984.03
24	0.00	0.00	−15 447 524.88	−14 931 091.82	−38 092.04	−131 801.13	−25 394.69	−26 664.43	−15 511 011.62	−15 089 557.37
25	0.00	0.00	−16 219 901.13	−15 677 646.41	−38 472.96	−133 119.14	−25 648.64	−26 931.07	−16 284 022.73	−15 837 696.62
PV	R 0.00	R −1 653 167.13	R −84 748 502.27	R −81 915 237.43	R −351 801.17	R −1 217 256.71	R −234 534.11	R −246 260.82	R −85 334 837.55	R −85 031 922.09

which can be calculated from the first four columns in Table A3 (viz. capital, fuel, maintenance and labour), where “fuel” is the only column that represents an income as given in Eq. (A.5). Thus, the B/C ratio at the end of year 1 is calculated as

$$B/C = \frac{[1/(1+0.08)^1]\times 168135.79}{[1/(1+0.08)^0]\times 1653167.13 + [1/(1+0.08)^1]\times 74540.13 + [1/(1+0.08)^1]\times 1010}. \tag{A.6}$$

A.4. Cost of energy produced

The cost of energy generation has been calculated by summing the respective total costs of the system in question (i.e., diesel-only or hybrid) over the 25-year project lifetime, and then dividing by the power generated after that amount of time:

$$\text{Cost} = \frac{\sum_{k=0}^{N}(\text{PWF}(\text{MARR},k))\text{Expenses}_k}{\sum_{k=0}^{N}\text{Annual Energy Production}_k}. \tag{A.7}$$

Thus, the normal generation costs of the diesel-only system are calculated as (cost values can be seen at the bottom of Table A3)

$$\text{Cost} = \frac{0 + 84903277.43 + 351801.17 + 234534.11}{24\times 1061971}. \tag{A.8}$$

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