# TECHNICAL AND ECONOMIC EVALUATION OF
# THE UTILISATION OF SOLAR ENERGY
# AT SOUTH AFRICA'S SANAE IV BASE IN ANTARCTICA

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## Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously, in its entirety or in part, submitted it at any university for a degree.

Signature: ______________________ Date: ______________________

*Jürgen R. Olivier*

## Abstract

There are numerous challenges that have to be overcome in order to generate the electrical and thermal energy required to power Antarctic research stations in a technically, economically and environmentally suitable manner. Consequently the costs associated with generating energy at these latitudes are high, and ways are constantly being sought to improve energy generation methods and protect the pristine environment. These endeavours are strongly encouraged by the Antarctic Treaty.

This thesis aims to investigate the technical and economic feasibility of using solar energy at South Africa's SANAE IV (South African National Antarctic Expedition IV) station in Antarctica. The idea of using solar energy in Antarctica is not novel, and as is shown a number of stations have already capitalised on opportunities to generate savings in this manner. Similarly, at SANAE IV, there exists the opportunity to alleviate an increased summer energy load on the station and reduce diesel consumption through the proper implementation of such a system. There is also ample scope to use wind energy, which would have a marked positive impact on the base's operation.

The data used in this thesis was obtained mainly during the 2004/2005 takeover expedition to South Africa's SANAE IV station in Antarctica. Included are measurements of total and diffuse radiation that were measured during the months of January and February 2005, and which form an important part of the investigation. Since there are currently no radiation sensors, or any historical record of measured radiation at the station, the only measured data available from SANAE IV was the data recorded during the 2004/2005 takeover expedition. By further collecting archived values of fuel consumption, electricity generation and load profiles, an energy audit of the station was also completed during the 2004/2005 takeover expedition.

The expected savings that could be generated by solar systems were calculated by considering the use of both photovoltaic and solar thermal devices at the South African station. The 40 kW photovoltaic system that was investigated was able to significantly reduce the load on the diesel-electric generators, however it was only possible to fully recover the initial costs sunk into commissioning the system after 21 years. The installation of such a system would equate to a Net Present Value of 302 915 Rand at the end of the 25 year system lifetime (assuming a real hurdle rate of 8 % and fuel price escalation rate of 5 %), saving 9 958 litres of diesel annually 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.

Furthermore, it was found that a flat-plate solar thermal collector utilised with the snow smelter at SANAE IV is better suited to generating savings than photovoltaic devices. The average cost of generating electricity after commissioning such a system with a 143 $m^2$ collector field would be approximately 3.13 Rand/kWh, as opposed to the 3.21 Rand/kWh of the current diesel-only system, and would realise an annual fuel saving of approximately 12 245 litres. The system would arrive at a breakeven point after approximately 6 years, and represent a Net Present Value 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 over the expected 25 year project lifetime.

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.

## Opsomming

‘n Aantal unieke uitdagings moet oorkom word om die elektriese en termiese energie wat by navorsingstasies in Antarktika benodig word in ‘n toepaslike tegniese, ekonomiese en omgewingsbewuste manier op te wek. Die kostes verbonde aan die gebruik van energie by hierdie breedtegrade is om hierdie rede hoog. Daar is dus ook geen einde nie aan die soektog vir beter maniere van energieopewekking en omgewingsbeskerming, pogings wat deur die Antarktiese Traktaat ondersteun word.

In hierdie tesis word daarna gemik om die tegniese en ekonomiese lewensvatbaarheid van die gebruik van sonenergie by Suid Afrika se SANAE IV (Suid Afrikaanse Nasionale Antarktiese Ekspedisie IV) basis in Antarktika te ondersoek. Die aanwending van sonenergie in Antarktika is geensins ‘n nuwe idee nie, en soos hier gewys word het ‘n aantal navorsings stasies alreeds van sulke bespaaringsgeleenthede gebruik gemaak. In dieselfde manier bestaan daar die geleentheid by SANAE IV om die verhoogde somerenergielas op die basis se energiestelsels, en diesel verbruik te verminder. Die aanwending van windenergie kan ook ‘n merkbare positiewe verskil maak.

Hierdie tesis gebruik ook hoofsaaklik inligting wat versamel was gedurende die 2004/2005 ekspedisie na Suid Afrika se SANAE IV stasie in Antarktika. Ingesluit is lesings van totale en diffuse sonstralingsenergie gemeet gedurende die maande van Januarie en Februarie 2005, wat ‘n belangrike rol speel in die opeenvolgende ondersoek. Tans is daar geen sensors wat sonstralingsenergie by SANAE IV meet nie, en ook geen historiese sonstralingsenergiedata nie, en dus is die data wat gedurende die 2004/2005 ekspedisie versamel was die enigste huidige lesings van SANAE IV. Deur inligting te versamel gedurende die ekspedisie oor brandstofverbruik, elektrisiteitsopwekking en lasprofiele is ‘n energie oudit van die stasie ook voltooi.

Moontlike besparings wat deur die gebruik van sonenergiestelsels by Suid Afrika se basis gerealiseer kan word was bepaal deur die gebruik van beide fotovoltaaise en termiese stelsels te oorweeg. Verbeterde werkverrigting van dieselopwekkers is verkry met die gebruik van ‘n 40 kW fotovoltaaise sisteem, alhoewel projekkostes slegs na21 jaar herwin kan word. Die gebruik van so ‘n stelsel sal ‘n huidige waarde van 302 915 Rand verteeneewordig na die projekleeftyd van 25 jaar (gestel dat die *regte* hekkiekoers 8 % en brandstofstygingskoers 5 % is), jaarliks

omtrent 9 958 liter diesel bespaar en energie opwek teen ‘n koste van 3.20 Rand/kWh. Onder meer voordelige omstandgihede (m.a.w ‘n hoë tempo van brandstof kosteverhogings, min aantreklike alternatiewe bellegings en ‘n hoë klem op omgewingsake) sal ‘n fotovoltaaise sisteem heel waarskynlik na 10-15 jaar kan gelykbreek, terwyl dit terselfdetyd ‘n merkbare positiewe verskil sou maak aan die werksverrigting van die basis.

Daar is vasgestel dat ‘n platplaat termiese sonkollektor by SANAE IV vir gebruik met die stasie se sneeusmelter die hoogste bespaaringspotensiaal het. Die gemiddelde energiekostes na die instalering van ‘n platplaat termiese sonkollektorsisteem met 143 $m^2$ versamelveld sal ongeveer 3.13 Rand/kWh wees, in teenstelling met die 3.21 Rand /kWh van die huidige dieselstelsel. Daar sal ook jaarliks omtrent 12 245 liter diesel bespaar word. Die projekkostes hoort na 6 jaar gelyk te breek, en sal na 25 jaar ‘n Netto Huidige Waarde van 2 148 811 Rand verteenwoordig. Deur verder te kyk na kostes verbonde aan die verwydering van dieselbesmette sneeu en eselopwekker uitlaatgasse word die Netto Huidige Waarde met ongeveer 500 000 Rand vermeerder.

Die geleentheid om ‘n sonenergiestelsel by die SANAE IV basis in gebruik te neem vereis daarom dringende aandag. In ooreenstemming met die inhoud van die Antarktiese Traktaat bestaan daar besliste besparingspotensiaal, tesame met die geleentheid tot omgewingsbeskeming. Met omsigte beplanning en uitvoering sou so ‘n projek onderneem kon word en dit word gestel dat daarom ook behoort onderneem te word.

*"From whose womb comes the ice?*
*Who gives birth to the frost from the heavens,*
*When the waters become hard as stone,*
*When the surface of the deep is frozen?*
*Can you bind the beautiful Pleiades?*
*Can you loose the cords of Orion?*
*Can you bring forth the constellations in their seasons*
*Or lead out the Bear with its cubs?"*

*- Job 38:29-32*

Lorentzenpiggen, a mountain peak located directly south of SANAE IV (Olivier, 2005)

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## Nomenclature

### *Engineering Symbols:*

| | | |
|---|---|---|
| $A$ | = Area | [$m^2$] |
| $A_o$ | = Area on the outside of heat exchanger | [$m^2$] |
| $Al$ | = Altitude | [km] |
| $C_p$ | = Thermal heat capacity | [kJ/kg. K] |
| $E$ | = Available energy | [J] |
| $FC$ | = Fuel Consumption | [Litres] |
| $G$ | = Global radiation incident on a horizontal surface | [$W/m^2$] |
| $G_{cnb}$ | = Clear-Sky normal beam radiation | [$W/m^2$] |
| $G_d$ | = Diffuse radiation on a horizontal surface | [$W/m^2$] |
| $G_o$ | = Top of atmosphere radiation on a horizontal surface | [$W/m^2$] |
| $G_{on}$ | = Top of atmosphere radiation on a surface normal to the incoming rays | [$W/m^2$] |
| $\overline{H}$ | = Monthly-average daily insolation on a horizontal surface | [$kWh/m^2$] |
| $\overline{H}_O$ | = Monthly-average daily top of atmosphere insolation on a horizontal surface | [$kWh/m^2$] |
| $\overline{K}_T$ | = Monthly-average clearness index | [ ] |
| $K_T$ | = Daily-average clearness index | [ ] |
| $k_T$ | = Hourly-average clearness index | [ ] |
| $\dot{m}$ | = Mass flow-rate | [kg/s] |
| $NOCT$ | = Nominal Operating Cell Temperature | [°C] |
| $P$ | = Power | [W] |
| $PP$ | = Power Production | [kWh] |
| $Q$ | = Heat transfer | [J] |
| $\dot{Q}$ | = Rate of heat transfer | [J/s] |
| $R_T$ | = Thermal resistance | [$K/(W/m^2)$] |
| $T$ | = Temperature | [K] |
| $U_o$ | = Overall outside heat transfer coefficient | [$W/m^2K$] |

## Greek Engineering Symbols:

| | | |
|---|---|---|
| $\Delta T$ | = Temperature difference | [K] |
| $\rho$ | = Reflectivity | [ ] |
| $\beta$ | = Tilt of collecting surface away from horizontal (i.e. for a wall $\beta$ = 90°) | [°] |
| $\beta_p$ | = Temperature coefficient of module efficiency | [%/°C] |
| $r$ | = Climate coefficient | [ ] |
| $\tau$ | = Radiation transmissivity | [ ] |
| $\theta_Z$ | = Angle between incoming rays and zenith (i.e. at sunset $\theta_Z$ = 90°) | [°] |
| $\eta$ | = Efficiency | [ ] |
| $\mu_T$ | = Percentage decrease in efficiency with increase in temperature | [%/°C] |
| $\lambda$ | = Energy losses | [%] |

## *Economic Symbols:*

| | | |
|---|---|---|
| *BC* | = Benefit Cost ratio | [ ] |
| *C* | = Capital investment | [Rand] |
| *F* | = Fuel costs | [Rand] |
| *i* | = Interest rate | [%] |
| *IRR* | = Internal Rate of Return | [%] |
| *L* | = Labour costs | [Rand] |
| *M* | = Maintenance costs | [Rand] |
| *MARR* | = Minimum Attractive Rate of Return | [%] |
| *R* | = Rand (i.e. South African currency) | [Rand] |
| *n* | = Time | [Years] |
| *NAW* | = Net Annual Worth | [Rand] |
| *NPV* | = Net Present Value | [Rand] |
| *LCC* | = Life Cycle Costs | [Rand] |
| *O & M* | = Operation and Maintenance costs | [Rand] |
| *PW* | = Present Worth | [Rand] |
| *PWF* | = Present Worth Factor | [ ] |
| *US$* | = American dollars | [Dollars] |
| *X* | = Externalities | [Rand] |

## Abbreviations

| | |
|---|---|
| AAD | Australian Antarctic Division |
| AC | Alternating Current |
| AHU | Air Handling Unit |
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| ATSCM | Antarctic Treaty Special Consultative Meeting |
| AUD | Australian Dollar |
| BC Ratio | Benefit to Cost Ratio |
| BSRN | Baseline Surface Radiation Network |
| CEP | Committee for Environmental Protection |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| COMNAP | Council of Managers of National Antarctic Programs |
| DC | Direct Current |
| DEAT | South African Department of Environmental Affairs and Tourism |
| FCU | Fan Coil Unit |
| FRA | France |
| GEF | Global Environment Facility |
| GER | Germany |
| H&V | Heating and Ventilation System |
| HIT | Heterojunction with Intrinsic Thin layer |
| Hz | Hertz (i.e. cycles per second) |
| IEA | International Energy Agency |
| IGY | International Geophysical Year |
| IND | India |
| IRR | Internal Rate of Return |
| JAP | Japan |
| L | Litre |
| LCC | Life Cycle Costs |
| LPG | Liquid Petroleum Gas |
| MPPT | Maximum Power Point Tracker |
| NASA | National Aeronautic and Space Agency |
| NAW | Net Annual Worth |

| | |
|---|---|
| NOR | Norway |
| $No_x$ | Oxides of Nitrogen |
| NPV | Net Present Value |
| O&M | Operation and Maintenance |
| PLC | Programmable Logic Controller |
| PM | Particulate Matter |
| PV | Photovoltaic |
| PW | Present Worth |
| PWF | Present Worth Factor |
| R | South African Rand (i.e. South African currency) |
| ROW | Rest Of World |
| RUS | Russia |
| SAB | Special Antarctic Blend (i.e. special freeze resistant diesel) |
| SANAE IV | South African National Antarctic Expedition IV, or South Africa's fourth base in Antarctica. The Roman numeral is in reference to a base. |
| SANAE 4 | South African National Antarctic Expedition 4, or the fourth South African team to have overwintered on Antarctica (in 2005 SANAE 44 overwintered at SANAE IV). The ordinary numeral is in reference to a team of people. |
| SANAP | South African National Antarctic Programme (which administrates activities on South African controlled Southern Ocean islands as well as at SANAE IV) |
| SAWS | South African Weather Services |
| SCAR | Scientific Committee on Antarctic Research |
| $SO_2$ | Sulphur Dioxide |
| SRB | Surface Radiation Budget dataset collated by NASA |
| SSE | Surface meteorology and Solar Energy dataset collated by NASA |
| STC | Standard Testing Conditions |
| SWE | Sweden |
| TOA | Top Of Atmosphere |
| UNEP | United Nations Environment Programme |
| US$ | American Dollars (i.e. American currency) |
| VLF | Very Low Frequency |
| VOC | Volatile Organic Compounds |

# Chapter 1 – Introduction

## *1.1 Background*

South Africa's current Antarctic station, named the South African National Antarctic Expedition IV (SANAE IV), is positioned at 70° 40' 25" South and 2° 49' 44" West, approximately 4 500 km from Cape Town in South Africa and 3 000 km from the geographical South Pole. The base is one of seven overwintering stations (viz. Maitri [IND], Molodezhnaya [RUS], Neumeyer [GER], Novolazarevskaya [RUS], Syowa [JAP], SANAE IV [SA] and Troll [NOR]) operational in Queen Maud Land during the winter and one of fifteen stations to run programmes in Queen Maud Land during the summer (SCAR, 2005). The German Neumeyer and Norwegian Troll stations are SANAE IV's closest neighbours (located approximately 300 km to the northwest and 360 km to the east respectively) and in conjunction with SANAE IV are three of forty-seven overwintering stations that currently operate in Antarctica and the surrounding islands (an area collectively referred to as the Antarctic) all year round.


Figure 1.1: SANAE IV located in Queen Maud Land (Perry-Castañeda, 2005)

All of these countries administrating stations in the Antarctic do so under the terms of the Antarctic Treaty. Established in Washington on 1 of December 1959, this treaty was one outcome of the 1st International Geophysical Year (IGY), the first scientific research effort to undertake concurrent scientific activities that spanned the globe. Forty-five countries have since ratified the Antarctic Treaty, although originally only twelve had signed the agreement in 1959. South Africa was one of the original twelve signatories. South Africa is currently also: one of twenty-seven consultative parties to the Antarctic Treaty, a member of the Council of Managers of National Antarctic Programmes (COMNAP), a member of the Committee for Environmental Protection in Antarctica (CEP) and a national member of the Scientific Committee on Antarctic Research (SCAR). Furthermore, since the first South African overwintering team was dispatched to the SANAE I station in 1961, forty-four expeditions have overwintered on the continent, and carried out numerous scientific and logistical activities.

Figure 1.2: South Africa's SANAE IV base atop Vesleskarvet, a rocky outcrop (Olivier, 2005)

Currently expeditions to SANAE IV allow South Africa the opportunity to participate in a number of projects requiring not only proximity to the magnetic South Pole but also a high level of scientific expertise. In conjunction with Britain and Japan, for example, South Africa is a partner in the internationally collaborative SHARE project. SHARE contributes to the larger worldwide Super Dual Auroral Radar Network (SuperDARN) used to study electric fields, velocities and irregularities of the Earth's upper atmosphere by investigating data obtained from fifteen radar stations around the globe (nine in the Northern Hemisphere and six in the Southern Hemisphere). Ultimately this information is used to study changes in the Earth's biosphere that shields life from harmful cosmic rays.

South Africa also participates in the Solar Terrestrial Energy Programme (STEP), which investigates energy-transfer processes in the Earth's magnetosphere and ionosphere. By using magnetometers, auroral imaging devices, Very Low Frequency (VLF) direction finding systems and a host of other instrumentation, the processes that are known to *"…disrupt radio communications, cause damage to satellites, disrupt or destroy large networks of electric power lines and on occasion threaten astronauts and Concorde passengers with harmful levels of proton fluxes"* (SANAP, 2005) can be studied.

Neutron count-rates are also recorded and forwarded to global data-centres, assisting research into ground-based solar events initiated by changes on the sun's surface. Total ozone column and UV-fluxes are monitored to supplement satellite measurements, making it possible to calculate the size of the Earth's ozone hole. The Southern Hemisphere telemetry for Sweden's Astrid-2 satellite is operated from the station, and can be used in a joint Swedish, Danish and South African collaboration by incorporating the Oersted satellite. This has allowed South Africa access to all data and software on the satellite in return for simultaneous ground-based aurora, magnetometer and VLF radio-wave measurements. Through SANAE IV South Africa also contributes to the IGS Programme (International GPS for Geodynamics Programme, involving 140 other partners), undertakes geological studies, serves as a weather station for the SAWS (South African Weather Services), is the centre for casualty evacuations in Queen Maud Land and is a partner with Germany in joint logistical operations.

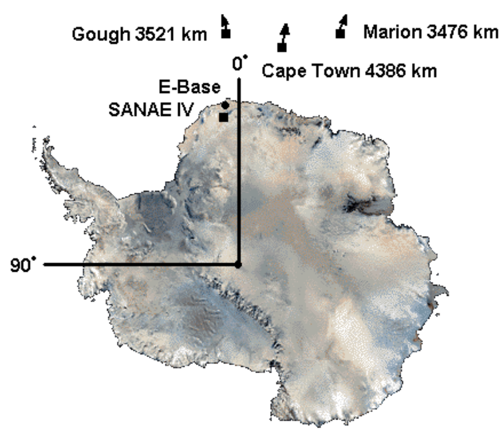


Figure 1.3: Map of SANAP operations in Antarctica (Theodora Maps, 2005)

Yet SANAE IV is not the only South African station in the Antarctic (refer to figure 1.3). South African Southern Ocean research stations also include: Marion Island (located 3 476 km from SANAE IV), Gough Island (3 521 km from SANAE IV) and E-Base (which exists purely in case of emergencies at SANAE IV and has no personnel that reside there). The necessary provisions are supplied to these stations by South Africa's well-known ice-reinforced relief vessel, the SA-