PERFORMANCE EVALUATION OF PHOTOVOLTAIC AND DIESEL ELECTRICITY GENERATION APPLICATIONS IN THE KRUGER NATIONAL PARK

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DECLARATION

I declare that this dissertation is my own, original work. It is being submitted in partial fulfilment for the degree of Master of Science in Energy Engineering in the University of Cape Town. It has not been submitted before for any degree or examination in any other university.

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21.........day of OCTOBER..............., 1988...

ABSTRACT

This dissertation documents a research study on the comparative technical and economic performance of photovoltaic and diesel gensets as off-grid electrical power supply systems.

The provision of reliable energy supply infrastructures has been identified as a key pre-requisite for social and economic development. The convenience and versatility of electricity have established it as the preferred form of energy for industrial, commercial, agricultural and domestic applications. However, the dispersed geographical nature and low energy consumption of potential electricity consumers in under-developed and rural areas in Southern Africa preclude the extension of the national electricity grid to meet these demands. Traditionally diesel generator sets have been used for off-grid power supply, but the advent of silicon based photovoltaic technology has introduced PV systems as an elegant and increasingly cost effective alternative to diesel gensets.

Although studies have been conducted internationally, scant information is available on the relative performance and suitability of these two contrasting technologies in the Southern African context. In addition to conventional diesel genset systems, the introduction of an energy storage reservoir, in so-called genset-plus systems, represents a refinement in the operating characteristics of diesel gensets which also has not been critically evaluated. This study addresses the need for reliable and empirically derived data regarding the operating characteristics of PV and genset based off-grid power systems.

The method adopted for this study employed remote electronic data capture systems to provide data for the technical evaluation. The economic evaluation of the systems was an annuity method approach, based on the net present value of the life-cycle operating cost reduced to an annuity.

The four off-grid power supply systems selected for monitoring were situated in the Kruger National Park and were selected to provide a range of different technologies and system sizes. They included :

- an 800 W_p AC PV system supplying lighting loads at Jock of the Bushveld private camp;
- a 3360 W_p DC PV system supplying lighting, ventilation, and refrigeration loads at Boulders private camp;
- a 5,6 kW/45 kWh genset-plus system supplying domestic and small workshop loads at Woodlands ranger's camp; and
- a 180/200 kW twin genset system supplying power to the Shingwedzi main tourist camp.

Based on a technical and economic analysis of the systems, the optimality of the system configuration and system design is discussed with reference to the electricity requirements of the loads, the available insolation in the Kruger National Park, the operating dynamics of the components within each system and the overall life-cycle operating costs.

The conclusions drawn include broadly identified classes of off-grid loads that would be optimally supplied with electricity from PV, genset or genset-plus systems. In addition, some criteria are presented on which decisions can be made regarding AC or DC configurations for PV systems, and the optimality of the four systems is reported. Finally, the potential for optimization of diesel genset technology in genset-plus configurations systems is emphasized.

Overall, the fundamental value of this study lies in the incremental enhancement of the understanding amongst system designers and potential users of the operating characteristics and costs of PV and genset based off-grid power systems in the Southern African context.

ACKNOWLEDGEMENTS

The project on which this dissertation is based would not have been possible without the initiative and guidance of the project leader, Dr Anton Eberhard, who also supervised the dissertation.

The ERi electronics and instrumentation engineer, Chris Wozniak, designed and built the monitoring systems and his considered opinions on a range of technical and non-technical issues also served as vital contributions to the project. Bill Cowan, of the Department of Sociology, UCT, inspired a lucid and critical perspective for the analysis and discussion in the dissertation.

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TABLE OF CONTENTS

Page No.

1. INTRODUCTION

2. LITERATURE REVIEW

3. DESCRIPTION OF MONITORED SITES

4. METHOD OF INVESTIGATION

Page
No.

5. FINDINGS AND ANALYSIS

6. DISCUSSION

APPENDICES : A - Schedule of existing KNP power generating installations
- B - System specifications
  - B.1 Jock of the Bushveld
  - B.2 Boulders
  - B.3 Woodlands
  - B.4 Shingwedzi
- C - Schedules of loads
  - C.1 Jock of the Bushveld
  - C.2 Boulders
  - C.3 Woodlands
  - C.4 Shingwedzi
- D - Interface monitor circuit diagrams
- E - Data logger input and output programs
- F - AC current and voltage waveforms
  - F.1 Jock of the Bushveld inverter output
  - F.2 Woodlands genset output
  - F.3 Woodlands inverter output
- G - Schedules of Maintenance
  - G.1 Woodlands : K122
  - G.2 Shingwedzi : K16
  - G.3 Shingwedzi : K125
- H - Schedules of fuel consumption
  - H.1 Shingwedzi : K16 and K125
- I - General comments on off-grid power system design techniques

LIST OF ILLUSTRATIONS

FIGURES

Page number

Page no.

Page
no.

TABLES

Page no.

Page no.

GLOSSARY

ADMD : after diversity maximum demand. A measure of the reduction in instantaneous maximum load power demand due to the diversity of the loads.

Ambient temperature : temperature of the surroundings; normally applied to the temperature of the surrounding air. (°C)

Array : a grouping of PV modules coupled in series and parallel to obtain a combined output.

ASCII : American National Standard Code for Information Interchange. The standard code used for exchanging information among data processing systems and associated equipment.

Autonomy : the number of consecutive days of independent energy supply provided by a system without any energy input, (solar or chemical).

Availability : the fraction of the year for which the instantaneous load power demand is available from an energy supply system.

Azimuth : the angle between North (or South) direction and the projection of the surface normal to the horizontal plane. (°)

Capacity factor : the dimensionless ratio of nett energy supplied to the load over a given period of time divided by the maximum potential nett energy supplied at full continuous rated system output over the same time interval.

Cash flow : the balance of cash inflows and outflows during a specified period within the service life of an investment.

Cell area : front surface area of a PV cell including the area covered by the grids and finger contacts. (m^2)

Declination : the angular position of the sun at solar noon with respect to the plane of the equator ie. angle of the sun north or south of the equator; a function of the time of year. (°)

Design life : the period of time during which a system or component is expected to perform its intended function, without significant degradation of performance.

Diffuse radiation : a) solar radiation which is scattered in transmission through the atmosphere (sky radiation); b) beam and or sky radiation reflected from non-specular surfaces. ($kWh/m^2/day$ or $MJ/m^2/day$)

Direct conversion : conversion of energy directly into electricity without the use of a heat engine.

Diurnal : the variation of a quantity during the course of a twenty-four hour day.

EPROM : Eraseable Programmeable Read Only Memory. A solid state micro-chip used as a data storage medium.

ERi : Energy Research Institute at the University of Cape Town.

ESKOM : the Electricity Supply Commision.

Fill factor : the ratio of maximum power output of a PV cell or array to the product of the open circuit voltage and short circuit current.

Flat plate : a non-concentrating essentially planar PV module.

Global radiation : refers to solar radiation as received on earth; the sum of direct (or beam) and diffuse components. ($kWh/m^2/day$ or $MJ/m^2/day$)

Grid : national electrical energy distribution network comprising HV transmission lines and power transformer sub-stations.

Gross array area : total frontal area of an array including the borders, frame and intercell area. (m^2)

Insolation : electromagnetic radiation received from the sun.

Life-cycle cost : an estimate of the total cost of owning and operating an energy supply system over the period of its useful life; usually expressed in terms of the net present value (present worth) of the cost.

Load diversity factor : the dimensionless ratio of the actual load power demand over the installed maximum load power demand. (%) A measure of what proportion of the total possible load that is used at any instant.

Load energy demand : the amount of energy required by the connected loads over a given period, generally a 24 hour daily cycle. (kWh/day or MJ/day)

Load factor : the dimensionless ratio of average load power demand for a given period of time (usually a 24-hour interval) divided by the peak instantaneous load power demand during that time interval.

Load power demand : the instantaneous power required by the connected loads. (W or kW)

LOEP : loss of energy probability; the estimated probability that, during a given time period, the energy output of the power system will be insufficient to meet the load energy demand.

LOPP : loss of power probability: the estimated probability that, during a given time period, the energy output of the power system will be insufficient to meet the instantaneous load power demand.

Module : smallest independent unit of a PV array.

Monocrystalline : refers to a material which is composed of a single crystal.

Net Present Value : (or present worth); the amount of money which must be invested today at the market discount rate in order to have a specified amount at some specified future date.

Open circuit voltage : a) referring to a PV cell; the voltage across an unloaded (open circuit) PV cell/module measured with a voltmeter that has an internal resistance of at least 20 kΩ per volt. b) referring to an electrical storage battery; the voltage across an unloaded (open circuit) cell/battery measured as for PV but after sufficient elapsed time following charge or discharge to allow the SG and voltage to stabilize.

O&M cost : the operating and maintenance costs.

Peak watt : the maximum power output of a photovoltaic module under standard conditions of 1000 W/m^2 and 25^{o}C. (W_p)

Power factor : dimensionless ratio of actual AC power (kW) to apparent power (kVA). $P=V_{rms}A_{rms}\cos\phi$

RAPS : Remote area power system.

Solar degradation : the deterioration produced by exposure to solar radiation.

Solar noon : that instant of any day at which the sun crosses the meridian of an observer and thus has its maximum altitude.

Specific gravity : the ratio of the density of the electrolyte in a lead acid cell to that of water.

Tracking : the process whereby a PV array follows the apparent motion of the sun across the sky.

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND RATIONALE

The convenience and versatility of electricity as a form of energy has established it as the preferred option for many industrial, commercial and domestic energy applications. Although the generation and distribution of electricity for most consumers in South Africa is provided by the para-statal electricity supply commission, ESKOM, there are many small consumers and potential consumers, who remain unconnected to the national grid. In general these consumers are situated in remote, rural areas outside the urban and peri-urban centres. They are reliant on independent, small-scale electricity generating technologies or so-called Remote Area Power Systems (RAPS) for their electrical energy needs.

Until recently diesel generator sets have been generally considered to be the most appropriate means of providing electrical power in underdeveloped or rural areas where access to grid electrification is unavailable. These systems have often proved to be inefficient, expensive and unreliable. Windcharger and hydropower systems have also been used with varying degrees of success in selected applications.

Over the last decade, the direct conversion of solar energy by means of photovoltaic cells has become a viable technical alternative to diesel, wind and hydropower systems.

The cost of increasingly expensive petroleum and coal based liquid fuels, and the additional recurrent costs of maintenance for petrol and diesel gensets compared to the minimal operating costs and decreasing capital cost of photovoltaic (PV) installations, have made PV systems an increasingly attractive option for off-grid electrical power generation despite the high initial cost.

PV systems are considered potentially viable for a number of remote power applications. Some typical PV applications are : telecommunications, navigational aids, environmental sensors, intrusion detectors, battery charging, lighting, refrigeration, ventilation, water pumping, water purification and cathodic protection (Borden et al, 1984).

The modularity and elegance, the silent and pollution free operation, and the proven reliability of PV systems are attractive but less quantifiable characteristics which favour PV.

Alternatively, the optimization of diesel genset operation through the configuration of genset-plus systems (ie. diesel generator plus battery storage), as a means of reducing recurrent costs, is a viable and rational utilization of existing diesel genset technology.

Although diesel gensets are a tried and trusted technical solution to off-grid power supply, very little objective data regarding the actual life-cycle cost and reliability is available on which to draw economic comparisons with alternative solutions such as the direct conversion of solar energy into DC electricity using photovoltaic (PV) systems. Furthermore, the design, sizing and optimization of diesel genset-plus systems appears to be a murky technical area and no data on the technical performance or life-cycle costs is available.

In January 1987 the CSIR´s National Programme of Energy Research and the National Parks Board requested the Energy

Research Institute, ERi, at the University of Cape Town to conduct a monitoring programme of photovoltaic and diesel electricity generating applications in the Kruger National Park and to present a report on the performance of these installations in comparison with existing diesel generator plant.

The wildlife conservation and tourism facilities of the South African National Parks Board are typical of the non-electrified rural areas reliant on these off-grid energy supply systems. The Kruger National Park situated in the Eastern Transvaal Lowveld is the largest game reserve administered by the National Parks Board and has small-scale and widely dispersed electrical power requirements for the tourist camps, rangers' houses, water holes etc. which are representative of those in rural and underdeveloped areas throughout Southern Africa.

A schedule of power requirements and the corresponding sources of supply in the Kruger National Park is presented in Appendix A.

The history of the Kruger National Park dates back to 1898 when the Sabie Game Reserve was proclaimed and later consolidated, in 1926, with areas between the Sabie and Limpopo Rivers into the present boundaries of Kruger National Park. It was a sparsely populated area which had never been an industrial or commercial centre, apart from the limited mining activity in the Eastern Transvaal and transport riding to and from Mozambique. Initially the energy requirements were largely met through candles, paraffin and woodfuel, for lighting, space heating, water heating and cooking, and animal power for transport.

The development of the Kruger National Park as a tourist facility has required commercial scale cooking, refrigeration, water heating and lighting facilities as well as energy for maintenance workshops, administrative infrastructure and development. The forms of energy used to provide these services have been woodfuel, paraffin, gas and electricity from petrol or diesel powered electrical power generators. More recently some of the larger and more accessible tourist camps have been connected to the ESKOM national grid. Nevertheless there are still a number of tourist camps as well as game rangers' houses, entrance gates, water supply installations and communications facilities for which grid electrification is impractical for technical or economic reasons.

The environmental considerations of avoiding overhead power lines and the associated disruption of the ecology during construction and maintenance for grid electrification present further incentives for the effective provision of self-contained, de-centralized, independent and economically competitive alternatives to grid electrification in the Kruger National Park. The Cahora Bassa power lines from Mozambique, as well as those supplying selected camps in the Park, already scar the Park.

For the Kruger National Park the alternative options to diesel gensets, such as windchargers and micro or mini-hydro, are not practicable due to poor wind regimes and lack of perennial rivers with suitable hydro sites at the point of demand.

The National Parks Board is however concerned about the operating and maintenance costs of their diesel gensets. Their estimated cost of diesel in 1986 for the Shingwedzi main tourist camp alone was R 400 000. They have installed PV systems at three private tourist camps in the Kruger National Park (Jock of the Bushveld, Roodewal and Boulders) and, following some evaluation of PV water pumping applications, six PV water supply systems have been installed on a trial basis to replace wind pumps. In addition PV systems have been installed to energize electric fences and power UHF repeater stations.

Two ranger's house compounds at Woodlands and Stolznek in the Kruger National Park have genset-plus systems installed for domestic energy requirements.

This thesis aims to investigate four RAPS in the Kruger National Park and provide comparative data on the technical and economic implications of small and larger diesel and PV installations on which future decisions for off-grid electrical power supply can be arrived at for applications both in the Kruger National Park and more generally in rural and underdeveloped areas in Southern Africa.

The research project was funded by the CSIR's National Programme for Energy Research and additional support was given by the National Parks Board who provided an engineer and facilities for maintenance and supervision of the data logging equipment.

1.2 OBJECTIVES

The objectives of this project were to :

1. assess the technical and economic performance of the existing photovoltaic power generating installations in the Kruger National Park;
2. compare the performance of the photovoltaic power plant with existing diesel plant in the Park and
3. make recommendations concerning further photovoltaic applications.

Specific questions to be addressed in the project were :

1. Under which conditions are photovoltaic applications more favourable than diesel for rural or off-grid power supply?

2. How well do the existing photovoltaic systems in - the Kruger National Park match the solar radiation availability and load demands?

3. What are the advantages of DC versus AC photovoltaic and diesel hybrid power plant?

1.3 OUTLINE OF THE THESIS

The approach adopted in the presentation of this thesis is one which follows the format of an investigative report :

Chapter 2 briefly reviews some PV, diesel and genset-plus installations and discusses available unit energy cost data for RAPS.

Chapter 3 discusses the choice of the sites and systems to be monitored and describes the respective installations.

Chapter 4 outlines the method of technical and economic investigation.

Chapter 5 describes the monitored data and discusses the technical and economic implications of each system.

Chapter 6 presents a more general discussion of the design and optimization of PV, diesel and genset-plus RAPS.

Chapter 7 outlines some conclusions and recommendations based on the research project.

A list of references and selected appendices complete the thesis.

CHAPTER TWO

LITERATURE REVIEW

2.1 REVIEW OF DIESEL GENSET AND PV POWER SYSTEMS

2.1.1 Diesel genset systems

Diesel genset systems are the most commonly used off-grid electrical power source and are available in a wide range from a minimum of 3 kW to over 500 kW, (Kenna, 1987; Fraenkel, 1979; Williams, 1986). They have high power to weight ratios and are compact. A typical installation would include a reciprocating, internal combustion, compression ignition, diesel engine as a prime mover coupled to a DC generator or more often to an AC alternator. The diesel engine and AC alternator are often supplied as a unit to provide single phase electrical AC power at 220-250 V and 50 Hz. Larger gensets produce three phase power at 380 V and 50 Hz. Ancillaries would include radiators or cooling towers for water cooled engines, fuel tank and fuel supply systems, electrical or compressed air starting systems, control panels and a mounting base.

A diesel genset system must be sized to meet the peak or an acceptable proportion, (>75%), of the instantaneous load power demand, regardless of the average load power demand, and simultaneously maintain the AC supply at the required voltage and a constant frequency. Combined with typically low load factors, the result of this requirement is the exceedingly poor systems match and low capacity factor, and correspondingly high operating cost, which is typical of small diesel genset systems, as reported by Williams (1988) and Kenna (1987).

The implications of a poor capacity factor are illustrated in Figure 2.1 from Paul (1981). The shape of the curve of unit energy cost (c/kWh) vs. capacity factor illustrates that the unit energy cost at a 10% capacity factor is six times that of a genset loaded at a 100% capacity factor.

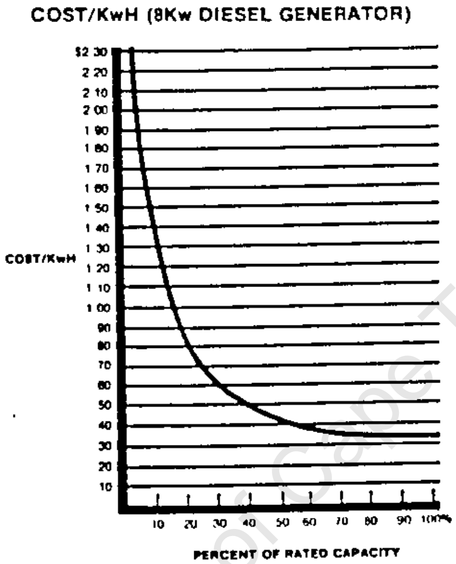


Figure 2.1 : Generalized graph illustrating the unit cost of electricity as a function of capacity factor for diesel gensets (Paul, 1981)

Kenna (1987) conducted short and long term tests on three diesel gensets in Kenya. Figure 2.2 illustrates the characteristic correlation between the genset efficiency and time after start-up for different capacity factors for small gensets. The efficiency of a diesel genset is defined as the quotient of the average electrical output power over the average fuel input power expressed as a percentage. It can be seen that the efficiency increases with increasing capacity factor, approaching a maximum of approximately 30%, based on the electrical power output. In addition, the poor operating efficiency following a cold start is clearly indicated.

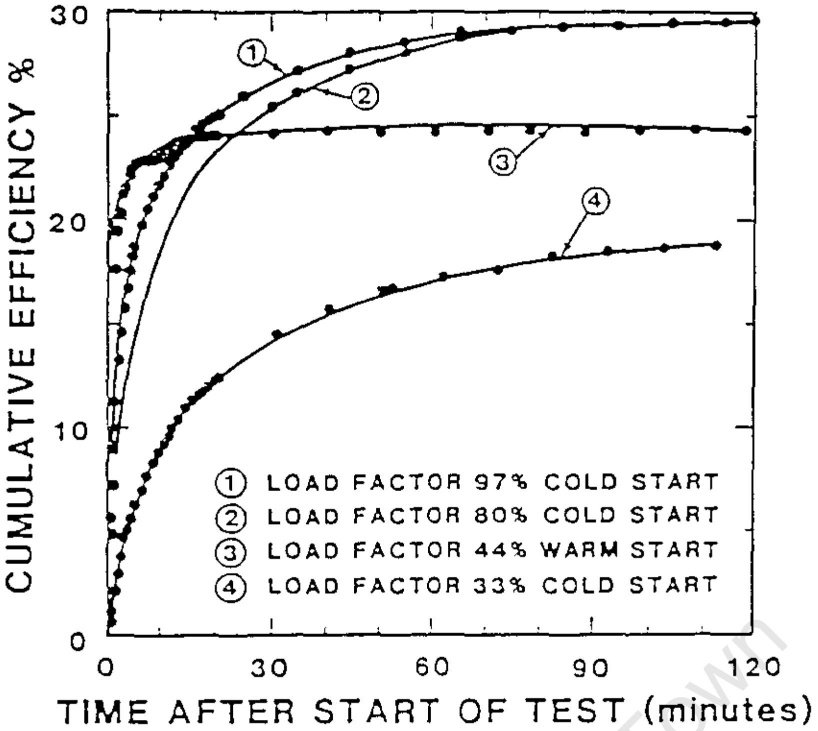


Figure 2.2 : Short term test results for LISTER ST2 diesel genset (Kenna, 1987)

The relationship between efficiency and capacity factor is more explicitly shown in Figure 2.3, whereas Figure 2.4 illustrates the scatter of points relating the efficiency to the daily energy production.

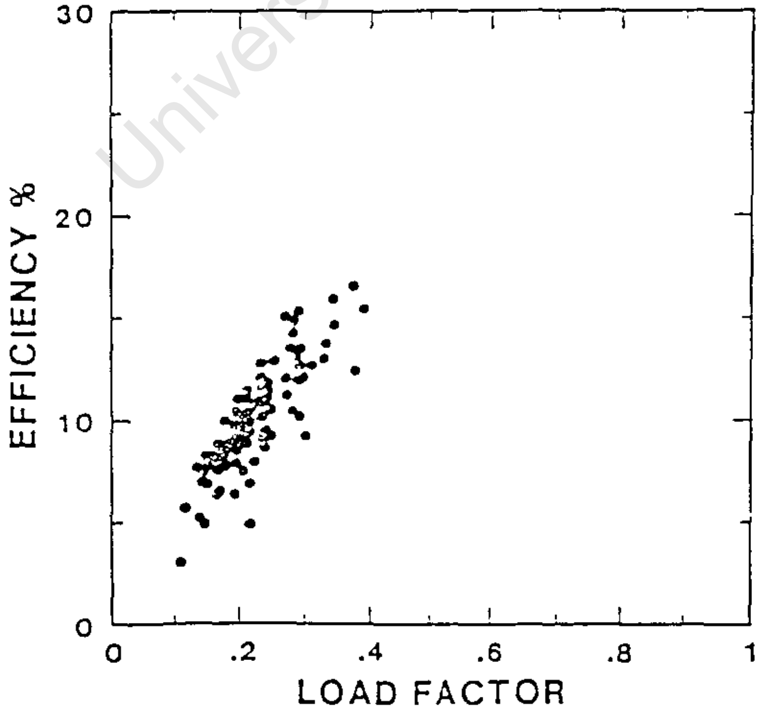


Figure 2.3 : Daily efficiency versus capacity factor for LISTER ST2 diesel genset (Kenna, 1987)

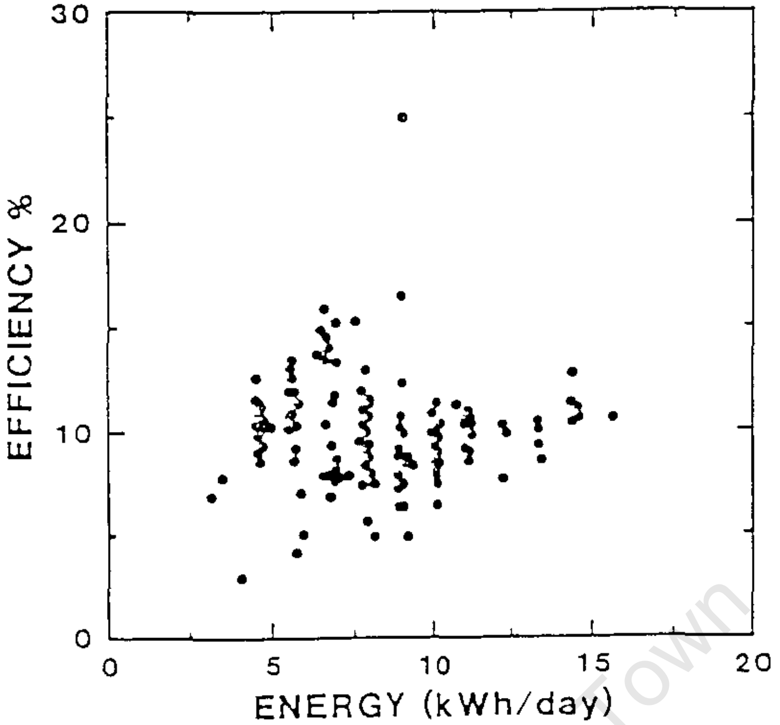


Figure 2.4 : Efficiency versus energy production for LISTER ST2 diesel genset (Kenna, 1987)

The reliability of diesel genset systems is highly dependent on rigorous adherence to planned maintenance schedules. In practice the maintenance on the majority of installations in rural areas is reduced to service intervals determined on a breakdown to breakdown basis.

There is clearly scope for optimization in the application of the diesel gensets for RAPS. Reduction in the overall operating and maintenance, O&M, costs, and hence life-cycle costs, of genset systems may be achieved through better system design with improved load matching and higher capacity factors combined with effective planned maintenance.

2.1.2 Genset-plus systems

The use of unnecessary loads as "dump loads" to increase the capacity factor of a given genset system does not address the essential problem of poor load matching and despite an apparent increased capacity factor due to the artificial dump loads, the unit cost of useful electricity supplied to the user could in fact increase. One realistic means of mitigating poor load matching, and associated low capacity factor, is the use of excess power for water heating. Ultimately the most effective means of increasing the capacity factor is by improving the load factor through load management and hence enabling a better systems match between the genset and load. There are however limits to which load management can improve the load factor. The use of multi-set genset installations has been applied to larger systems as a device for increasing the capacity factor of the overall system, (and providing reserve or backup capacity).

The so-called genset-plus system configuration is a mechanism for increasing the capacity factor and flexibility of small single diesel gensets in independent power systems by introducing an energy storage reservoir, ie. electrical storage batteries together with a battery charger and a suitably rated DC/AC inverter. Paul (1981) has advocated genset-plus systems for reliable independent power systems.

Genset-plus systems may be configured to allow operation of the genset and charging of the batteries entirely independently of the instantaneous load power demand, but in practice the more accepted arrangement is for the genset to be operated at optimum rated output whilst charging batteries and simultaneously supplying the load power demand. The genset is shut down when the batteries are fully charged, after which the load power demand is met by the batteries via an inverter. The genset therefore only operates at close to its optimum efficiency at its continuous full load rating instead of running continuously at relatively low loads and a constant frequency of 1500 rpm, with intermittent and brief peak load power demands. Figure 2.5 illustrates the basic genset-plus system configuration.

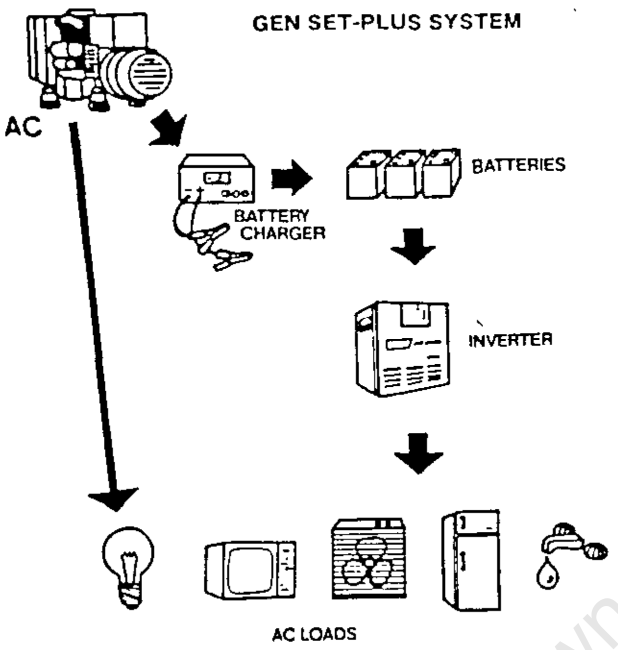


Figure 2.5 : The basic genset-plus system configuration, (Paul, 1981)

The sizing of a genset-plus system is much less sensitive to the load factor and the concept of capacity factor becomes redundant.

Essentially a genset-plus system relies on the battery and an inverter to meet the instantaneous load power demands whilst the daily (or weekly) load energy demand is met indirectly by the genset which is less dependent of load power demand constraints and can therefore operate more optimally at close to the ideal capacity factor of unity.

Well designed genset-plus systems with planned maintenance schedules could deliver power with an availability of close to 100%.

In practice there are only a handful of genset-plus installations in Southern Africa and no data on operating characteristics or costs is reported in the literature.

2.1.3 PV systems

Stand-alone photovoltaic power systems comprise an array of PV modules, connected in parallel and series on a fixed or a tracking support, which charge electrical storage batteries via DC power conditioning equipment. The batteries may in turn provide DC power directly to DC loads or AC power to conventional 220 V AC loads via an inverter.

PV modules are available in a wide range of combinations of nominal voltage and power outputs. Modules usually have a nominal voltage of 12 V and peak power output of between 15 and 60 W under standard conditions of 1000 W/m^2 incident global solar radiation and a module temperature of 25°C. These modules are the basic elements in arrays which form the basis for systems ranging from 30 W_p domestic energy systems for lighting to large computer controlled systems of up to 6 MW_p for centralized grid power stations.

PV systems have been advocated as being ideally suited for off-grid power supply. Worldwide there have been demonstration projects and working systems which have explored the viability of PV in a range of applications. Eskenazi et al (1986) have reported on the experience associated with 2 700 PV systems in 45 developing countries.

The application of PV systems in Southern Africa has primarily been for telecommunications systems. In recent years numerous small installations (<100 W) for minimal domestic electricity requirements have been installed for holiday homes and in urban townships. Two such systems were the subject of an ERi research project (Müller, 1987) to investigate their operation in the contrasting insolation regimes of the dry Northern Cape Province and the winter rainfall area in the Western Cape Province.

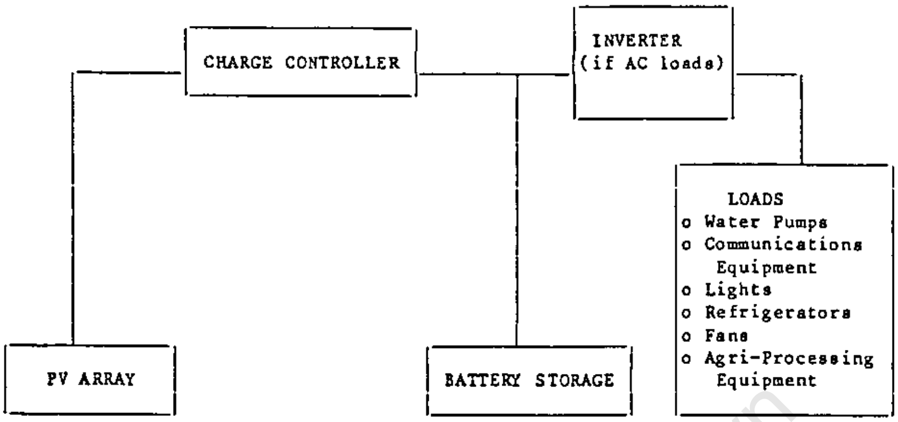
Conclusions drawn by Müller based on this project were :

- solar radiation data for PV system design should be based on statistical meteorological data which accounts for the variability of the insolation.
- load evaluation should be conducted in consultation with the user(s) and should include the annual variation in the load curve for both the current and projected usage.
- system reliability should be based on LOEP (loss of energy probability) methods to meet levels of availability that are acceptable to the user(s).
- reliable and efficient regulators and power conditioning equipment are not freely available in South Africa and that the development of these is important.
- financing of PV systems for individual domestic electricity supply requires more affordable capital financing than the loan schemes currently available.

A handful of larger installations (≈3 kW_p) have been installed on farms for domestic and light workshop or refrigeration loads. An interim report, (van Niekerk, 1986), on a monitoring programme of a 1,54 kW_p AC PV system installed on a Western Transvaal farm hinted at the need for careful attention to system design but did not venture to evaluate the economic performance of the system.

Eskenazi et al (1986) evaluated 42 so-called "multi-use" PV systems in 22 countries which are similar in size and function to PV systems in the Kruger National Park. Multi-use systems are those supplying electricity for an assorted mix of loads such as water supply, communications equipment, lighting, refrigeration, ventilation and light agricultural or industrial loads. Figure 2.6 and Table 2.1 show the distinctions between centralized load centres as opposed to mini-utility types of multi-use PV systems.

Schematic of a PV-Powered Load Center System
(Centralized Loads)



Schematic of a PV-Powered Mini-Utility System
(Decentralized Loads)

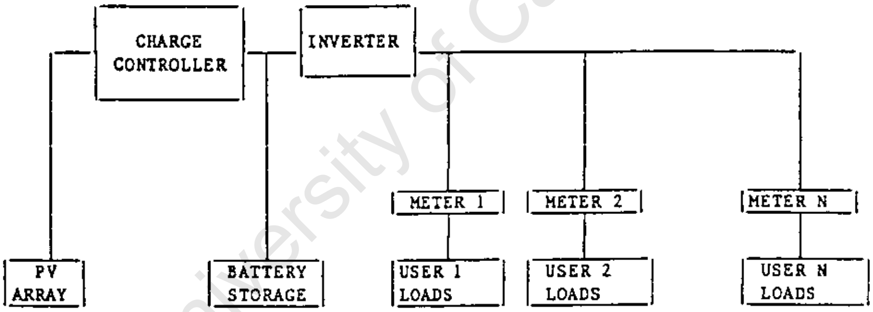


Figure 2.6 : Schematics of load centre and mini-utility types of multi-use PV system (Eskenazi et al, 1986)

The Kruger National Park systems are all load centre type systems which supply a variety of loads at a particular site, but in general both categories would be appropriate for the electrification of rural or underdeveloped areas in Southern Africa.

Table 2.1 : Distinctions between PV powered multi-use systems (Eskenazi et al, 1986)

CHARACTERISTIC	MULTI-USE SYSTEM TYPE	
	LOAD CENTERS	MINI-UTILITIES
Array Size	< 5 kW	> 5 kW (up to about 30 kW)
Type of Power Output	AC or DC	AC
Power Conditioning	• Charge controller (with load-shedding capabilities) • Inverter (if AC loads)	• Charge controller • Inverter (with load-shedding capabilities) • Metering
Power Distribution System	Only within one facility	• Throughout entire village • Metering
Infrastructure	• Supply of spare parts • System repair	• Supply of spare parts • System repair • Billing system • Power management

Key factors that were identified by Eskenazi et al for the implementation of these systems are categorized as follows :

i) <u>Technical</u>

Reliability and complexity of power conditioning equipment are vital factors.

Balance of systems (ie. excluding PV modules) equipment should be selected on the basis of proven field performance and factory testing should be mandatory as part of the purchase specifications. Lower power inverters have been a weak link, with reliability problems and poor efficiencies. It is recommended to install DC systems where possible and where transmission distances are not great.

So-called "user-oriented product engineering" of PV system components is proposed to provide an uncomplicated user interface and reduce the real and/or perceived complexity of the systems.

Furthermore, design data should be properly obtained and effectively used.

Rural electrification policy is also an important technical consideration for multi-use systems in relation to dispersed systems at the point of demand or centralized systems with distribution and metering.

ii) Financial

Financial evaluation of PV and alternative power supply options should be based on a life-cycle cost analysis. Despite the high initial cost of PV systems, they can be shown to be more cost effective than conventional genset type systems over the overall lifetime of the system.

The capital intensive nature of PV systems does however require institutional loans, as opposed to commercial loans, or government subsidized loans for individuals to become purchasers.

iii) Institutional

PV systems require less institutional support than conventional systems. However as a new technology, even the minimal institutional support required is not generally available.

An effective field support infrastructure is necessary for maintenance and replacement parts. Similarly, effective training to users and repair personnel is vital.

In addition the involvement of the user(s) throughout the design, construction and operating phases of a PV system is necessary to encourage a sense of ownership and responsibility. This is particularly important for a new technology such as PV.

2.2 COST OF ELECTRICITY GENERATED BY PV AND DIESEL GENSETS

2.2.1 General comments regarding the cost of electricity

The evaluation of real, comparative costs of off-grid energy supplied is vital to facilitate and support engineering decisions on investments in alternatives such as PV and diesel gensets.

The cost of electricity has four implicit components: an energy related cost, an instantaneous power related cost, a reactive power cost and an administrative and metering related cost.

The first reflects the cost of generating and distributing a given amount of energy (kWh) regardless of instantaneous power demand. The second reflects the cost of installing power plant and distribution capacity capable of meeting the instantaneous maximum load power demand (kW). The reactive power cost component reflects the cost of poor power factors of the consumers which require the utility to generate and distribute kVA in excess of the kW consumed, due to non-unity power factors. Finally, in addition to the above three, tariffs include a minimum monthly flat rate service charge for administrative and metering costs. Ultimately for a given energy requirement, the compound overall cost can be reduced to a unit energy cost specific to that particular application by simply evaluating the quotient of the total compound cost over the total energy consumed.

For the applications considered in this thesis, the cost of electricity is best measured as the unit energy cost in c/kWh, ie. the overall unit energy cost as defined above.

Any figures quoted for unit energy costs of electricity must be qualified because they are dependent on the country for which they are quoted and such factors as : exchange rates, import duties, location, labour rates, interest rates, inflation, system lifetimes and the economic costing technique.

Various economic evaluation techniques have been suggested for off-grid energy supply options. The life-cycle costing methodology suggested by Borden et al (1984), is intended primarily for estimating the viability of PV power systems compared to non-PV alternatives and is not intended as a precise cost estimating procedure.

The method of economic evaluation adopted by McNelis (1986), in a comparative study of PV and diesel systems, is one of comparative NPV (nett present value or present worth) life-cycle costs of competing systems divided by the energy produced over a common twenty year evaluation period or system lifetime. Although the basis on which the evaluation is made is not spelt out, the NPV method assumed to be used for the evaluation does not necessarily account for differences in the capital requirements or individual lifetimes of the generating plant. Finck and Oelert (1985) suggest that the annuity method, based on NPV calculations, would most accurately reflect the comparative costs of competing alternatives with different projected design lifetimes and differing cashflow requirements. This method is described in more detail in Section 4.7.

2.2.2 Unit energy costs of off-grid electrical energy

McNelis (1985) reported that the energy costs of electricity generated by autonomous wind, PV or diesel gensets was between 0,50 and 2,00 \$/kWh compared to mains electricity at 0,08 \$/kWh. PV was considered to be competitive with diesel for loads of less than 5 kWh/day with solar radiation levels in excess of 20 $MJ/m^2/day$ and for loads of less than 1 kWh/day with solar radiation levels in excess of 15 MJ/m^2/day. For PV system installation costs of less than 10,00 \$/W$_p$, PV would be cheaper than diesel for energy demands of up to 10 kWh/day.

In a more recent comparison between PV and diesel generated electricity, an analysis of the energy costs for systems supplying an annual average of 5 kWh/day (annual max. energy demand of 7,5 kWh/day) for a 3,0 kW diesel genset and a 2,6 kW$_p$ PV system is presented, McNelis (1986). The results are summarised in Table 2.2.

Table 2.2 : Comparative electricity unit cost for diesel genset and PV (McNelis, 1986)

1.	Diesel generator power rating	3,0 kW
	Average load factor	11,9 %
	Diesel fuel cost	0,75 \$/litre
	Diesel system availability	90,0 %/year
	Diesel genset life	6,0 years
	Diesel NPV unit energy cost	2,43 \$/kWh
2.	PV array peak power	2,6 kW$_p$
	Insolation	18,0 MJ/m^2/day
	Inverter power rating	2,0 kW
	Battery storage size	37,5 kWh
	PV system availability	98,0 %/year
	PV array life	20,0 years
	Battery life	5,0 years
	PV NPV unit energy cost	1,34 \$/kWh

The sensitivity of the unit cost of electricity supplied by diesel gensets to the capacity factor and economies of scale is highlighted.

Figure 2.7 shows the relative unit cost of electrical energy for PV and diesel as a function of load energy demand. PV energy systems are seen to be cheaper than diesel for loads less than 6 kWh/day whereas in the range between 6 kWh/day and 16 kWh/day either system would be cheaper depending on the specific application and circumstances.

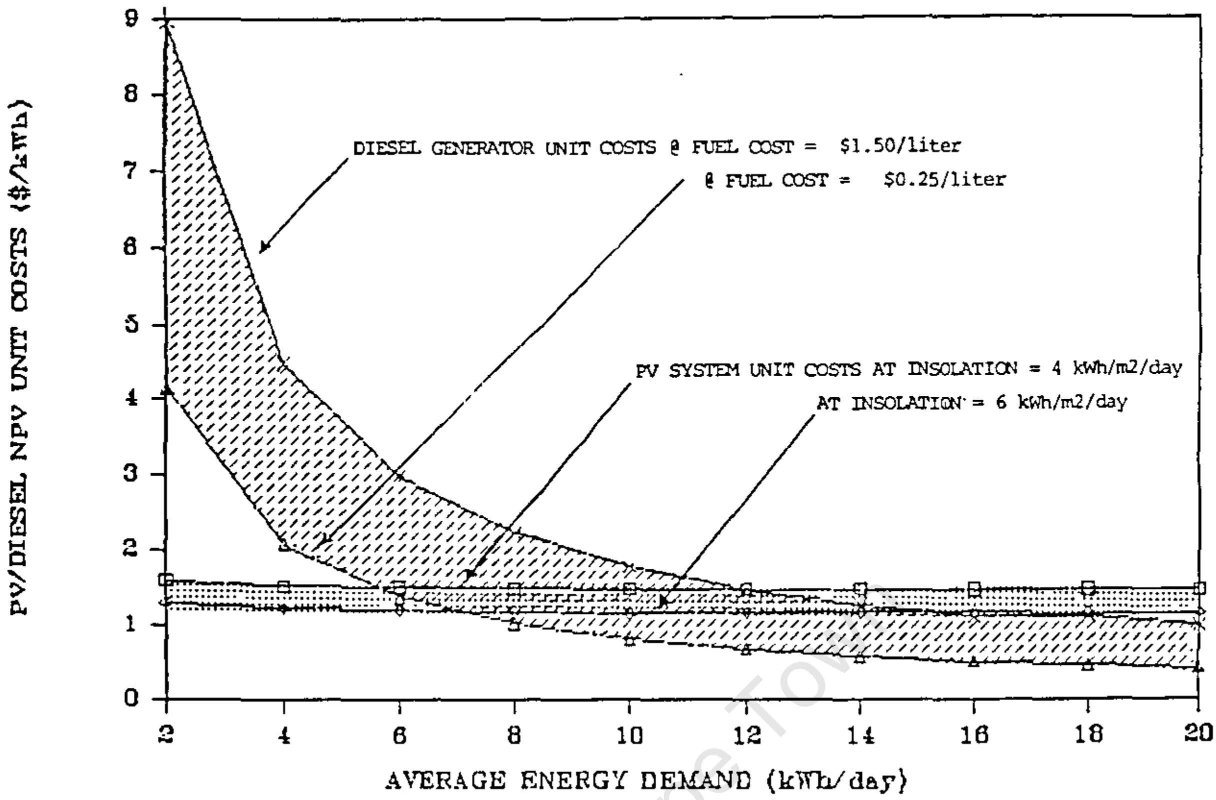


Figure 2.7 : Unit cost of energy for PV and diesel power systems as a function of load energy demand (McNelis, 1986)

Figure 2.8 summarizes a similar comparative financial analysis conducted by Eskenazi et al (1986) for multi-use PV and diesel genset systems. The evaluation concluded that PV systems are the lower cost option for average daily load energy demands of less than 2 kWh/day, based on unfavourable financial assumptions, and up to 16 kWh/day, for more favourable assumptions.

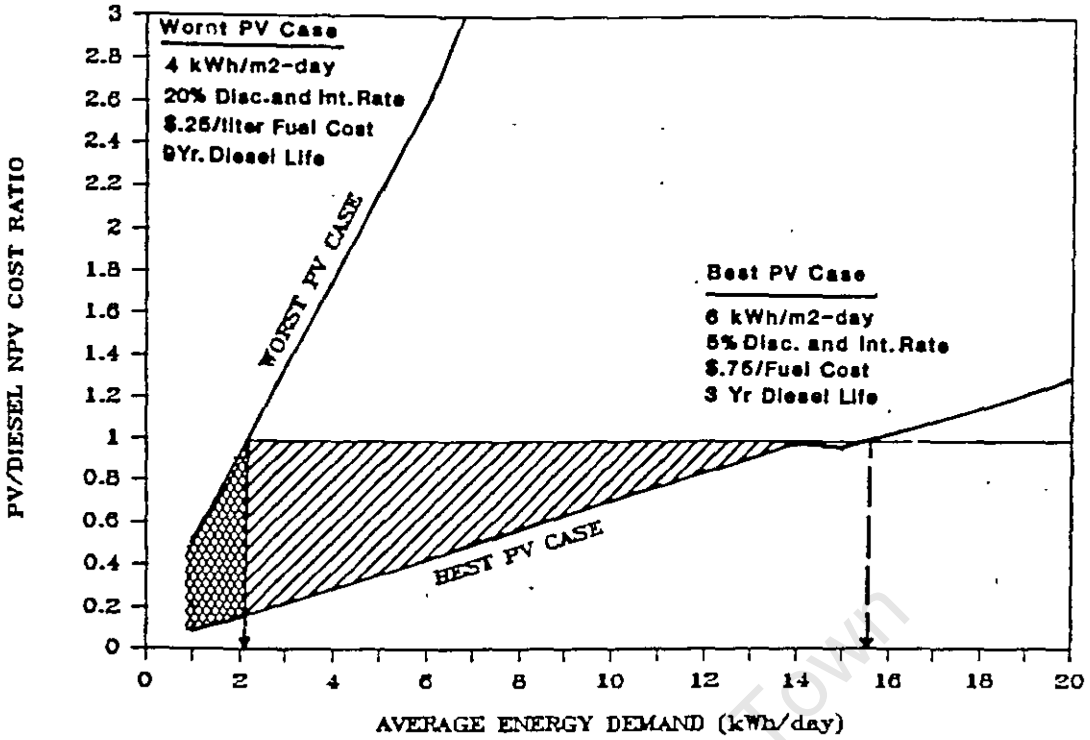


Figure 2.8 : Sensitivity of the benefits of PV over diesel for multi-use systems for worst and best case assumptions (Eskenazi et al,1986)

The assumptions and life-cycle system costs for this comparison are tabulated in Tables 2.3 and 2.4.

Table 2.3 : Life-cycle costs of a multi-use PV system

SPECIFICATION	COST
Initial Capital Costs (FOB Manufacturer)	
- PV Array (3.94 kW)	$31,521
- Battery (37.5 kWh)	5,625
- Controller	1,576
- Inverter (2 kW)	2,000
Total Capital Cost	$40,722
Recurring Capital Costs (FOB Manufacturer)	
- Battery Replacement	$5,625 every 5 years*
- Controller Replacement	$1,576 every 10 years*
- Inverter Replacement	$2,000 every 10 years*
Other Recurring Costs	
(% Initial Capital Cost)	
- Maintenance & Repair	0.1%/year*

* Plus appropriate escalation due to general inflation.

Table 2.4 : Life-cycle costs of a multi-use genset system

SPECIFICATION	COST
Initial Capital Costs (FOB Manufacturer)	
- Diesel Gen-Set (3 kW)	$4,771
Recurring Capital Costs (FOB Manufacturer)	
- Diesel Gen-Set Replacement	$4,771 every 6 years*
Other Recurring Costs	
- Maintenance & Repair	2% of gen-set cost per year
- Overhaul	15% of gen-set cost every 3 years
- Fuel (3,408 liters at $0.50/liter)	$1,704/year*

* Plus appropriate escalation due to general inflation.
\+ No overhaul during diesel replacement year.

Müller (1987) calculated the unit energy cost of electricity supplied by the two Southern African domestic lighting PV systems monitored in an ERi project. The basic assumptions and results of the financial analysis based on a NPV annualised unit energy cost method are summarized in Table 2.5 and Table 2.6. Although these systems are much smaller than the Kruger National Park installations they serve to indicate the approximate costs for PV systems in South Africa.

Table 2.5 : Basic assumptions of the financial analysis of the PV systems monitored by Müller (1987)

Assumptions :

Battery life : 3 years
Battery efficiency : 85 %
Salvage value : 12 %
Discount rate : 4 %
Escalation rate : 0 %
O&M costs : 1 % of initial costs
Lifetime : 20 years
No engineering, project management, installation or commissioning fees were included.

Table 2.6 : Basic specifications and unit energy costs of the PV systems monitored by Müller (1987)

System specifications and unit energy cost			
SITE	:	UITSIG	OMDRAAISVLEI
Design insolation	:	14,5 $MJ/m^2/d$	21,7 $MJ/m^2/d$
Array output	:	94 W_p	82 W_p
Battery capacity	:	90 Ah	98 Ah
Ave. daily load	:	192 Wh/day	366 Wh/day
Unit energy cost	:	251 c/kWh	149 c/kWh

The operating and maintenance (O&M) cost of electricity supplied by diesel gensets is reported by Kenna (1987). O&M costs, evaluated for three gensets in Kenya over a five month period, display an inverse relationship between O&M cost, ranging from 0,20 \$/kWh to 0,95 \$/kWh, and system ratings of between 45 kVA and 6 kVA. No evaluation of the unit cost of energy based on overall life-cycle costs was attempted.

Fraenkel (1979) suggests that a rough rule of thumb for the maintenance and repair of gensets should include lubricant consumption costs as 1-5% of fuel costs and annual servicing and routine engine replacement parts as 2% per year of the initial genset cost.

Williams (1988) calculated the unit cost of electricity from ten diesel gensets monitored for three months in the Eastern Cape to be between 85 c/kWh and 171 c/kWh. These figures are tabulated in Table 2.7 and are "levelised annual costs" based on the following assumptions :

Real discount rate : 5 %
Real escalation rate : 0 %
Engine replacement age : 15 000 hrs
Diesel fuel price : 55 c/litre
Operation & maintenance : 50 % of the capital cost spread over engine life

Table 2.7 : Summary of electrical energy cost data from field tests on diesel gensets (Williams, 1988)

Genset rating (kW)	Capacity factor	Run time (hrs/day)	Energy demand (kWh/day)	Unit cost (c/kWh)
9,4	0,24	6,0	14,13	84,66
9,0	0,34	8,0	16,44	90,80
4,9	0,25	4,0	5,07	114,42
7,5	0,23	4,0	5,58	120,95
7,5	0,20	8,0	9,42	124,21
3,7	0,30	6,0	5,37	145,61
7,5	0,17	8,0	8,37	145,50
3,7	0,18	8,0	4,32	158,75
7,5	0,17	6,0	6,22	171,11

These figures represent the most reliable indication of the real cost of electricity generated by diesel genset systems in South Africa.

No energy cost data appears to have been reported for genset-plus systems, except that Paul (1981) suggests that the unit energy cost of electricity supplied by a genset-plus system should be 74% less than that of a straight genset system.

The dearth of empirically derived data regarding the relative costs of operating and maintaining diesel gensets and genset-plus systems, particularly in the Southern African context, constitutes one of the major imperatives, in addition to the technical and economic evaluation of larger multi-use PV sytems, for the research project described in this thesis.

CHAPTER THREE

DESCRIPTION OF MONITORED SITES

3.1 CHOICE OF SITES

The sites considered for monitoring in this project were selected from existing National Parks Board energy supply systems that would be representative of a range of alternative PV and diesel technologies for supplying decentralized electrical energy. The range of rated system capacities was hoped to provide some added depth to the study.

Initially three installations in the Kruger National Park were to be monitored using remote electronic data logging systems; a small 800 W_p AC photovoltaic installation at Jock of the Bushveld private camp, a larger 3300 W_p DC PV installation at Boulders private camp and the 225/250 kVA diesel genset installation at Shingwedzi main tourist camp. After a site visit to Shingwedzi in May 1987, it was decided that the existing handwritten logbooks were sufficiently comprehensive to allow the electronic data logger system destined for Shingwedzi to be dedicated to a 7 kVA genset-plus system installed at a ranger's house/compound at Woodlands.

The locations of the four monitored sites in the Kruger National Park are shown overleaf on the map in Figure 3.1. The sites are all located at elevations of less than 500 m above mean sea level.

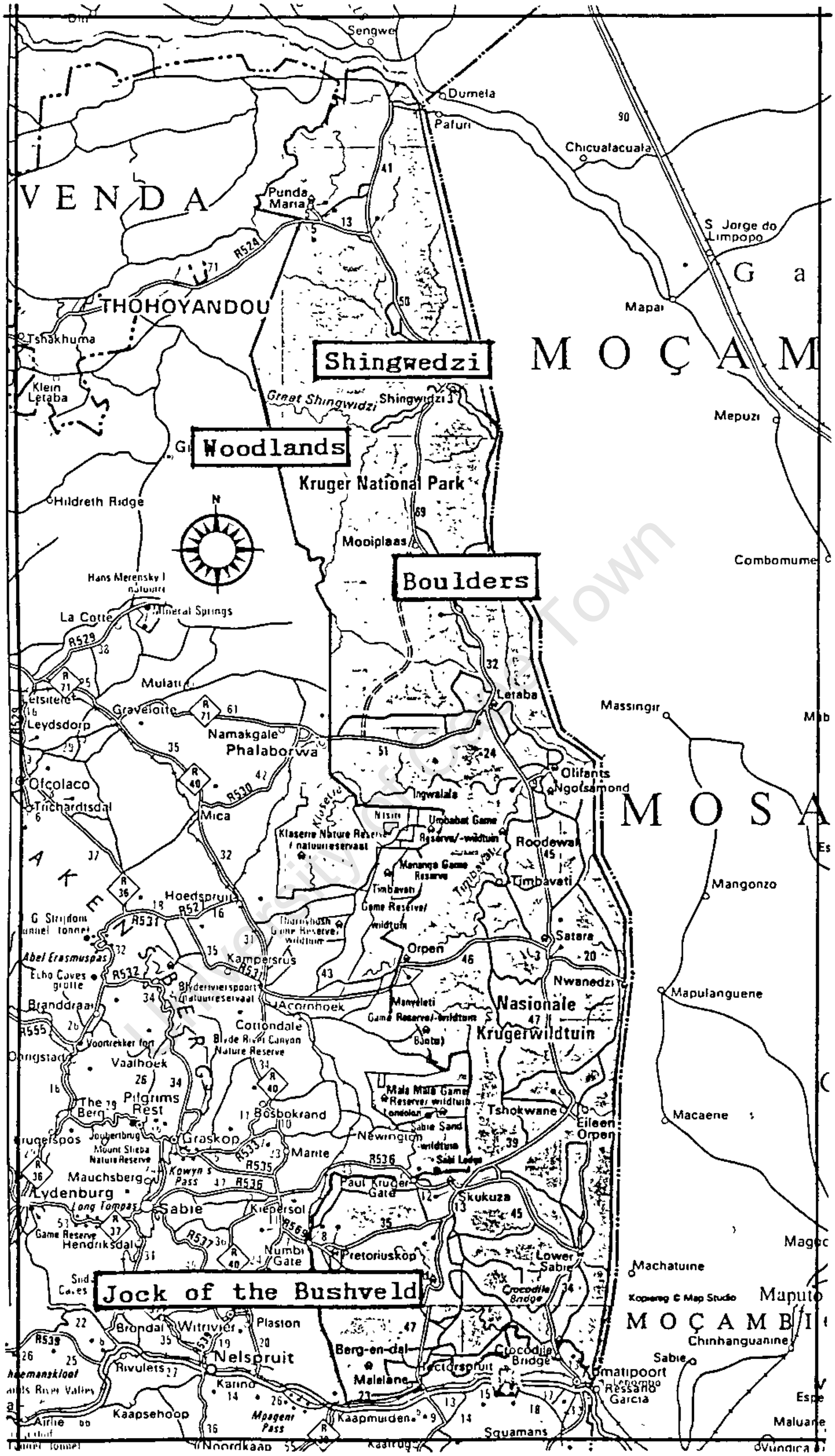


Figure 3.1 : Map of the Kruger National Park showing the location of the four monitored sites

The approximate co-ordinates of the sites are listed in Table 3.1.

Table 3.1 : Co-ordinates of the four monitored sites

Site	Latitude	Longitude
Jock of the Bushveld	25°12′	31°35′
Boulders	23°35′	31°20′
Woodlands	23°15′	31°12′
Shingwedzi	23°08′	31°35′

3.2 JOCK OF THE BUSHVELD

3.2.1 General description

Jock of the Bushveld is located three kilometres off the Skukuza/Malelane tar road (H3) at the confluence of the Mitomeni and the Mbyamiti rivers.

It is a private tourist camp with accommodation for up to twelve people in three pairs of double huts. Each pair of double huts is provided with two bathrooms and toilets. A central lounge, dining room, kitchen, braai area and cloakroom provide facilities for eating and relaxing. The entire camp is booked en bloc regardless of the number of people in the party. The occupancy therefore varies between zero and twelve persons. Three camp attendants live in staff accommodation which is not supplied with electrical power.

3.2.2 System description

The electrical power supply system is a 792 W_p 220 V AC photovoltaic system comprising twenty-four monocrystalline photovoltaic panels, a voltage regulator, a 36 V (nominal) battery of nine 4 V tubular plate, lead acid, "Farm Lighting" batteries in series and a 36 V DC/220 V AC 3,0 kW square wave inverter. The PV array charges the batteries during the day via the voltage regulator.

The inverter is manually switched on at sunset and switched off at sunrise by the camp attendant. There is therefore no energy consumption from the batteries during the day. Instrumentation of the system includes an analogue battery voltmeter and a charge current ammeter.

Provision has been made on the array support for additional panels for a proposed independent PV system for water supply. This function is currently executed by means of a single cylinder Petter diesel water pump.

A system diagram for the installation is shown in Figure 3.2.

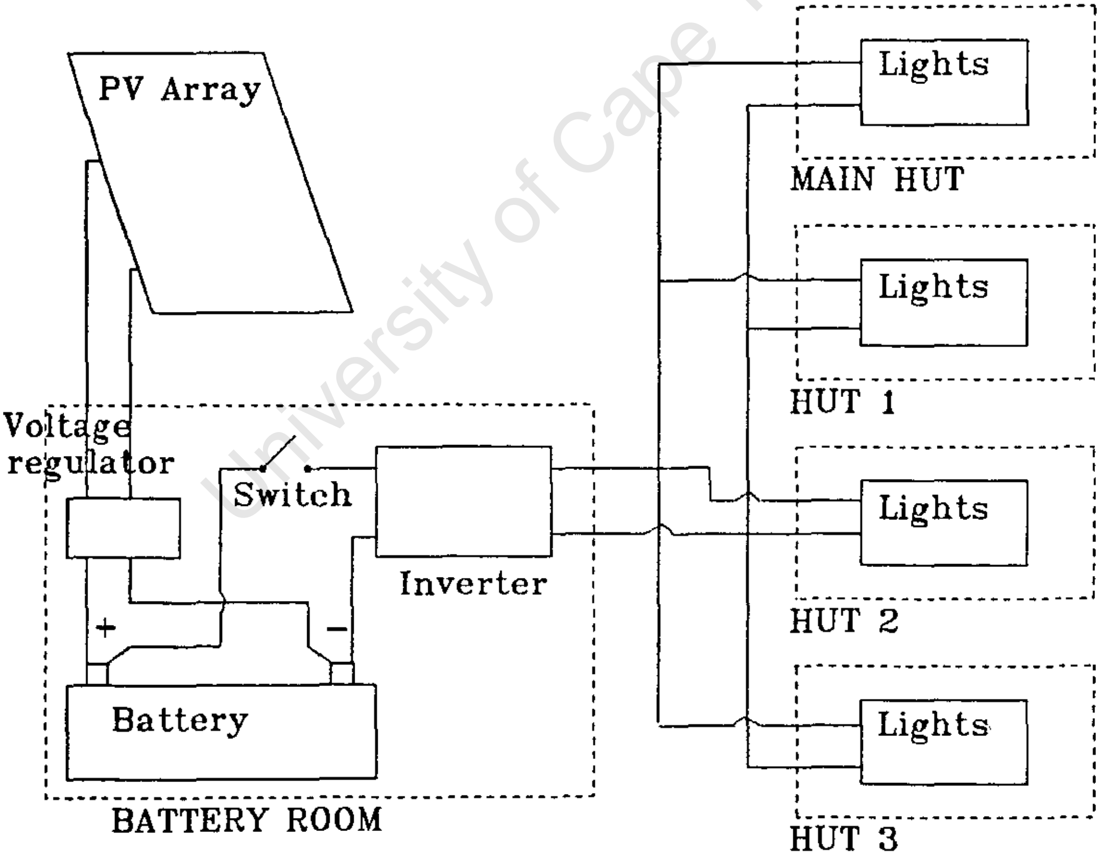


Figure 3.2 : System diagram for Jock of the Bushveld AC photovoltaic system

A detailed system specification for Jock of the Bushveld appears in Appendix B.1

3.2.3 Load description

The camp has a total of seven 16 W double tube fluorescent fittings and seventeen 18 W Phillips mercury vapour light fittings. Cooking, refrigeration and hot water heating is by bottled LPG. There are no fans. The total installed load is 418 W, ie. 34,8 W/bed.

A detailed schedule of loads is listed in Appendix C.1

3.3 BOULDERS

3.3.1 General description

Boulders is also a private tourist camp. It is located approximately six kilometres north of the new tar road from Phalaborwa Gate to Mooiplaas. The camp nestles between three boulder outcrops and also accommodates parties of up to twelve tourists. The camp comprises four double bed huts and one four bed hut, each with a bathroom and toilet. In addition there is a main complex, with kitchen, pantry, lounge, bar, toilets and a store room.

3.3.2 System description

The system is a 3360 W_p 12 V DC photovoltaic installation comprising 96 monocrystalline PV modules, mounted on the roof of a ventilated battery room, which charge thirty 2 V flat-plate stationary type lead acid cells via a 60 A voltage regulator. The 60 V (nominal) battery bank supplies 12 V loads in the camp by means of a 150 m long 60 V main feeder cable to a combination of one 40 A and six 20 A independent 60 V to 12 V DC to DC converters in the huts. Instrumentation comprises a battery voltmeter, a charge current ammeter and an ampere-hour meter on the main 60 V feeder cable to the camp.

The system was installed in 1985 and handed over on 15 October 1986.

The system diagram of the Boulders installation is shown in Figure 3.3

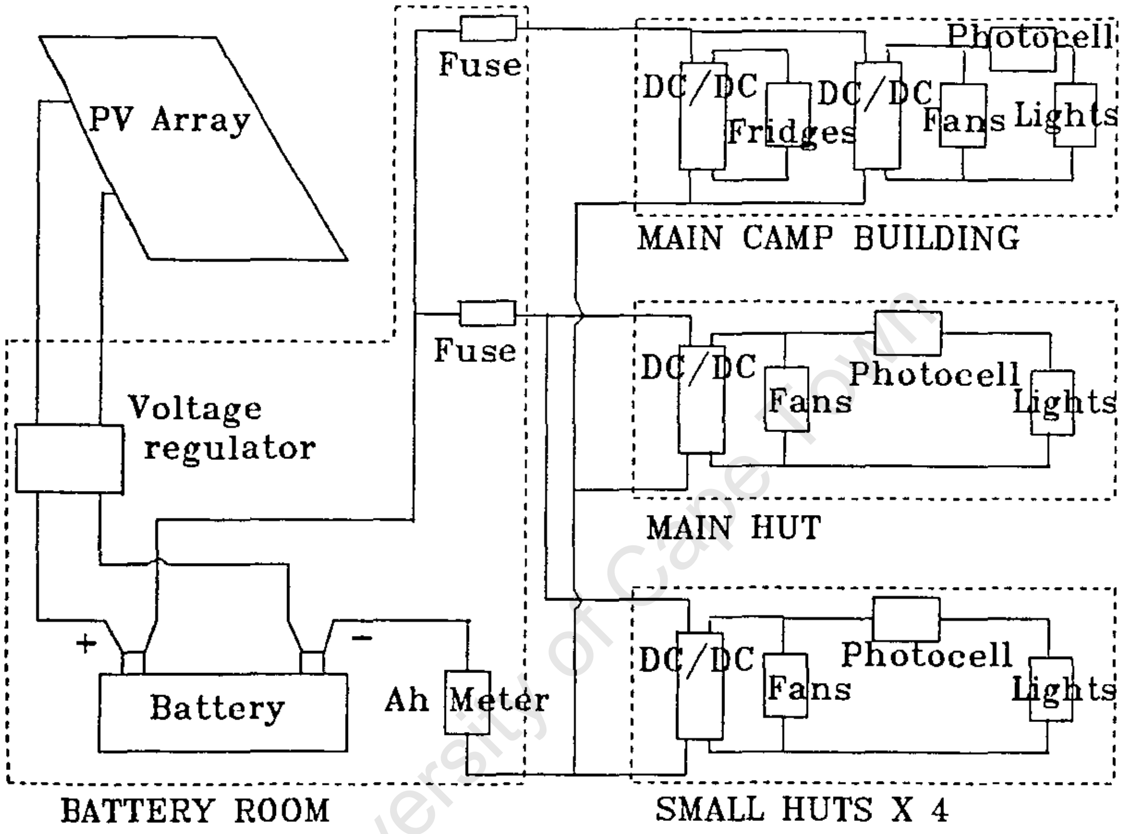


Figure 3.3 : System diagram for Boulders DC photovoltaic system

A detailed system specification for Boulders appears in Appendix B.2

3.3.3 Load description

The forty-three 20 W incandescent lights, fifteen 15 W fluorescent lights, nine 60 W fans, two 60 W fridges and three 60 W freezers in the huts and main complex are powered by 12 V DC electricity. Hot water and cooking facilities are powered by bottled LPG. A self-contained PV powered light illuminates a braai area. Water is supplied from a borehole by an air-cooled Lister diesel water pump. The total installed load is 1925 W, ie. 160,4 W/bed.

A detailed schedule of loads at Boulders camp is listed in Appendix C.2

3.4 WOODLANDS

3.4.1 General description

Woodlands is situated roughly 35 km west of Shingwedzi in a bend of the Shingwidzi river to the north-west of the Tshange dam. It is a game ranger´s compound comprising a three bedroomed house, ranger´s office, a garage, store rooms and a separate compound for the African rangers and service staff. The African staff compound comprises eight single huts, a double hut, a kitchen and an ablution block. Only the ranger´s house and outbuildings are currently provided with power although it is intended to extend the distribution to the African staff compound in the future.

During the period under consideration Woodlands was occupied by a ranger, his wife and their pre-school daughter and eight service staff.

3.4.2 System description

The electrical power plant is a genset-plus installation comprising a 8,9 kW two cylinder air-cooled Lister diesel genset with a 7,0 kVA single phase alternator which supplies the household energy requirement and charges two banks of nine 4 V tubular plate, farm lighting type, lead acid electrical storage batteries via a 36 V 100 A DC battery charger. The 36 V battery bank in turn supplies the 220 V AC loads via a 36 V DC/ 220 V AC 3 kW ferro-resonant sine wave inverter during the night when the genset is switched off.

The genset-plus configuration of the system currently operates on the basis of using the diesel genset during the day to simultaneously supply the load requirements in the compound and charge the battery bank and then relying on the battery bank and inverter to provide power from sunset until dawn during which period the genset is switched off to eliminate the noise.

The system diagram of the Woodlands installation is shown in Figure 3.4

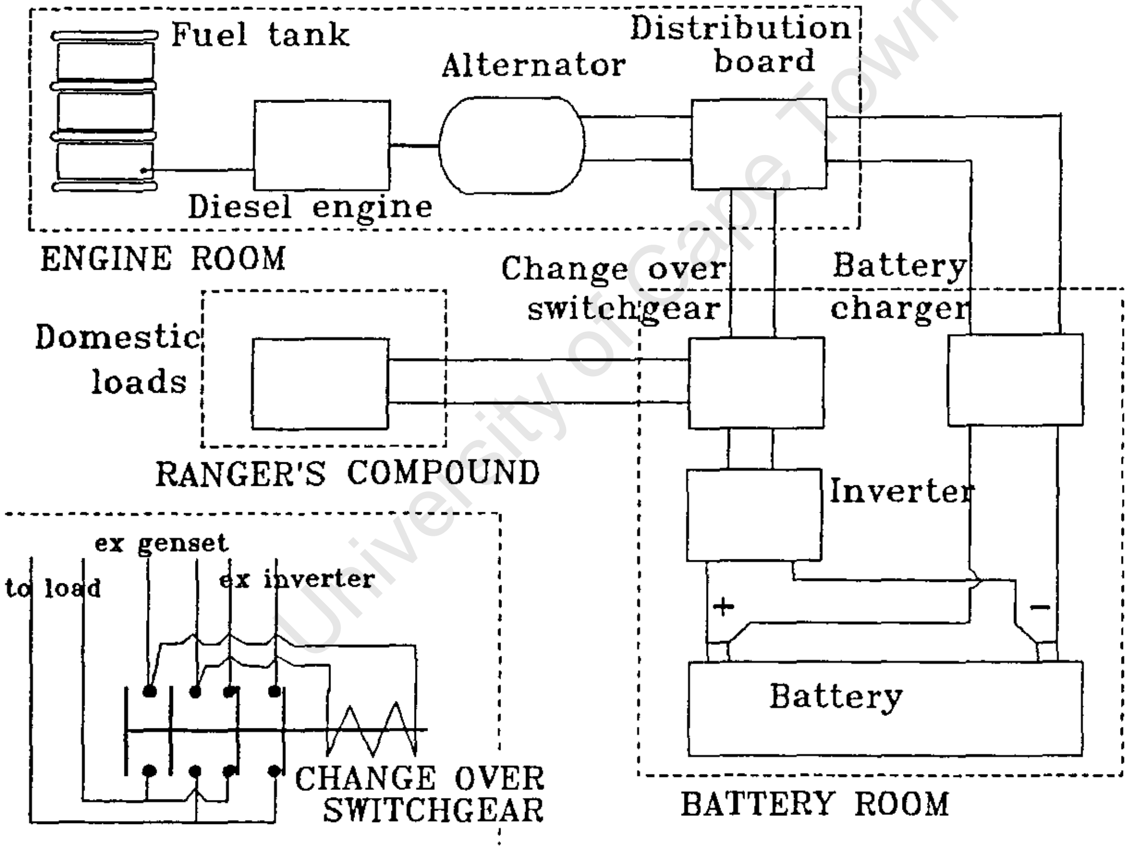


Figure 3.4 : System diagram for Woodlands genset-plus system

A detailed system specification for Woodlands appears in Appendix B.3

3.4.3 Load description

The loads include lighting and typical domestic household appliances with an installed maximum demand of 8350 W, and a 2 hp borehole pump giving a total installed maximum demand of approximately 9800 W.

A detailed schedule of loads is listed in Appendix C.3

3.5 SHINGWEDZI

3.5.1 General description

Shingwedzi is a large tourist camp in the north of the Kruger National Park. Accommodation facilities for up to 600 people include five houses, four flats, 79 huts, a guest house and a caravan park. In addition there is a restaurant, a shop, camp administration offices and a large engineering and maintenance workshop.

3.5.2 System description

The Shingwedzi power generating plant comprises two CAT diesel gensets supplying 380 V 3-phase AC power to the camp and service infrastructure via a 2 km long 6,6 kV transmission line. The two diesel alternators operate alternately as duty and standby on successive days with a changeover being effected daily at 06h00. Under peak demand conditions the standby set is used to provide the additional power required in excess of the continuous load rating of the duty set. The three phases in the distribution network are balanced in terms of the loads connected to each 220 V phase. Instrumentation in the power station includes two complete control panels with ammeters for each phase, a voltmeter, frequency meter, instantaneous power meter, kWh meter, kVAh demand meter and synchronizing gauge.

The system diagram of the installation is shown in Figure 3.5

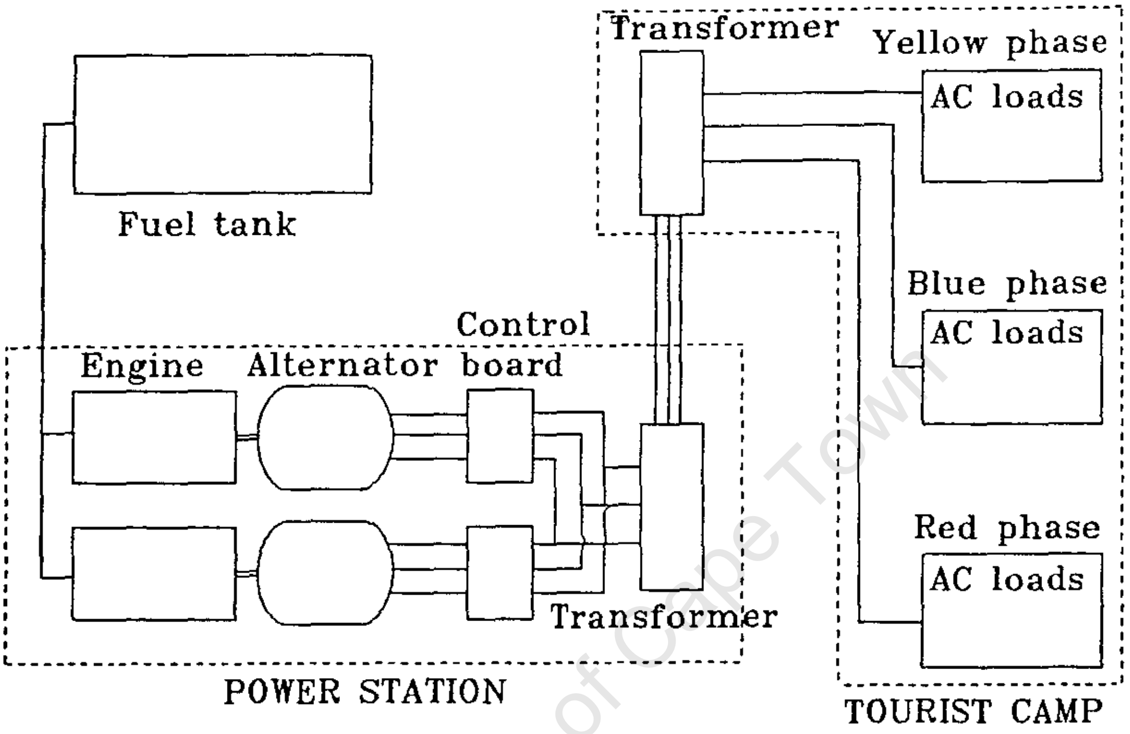


Figure 3.5 : System diagram for the 225/250 kVA Shingwedzi genset system

A detailed system specification for Shingwedzi appears in Appendix B.4

3.5.3 Load description

The loads at Shingwedzi include lighting (13,4%), air-conditioning (34,7%), refrigeration (5,8%), hot water cylinders (23,8%), office equipment, water pumps (2,6%), shop display coolers, restaurant catering appliances (12,5%) and workshop equipment. The percentages in brackets are the respective proportions of the installed maximum power demand of 454 kW, ie. 757 W/bed.

A detailed schedule of loads appears in Appendix C.4.

CHAPTER FOUR

METHOD OF INVESTIGATION

The technical and economic evaluation of the independent power systems described in Chapter Three was based on routine logs and records maintained by the Electro-mechanical Engineer and more detailed data provided by remote electronic data logging systems. These were installed at Jock of the Bushveld, Boulders and Woodlands.

The three electronic data logging systems comprised sensors coupled to analog signal processing interfaces and digital programmable data loggers. Data was recorded on solid state memory modules (EPROM´s) which were posted to ERi. An EPROM reader together with communications software and an IBM compatible PC completed the data retrieval system.

Project support staff in the Kruger National Park comprised a graduate electronics engineer-in-training under the supervision of the Electro-mechanical Engineer.

The data logging systems were installed and commissioned by an ERi electronic engineer in June 1987. After some initial experience with the dynamics of operating a remote logging programme from Cape Town, a fortnightly routine was established for exchanging memory modules, data logger batteries and interface batteries. This included completing a form confirming the system status and which was posted to ERi together with the corresponding "full" EPROM.

A major system failure at Woodlands and the further development of interface cards precipitated a ten day site visit in October 1987 by the author and the ERi electronic engineer. The opportunity was used to collect raw data from the Electro-mechanical Engineer and verify selected channels of the data logging systems with manually recorded data.

4.1 DATA LOGGING SYSTEMS DESCRIPTION

4.1.1 Jock of the Bushveld

The system parameters monitored and recorded on the 800 W_p DC PV system at Jock of the Bushveld are listed in Table 4.1.

Table 4.1 : System parameters monitored and recorded at Jock of the Bushveld

System parameter	Range	Uncertainty
Panel temperature	-10 - 100°C	±5%
Ambient temperature	0 - 100°C	±5%
Battery voltage	0 - 43 V	±1%
AC Power into the load	-2,2 - 2,2 kW	±10%
Current into the batteries	0 - 50 A	±2%
Current out of the batteries	0 - 50 A	±2%
Solar radiation	-100 - 1400 W/m²	±5%

The uncertainty levels are quoted as a percentage of the average reading of each system parameter.

Figure 4.1 illustrates the monitoring system diagram for Jock of the Bushveld.

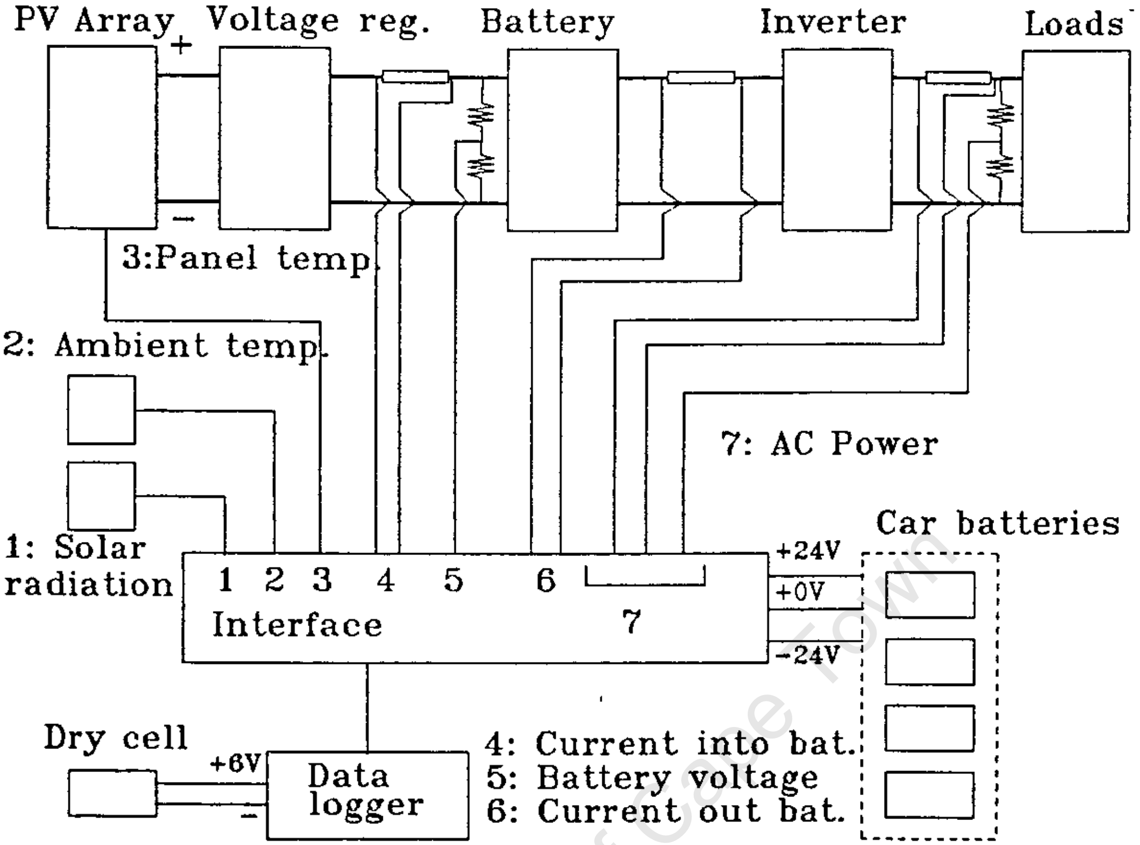


Figure 4.1 : Block diagram of the digital electronic data logging system for Jock of the Bushveld

Accommodation data for Jock of the Bushveld were obtained from the tourism records maintained at Berg-en-dal.

Maintenance data for the PV system were obtained from the company which supplied the system.

4.1.2 Boulders

The system parameters monitored and recorded on the 3300 W_p AC PV system at Boulders are listed overleaf in Table 4.2 :

Table 4.2 : System parameters monitored and recorded at Boulders

System parameter	Range	Uncertainty
Panel temperature	-10 - 100°C	±5%
Ambient temperature	0 - 100°C	±5%
Battery voltage	0 - 70 V	±0,5%
Current into the batteries	-1 - 100 A	±2%
Current out of the batteries	-50 - 50 A	±2%
Solar radiation	-100 - 1400 W/m²	±5%

Figure 4.2 illustrates the monitoring system diagram for Boulders.

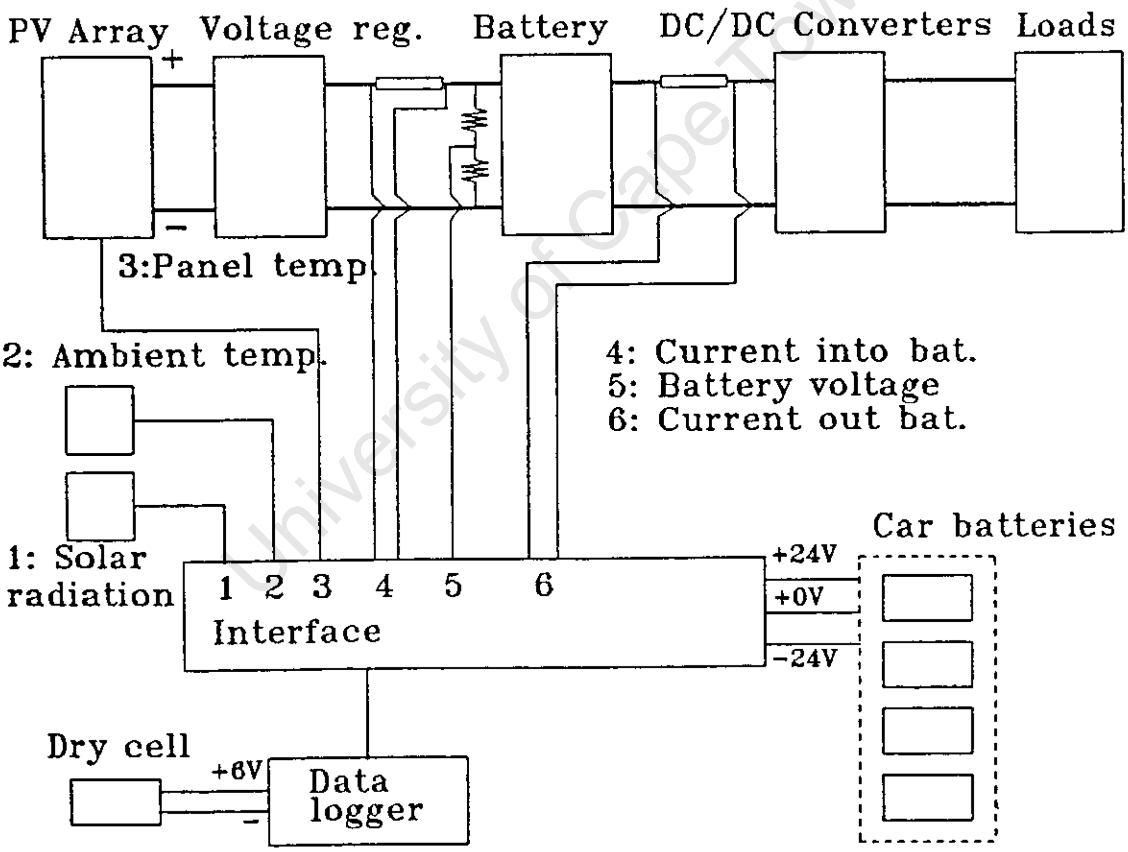


Figure 4.2 : Block diagram of the digital electronic data logging system for Boulders

The inputs and outputs across the seven DC/DC converters were not monitored due to their distance from the logger and consequently evaluation of these components of the system was not possible.

Accommodation data for Boulders were obtained from the tourism records maintained at Letaba.

A handwritten log of energy consumption (Ah/day), recorded by the camp attendant, together with an indication of whether the camp was occupied for the period 23/11/85 to 31/01/87 provided longer term indicators of the system performance.

4.1.3 Woodlands

The system parameters monitored and recorded on the 7 kVA genset-plus system at Woodlands are listed in Table 4.3 :

Table 4.3 : System parameters monitored and recorded at Woodlands

System parameter	Range	Uncertainty
Battery temperature	-10 - 100°C	±5%
Battery voltage	0 - 42 V	±1%
Genset AC Power	-1,42 - 11,0 kW	±2,5%
AC Power into batt. charger	-4,4 - 4,4 kW	±2,5%
Inverter AC Power	-0,5 - 4,4 kW	±2,5%
Current into the batteries	-1 - 100 A	±1,5%
Current out of the batteries	-1 - 100 A	±1,5%
Fuel level	0 - 16 litres	±0,1%

Longer term fuel consumption and maintenance records for Woodlands over the period 22/12/85 to 20/04/87 were obtained in the form of fuel logs and job cards from the Electro-mechanical Engineer.

Figure 4.3 illustrates the monitoring system diagram for Woodlands.

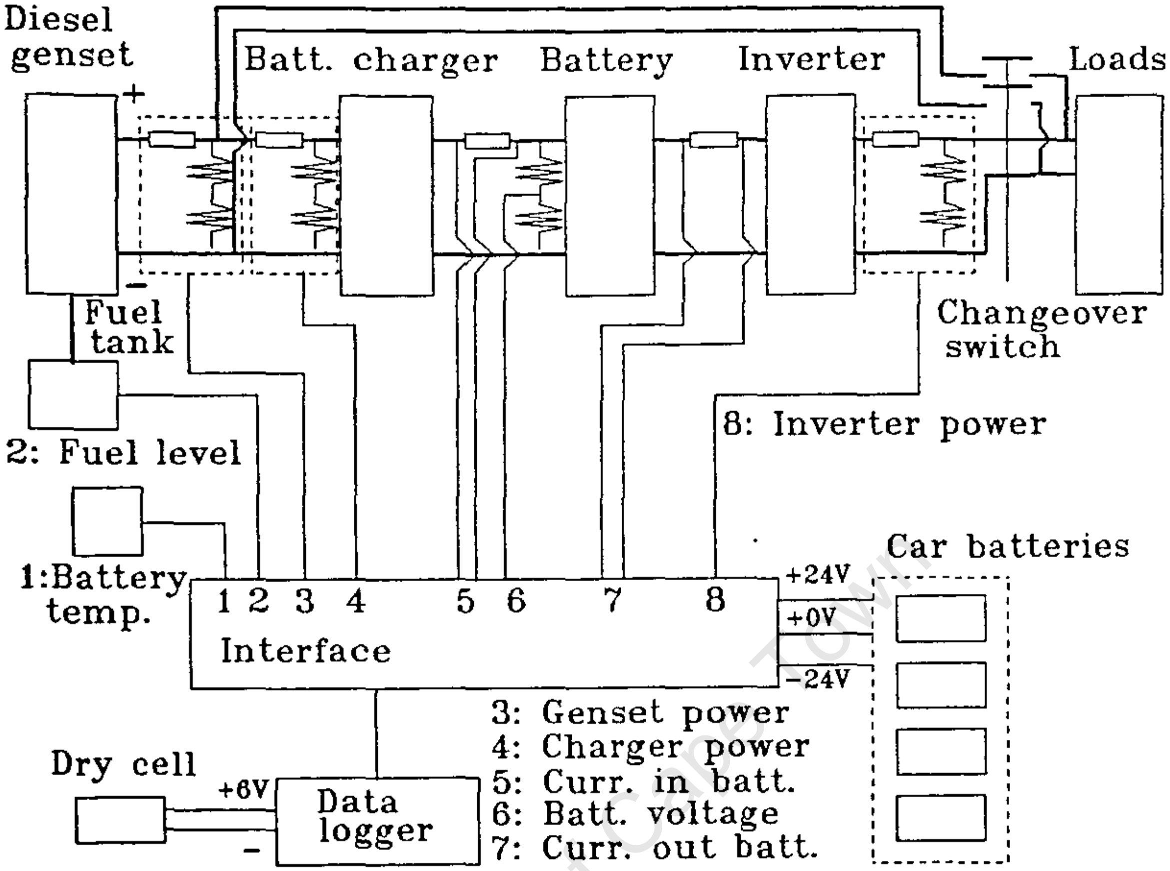


Figure 4.3 : Block diagram of the digital electronic data logging system for Woodlands

4.1.4 Shingwedzi

The data for Shingwedzi were recorded by the power station operator on two twelve hour shifts. Hourly readings of the instantaneous power in kW were recorded in hardcover logbooks.

Fuel and oil consumption was recorded on standard National Parks Board Motor vehicle log sheets (Motorvoertuig-logstaat) by the diesel fitter at Shingwedzi.

Accommodation data were obtained from the tourism officials at Shingwedzi and were provided in the form of monthly records of the daily number tourists in the camp and the type of accommodation occupied.

Job cards for the period between 31/12/85 to 03/11/87 provided maintenance records for the two gensets.

4.2 PHYSICAL SENSORS

The sensors used to monitor the system parameters are discussed in terms of type, principle of operation, range, accuracy, stability and choice.

4.2.1 Temperature

National Semiconductor LM 35 D integrated circuit temperature sensors, giving a 10 mV output per degree Celsius, were used to monitor the panel and ambient temperatures at Jock of the Bushveld and Boulders and the battery temperature at Woodlands. The sensors operating range is 0°C to 100°C and require a 0 V to +35 V supply.

The temperature sensors measuring panel temperature were epoxied to the back of the PV arrays at Jock of the Bushveld and Boulders. The sensor at Woodlands was similarly epoxied to the battery casing. The ambient temperature sensor at Jock of the Bushveld was suspended in the air below and behind the array whereas the sensor at Boulders was suspended inside the ventilated battery room.

The IC temperature sensors were chosen instead of thermocouples because of their accuracy, response, versatility and low cost.

4.2.2 Voltage

DC and AC voltages were measured by means of simple voltage divider circuits. These afforded cheap, robust and repeatable inputs for the interface and data logger.

4.2.3 Current

DC and AC current was measured by means of thermally stable, calibrated 50 mV current shunts.

4.2.4 AC Power

AC power was measured by integrating the instantaneous product of AC voltage and AC current, measured by means of simple voltage divider circuits and current shunts respectively. The conversion of these inputs into power, kW, was performed by two cards within the signal processing interface. The mathematical basis for the integration is elaborated on in Appendix D together with the analog circuit diagrams of the interface monitor.

4.2.5 Solar radiation

Solar radiation was measured at Jock of the Bushveld and Boulders using cosine corrected Li-Cor pyranometer sensors which produce a microamp output proportional to the solar radiation in W/m^2. The pyranometers were calibrated under natural daylight conditions by LI-Cor against an Eppley Precision Spectral Pyranometer on 12/11/85 and 07/04/86 respectively. The maximum uncertainty in the calibration is ±5%. The pyranometers were mounted on the array support structures at the same angle of tilt as the arrays.

4.2.6 Fuel level

The diesel fuel level of the genset installation at Woodlands was measured using a Phillips pressure transducer in a fabricated fuel tank.

The fuel tank has a capacity of 16 litres and allows approximately eight hours operation between refuelling. The tank and transducer were calibrated in the ERi workshops before installation on site on 28/09/87. Further on site calibration confirmed the accuracy and linearity of the output over a range of 0 to 16 litres. The uncertainty in the fuel level was less than 9 ml.

4.3 ANALOG SIGNAL CONDITIONING INTERFACE

The analog output signals from the sensors are converted into input signals in the 0-2000 mV range required by the data logger by an analog signal conditioning interface.

The modular interface monitor was designed and built in the ERi workshops. It is designed to accommodate twelve channels of input and output signals with up to two cards per channel. The interface cards are adjustable for range and offset.

The interface requires a 20-35 V DC power supply and draws between 30 and 100 mA. The interface power supply cards for this application provided ±15 V to the power supply rails in the interface from two pairs of 40 Ah automotive lead acid batteries in series providing unattended operation of between fifteen and fifty days.

Descriptions of the power supply and individual cards including the circuit diagrams, stability, linearity and accuracy are presented in Appendix D.

4.4 DIGITAL ELECTRONIC DATA LOGGER

The three data loggers used were programmable digital solid state micro-processor driven multi-channel devices supplied by MC Systems in Cape Town. The individual, zero to 2000 mV, analog input signals on each channel are scanned every 60 seconds and converted into digital signals for manipulation by the logger before being stored on the EPROM memory module. Each output channel, (except that of the fuel level), was programmed to evaluate the average of a given signal over a given log interval (usually fifteen, twenty or thirty minute intervals). The instantaneous input of the fuel level was logged at the end of each log interval. The output signal onto the EPROM was converted into a meaningful range by individual channel multiplication factors and offsets programmed into the logger input programmes.

The MCS data logger and an EPROM memory module are shown in Figure 4.4.

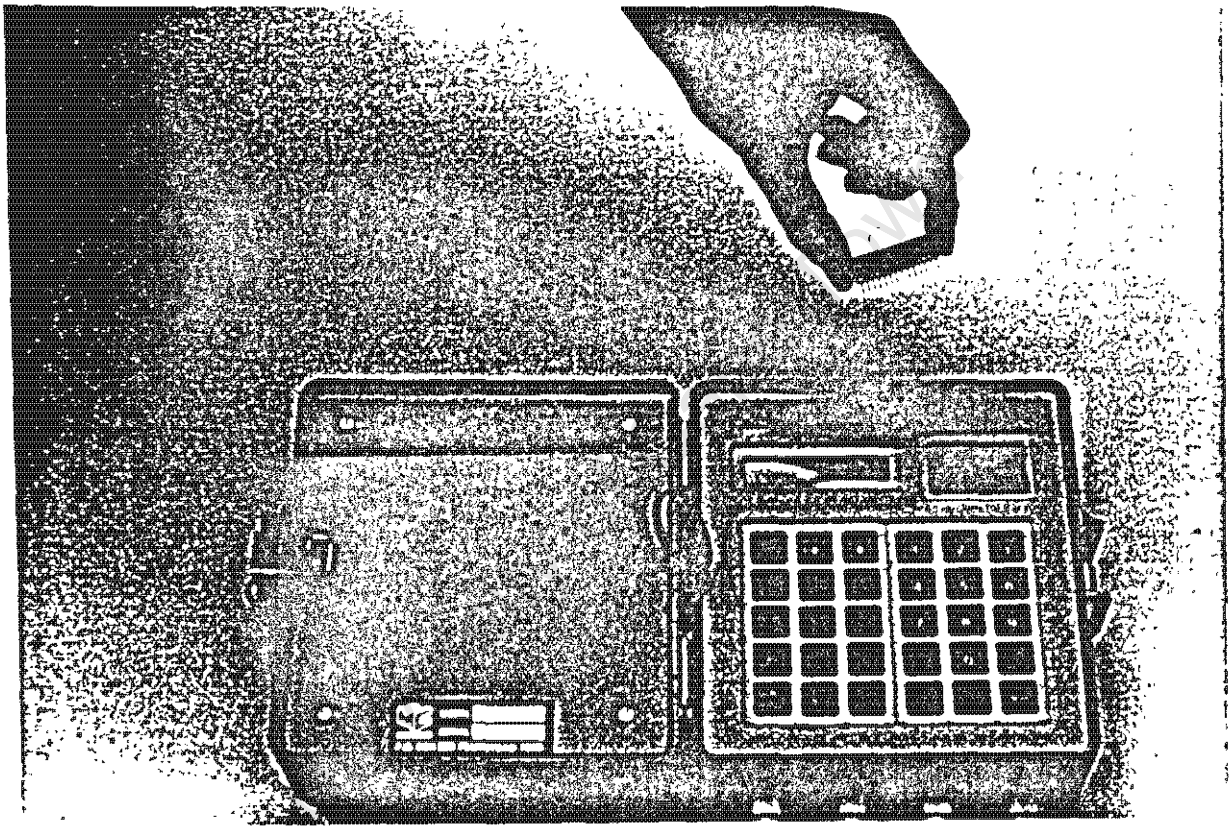


Figure 4.4 : Photograph of the MCS digital data logger and an EPROM memory module

The loggers recorded up to twenty days of data at thirty minute intervals (based on data input scans at one minute intervals), from between six and eight channels onto 128 kilobit EPROM's. The removal of "full" EPROM's and replacement with erased EPROM's was performed every two weeks by National Parks Board personnel who also checked and replaced interface or data logger batteries. The "full" EPROM's were wrapped in aluminium foil for protection against erasure by UV radiation before posting to ERi from Skukuza. The data was off-loaded in ASCII format onto 5 ¼" floppy discs using a PC based EPROM reader and serial communications software at ERi. The data loggers are powered by four D size DURACELL cells.

For the most of the monitoring period the data loggers were programmed to log data at thirty minute intervals. Fifteen and twenty minute intervals were used on some days during the monitoring period especially during commissioning. The input and output programs were calculated according to the calibration of the interface card outputs and checked in the field.

Logger input and output programs for the three sites are listed in Appendix E.

4.5 DATA MANIPULATION

4.5.1 Data scanning and screening

After down-loading the data from the EPROM's the ASCII data was imported into LOTUS 123 spreadsheets to facilitate data manipulation and analysis. The raw data was scrutinized in conjunction with the system status information recorded by the Kruger National Park engineer on removal of the EPROM to assess the veracity of the data.

Having determined whether the sensors, interface and data logger had been operating correctly during the logging period, the raw data was then manipulated into manageable spreadsheet files and all spurious or erroneous readings were individually assessed and smoothed by three point linear extrapolation.

Graphs of the raw data were plotted for successive days to facilitate analysis. Only days for which all the data recording channels were logging cleanly were considered for further processing.

4.5.2 Jock of the Bushveld

Fourteen days' data over the period 03/10/87 to 05/10/87 and 08/10/87 to 18/10/87 were regarded as acceptable at Jock of the Bushveld despite a persistent malfunction of the inverter AC power channel. Data was logged at twenty minute intervals over the first period and thirty minute intervals over the second. The AC power measurement channel of the interface monitor began to drift after 09/10/87 and therefore data for the inverter output was disregarded after this date..

The continuously logged data was separated into individual days and each day was stored in a spreadsheet. The data for each channel was corrected for zero offset and columns were set up to calculate the DC power into and out of the battery and inverter efficiency. The following system parameters were then calculated for each day :

- daily global solar radiation ($W/m^2/day$)
- daily available energy incident on the gross panel area (MJ/day)
- daily energy supplied into the battery (MJ/day)
- daily energy supplied from the battery (MJ/day)
- daily energy supplied from the inverter (MJ/day)
- average daytime panel temperature (°C)
- average daytime ambient temperature (°C)
- average combined array and voltage regulator efficiency (%)
- average inverter efficiency (%)
- average daily overall system efficiency (%)

The calculated combined array and voltage regulator efficiency is based on gross panel area and not the active cell area.

4.5.3 Boulders

Thirty-six days' of acceptable data were selected from the raw data for Boulders.

As for Jock of the Bushveld, the raw data for Boulders was arranged into separate spreadsheets for individual days. The data was adjusted for zero offset and columns were set up to calculate the DC power into and out of the battery. System parameters calculated for each day were :

- daily global solar radiation (W/m^2/day)
- daily available energy incident on the gross panel area (MJ/day)
- daily energy supplied into the battery (MJ/day)
- daily energy supplied from the battery (MJ/day)
- average daytime panel temperature (°C)
- average daytime ambient temperature (°C)
- average combined array and voltage regulator efficiency (%)
- average combined array and voltage regulator boost charge efficiency (%)
- average daily overall system efficiency (%)

Similarly the calculated combined array and voltage regulator efficiency is based on gross panel area and not the cell area. The boost charge efficiency is based on the periods during which the battery voltage was less than the voltage regulator maximum cut-off voltage. The voltage regulator did not switch the array to open circuit during these periods.

4.5.4 Woodlands

The Woodlands data logging system was the most troublesome. Only seven days' data were considered useful. The AC power measurement channels continually caused spikes and noise to interfere with the data logger resulting in drift on the recorded data and disruption of the other channels in a cascade effect.

The seven days' data were also stored in separate spreadsheets for individual days. The respective channels were adjusted for zero offset and columns were set up to calculate DC power into the inverter, inverter efficiency, AC power into the loads and genset efficiency. System parameters that were calculated were :

- daily run time (hours)
- daily fuel consumption (l)
- average fuel consumption (l/hour)
- daily energy in the fuel (MJ/day)
- daily energy out of the genset (MJ/day)
- daily energy into the battery charger (MJ/day)
- daily energy into the loads (MJ/day)
- daily energy out of the battery (MJ/day)
- daily energy out of the inverter (MJ/day)
- average daily genset efficiency (%)
- average genset load factor (%)
- average genset capacity factor (%)
- average battery charger efficiency (%)
- average inverter efficiency (%)
- average inverter load factor (%)
- average daily overall system efficiency (%)

In addition, the fuel consumption log sheets and maintenance job card data were typed into LOTUS 123 spreadsheets for the periods 22/12/85 to 08/01/87 and 18/03/86 to 12/11/86 respectively. Average daily run times and average fuel and oil consumptions were calculated from the data. The maintenance cost of the system was also calculated, based on the manufacturer's spares prices and National Parks Board rates for travel and artisan's labour rates.

4.5.5 Shingwedzi

The raw data for Shingwedzi, in the form of handwritten, twenty-four hour per day, logs of hourly power output, fuel and oil consumption and maintenance job cards were typed into LOTUS 123 spreadsheets. The hourly power output data for each day for the one year period between 01/10/86 and 30/09/87 was selected to cover seasonal variations. The data was evaluated on a monthly basis to establish a typical average load curve for each month.

The fuel consumption and maintenance data were compiled for longer periods between January 1986 and September 1987, and between January 1986 and November 1987, respectively. The data was evaluated as for Woodlands to provide average fuel and oil consumption data and maintenance costs for each of the two CAT gensets.

4.6 PROBLEMS WITH THE DATA LOGGING SYSTEMS

The primary problem with the three remote electronic data logging systems was a lack of robustness. Despite efforts to anticipate problems and test the logging systems at ERi during the pre-commissioning phase, the operation of the logging systems in the field was fraught with partial or complete system failures. These were due to both technical and logistical reasons.

Problems included :

- exhausted dry cells for the logger power supply
- discharged car battery/ies for the interface power supply
- programming errors in the logger input or output programs
- drift on the interface output
- negative inputs to the logger causing logger over-scale readings
- damage to the Woodlands interface through a 220 V AC short
- availability of field support staff to maintain the systems
- a hardware failure on the Jock of the Bushveld logger requiring repair at MC Systems in Cape Town

The above-mentioned problems were exacerbated by a minimum postal turn-around time of four weeks between Skukuza and ERi which hampered adjustments and modifications to the logging systems. Problems identified in the EPROM data were only rectified between two weeks and a month after the problem initially occurred.

4.7 ECONOMIC EVALUATION TECHNIQUE

The evaluation of economic feasibility and comparative costs of independent power systems can be performed using a host of techniques. These include static methods, such as direct cost comparison, cost annuity comparison, return on investment and static payback, or dynamic methods which take into account the time value of costs incurred at different times, such as net present value, internal rate of return, annuity method, dynamic cost annuity and payback methods, (Finck and Oelert, 1985).

The method adopted for the purposes of this project was required to reflect the economic implications of investment in PV, diesel or genset-plus for the user (ie. the National Parks Board) and not necessarily the wider ramifications for national energy or economic policy (ie. ESKOM or local content incentives to reduce foreign exchange requirements etc.). It had to accommodate analyses of capital intensive power systems with minimal recurrent operating and maintenance costs (such as PV), as well as power systems with lower initial costs but high recurrent O&M costs (such as diesel and to a lesser extent genset-plus).

The majority of economic evaluation techniques do not address non-quantifiable factors or benefits such as the effect on national economics, politics, sociological or environmental factors.

In general, the requirements of a economic evaluation technique for independent power systems should include :

(i) the total life-cycle costs of the system including :

- capital costs of : planning
  land acquisition/leasing
  civil works
  plant buildings and site infrastructure

power plant and equipment
transport of equipment to site
installation and commissioning
customs, tax and engineering fees
plant and equipment replacement

- residual value of plant and equipment
- financing charges
- personpower costs : plant operators and administration
- repair and maintenance costs
- energy related costs : fuel
- auxiliary materials : oil, grease etc.
- administrative infrastructure : excluding personpower
- taxes and duties

(ii) the cashflow of a power system over its lifetime

(iii) the time value of money

(iv) the availability and cost of investment capital

(v) inflation

(vi) sensitivity analyses

The annuity method suggested by Finck and Oelert (1985) was adopted for the economic evaluation of the four off-grid energy supply systems investigated in this thesis. The annuity method converts all net cashflows connected to an investment project into a series of annual payments of an equal amount. The conversion takes place by multiplying the net present value (NPV) by a recovery factor RF(i,T) for a predetermined interest rate (i) and a known planning period (T).

The annuity, a constant annual payment for a long term investment, is calaculated from the formula :

$$A = NPV * RF(i,T)$$

where $$NPV = I_o + I_t * q^{-t} + L_T * q^{-T}$$

$$q^{-t} = (1 + i/100)^{-t}$$

$$RF(i,T) = \frac{(1+i/100)^t * i/100}{(1+i/100)^t - 1}$$

NPV	net present value of the investment project at the point in time t=0
I_o	the initial investment cost at time t=0
I_t	the investment cost in time period t
q^{-t}	discounting factors
i	real interest rate
L_T	liquidation yield at the end of the service life

The annuity can be further be broken down into separate components of say, investment costs, operating and maintenance costs and annuity of liquidation yield. In addition it is recommended to evaluate the implications of investing or borrowing the difference in capital investment costs of competing alternatives if the interest on borrowed capital and return on invested capital are not the same or if sufficient capital is not available.

The annualized unit energy cost was calculated as the quotient of the annuity over the annual average number of units of energy, (kWh/year), produced by the power supply system, averaged over its operating lifetime.

The economic evaluation was performed using a simple LOTUS 123 spreadsheet incorporating macro routines to evaluate the NPV of the replacement costs of the batteries in course of the stated overall system life.

4.7.1 PV systems

The two PV systems were evaluated in terms of the initial capital investment in PV modules, batteries and balance of system costs and the recurrent annual costs of maintenance and less frequent battery replacement costs. The lifetime over which the systems were evaluated was the anticipated twenty year lifetime of the PV modules. Detailed assumptions for the evaluation are discussed in Sections 5.2.2 and 5.3.2.

4.7.2 Genset-plus system

Similarly, the Woodlands genset-plus system was evaluated in terms of initial capital costs such as genset, batteries, battery charger and inverter and the recurrent costs such as fuel and oil, routine genset maintenance and replacement of the batteries. The period over which the system was evaluated was the estimated seven year operating lifetime of the genset. Detailed assumptions for the evaluation are discussed in Section 5.4.2.

4.7.3 Genset system

The economic evaluation of the genset installation at Shingwedzi was in terms of the initial capital costs of the gensets, fuel tank, exhaust systems and control equipment and the recurrent costs of power station operators, fuel and oil, and routine maintenance. The period over which the system was evaluated was the fifteen year expected operating lifetime of the gensets. Detailed assumptions for the evaluation are discussed in Section 5.5.2.

CHAPTER FIVE

FINDINGS AND ANALYSIS

The total dependence of PV systems on the characteristics of the incident solar radiation represents the fundamental difference between PV and the environmentally insensitive diesel genset and genset-plus systems. Therefore, before considering the technical and economic findings and analyses of the four off-grid power systems, the solar resource in the Kruger National Park is evaluated.

The findings and analyses for each system are presented individually in terms of technical and economic considerations respectively.

5.1 SOLAR RADIATION AND AMBIENT TEMPERATURE DATA

The veracity of available solar radiation data is vital for the optimal sizing and design of PV systems. Similarly, reliable data for the daytime ambient temperature is important for estimating the reduction in PV system power output due to the negative effect of panel temperatures in excess of the standard panel specification conditions of 1000 W/m² and 25°C.

The solar radiation and ambient temperature data recorded during the monitoring period serve to extend the PV design database for the Kruger National Park. Furthermore, comparison with South African Weather Bureau (SAWB) data for Nelspruit can lead to more confident extrapolation of that data for PV systems in the Park.

Figure 5.1 shows the typical bell shaped profile of the global solar radiation recorded at Jock of the Bushveld on a clear day as opposed to the erratic profile of an overcast day. The bulk of the available solar energy on the clear day occurs between 09h00 and 15h00. The solar noon occurred slightly before 12h00 which corresponds to the longitude of the site being slightly East of 30°E on which S A Standard Time is based. Sunrise occurred between 05h30 and 06h00 and sunset was between 18h00 and 18h30. A twilight period of about twenty minutes at dawn and sunset is represented by levels of global solar radiation of less than 50 W/m². This is less well defined on overcast days.

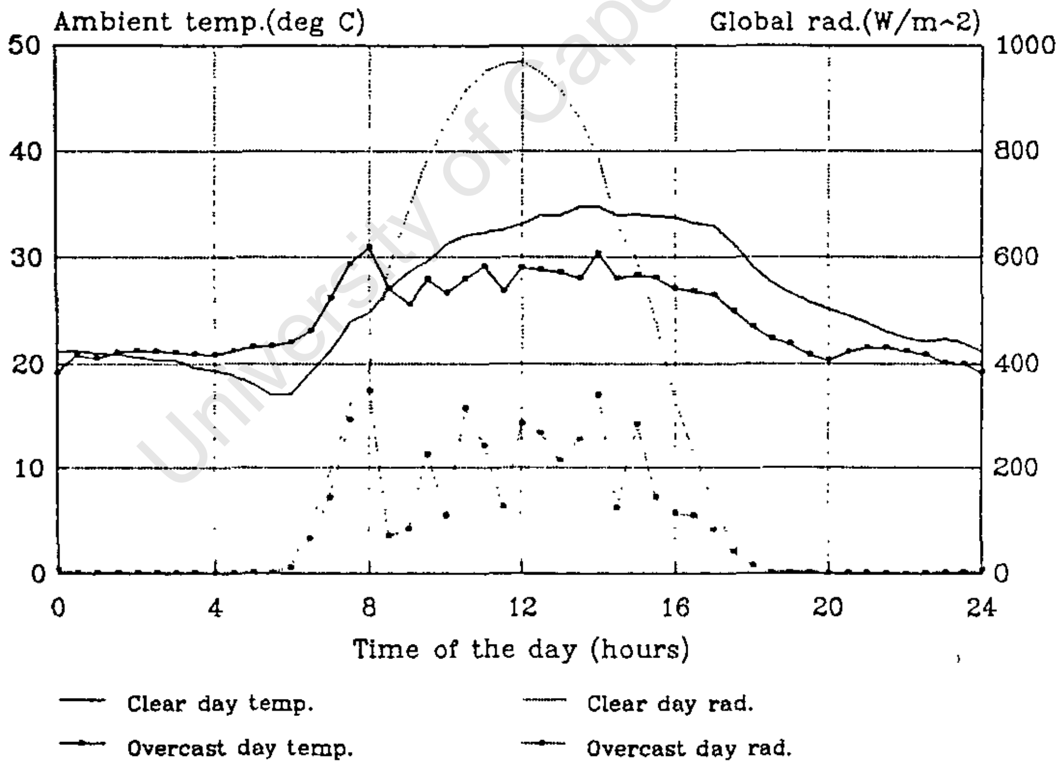


Figure 5.1 : Global solar radiation and ambient temperature profiles for clear and overcast sky conditions at Jock of the Bushveld

Ambient temperature is a function of insolation and radiant heat transfer with the sky. On the clear day the ambient temperature can be seen to drop quite sharply immediately before dawn and then increase gently until about 16h00 before tailing off into the night. The ambient temperature profile for the overcast day is erratic in sympathy with the global radiation profile, but shows a small nett increase between dawn and sunset.

Despite only fourteen days' of acceptable data having been recorded for Jock of the Bushveld and thirty-five for Boulders, a comparison between the corresponding data at the two sites and SAWB data is illuminating.

Table 5.1 presents comparative solar radiation data as well as ambient temperature data for Jock of the Bushveld and Boulders.

Table 5.1 : Solar radiation and ambient temperature data for Jock of the Bushveld and Boulders

Date	Jock global rad. (MJ/m^2/day)	Boulders global rad.	Jock ambient temp. (°C)	Boulders ambient temp. (°C)
02-Oct		7,87		19,51
03-Oct	8,95	11,28	20,22	18,29
04-Oct	27,49	22,00	25,44	18,68
05-Oct	27,82		27,48	
06-Oct		26,58		21,88
07-Oct		25,79		23,80
08-Oct	24,75	25,14	29,53	24,53
09-Oct	25,26	25,56	31,76	25,38
10-Oct	7,75	23,48	27,37	26,89
11-Oct	23,16	25,13	33,95	26,58
12-Oct	12,87	25,97	29,48	28,21
13-Oct	3,88	9,15	22,60	22,98
14-Oct	11,95	11,80	27,93	21,52
15-Oct	13,76	16,24	28,47	22,67
16-Oct	25,10	19,16	27,92	21,49
17-Oct	30,91	27,69	28,88	21,46
18-Oct	26,50	23,34	30,33	21,84
Average	19,30	20,39	27,95	22,86

The ambient temperature data measured at Jock of the Bushveld reflects the air temperature 150 mm below the back of the PV array, whereas the data for Boulders is the ambient temperature inside the ventilated battery storage room. These ambient air temperatures are therefore not directly comparable, as the measurements made at Jock of the Bushveld would be subject to radiative heat transfer from the back of the array as well as convective cooling due to winds. The ambient air temperature recorded at Boulders is a more representative indicator of the ambient air temperature in the shade.

Figure 5.2 shows the correlation between the global radiation at the two sites illustrating a common synoptic trend for the corresponding logging period between 03/10/87 and 18/10/87. The low level of global solar radiation recorded at Jock of the Bushveld on 10/10/87, relative to that recorded at Boulders on the same day, was due to overcast weather over the southern parts of the Park and clear skies over the central parts.

The maximum recorded incident global radiation averaged over one log period at Jock of the Bushveld and Boulders were 1158 W/m^2 between 11h00 and 11h30 on 17/10/87 and 1101 W/m^2 between 10h30 and 11h00 on 02/11/87 respectively.

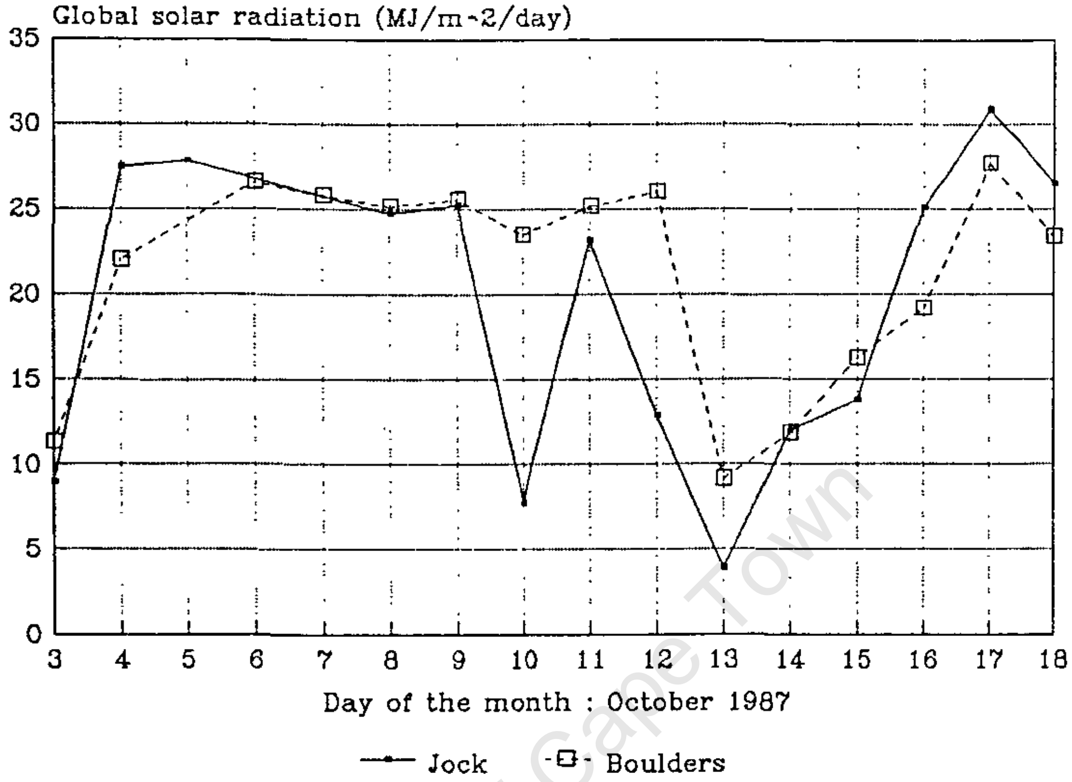


Figure 5.2 : Comparative solar radiation data for Jock of the Bushveld and Boulders between 03/10/87 and 18/10/87

For comparison with the SAWB data, Table 5.2 presents a matrix of monthly average global radiation for Nelspruit, on a surface facing due North, tilted at angles varying between 0° and 45° to the horizontal. These monthly average values of global radiation on tilted surfaces are calculated from SAWB data (Tegen, 1988) for the global radiation on a horizontal plane. They are based on a ground reflectivity of 0,15 which corresponds to gravel.

Table 5.2 : Monthly average global radiation (MJ/m2/day) for tilted surfaces between 0 deg and 45 deg, calculated from South African Weather Bureau data for Nelspruit

Existing site : optimum angle for max. annual radiation

Site : NELSPRUIT

Ground reflectivity : .15

GLOBAL RADIATION FOR TILTED SURFACE : I(gt)

Angle :	0.00	5.00	10.00	15.00	20.00	25.00	30.00	35.00	40.00	45.00
JAN	26.60	26.40	26.04	25.54	24.89	24.10	23.17	22.12	20.94	19.66
FEB	21.14	21.21	21.15	20.98	20.69	20.29	19.78	19.16	18.43	17.61
MAR	18.56	18.91	19.15	19.29	19.31	19.23	19.03	18.73	18.32	17.81
APR	17.07	17.86	18.54	19.11	19.56	19.89	20.09	20.17	20.12	19.95
MAY	14.96	16.09	17.12	18.04	18.84	19.52	20.07	20.50	20.78	20.93
JUN	14.01	15.28	16.46	17.53	18.48	19.31	20.02	20.59	21.03	21.33
JUL	14.85	16.13	17.31	18.37	19.31	20.13	20.81	21.36	21.76	22.02
AUG	16.05	16.97	17.78	18.48	19.06	19.53	19.87	20.09	20.18	20.14
SEP	17.68	18.19	18.59	18.89	19.07	19.14	19.10	18.94	18.67	18.30
OCT	18.52	18.68	18.73	18.67	18.52	18.26	17.90	17.45	16.90	16.26
NOV	19.34	19.26	19.07	18.79	18.40	17.92	17.35	16.68	15.93	15.11
DEC	21.00	20.80	20.50	20.08	19.56	18.94	18.22	17.40	16.50	15.53
TOTAL :	219.78	225.77	230.44	233.76	235.70	236.26	235.42	233.19	229.59	224.64

The average global radiation recorded at Jock and Boulders, of 19,30 MJ/m^2/day (5,36 kWh/m^2/day) and 20,39 MJ/m^2/day (5,66 kWh/m^2/day) respectively, are 7,8% and 10,0% greater than the calculated values of 17,90 MJ/m^2/day and 18,52 MJ/m^2/day for global radiation for Nelspruit at the respective tilt angles of approximately 30° for Jock and 20° for Boulders. The lower figures for Nelspruit could be due to local weather variation or as a result of generally higher levels of moisture in the atmosphere due to mist over Nelspruit in the Crocodile River valley.

The incident solar radiation on tilted surfaces is primarily a function of the time of the year (variation in air mass and solar declination), the azimuth angle and the angle of tilt of the surface. Based on the calculated values above, the optimum angle of tilt for the maximum annual incident solar radiation for Nelspruit would be approximately 24°. However for PV applications with seasonal variations in load energy demand, angles of tilt should be investigated for which the seasonal variation of incident energy most closely follows that of the load energy demand. At the site latitudes, tilt angles greater than 25° favour winter load peaks whereas those less than 25° favour summer load peaks. Two axis tracking devices are employed in large PV systems to dynamically optimize the array output for daily and seasonal variation in the apparent motion of the sun across the sky.

5.2 JOCK OF THE BUSHVELD

5.2.1 Technical evaluation

The technical performance of the 800 W_p, 220 V AC PV system at Jock of the Bushveld is discussed in terms of a summary of the overall system performance followed by a detailed evaluation of individual system components in the light of technical considerations, the recorded load curves and solar radiation data.

5.2.1.1 Overall results and daily operating characteristics

Table 5.3 on the following page presents a summary of the system performance for the logging period.

The array and regulator efficiency referred to in the table is the combined efficiency of the array and voltage regulator as determined by the quotient of the total energy per day into the battery over the daily solar energy incident on the gross panel area of the array.

Similarly the overall system efficiency is the quotient of the daily energy consumption over the daily incident solar energy on the array. The overall efficiency of the system varied between 1% and 4%.

The daily operating characteristics of the system on a clear day, 08/10/87, and an overcast day, 10/10/87, are illustrated in Figures 5.3 and 5.4 which plot system parameters such as solar radiation, panel temperature, ambient temperature, battery voltage, current, into and out of the battery, against the time of day. The performance of the system for these two representative days is summarized in Tables 5.4 and 5.5.

Table 5.3 : Jock of the Bushveld overall system performance from 03/10/87 to 18/10/87

Date	Daily solar rad. MJ/m^2/d	Daily energy avail. MJ/day	Daily energy in bat. MJ/day	Daily energy ex inv. MJ/day	Ave. panel temp. °C	Ave. amb. temp. °C	Array & reg. eff. %	Ave. inv. eff. %	Overall system eff. %	Occ. person
03-Oct	9,0	79,0	4,9	3,2	22,1	20,2	6,2	48,6	4,0	12
04-Oct	27,5	242,6	15,4	2,4	32,0	25,4	6,4	44,5	1,0	12
05-Oct	27,8	245,5	15,4	5,4	33,3	27,5	6,3	37,8	2,2	12
06-Oct										
07-Oct										
08-Oct	24,8	218,4	13,5	4,8	36,3	29,5	6,2	49,0	2,2	12
09-Oct	25,3	223,0	13,8	4,9	37,0	31,8	6,2	45,3	2,2	12
10-Oct	7,8	68,4	3,9	(6,2)*	26,8	27,4	5,6	(62,2)*		12
11-Oct	23,2	204,4	12,4		34,6	34,0	6,1			12
12-Oct	12,9	113,6	6,7		26,9	29,5	5,9			12
13-Oct	3,9	34,3	1,5		18,5	22,6	4,2			12
14-Oct	12,0	105,5	6,8		26,8	27,9	6,4			0
15-Oct	13,8	121,4	6,6		25,9	28,5	5,5			12
16-Oct	25,1	221,6	11,8		27,4	27,9	5,3			12
17-Oct	30,9	272,8	14,3		30,5	28,9	5,3			12
18-Oct	26,5	233,9	11,7		30,3	30,3	5,0			12
Ave.	19,3	170,3	9,9	(4,1)	29,2	28,0	5,8	(45,0)	(2,3)	11,1
Std dev.	8,6	76,2	4,5	(1,1)	5,1	3,4	0,6	(4,0)	(1,0)	3,1
Max.	31,0	272,8	15,4	5,4	37,0	34,0	6,4	49,0	4,0	12,0
Min.	3,9	34,3	1,5	2,4	18,5	20,2	4,2	37,8	1,0	0,0

* values suspect due to drift on AC power interface channel.

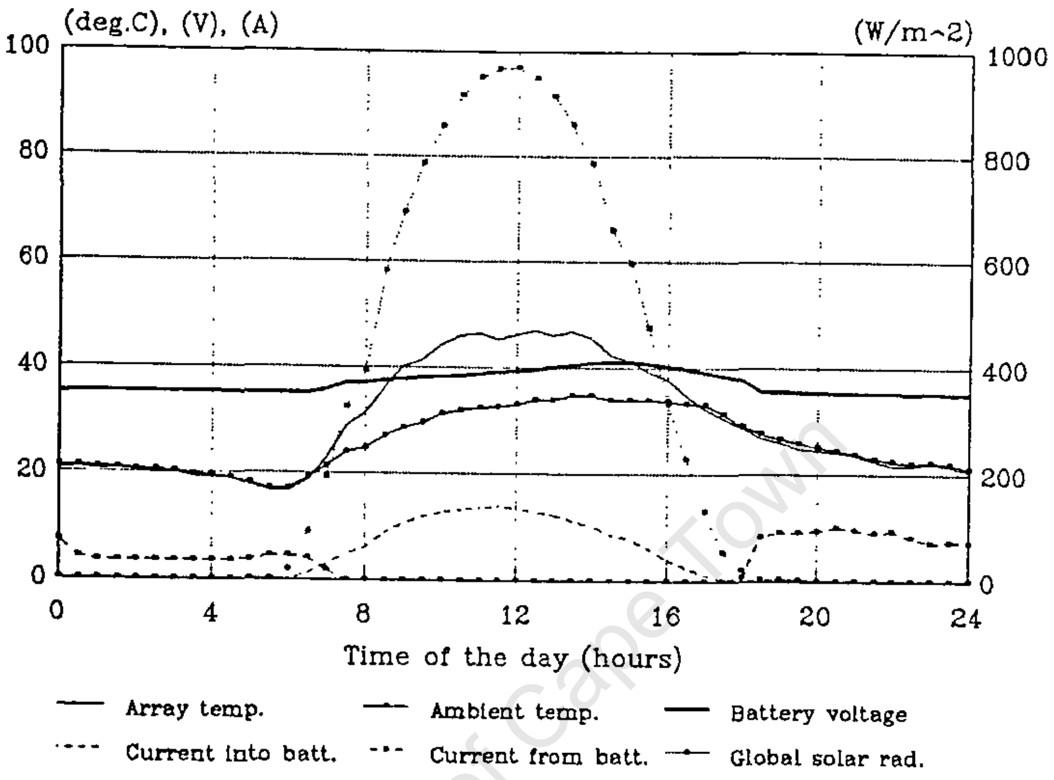


Figure 5.3 : Daily operating characteristics of the Jock of the Bushveld AC PV system for a clear day, 08/10/87

Table 5.4 : Jock of the Bushveld AC PV system performance for a clear day, 08/10/87

Daily solar radiation :	24,8 MJ/m²/day
Daily energy available :	218,4 MJ/day
Daily energy in battery :	13,5 MJ/day
Daily energy out battery :	9,9 MJ/day
Daily energy out inverter:	4,8 MJ/day
Ave. load power demand :	103 W
Ave. nighttime voltage :	35,3 V
Ave. daytime panel temp. :	36,3 °C
Max. panel temp. :	47,0 °C
Ave. daytime amb. temp. :	29,5 °C
Ave. array & charger eff.:	6,2 %
Ave. inverter eff. :	49,0 %
Ave. overall system eff. :	2,2 %
Occupation :	12 persons

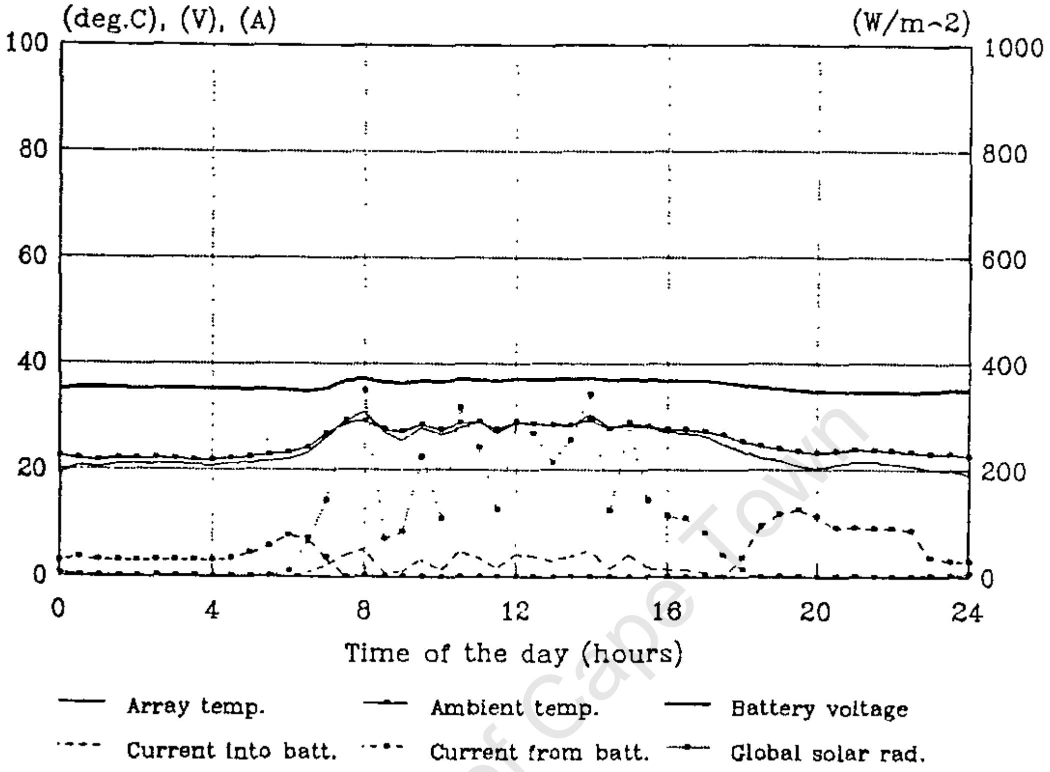


Figure 5.4 : Daily operating characteristics of the Jock of the Bushveld AC PV system for an overcast day, 10/10/87

Table 5.5 : Jock of the Bushveld AC PV system performance for an overcast day, 10/10/87

Daily solar radiation	:	7,8 MJ/m²/day
Daily energy available	:	68,4 MJ/day
Daily energy in battery	:	3,9 MJ/day
Daily energy out battery	:	10,0 MJ/day
Daily energy out inverter	:	4,5 MJ/day
Ave. load power demand	:	93 W
Ave. nighttime voltage	:	35,1 V
Ave. daytime panel temp.	:	26,8 °C
Max. panel temp.	:	30,9 °C
Ave. daytime amb. temp.	:	27,4 °C
Ave. array & charger eff.	:	5,7 %
Ave. inverter eff.	:	not available
Ave. overall system eff.	:	not available
Occupation	:	12 persons

5.2.1.2 Load energy demand and load curve

The average daily load energy demand for the camp while occupied, recorded over five days while the inverter AC output channel was working, was 1,15 kWh/day. The camp was occupied for thirteen of the fourteen day monitoring period. Based on the energy drawn from the battery and an average inverter efficiency of 45% (see Section 5.2.1.3.1), the average daily load energy demand for the camp occupied was 1,09 kWh/day. The daily load energy demand for the camp unoccupied was zero. The recorded maximum was 1,50 kWh/day.

Figure 5.5 presents the average load power demand curve for the monitored period which represents the AC load power demand averaged over each log interval.

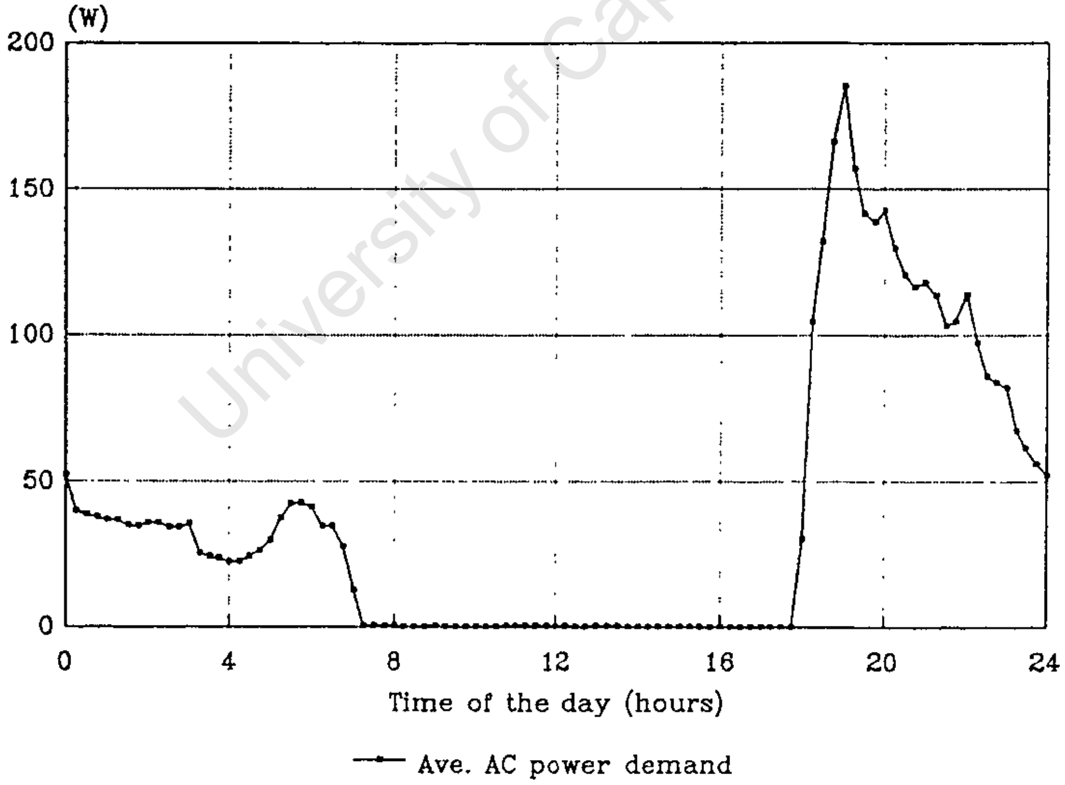


Figure 5.5 : Average load curve for Jock of the Bushveld representing AC power into the loads averaged over the log intervals

The inverter is switched on by the camp attendant at about 07h15 and switched off again at about 17h45. There is therefore no power available for approximately 10,5 hours during the day. An early morning load demand peak and a much more significant evening load demand peak are reflected in the load curve. The base load, while the inverter was on-line, of approximately 30 W, represents the power demand of two lights switched on throughout the night.

The average load power demand for the monitoring period was 87 W. This corresponds to a continuous load of five lights.

The maximum recorded average load demand over one logging interval was 357 W, averaged between 18h20 and 18h40 on 05/10/87, corresponding to an equivalent load of twenty-one of the twenty-four lights installed.

The average load factor for the logging period was 0,24.

5.2.1.3 System component performance

5.2.1.3.1 Inverter

The function of the inverter in the system is to supply a 220 V 50 Hz alternating current to the mercury vapour and fluorescent lights from a 36 V (nominal) lead acid storage battery (ie. DC supply). The light fittings require AC current to operate.

The 3000 W square wave static inverter is vastly oversized, being rated 614% greater than the required rating of 420 W for the maximum 420 W continuous AC load power demand. No oversizing is required to meet startup peak loads because the lights are unlikely to all be switched on simultaneously.

The implications of this poor match, ie. average efficiency of 45%, of what is possibly the most crucial component in an AC PV system, are an unnecessarily large array, voltage regulator and battery bank.

Figure 5.6 illustrates the relationship between the efficiency of the inverter as function of the AC power demand. Figure 5.7 shows DC power input to the inverter as function of AC power demand on the output. In both graphs the more scattered square data plots correspond to efficiencies calculated from the fourteen day monitoring period. The triangular points relate to a specific inverter efficiency test conducted on 05/10/87 and correspond to sequential increases of the AC load by switching the lights in each of the huts.

The inverter efficiency increases from 0% to approximately 75% as the AC power demand increases from zero to 370 W. The manufacturer's claimed efficiency for this particular square wave inverter is of the order of 90%. Based on the linear regression of the data in Figure 5.7, the efficiency at the full rated capacity of 3 kW would be 93%.

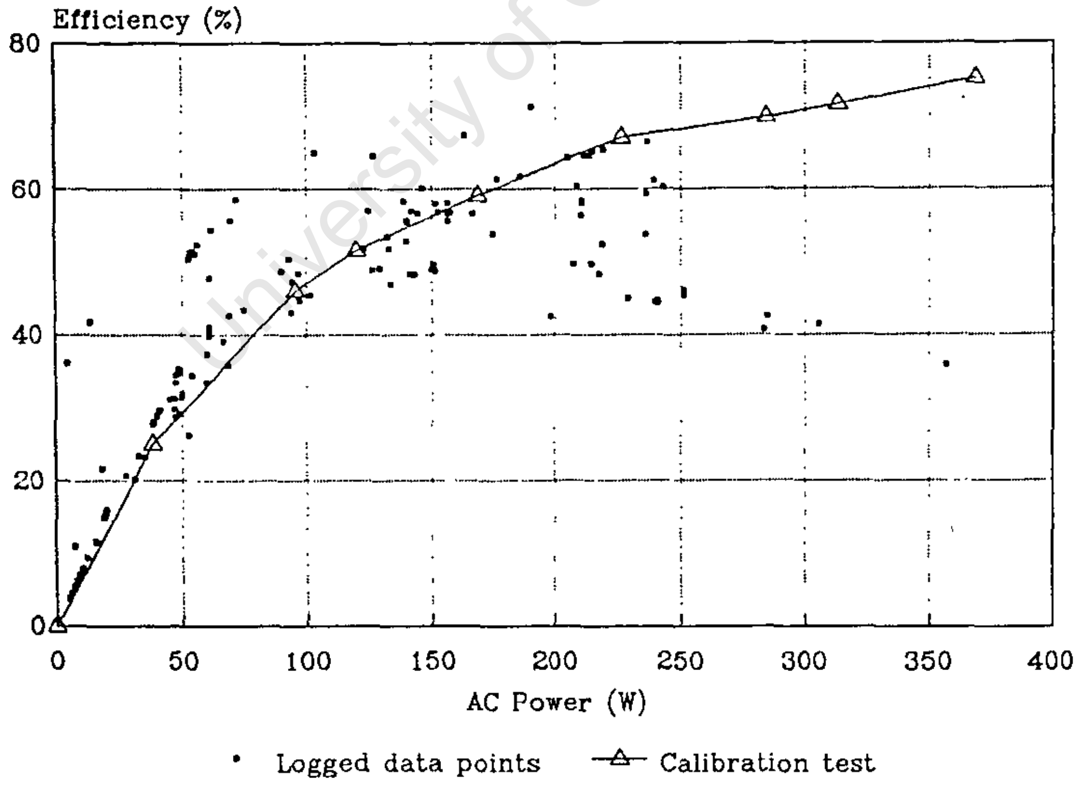


Figure 5.6 : Graph of efficiency as a function of AC power demand for the 3 kW square-wave inverter at Jock of the Bushveld

The scatter of data points recorded for AC power outputs in excess of 200 W, which fall below the calibration test curve, are judged to be a function of the unreliability of the AC power measurement channel of the data logging system. The calibration test curve is typical of the efficiency characteristic of square-wave inverters.

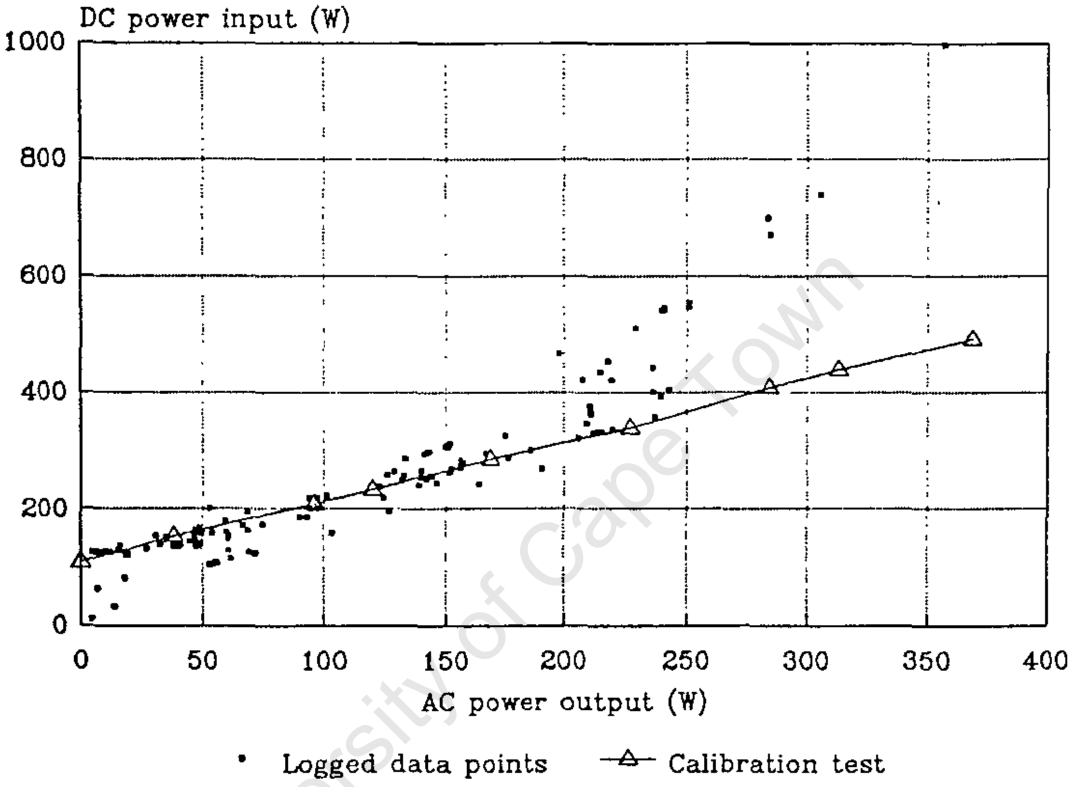


Figure 5.7 : Graph of DC power input as a function of AC power demand on the output of the Jock of the Bushveld 3 kVA square-wave inverter

The DC power requirement of the inverter is plotted as the dependent variable so as to emphasize the DC power required from the PV array and storage battery for a given AC load on the inverter.

The idling loss at no load is approximately 110 W. For AC power outputs of less than 200 W, the relationship between the AC output and the DC power input is approximated by the linear relation :

$$P_{DC} = 1{,}037\ P_{AC} + 109 \text{ Watts}$$

The measured average AC load power demand of 87 W corresponds to a DC power input of approximately 200 W and an inverter efficiency of approximately 44%, which is slightly less than the calculated average inverter efficiency of 45%.

The wave forms of AC current and voltage on the output of the inverter for a load of approximately 250 W are shown in Appendix F.1.

The power factor of the inverter under this load was approximately 0,9.

Power surge capability, voltage regulation, frequency regulation and harmonic distortion were not evaluated because these refinements are not as crucial as sizing and efficiency for the application of lighting. The harmonic distortion for square-wave inverters is approximately 40% and this would lead to unacceptable heat rise in AC motors. This is not an issue for this load requirement.

Load sensing inverter control reduces the average daily load energy demand by switching the inverter off during periods of no load and thereby eliminating the no-load loss of 110 W.

The final voltage cut-out function of the inverter appears not to have limited the battery discharge at any stage during the monitoring period. The manufacturer's specification for the minimum voltage protection setting is 34 V. The exact setting for this function was not investigated beyond the observation that voltage under discharge dropped as low as 31,8 V (1,77 V/cell) for an AC load on the inverter of 125 W, averaged over the twenty minute log interval between 20h00 and 20h30 on 13/10/87. The theoretical suggested setting would be of the order of 33,3 V (1,85 V/cell). (see Section 5.2.1.3.2)

5.2.1.3.2 Storage battery

The function of the battery in the system is to act as an electrical storage reservoir, enabling the system to both deliver power at night and compensate for successive days of overcast weather. It is the heart of an off-grid PV energy supply system.

Figure 5.8 illustrates three typical charge/discharge cycles for the battery voltage and current into and from the battery.

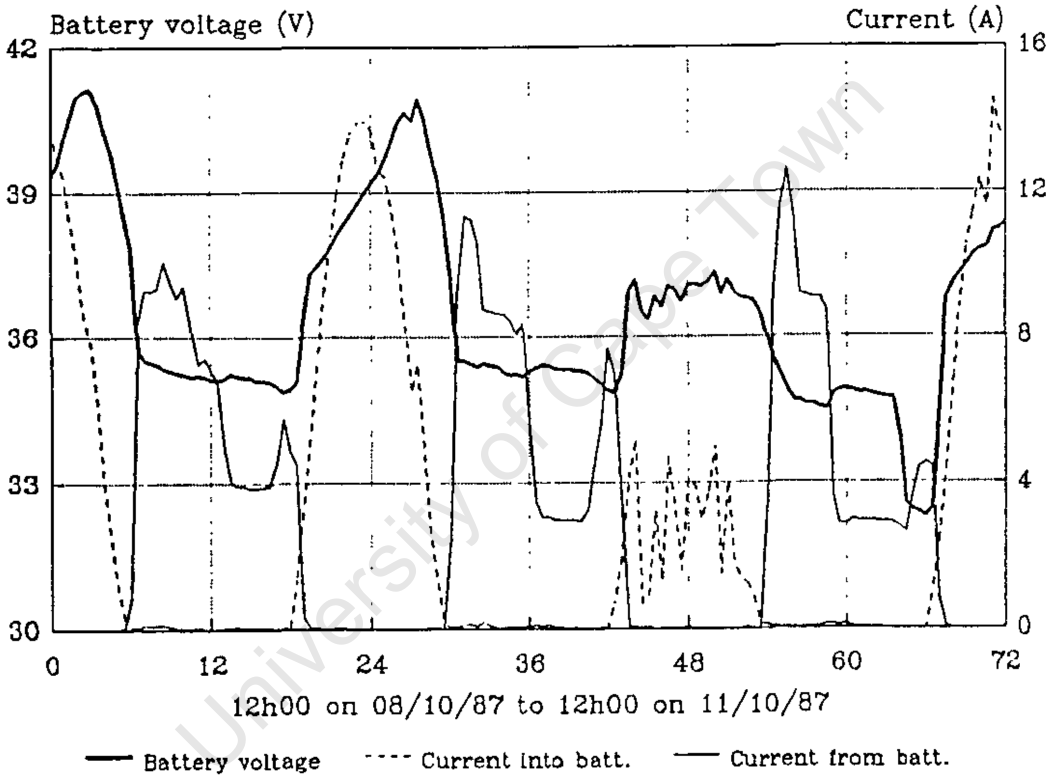


Figure 5.8 : Three typical charge/discharge cycles of the battery for the 72 hour period between noon on 08/10/87 and noon on 11/10/87

As shown in Figure 5.8 the battery is not subject to the more common constant current charge regimes for stationary lead acid battery installations and the discharge characteristics are even more erratic. The most meaningful method of analysis of batteries in a PV system would be a statistical one. The small sample of data recorded in this case precludes a rigorous statistical approach. A more qualitative analysis is adopted to evaluate the battery performance.

The batteries installed at Jock of the Bushveld are stationary type, tubular plate, 4 V lead acid batteries with lead antimony plates and synthetic rubber cases.

The short term storage for the average night-time lighting loads of 1,09 kWh is easily achieved by the nominal initial battery capacity of 590 Ah, as testified by the apparent satisfaction of the tourist users and camp attendant. The average daily depth of discharge is approximately 12% of the 590 Ah nominal initial capacity (ie. assuming no battery deterioration and consequent reduction in capacity) and the maximum daily depth of discharge was 17,4% corresponding to a 112,9 Ah discharge on 05/10/87.

The capacity of the battery is affected by physical and operating factors such as :

- rate of discharge
- practical limit of the final voltage
- temperature of the battery
- specific gravity and volume of electrolyte
- amount of active material
- design and number of plates
- age and history of the battery

The initial nominal capacity is quoted for an 8 hour discharge rate ie. 74 A for 8 hours at 20°C, an initial specific gravity of 1,250 and a final voltage of 1,75 V/cell. Under the average discharge current of 5 A (120 hr rate) and a final voltage of 1,85 V/cell, the battery capacity would be expected to be 10-15% greater than the nominal 8 hour rate. The more likely average daily depth of discharge would be approximately 10% of the initial nominal battery capacity. As noted in Section 5.2.1.3.1, the battery voltage dropped as low as 1,77 V/cell implying a dramatic irreversible loss of actual battery capacity combined with a possible reduction in charge acceptance and the consequent likelihood that the batteries do not get fully charged.

The useful life of the battery, in terms of the number of charge/discharge cycles, is a linear-log function of the depth of discharge of the battery. The useful cycle life of a battery discharged to 80% capacity is of the order of six times that of a battery discharged to 20% capacity (Komp, 1983:51). A balance must be struck between the opposing criteria of increased installed battery capacity at the expense of potential loss of capacity due to infrequent fully charged conditions and the associated sulphation of the plates. A lead acid battery is considered worthless when its capacity has fallen to about 80% of its nominal capacity rating, (Smith, 1980:40).

The average daily discharge from the battery was 69,0 Ah, equivalent to all the lights on for about 4,35 hours/day. The maximum daily discharge of 112,9 Ah on 05/10/87, corresponds to the full lighting load of 418 W switched on continuously for 7,12 hours. Figure 5.9 shows the energy into and out of the battery during the monitoring period.

On 03/10/87, 10/10/87, 12/10/87, and 13/10/87 the DC energy demand on the battery exceeded the DC energy supplied by the PV array and voltage regulator and there was a nett outflow of energy from the battery.

The nominal days of autonomy provided by the batteries is five completely overcast days with minimal insolation, based on a maximum allowable depth of discharge of 60% of the 590 Ah initial nominal capacity, the average recorded daily load energy demand of 1,09 kWh/day and the recorded average inverter efficiency of 45%.

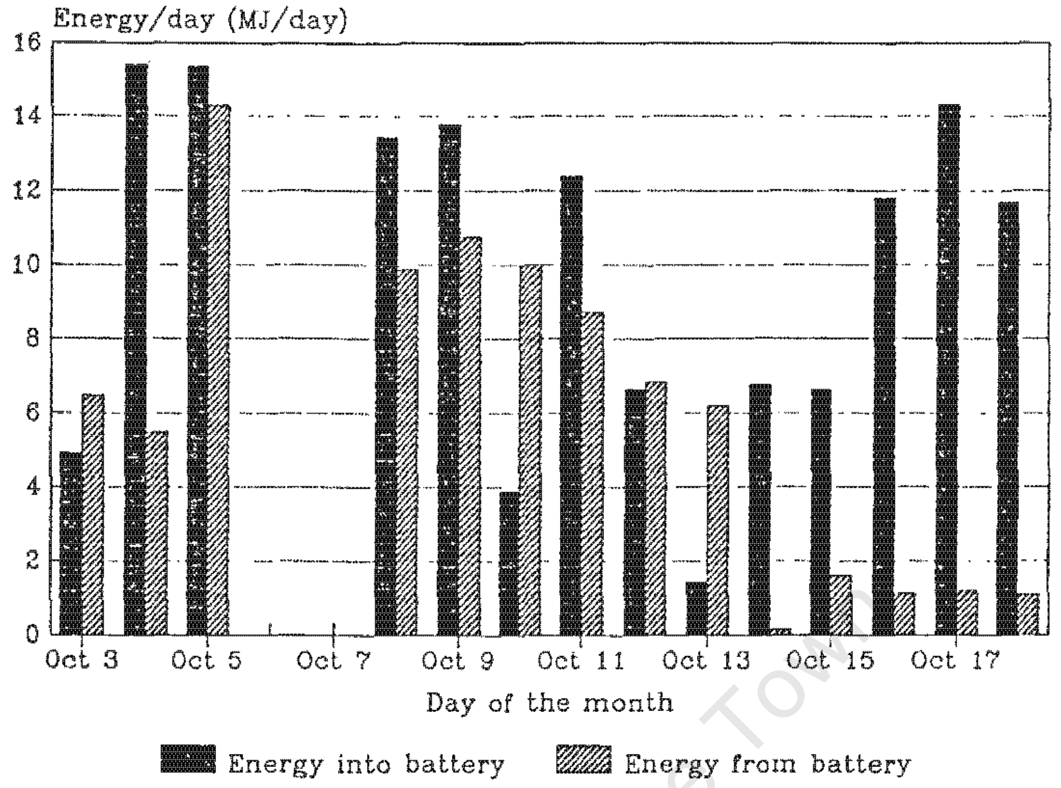


Figure 5.9 : Graph of energy into and out of the 590 Ah (nominal) battery at Jock of the Bushveld

Based on the average recorded daily PV array charge energy input of 74,3 Ah/day, the batteries would require at least 5,3 days to recover to full charge from a state of charge of 40%. The minimum charge period would be 3,7 days, corresponding to the maximum PV array output of 107,3 Ah/day. This is however, statistically unlikely to occur often.

The maximum battery voltage recorded was 41,3 V, corresponding to 2,30 V/cell, averaged over the log interval between 14h20 and 14h40 under charge on 05/10/87. The final voltage under constant current charging would be expected to be approximately 43,2 V (2,4 V/cell). The minimum battery voltage was 31,8 V (1,77 V/cell) averaged between 20h00 and 20h30 under load on 13/10/87, following four days of overcast weather. This condition is well below the suggested final voltage of 1,85 V/cell and the battery must have been practically fully discharged. As suggested earlier the under-voltage protection function of the inverter did not operate at the suggested final voltage of 33,3 V.

The average voltage under discharge was 35,2 V (1,95 V/cell) and the average voltage under charging was 37,8 V (2,10 V/cell).

The open circuit voltage of the battery at full charge would be expected to be 37,62 V, based on the initial specific gravity of 1,250. The maximum open circuit voltage recorded was 35,9 V at 06h00 on 15/10/87. The battery appeared not to have been fully charged at any stage during the monitoring period. Based on the stabilized battery voltage, (open circuit voltage), immediately before dawn on nights when there had been no discharge into the load for at least eight hours, the specific gravity was calculated according to the linear expression :

$$SG = V_{cell} - 0,84$$

where V_{cell} is the open circuit cell voltage (Smith, 1980)

On the mornings of 14/10/87 to 18/10/87 the SG hovered between 1,085 and 1,156. The SG of a discharged lead acid cell such as the Jock of the Bushveld batteries is 1,100. As suggested earlier, this implies that the batteries were practically exhausted despite receiving a daily average nett positive energy charge of 5,3 Ah/day. The resolution and stability of the battery voltage data logging channel was not high enough to allow a determination of the absolute state of charge for comparison between successive days of nett energy input. No record of the SG was available to trace long term changes in the condition of the cells.

The ampere-hour efficiency of the batteries was 72% and the watt-hour efficiency was 66%. The latter is an energy related efficiency which is relevant in the overall efficiency of an off-grid energy system. These efficiencies were calculated on the basis of the quotient of the nett Ah, or nett energy, out over the nett Ah, or nett energy, in over the monitoring period. The efficiency calculation should ideally be based on an interval between two instants of equal state of charge of the battery. In this case the interval was selected between two instants when the open circuit voltage before dawn were judged to be equal.

These efficiencies are low compared to the Ah efficiency of approximately 90% and Wh efficiency of 75-80% quoted for lead acid batteries by manufacturers and standard texts, (Willard:26; Vinal:334; Smith:46).

The batteries were clearly not accepting charge and they are most likely to have permanently lost much of their initial capacity.

Over-discharging, infrequent battery maintenance and particularly the lack of any evidence of equalizing charges are likely to have severely reduced the original battery capacity and consequently shortened the useful life of the batteries. In addition, the maximum charge voltage function of the voltage regulator had been bridged out allowing PV output currents in excess of the nominal trickle-charge current to cause over-heating and gassing of the battery when it approached full charge.

5.2.1.3.3 Voltage regulator

The primary function of the voltage regulator in a PV system is to prevent overcharging of the storage batteries. The most likely scenario in which overcharging is likely is under conditions of high levels of insolation and low panel temperatures. A further function would typically involve a diode to prevent discharge of the batteries during periods of low insolation and at night.

The potential for overcharging is greatest for PV installations for which the rated output of the PV array is large in relation to the battery storage capacity. In these cases the array output current could exceed the maximum trickle charge current specified for the batteries. No voltage regulation is required for PV systems for which the array output current is less than a trickle charge rating of 0,6-1,5 A per 100 Ah battery storage capacity, (Komp, 1983:47).

The 30 A 36 V voltage regulator installed at Jock of the Bushveld is approximately 40% larger than that required to handle the 792 W_p array output and the short circuit, array peak current output of 18,4 A.

The mean current through the regulator was 5,95 A, averaged over the periods during which there was a charging current. The peak current through the regulator was 16,2 A averaged over the twenty minute log interval between 11h20 and 11h40 on 04/10/87. The instantaneous peak current would not exceed the array short circuit current of 18,4 A.

The maximum voltage cut-out of the voltage regulator had been bridged out and consequently the regulator did not restrict the current into the battery during the monitoring period. The blocking diode did however appear to fulfill its function.

Neither the PV array voltage output nor the voltage drop across the regulator were monitored and therefore the efficiency of the voltage regulator is implicit in the calculated combined efficiency of the PV array and voltage regulator.

An average voltage regulator efficiency in excess of 93% would be expected for this type of device according to Müller (1988).

5.2.1.3.4 PV array

The 792 W_p PV array at Jock of the Bushveld is tilted at 32° to the horizontal on a fabricated steel support structure. The electrical output of the array is a function of :

- insolation
- cell temperature
- the impedance of the load

The electrical characteristics of a PV array are described in terms of a range of current vs. voltage curves, known as I-V curves, for a corresponding range of combinations of insolation levels and cell temperatures. The array output power is the product of the output voltage and the corresponding array current for a given insolation and cell temperature. The peak power output is found at the optimum output voltage on the knee of the I-V curve.

The short circuit current of the array is more or less proportional to the level of insolation, whereas the open circuit voltage is a logarithmic function of insolation. The power output of the array is approximately a linear function of insolation for an application with minimal load voltage variation such as at Jock of the Bushveld (and Boulders).

The short circuit current increases linearly with increased cell temperature and the open circuit voltage decreases linearly with increased cell temperature. The nett effect of increased cell temperature is an overall reduction in array power of about 0,5% per degree Celsius rise in cell temperature.

The impedance of the load determines the actual operating point of the array output by fixing the output voltage. This is an important consideration in selecting a combination of array and storage battery to optimize the system matching of these components.

Figure 5.10 shows three array I-V curves for the Jock of the Bushveld array generated by a method suggested by Singer, et al (1984). The method provides a sufficiently good fit for the measured I-V curve of a PV array using only three measurable parameters: the open circuit voltage, the short circuit current and the maximum power. In addition, based on the temperature and insolation coefficients, an I-V curve for any combination of cell temperature and insolation may be plotted. The method is particularly useful in this instance where no manufacturer's I-V curves are available for the ARCO SOLAR ASI-16-2000 modules. The curves are based on the manufacturer's specifications for the three parameters.

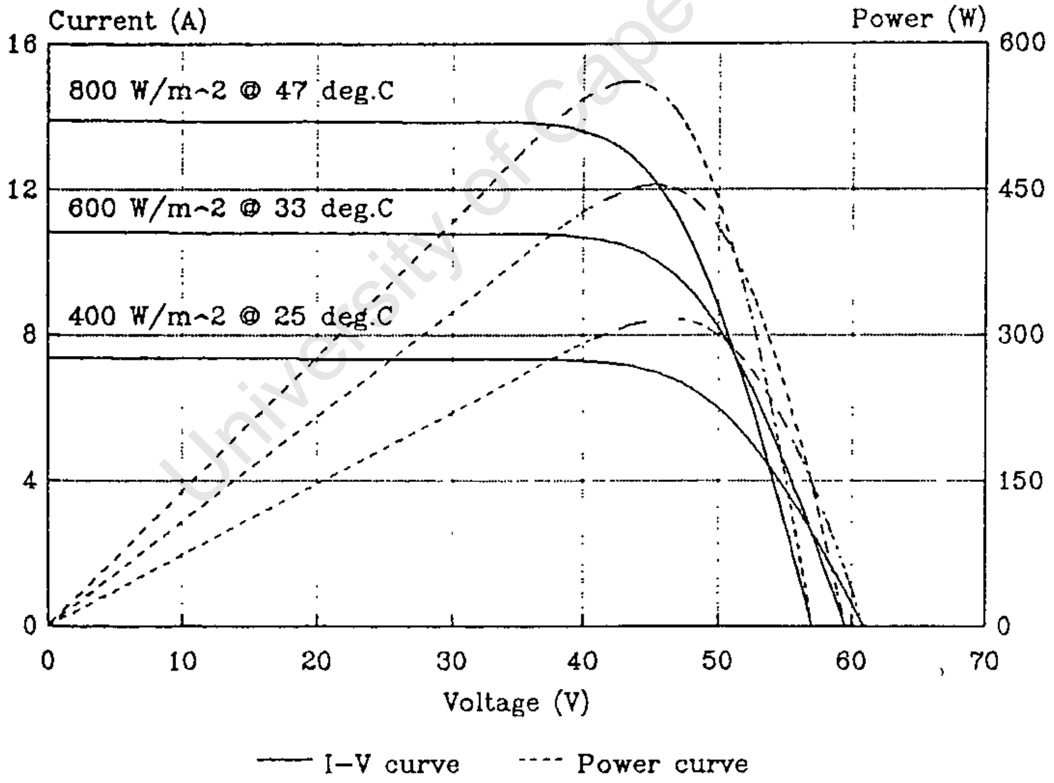


Figure 5.10 : I-V and array power curves for the Jock of the Bushveld ARCO array as generated by the method suggested by Singer et al (1984)

The three I-V curves correspond to representative operating combinations of insolation and cell temperature.

In addition the curves of array power as a function of output voltage are plotted to show the optimum output voltage for the three representative array operating conditions.

Based on these curves the optimum output voltage for the array is between 44 V, for high insolation and high cell temperature conditions, and 47 V, for low insolation and low cell temperature conditions.

Some selected comparative operating points for the predicted and measured output of the array are listed in Table 5.6.

Table 5.6 : Calculated (Singer et al) and recorded array output for Jock of the Bushveld

Time	Date	Temp.	Insol	Voltage		Amps		Power	
				Act.	Calc.	Act.	Calc.	Act.	Pred.
(00h00)		(°C)	(MJ/m^2/d)		(V)	(A)	(A)	(W)	(W)
08h40	4-Oct	33,0	723	38,4	38,4	11,2	12,9	431	495
13h40	5-Oct	46,3	976	41,2	41,1	11,7	16,3	479	671
11h00	4-Oct	44,5	1158	39,6	39,6	16,2	19,8	641	783

Discrepancies between the predicted and the recorded power are due to uncertainties in the temperature coefficients, the array degradation and, to a lesser extent, the approximations in the method.

As a measure of the systems match between the array and the battery charging load, a graph of the load curve of logged battery voltage vs. charging current is shown in Figure 5.11 superimposed on the I-V curves generated by the Singer method.

The average battery voltage, under charge, was 37,8 V (see Section 5.2.1.3.2), varying between 34,6 V and the maximum of 41,3. Assuming a voltage drop of approximately 2 V across the transmission wires to the regulator and across the regulator, the array would have been operating at the less than optimal average load voltage of 40 V, varying between 37 V and 43 V.

The main cause for the poor match between the average battery charge voltage of 37,8 V (2,10 V/cell) and the optimum PV array voltage of between 44 V and 47 V is the extent of the battery degradation. A battery in good condition would typically charge at voltages between 41,4 V (2,3 V/cell) and 43,2 V (2,4 V/cell). The corresponding array voltages would be 43-45 V assuming a voltage drop of 2 V between the array and the battery.

However, the effect of this sub-optimal array and battery systems match is a power loss of between 3% and 12%, which is relatively small.

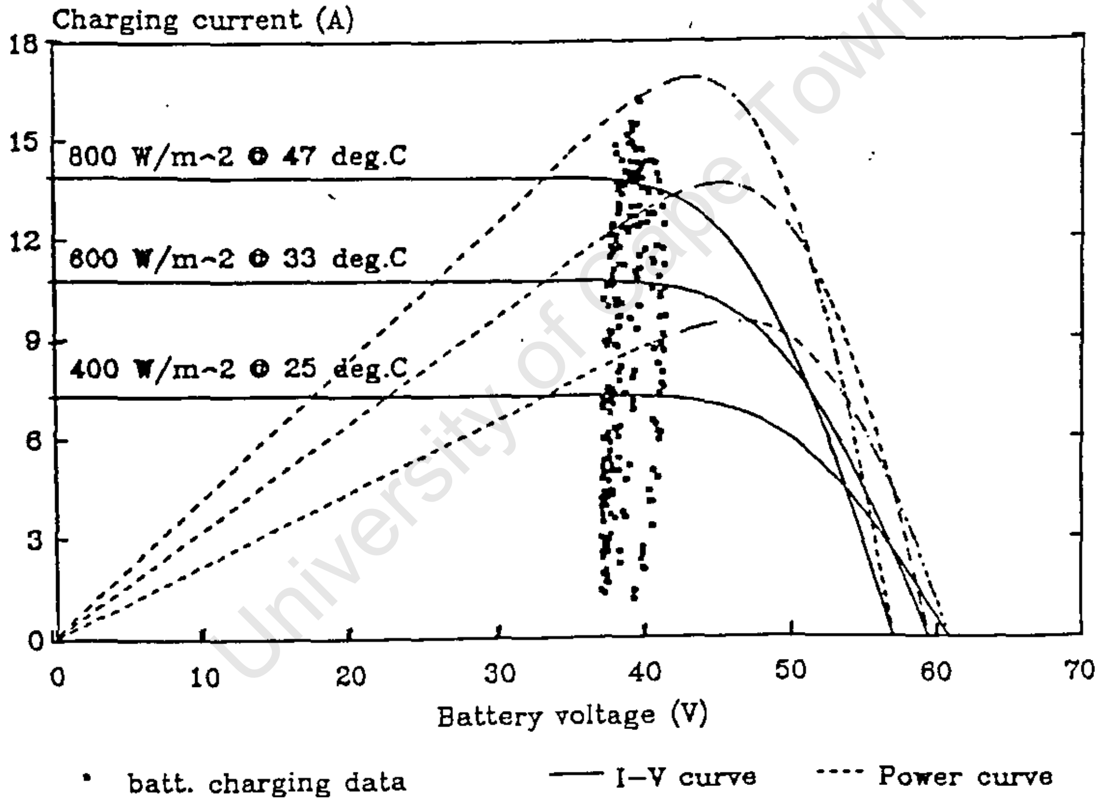


Figure 5.11 : I-V curves and load characteristic for Jock of the Bushveld battery charging as logged between the voltage regulator and battery

The maximum recorded output of the array was 640,9 W averaged over the logging interval between 11h20 and 11h40 on 04/10/87 under averaged conditions of solar radiation of 1158 W/m² and a panel temperature of 44,5°C. The predicted array output for the conditions above is 783 W.

The average combined array and voltage regulator efficiency for the logging period was 5,75%. The efficiency of the PV array is estimated to be 6,2% based on an estimated efficiency of 93% for the voltage regulator (see Section 5.2.1.3.3). The maximum daily average array efficiency was 6,9% and the minimum was 4,54%. The peak efficiency averaged over one log interval was 7,8% under conditions of 945 W/m^2 and an array temperature of 40,4°C. As expected these daily average recorded efficiencies are lower than the claimed rated efficiency of 8,97% for new ARCO ASI-16-2000 modules at standard conditions of 1000 W/m^2 and 25°C. As discussed earlier, the array efficiency is a function of cell temperature (and degradation), and therefore dependent on the ambient temperature and indirectly on the global radiation through heating. Increased temperature increases lattice vibrations in the silicon cells which interfere with the free passage of charge carriers. In addition high cell temperatures accelerate the degradation of the module output over the longer term.

Based on the particular configuration of the temperature sensors at Jock of the Bushveld, the relation between the array temperature, ambient temperature and global radiation is :

$$T_{array} = 0{,}0883\ I_{gt} + T_{amb} + 0{,}34 \qquad (r^2 = 0{,}551)$$

The logged data and a plot of the linear regression and standard deviation is shown in Figure 5.12.

The scatter in the recorded data points renders the linear regression worthless for predicting precise array temperature except to demonstrate the general trend. The scatter is a function of the measurement method which employed an ambient temperature probe that dangled beneath the array in the wind.

The maximum recorded array temperature was 47,0°C, corresponding to an ambient temperature of 34,0°C and global solar radiation of 949,4 W/m², averaged over the log interval between 12h00 and 12h30 on 08/10/87. The average array temperature over the logging period was 29,2°C.

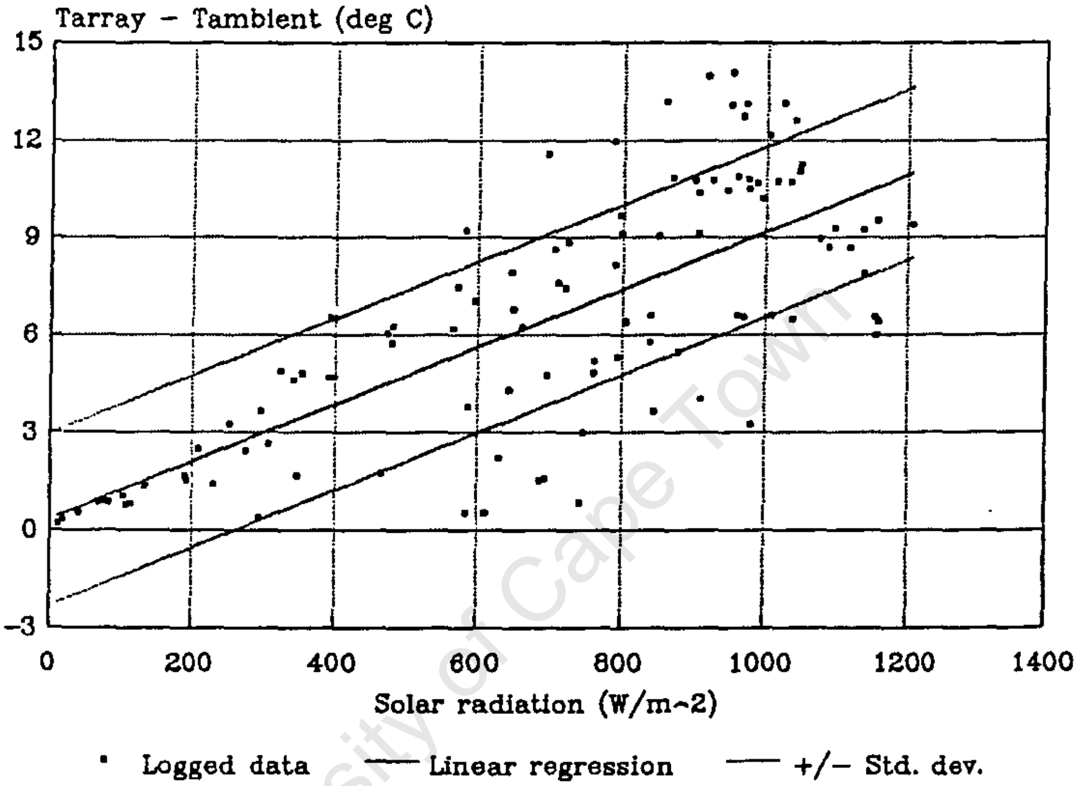


Figure 5.12 : **Array and ambient temperature data vs. global solar radiation and best fit linear regression for Jock of the Bushveld**

The combined effects of global radiation and array temperature on efficiency are shown in Figure 5.13 which shows plots of these parameters against the time of day for 08/10/87 and 10/10/87 respectively.

The negative effect of increased array temperature is illustrated by the drop of 0,4% in array efficiency corresponding to a 14,6°C increase in array temperature between 08h00 and 13h00 on a clear day. However the array efficiency is highly sensitive to low levels of global radiation as shown by the variation between 6,65% and 4,37% for fluctuation of global radiation levels between

348 W/m^2 and 71 W/m^2 over one thirty minute log interval on a cloudy day.

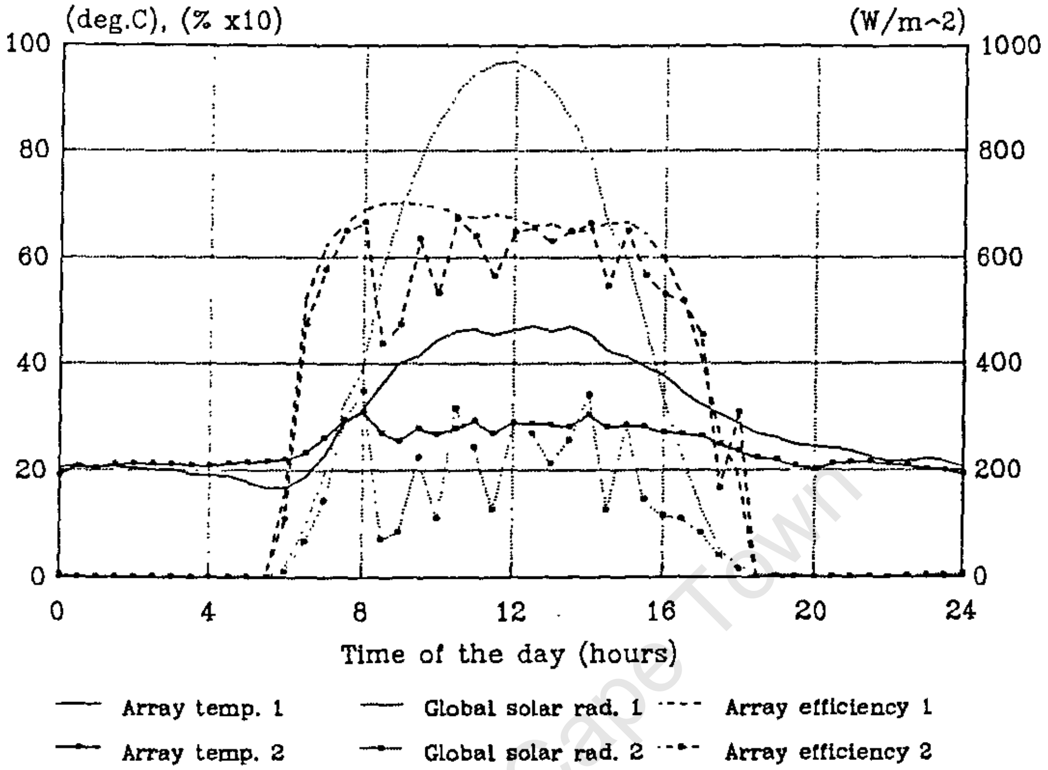


Figure 5.13 : **Graph of combined array efficiency, global radiation and panel temperature against the time of day on a clear (1) and an overcast (2) day**

5.2.1.4 System availability

No empirical data regarding the availability of the system was available. The system has apparently met the load requirements to the satisfaction of the National Parks Board. As discussed previously, this has been possible through gross oversizing of particularly the battery, which, despite apparently severe degradation, was still fulfilling the requirement.

It would appear that the only loss of availability has been due to component failures. The voltage regulator has apparently been a source of concern as indicated by the bridging out of the maximum charge voltage protection. The reasons for this modification are not clear. In addition the inverter has on occasion been repaired for unspecified failures. No failures of PV modules have occurred. In practice an inverter malfunction would cause a total loss of power whereas the modularity of the PV energy source and the designed system autonomy reduce the impact of PV module or voltage regulator failures. Degradation of the battery capacity or the PV array output over time would merely reduce the autonomy and availability of the system.

The system's night time operating regime and the camp's occupancy/vacancy ratio allows approximately ten hours per day of uninterrupted maintenance time for most of the year without noticeably reducing the system availability.

Any short term loss of supply can be met within a maximum delay of two hours by the substitution of the inverter and PV/regulator sub-system with a small portable 220 V AC petrol genset from the Skukuza or Berg-en-dal maintenance workshops.

5.2.1.5 Operation and maintenance considerations

The Jock of the Bushveld AC PV system is operated on a day to day basis by the resident camp attendant and indirectly by the tourists in the camp. The extent of the attendant's involvement is limited to switching on the inverter at dusk if the camp is occupied and switching it off again on the following morning. Any irregularities or system faults are reported to the engineering maintenance department for repair. The tourists' role is limited to their patterns of electricity consumption in terms of their lighting needs.

The maintenance of the system is limited to four site visits per year by the Johannesburg based manufacturer which supplied the system. These site visits are a contracted service to the National Parks Board charged at a flat rate of R 450 per visit.

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The maintenance of the system is limited to four site visits per year by the Johannesburg based manufacturer which supplied the system. These site visits are a contracted service to the National Parks Board charged at a flat rate of R 450 per visit.

The maintenance comprises :

- checking the electrolyte levels in the batteries
- general checks on connectors, voltage regulator and inverter

No maintenance records for battery SG are available.

Minimal administrative overheads are incurred for the O&M of the system. No processing of maintenance job cards and no accounting or storage of operating consumables and spares are required.

The maintenance of the light fittings and wiring in the camp is performed by a National Parks Board electrician based at Berg-en-dal.

5.2.2 Economic evaluation

The economic evaluation was performed as outlined in Section 4.7. The analysis was intended to evaluate the actual costs of the system to the National Parks Board.

All plant and equipment prices are January 1988 prices.

5.2.2.1 Assumptions on which the economic analysis is based

The assumptions on which the economic evaluation for the Jock of the Bushveld AC PV system is based are summarised overleaf in Table 5.7 :

Table 5.7 : Summary of assumptions for the economic evaluation of the Jock of the Bushveld AC PV system

System lifetime	20 years
Battery life	10 years
Discount rate	4 %
Escalation rate	0 %
GST	12 %
PV module costs	R 15 000 (19 R/Wp)
Voltage regulator cost	R 965 (0,82 R/W)
Battery cost	R 5 300 250 R/kWh)
Inverter cost	R 3 370 (1,12 R/W)
Residual batteries value	10 % of initial cost
Planning costs	0 % of installed system cost
Cost of land	R 0
Array support cost	R 300 (34 R/m^2 array area
Battery room cost	R 0 (70 R/kWh)
Wiring cost	R 90 (10 R/m^2 array area
Battery repl. labour cost	R 40 (2 R/kWh)
Transport to site	R 0
Installation cost	3 % of equipment cost
Commissioning cost	0% of equipment cost
Engineering fees	0 % of installed cost
Admin. infrastructure cost	200 R/year
Maint. and labour cost	1 800 R/year
Ave. daily energy output	1,15 kWh/day

Twenty years is an accepted design lifetime for PV systems based on accelerated lifetime testing of PV modules. In addition, the National Parks Board is a para-statal organization which is likely to plan for energy requirements over a longer term than the 5-10 year planning horizon of private individuals or small enterprises. In general longer system lifetimes favour high initial cost ventures such as PV energy systems.

The estimated battery life is based on a cycle life of 500 cycles and an annual total of 50 deep cycles per year.

A real discount rate of 4% was considered reasonable for the National Parks Board, which has access to large established financial institutions. The life-cycle costs of investment projects with high initial costs are highly sensitive to the discount rate. High discount rates favour projects with high operating and maintenance costs spread over the lifetime of the investment. Discount rates of approximately 10% would be more appropriate when evaluating the cost to investors in less secure financial environments and are less favourable to projects with long term benefits.

The escalation rate is a measure of the relative escalation of energy related costs and the general price index escalation due to inflation, ie. an estimate of the projected costs of plant, equipment and O&M costs relative to the overall costs of living.

General sales tax is charged for plant and equipment.

The estimated cost of the discontinued range of ARCO ASI-16-2000 modules is R 630,00 each.

The battery cost is based on manufacturer's quoted price of R 590,00 ex factory per RAYLITE 2 IMR 4 V battery (inclusive of lead surcharge) Estimated scrap value of the batteries at the end of their useful life is 10%.

The planning was assumed to be done by the National Parks Board and these costs have been omitted. The land was assumed not to have cost the National Parks Board anything.

The estimated cost of the array support structure is for a fabricated steel array support on concrete foundations.

The cost of the 4 m^2 thatched and ventilated battery room was omitted.

The wiring cost is the estimated cost of the inter-module connection and array to battery room wiring.

The battery replacement cost is the estimated cost of removing and installing new batteries.

Estimated cost of installation is based on the initial equipment cost inclusive of GST.

Estimated cost of commissioning would be based on the initial equipment cost inclusive of GST. No commissioning costs were included.

Estimated cost of professional fees for engineering design and project management would similarly be based on the total installed project cost. No such fees were incurred for a small project such as Jock of the Bushveld.

The administrative infrastructure costs are the estimated costs of administrative overheads for the system. (see Section 5.2.1.5)

The estimated annual O&M cost is based on four quarterly site visits by the system supplier at R 450,00 per visit. No cost has been included for the camp attendant's role in operating the system.

The calculation of the unit cost of energy is based on the estimated average daily energy output of the system. This figure is the measured average system output during the monitoring period.

5.2.2.2 Capital costs

The initial capital cost of the system is calculated as :

PV module	:	15 000,00
Array support	:	300,00
Voltage regulator	:	965,00
Batteries	:	5 300,00
Inverter	:	3 370,00
Wiring	:	90,00
Sub total	:	25 025,00
GST	:	3 000,00
Installation	:	840,00
TOTAL	:	28 870,00

5.2.2.3 Operating and maintenance costs

No. of battery replacements : 1

Battery replacement costs (NPV) : 3 250,00
Residual value of batteries (NPV) : (242,00) negative NPV

Admin. costs (NPV) : 2 720,00
Maint. and labour costs (NPV) : 24 463,00

Overall O&M costs (NPV) : 27 183,00

5.2.2.4 Lifecycle cost

Total installed cost : 28 870,00
Battery replacement cost : 3 250,00
Residual value : (242,00)
Total O&M costs : 27 183,00

NPV lifecycle cost : 59 061,00

Annualized unit energy cost : 1 035 c/kWh

The cost components of the NPV life-cycle cost evaluated over twenty years are :

Investment costs : 49 %
O&M costs : 51 %

Figure 5.14 shows the cashflow for the project over the lifetime of twenty years and the annualized unit energy cost at the end of each year.

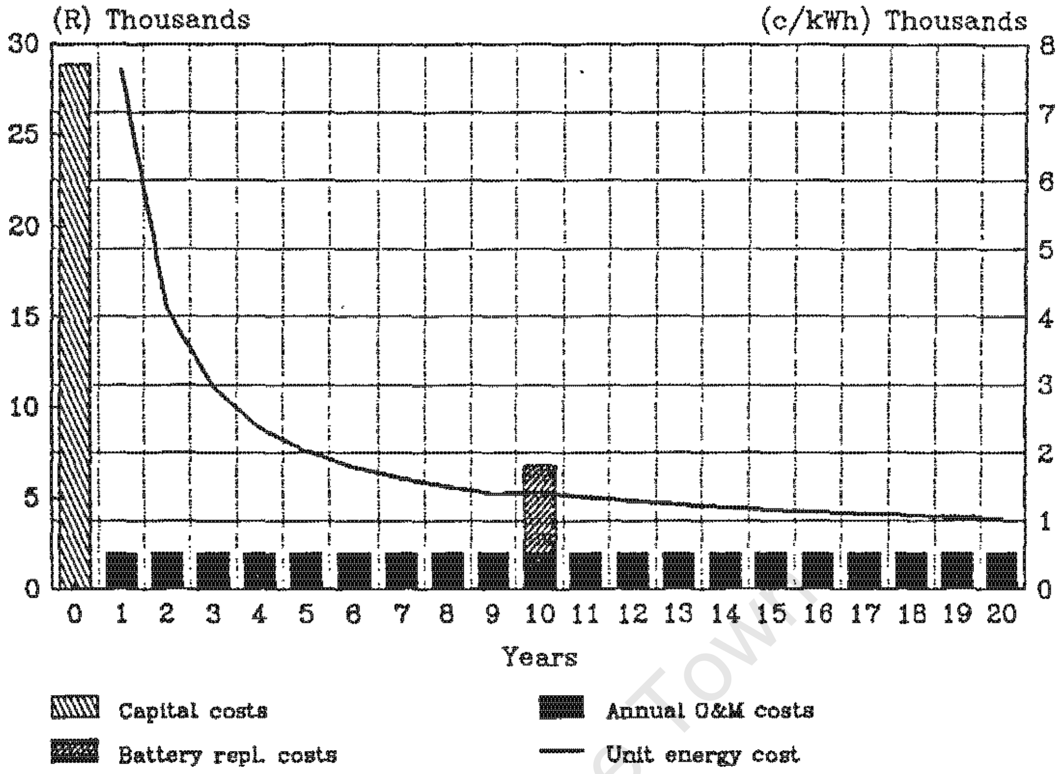

Figure 5.14 : The estimated cashflow and the estimated unit energy cost of kWh supplied for the Jock of the Bushveld AC PV system over a projected lifetime of twenty years

The graph illustrates the high initial costs of the AC PV system in year zero. The subsequent annual O&M costs for years one to twenty are relatively small. The battery replacement cost in the tenth year is the largest single operating cost during the system lifetime. The unit energy cost line represents the unit cost of electricity, calculated at the end of each year based on the total number of units generated up until that time. As expected, the unit cost of electricity generated decreases asymptotically to the limit which is the quotient of the annual O&M costs divided by the annual number of units generated, ie. 476 c/kWh. In practice the operating lifetime of the system sets the unit cost limit which in this case is 1 035 c/kWh over the twenty year lifetime.

5.2.3 Summary

The key areas of interest in the 800 W_p AC PV system at Jock of the Bushveld are the performance and interaction between the load and the inverter; and the battery, voltage regulator and array. The performance of the system as a whole as well as component performances are summarised in Table 5.8.

Table 5.8 : Summary of key indicators of the performance of the Jock of the Bushveld AC PV system

System description	36 V DC/220 V AC PV system
Array rating	792 W_p (24 off 33 W_p ARCO modules)
Voltage regulator	36 V 30 A
Battery storage	36 V 590 Ah (tubular plate)
Inverter rating	3 kW square wave
Installed load	418 W AC lighting load
Load per person	35 W/person
Peak load	357 W
Ave. load	87 W
Load factor	0,24
Ave. LED	1,15 kWh/day
LED per person	104 Wh/day
Ave. array eff.	6,2 %
Peak array eff.	7,8 %
Peak array output	641 W
Ave. array temp.	29,2 °C
Max. array temp.	47 °C
Voltage reg. eff.	93 % (assumed)
Battery Wh eff.	66 %
Ave.depth of disch.	12 %
Ave. inverter eff.	45,0 %
Overall system eff.	2,3 %
Installed cost	R 28 870,00
Batt. repl. cost	R 3 250,00
O&M costs	R 27 183,00
NPV life-cycle cost	R 59 061,00
Unit energy cost	1 035 c/kWh

The 3 kW inverter is grossly oversized for the peak installed AC load of 420 W, the average load power demand of 87 W and an average load factor of 0,24. The average lighting load corresponds to a load diversity factor of

21%. The consequences of the exceedingly poor matching between the load and the inverter are: i) an average inverter efficiency of 45%, as opposed to 80% for an appropriately selected square wave inverter; and ii) the associated increased battery capacity, PV array power and voltage regulator ratings required to compensate for the losses in the inverter. The battery under-voltage protection facility on the inverter appeared not to have been working, which would almost certainly have resulted in permanent sulphation of battery plates and loss of battery capacity due to sustained over-discharging.

The nominal battery capacity of 590 Ah is bigger than that required for the average daily inverter demand and corresponding average daily depth of discharge of 12%. The fact that the battery has performed satisfactorily despite clear indications of severe degradation, ie. Wh efficiency of 66%, is due to the oversizing of the initial 590 Ah nominal battery capacity. The accepted design Wh efficiency for lead acid batteries is 85%. Without the benefits of a physical examination and battery tests, it is suggested that these batteries were already approaching the end of their useful life. The poor condition of the batteries would have been due to a lack of under-voltage protection to prevent over-discharging, and the lack of any evidence of battery maintenance in the form of regular equalizing charges and specific gravity tests. Battery plate damage due to over-charging (and the resulting loss of electrolyte) could also have accelerated the deterioration of the cells in situations when the battery was fully charged and the voltage regulator did not limit the charge current.

The 30 A 36 V voltage regulator is 40% oversized for the maximum (short circuit), PV array current of 18,4 A. The voltage regulation function of the voltage regulator had been bridged out.

The PV array is marginally oversized for a system with inverter losses of 55%, and appears to have been performing more than adequately. Any excess in PV output is welcomed in terms of rapid charging cycles but at the expense of increased initial cost. The average array efficiency of 6,2% and peak array efficiency of 7,8% are lower than expected for newer modules. The quoted peak efficiency of the ARCO modules was 8,97% as opposed to newer technology modules with efficiencies of 11-12%.

The power losses due to mismatching of the optimum array voltage and battery voltage is a tolerable 3-12% power loss, but would be reduced if the batteries were in good condition.

The unreasonably high unit energy cost of 1 035 c/kWh is a direct result of the sub-optimal systems design, poor component sizing and lack of effective maintenance. In practice if the batteries were capable of delivering their rated capacity, the system could sustain an average daily load energy demand of approximately 1,3 kWh/day despite the inverter inefficiencies, ie. 12% greater than the recorded average on which the unit cost calculation is based.

The fact that the Jock of the Bushveld DC PV system was one of the first PV systems installed in the Kruger National Park combined with the novelty of the technology, would to some extent explain the conservative sizing of the system. The gross oversizing of the inverter is however inexplicable.

5.3 BOULDERS

The 3360 W_p, 60 V/12 V DC PV system at Boulders is evaluated in the same manner as the AC PV system at Jock of the Bushveld. The technical evaluation includes a summary of the overall technical performance and operating characteristics of the system which is followed by a discussion of the load demand and the performance of individual system components. An economic assessment in terms of overall life-cycle costs and the unit energy cost of the system as a whole concludes the evaluation of Boulders.

5.3.1 Technical evaluation

The technical evaluation of the Boulders system is restricted to technical considerations of the system up to and including the output of the battery. As noted in Section 4.1.2, the operating characteristics of the seven 60 V to 12 V DC/DC converters were not monitored by the data logging system.

5.3.1.1 Overall results and daily operating characteristics

Table 5.9 presents a summary of the technical performance of the DC PV system based on the thirty-six days of acceptable data out of the overall project period.

The 1 and 0 in the occupancy column indicate that the camp was either occupied (1) or not (0) as deduced from the logged data rather than from data supplied by the camp booking data made available by the Kruger National Park.

Table 5.9 : Overall performance of the Boulders PV DC system for the period 02/10/87 to 08/11/87

Date	Daily solar rad. MJ/m²/d	Daily energy avail. MJ/day	Daily energy in bat MJ/day	Daily energy from bat. MJ/day	Ave. panel temp. ℃	Ave. amb. temp. ℃	Array & reg. eff. %	Boost charge eff. %	Occ. pers.	Nett energy in bat MJ/day
02-Oct	7,9	257,3	21,0	33,7	17,5	19,5	8,2	8,2	12	-12,7
03-Oct	11,3	368,8	30,6	32,1	19,8	18,3	8,3	8,3	11	-1,5
04-Oct	22,0	719,0	57,7	34,0	25,9	18,7	8,0	8,0	11	23,7
05-Oct									11	
06-Oct	26,6	868,7	44,6	34,2	37,5	21,9	5,1	7,8	11	10,3
07-Oct	25,8	843,0	46,1	36,0	36,0	23,8	5,5	7,8	12	10,1
08-Oct	25,1	821,7	51,3	42,6	35,6	24,5	6,2	7,9	12	8,7
09-Oct	25,6	835,4	47,9	29,5	38,9	25,4	5,7	7,9	0	18,3
10-Oct	23,5	767,5	35,4	26,1	36,7	26,9	4,6	8,0	0	9,3
11-Oct	25,1	821,5	32,6	24,7	39,9	26,6	4,0	7,3	0	7,9
12-Oct	26,0	848,8	33,0	25,8	37,2	28,2	3,9	7,1	0	7,2
13-Oct	9,2	299,0	23,3	21,5	23,3	23,0	7,8	7,8	0	1,8
14-Oct	11,8	385,8	24,6	30,8	27,9	21,5	6,4	7,2	10	-6,2
15-Oct	16,2	530,7	42,7	37,6	28,0	22,7	8,0	8,0	10	5,0
16-Oct	19,2	626,1	42,5	33,3	26,9	21,5	6,8	7,8	10	9,3
17-Oct	27,7	905,0	41,2	35,2	32,0	21,5	4,6	7,9	10	6,0
18-Oct	23,3	762,9	41,6	31,2	34,0	21,8	5,5	7,8	1	10,5
19-Oct	27,1	886,2	42,2	32,3	32,8	22,6	4,8	7,8	1	9,9
20-Oct										
21-Oct	12,9	419,8	29,4	27,4	24,7	21,7	7,0	8,3	1	2,0
22-Oct	13,7	446,3	33,7	20,7	30,7	22,4	7,6	7,6	0	13,0
23-Oct	15,2	496,3	26,1	17,1	32,9	23,8	5,3	8,0	0	9,0
24-Oct	23,5	768,4	22,6	17,3	35,7	25,3	2,9	7,7	0	5,3
25-Oct	25,7	840,2	28,4	29,6	40,2	25,7	3,4	7,7	1	-1,1
26-Oct	24,5	801,9	43,3	39,9	34,9	26,7	5,4	7,9	1	3,4
27-Oct	8,9	291,1	23,6	33,9	25,9	23,8	8,1	8,1	1	-10,4
28-Oct	16,4	537,2	42,4	34,6	35,5	26,0	7,9	7,9	1	7,8
29-Oct	15,7	512,4	41,6	22,2	30,1	26,0	8,1	8,1	0	19,4
30-Oct	12,7	414,0	29,2	26,9	29,6	24,3	7,0	8,0	0	2,3
31-Oct	22,0	718,7	43,8	33,5	39,8	26,2	6,1	8,1	1	10,2
01-Nov	23,9	780,1	41,6	33,7	38,2	28,3	5,3	7,8	1	7,9
02-Nov	20,4	665,6	34,2	21,9	37,1	27,3	5,1	8,2	0	12,3
03-Nov	25,7	840,4	26,6	21,9	46,2	29,5	3,2	7,2	0	4,7
04-Nov	22,9	748,0	34,2	24,5	39,7	30,8	4,6	8,2	0	9,7
05-Nov	25,8	842,7	30,7	23,6	45,1	31,8	3,6	7,6	0	7,1
06-Nov	10,6	346,7	25,8	21,6	28,2	27,1	7,4	8,4	0	4,2
07-Nov	13,7	446,7	26,0	19,7	31,9	26,4	5,8	8,3	0	6,3
08-Nov	18,9	618,9	24,2	19,7	35,9	27,2	3,9	8,2	0	4,5
Ave.	19,6	641,2	35,1	28,6	33,1	24,7	5,9	7,9		6,5
S dev.	6,2	201,0	9,2	6,6	6,5	3,2	1,6	0,3		7,1
Max.	27,7	905,0	57,7	42,6	46,2	31,8	8,3	8,4		23,7
Min.	7,9	257,3	21,0	17,1	17,5	18,3	2,9	7,1		-12,7

Similarly, as for Jock of the Bushveld, the array and regulator efficiency refers to the average combined efficiency of these components for each day. The boost charge efficiency is the average combined efficiency of the array and regulator for periods during which the battery voltage was less than the maximum charging voltage cut-out setting of 69 V. Both efficiencies are based on the gross array area.

The overall system efficiency is approximately 3,8% based on an estimated DC/DC converter efficiency of 70%. Precise calculation of the actual efficiency was not possible because the data logging system did not monitor the voltage and current characteristics across the seven 60 V to 12 V DC/DC converters.

Four typical daily operating regimes that illustrate the daily operating characteristics of the system are shown in Figures 5.15, 5.16, 5.17 and 5.18. They are : 09/10/87, a clear day following a night during which the camp was occupied; 11/10/87, a clear day following a night during which the camp remained unoccupied; 28/10/87, a cloudy day following a night of occupancy of the camp and 07/11/87, a cloudy day following a night during which the camp remained unoccupied.

The system performance for these days is presented in Tables 5.10, 5.11, 5.12 and 5.13. The "overall" column refers to the performance over twenty-four hours per day, whereas the "boost" column refers to that portion of the day during which the voltage regulator did not restrict the PV array current output.

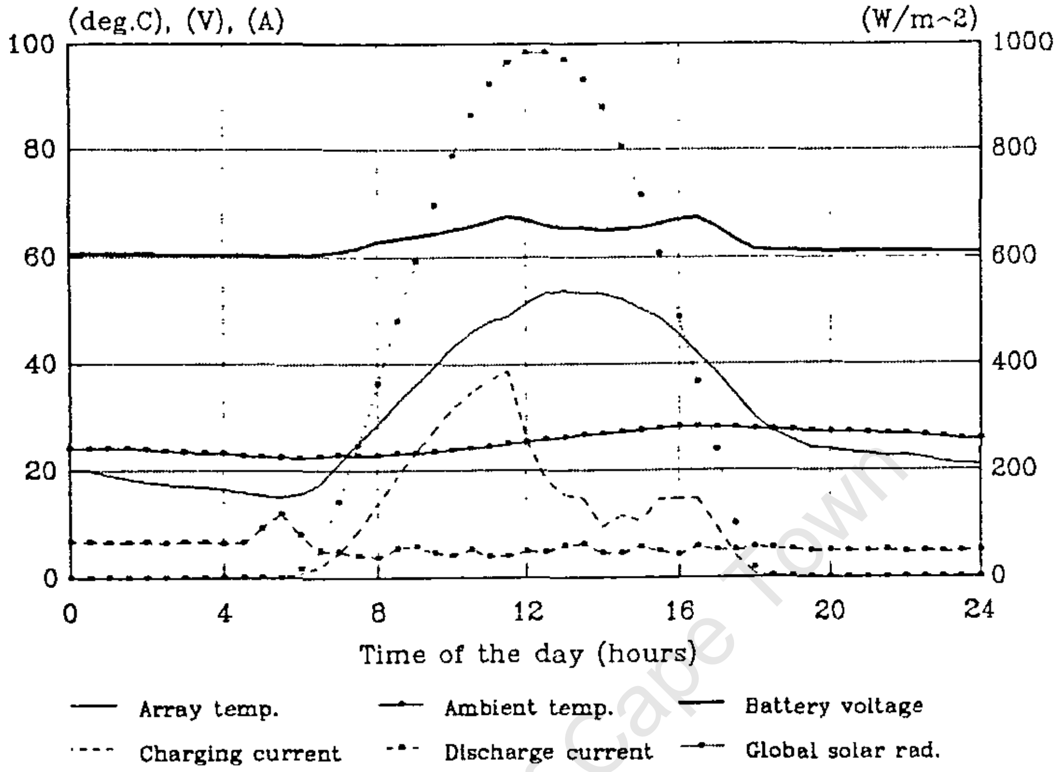

Figure 5.15 : **Daily operating characteristics for the Boulders DC PV system for a clear day and an occupied camp, 09/10/87**

Table 5.10 : **Summary of Boulders DC PV system performance for a clear day with the camp occupied**

Date : 09/10/87	Overall	Boost mode
Daily solar radiation :	25,6	12,3 MJ/m^2/day
Daily energy available :	835,4	402,4 MJ/day
Daily energy into batt. :	47,9	31,7 MJ/day
Daily energy from batt. :	29,5 MJ/day	
Ave. daytime panel temp. :	38,9 °C	
Ave. daytime ambient temp.:	25,4 °C	
Ave. DC/DC power demand :	341,8 W	
Ave. nighttime voltage :	60,9 V	
Ave. charge voltage :	65,1 V	
Ave. array & charger eff. :	5,7 %	7,9 %

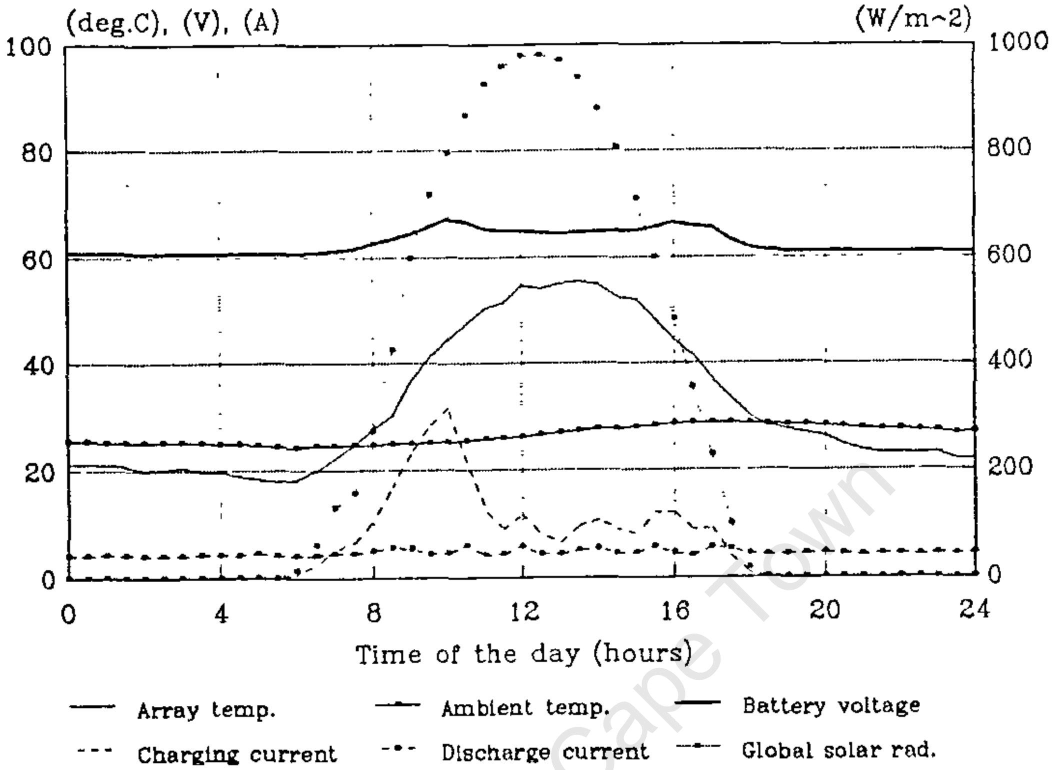

Figure 5.16 : Daily operating characteristics for the Boulders DC PV system for a clear day and an unoccupied camp, 11/10/87

Table 5.11 : Summary of Boulders DC PV system performance for a clear day with the camp occupied

Date : 11/10/87		Overall	Boost mode
Daily solar radiation	:	25,1	7,9 MJ/m²/day
Daily energy available	:	821,5	256,4 MJ/day
Daily energy into batt.	:	32,6	18,8 MJ/day
Daily energy from batt.	:	24,7 MJ/day	
Ave. daytime panel temp.	:	39,9 °C	
Ave. daytime ambient temp.	:	26,6 °C	
Ave. DC/DC power demand	:	286,2 W	
Ave. night time voltage	:	61,0 V	
Ave. charge voltage	:	64,6 V	
Ave. array & charger eff.	:	4,0 %	7,3 %

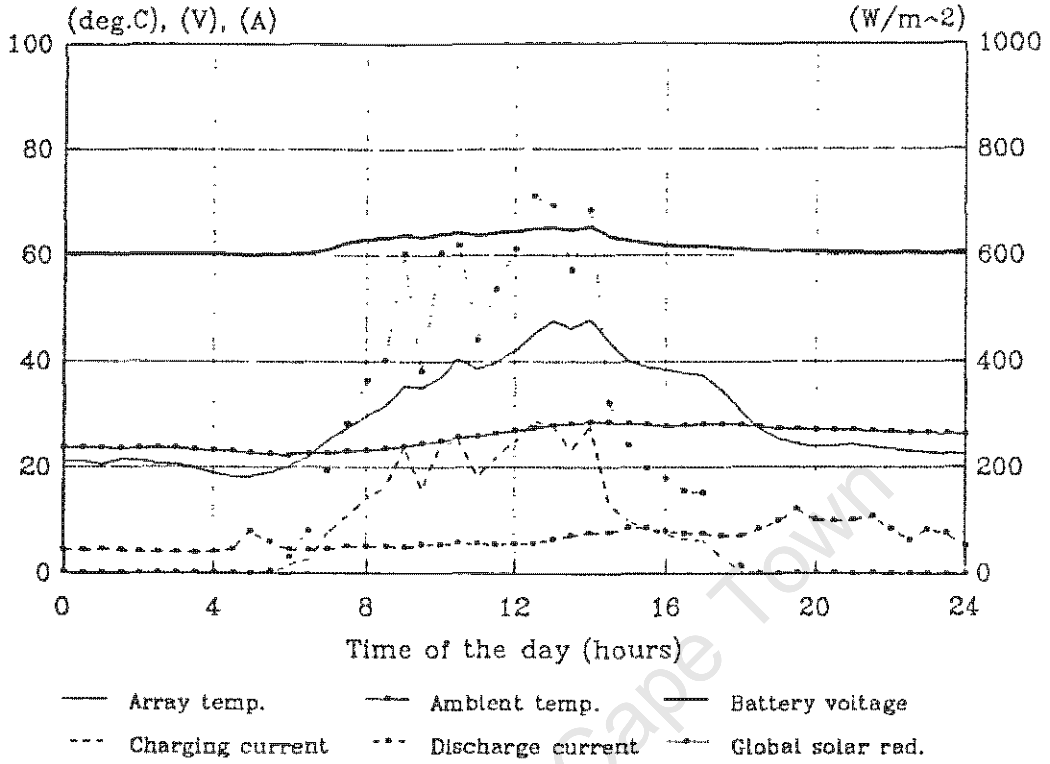

Figure 5.17 : Daily operating characteristics for the Boulders DC PV system for an overcast day and an occupied camp, 28/10/87

Table 5.12 : Summary of Boulders DC PV system performance for an overcast day with the camp occupied

Date : 28/10/87		Overall	Boost mode
Daily solar radiation	:	16,4	n/a MJ/m^2/day
Daily energy available	:	537,2	n/a MJ/day
Daily energy into batt.	:	42,4	n/a MJ/day
Daily energy from batt.	:	34,6 MJ/day	
Ave. daytime panel temp.	:	35,5 °C	
Ave. daytime ambient temp.	:	26,0 °C	
Ave. DC/DC power demand	:	400,3 W	
Ave. night time voltage	:	60,5 V	
Ave. charge voltage	:	63,2 V	
Ave. array & charger eff.	:	7,9 %	n/a

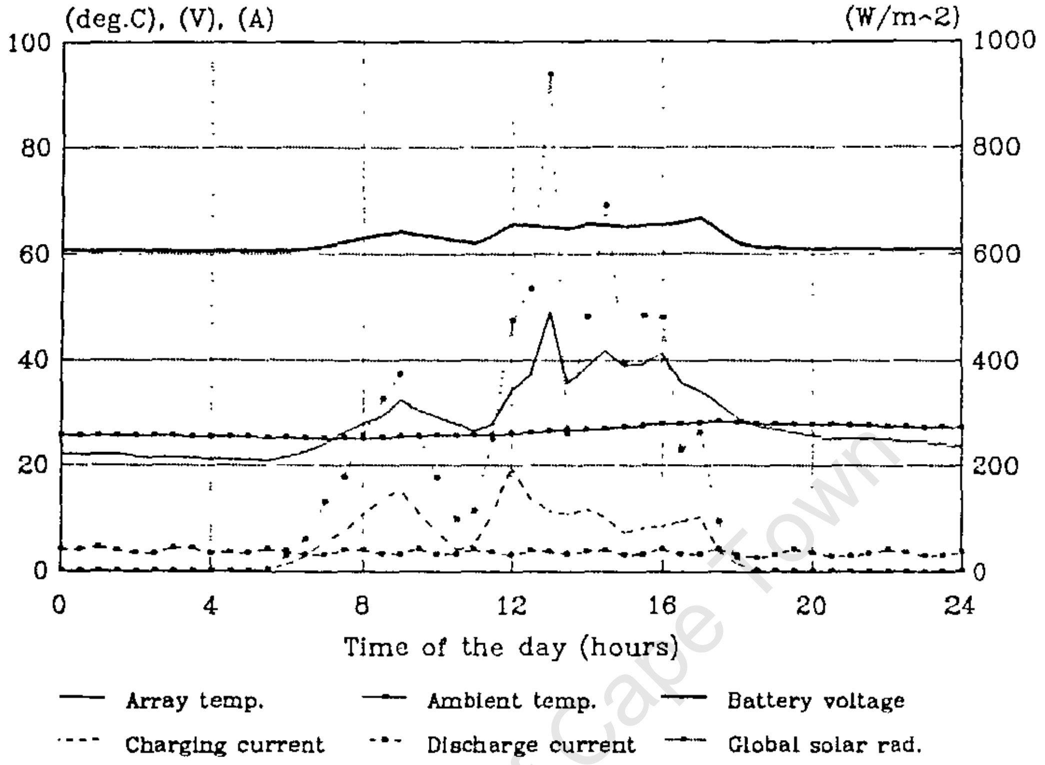

Figure 5.18 : Daily operating characteristics for the Boulders DC PV system for an overcast day and an unoccupied camp, 07/11/87

Table 5.13 : Summary of Boulders DC PV system performance for an overcast day with the camp unoccupied

Date : 07/11/87		Overall	Boost mode
Daily solar radiation	:	13,7	5,6 MJ/m²/day
Daily energy available	:	446,7	182,6 MJ/day
Daily energy into batt.	:	26,0	15,1 MJ/day
Daily energy from batt.	:	19,7 MJ/day	
Ave. daytime panel temp.	:	31,9 °C	
Ave. daytime ambient temp.	:	26,4 °C	
Ave. DC/DC power demand	:	228,3 W	
Ave. night time voltage	:	60,9 V	
Ave. charge voltage	:	64,1 V	
Ave array & charger eff.	:	5,8 %	8,3 %

Figure 5.17 is representative as one of the nine days during the logging period for which the battery voltage did not exceed the maximum charge voltage setting on the voltage regulator of 69 V. The voltage regulator did not restrict the PV array current output, and hence the DC power into the battery bank. The variations in PV charging current into the battery correspond closely to those of the recorded incident global solar radiation.

5.3.1.2 DC/DC converter energy demand and load curve

Figure 5.19 shows the average DC/DC converter power demand recorded over the thirty-six day monitoring period.

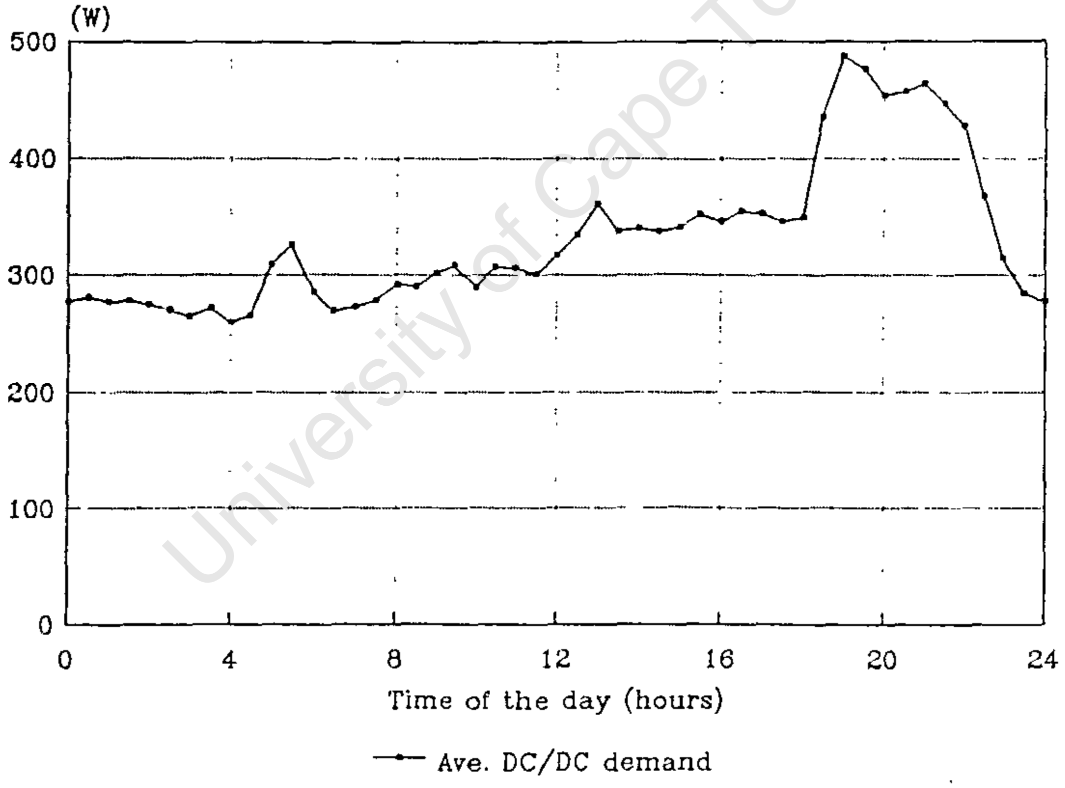

Figure 5.19 : Average DC/DC converter power demand curve for Boulders representing the DC power demand of the seven DC/DC converters averaged over the thirty minute log intervals

The DC/DC converter power demand curve shows a substantial base load throughout the day with peak power demands of up to 326 W between 04h30 and 06h00, 361 W around 13h00 and a major peak demand between 18h00 and 22h00. The average daily maximum power demand of 488 W peaked at 19h00.

The 260 W DC/DC converter base load is due to freezers, fridges and to a lesser extent fans. The variability of the load demand during the day is primarily due to the ventilation fans' installed rating of 540 W, because the lighting circuits are switched off during daylight hours by light sensitive switches in the DC/DC converters. The variable peak loads in the evening and during the night are due to fans and lighting.

Figure 5.20 shows the recorded DC/DC converter power demand plotted in terms of the power demand sorted in ascending order vs. the number of data points recorded as a percentage. The power demand averaged over the thirty minute log intervals is less than 400 W for 80% of the monitoring period.

The average daily DC/DC converter power demand was 332 W.

The peak DC/DC converter power demand averaged over a log interval was 898 W between 18h30 and 19h00 on 15/10/87 corresponding to a DC/DC converter load factor of 0,37.

The overall average daily DC/DC converter load energy demand was 7,95 kWh/day. The average load energy demand while the camp was occupied was 9,44 kWh/day. The maximum daily DC/DC converter load energy demand of 11,84 kWh/day occurred on 26/10/87. The average DC/DC converter load energy demand while the camp was vacant was 6,28 kWh/day.

The system design specification was for an average daily DC/DC converter load energy demand of 165 Ah/day or approximately 10 kWh/day, ie. load energy demand for the lights, fans, refrigerators and freezers of approximately 7 kWh/day.

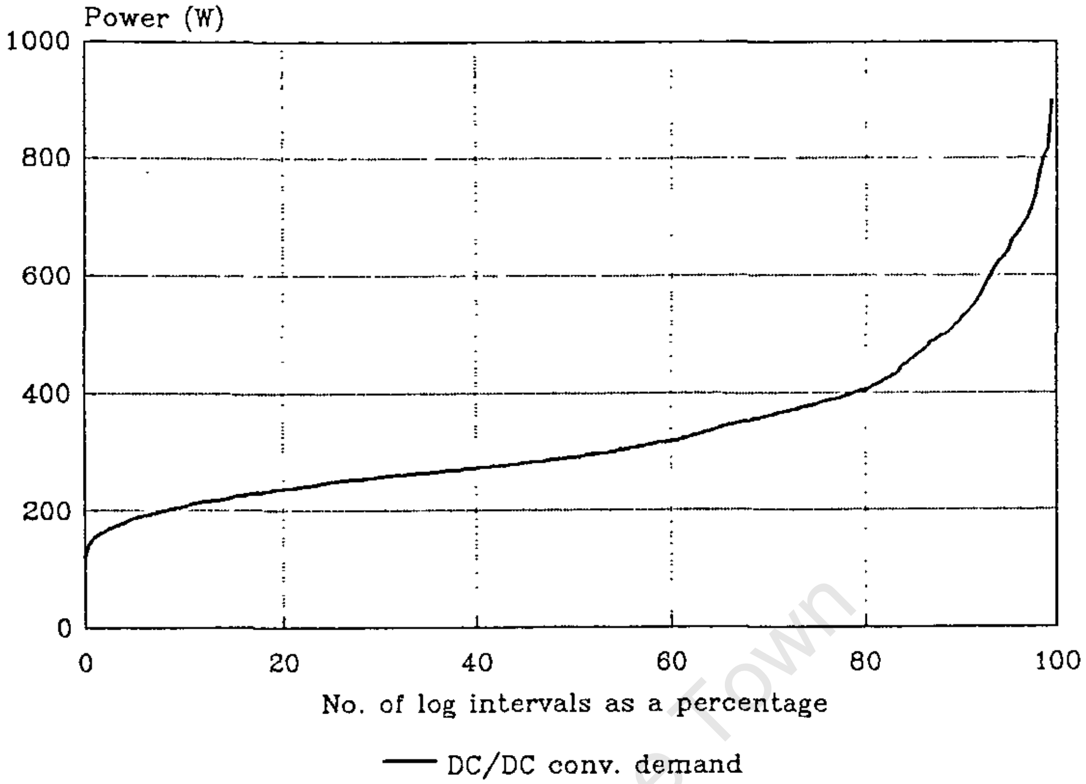

Figure 5.20 : Recorded DC/DC converter power demand sorted into ascending order vs. the no. of log intervals as a percentage of the monitoring period

Based on the daily log maintained by the camp attendant over the fifteen month period between 23/10/85 and 31/01/87, the average daily load Ah demand of the DC/DC converters was 174,1 Ah/day. Based on the recorded average battery voltage of 62,4 V for the monitoring period, the average daily DC/DC converter energy demand was 10,86 kWh/day, varying between 4,55 kWh/day on 27/04/86, when the camp was vacant, to 17,90 kWh/day on 25/11/85 when the camp was occupied immediately after commissioning.

Table 5.14 compares the data recorded over the thirty-six day monitoring period in 1987 with the corresponding handwritten Ah data for 1986 :

Table 5.14 : Comparison of DC/DC converter daily energy demand in 1986, based on handwritten Ah data, with the recorded daily energy demand for the monitoring period in 1987

	Overall		Occupied		Vacant	
	1986	1987	1986	1987	1986	1987
Average :	10,34	7,95	14,09	9,44	6,97	6,28
Maximum :	17,34	11,84	17,34	11,84	8,17	8,20
Minimum :	5,61	4,74	10,79	7,61	5,61	4,74

* note that the Ah/day readings recorded for 1986 were all converted into kWh/day based on an average battery voltage of 62,4 V.

The average daily energy demand, based on ampere-hour readings logged in 1986 over the corresponding period, for the occupied camp are 49% higher than those recorded in 1987 during the monitoring period. The 1986 values for the unoccupied camp are 11% higher than those recorded for 1987.

The discrepancy in the values for the camp occupied is largely due to the use patterns of the tourists, whereas the differences in daily load energy demand for the unoccupied camp would be a function of the vagaries of the weather. The nation-wide cold fronts associated with the Natal floods and generally cool weather in the Eastern Transvaal during the monitoring period may have contributed to reduced refrigeration and fan loads. The effect of the assumption that the average battery voltage in 1986 was the same as that recorded in 1987 would be typically less than 1%.

Figure 5.21 illustrates the relationship between occupancy and the average monthly DC/DC converter Ah demand per day, and in addition, the variation of this average monthly demand over the above-mentioned fifteen month period.

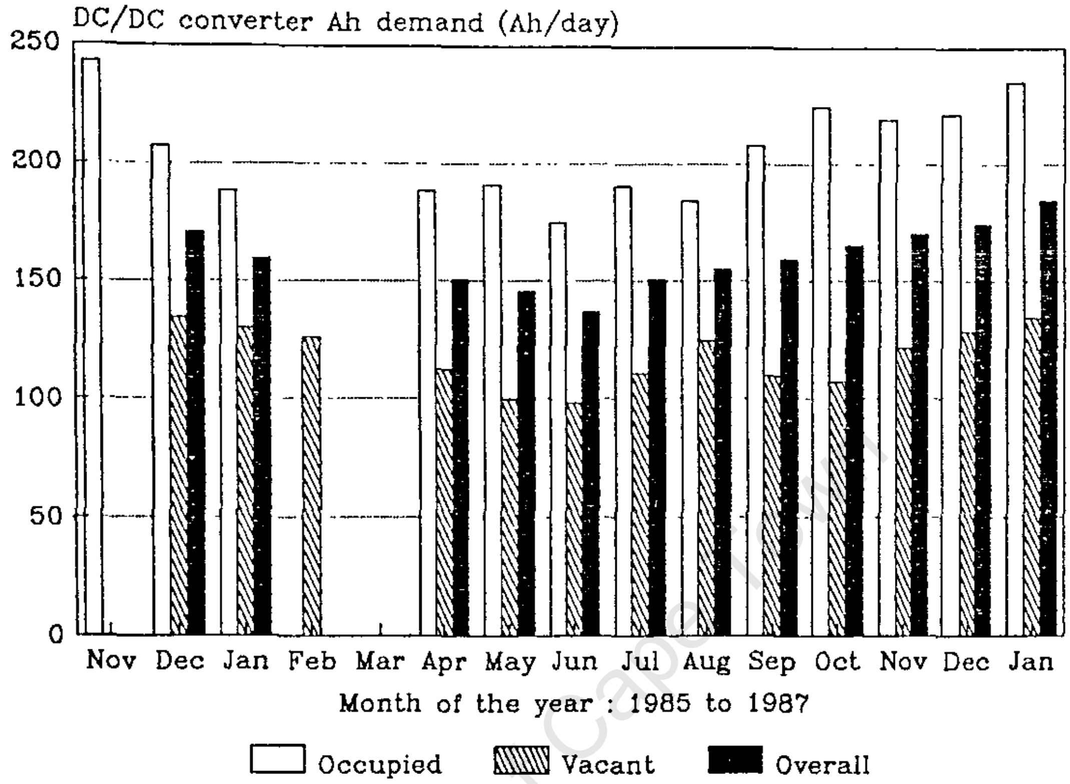

Figure 5.21 : DC/DC converter Ah demand per day for occupied and vacant camp at Boulders for the period November 1985 to January 1987

The daily energy demand is lowest in the months of May and June and highest in between October and January. The variation during the year is not dramatic because of the counter-acting effects of increased lighting load in winter due to reduced daylight hours and the simultaneous reduction of the refrigeration load due to lower ambient temperatures. The variation in the load energy demand for periods of occupancy can be seen to be proportionally greater than for periods of vacancy due to the diversity concomitant with tourists´ patterns of use of lights and fans.

5.3.1.3 System component performance

5.3.1.3.1 DC/DC converters

As noted earlier, the seven 60 V to 12 V DC/DC converters were not monitored for this project and no specific comments regarding the technical performance of the units can be made.

The DC/DC converters are low frequency square wave devices with load sensing, high and low voltage protection, fuses and a light sensitive switching facility to disconnect the lighting circuits during the day.

The maximum combined power rating of the six 20 A and one 40 A DC/DC converters is 1920 W which corresponds well to the maximum installed load power demand of 1925 W. In practice the loads are unlikely to be all on simultaneously and the units would generally incorporate some short term overload capacity.

The average DC/DC converter power demand of 332 W corresponds to 232 W actual load power demand based on the manufacturer's claimed average efficiency for the units of 70%. The peak recorded load power demand would have been approximately 628 W corresponding to a load diversity factor of 33%, ie. only 33% of the maximum installed load power demand.

The use of small dedicated units increases the overall average efficiency of the DC/DC conversion in the same manner as a single multi-stage device would.

5.3.1.3.2 Ampere-hour meter

The ampere-hour meter was similarly not monitored, except in the sense of the comparison of the daily load energy demand of the vacant camp for corresponding periods in 1986 and 1987. The daily load energy demand recorded for the vacant camp for the corresponding periods in 1986 and

1987 agree to within 11%, implying a degree of inaccuracy in the ampere-hour meter readings.

The handwritten log of the Ah/day and camp occupancy is however a valuable record of the daily load energy demand. A more useful device would, in addition, meter the incoming daily Ah of the battery charging current. The nett Ah/day is a valuable indication of the nett change in the state of charge of the battery over each day.

5.3.1.3.3 Storage battery

The lead acid battery bank in the Boulders PV system fulfills a similar energy storage function to that of the Jock of the Bushveld battery. The essential difference between the two is the fact that the Boulders battery is required to provide energy throughout the day as opposed to only at night as at Jock of the Bushveld. As at Jock of the Bushveld both the discharge and the charging currents are variable as illustrated in Figures 5.15 to 5.18.

The battery comprises thirty 2 V lead acid cells connected in series. The initial nominal battery capacity rating is quoted by the manufacturer as :

> 880 Ah to a final voltage of 1,85 V/cell @ 10 hr rate (ie. 88 A over ten hours), or
>
> 928 Ah to a final voltage of 1,75 V/cell @ 8 hr rate (ie. 116 A over eight hours)

These capacities are quoted for 25°C and an initial specific gravity of 1,250. As for Jock of the Bushveld a more likely battery capacity would be 10-15% greater than the 10 hr rate, ie. 970 Ah. In practice a battery capacity test should be conducted at the average discharge current of 5,32 A to determine the actual capacity for these batteries in this particular application.

The average daily DC/DC converter energy demand of 174 Ah, based on the fifteen month handwritten log, represents a daily depth of discharge of 18% of the initial capacity.

Based on a maximum depth of discharge of 60% the battery can provide approximately four of days of autonomy under totally overcast weather conditions.

The current drawn from the battery is approximately proportional to the DC power drawn by the DC/DC converters since the variation in battery voltage is not significant when the battery is not being charged. The discharge current is therefore a good indication of the load demand during the night.

The battery voltage rises and falls as the solar radiation varies during periods of boost mode battery charging. In boost mode the overall trend is an increase in battery voltage until the upper limit of the voltage regulator is reached. During periods of float charging the battery voltage fluctuates and during the night the voltage drops gradually as the load discharges the battery via the DC/DC converters.

Figure 5.22 shows a graph of the recorded battery voltage (and cell voltage) sorted into ascending order and plotted against the total number of log intervals as a percentage.

The recorded battery voltage for approximately 60% of the monitoring period was relatively constant. This corresponds to the night time periods during which the battery was only under discharge, ie. 14,4 hours/day. The remaining 40% of the data points reflect the variation in battery voltage under the combined effects of charge and discharge.

The average battery voltage for the monitoring period was 62,4 V with a standard deviation of 0,4 V of the daily average. The maximum battery voltage recorded during the

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The average battery voltage for the monitoring period was 62,4 V with a standard deviation of 0,4 V of the daily average. The maximum battery voltage recorded during the monitoring period was 68,2 V (2,27 V/cell) averaged under charge between 15h00 and 15h30 on 31/10/87 following two days during which the camp was vacant.

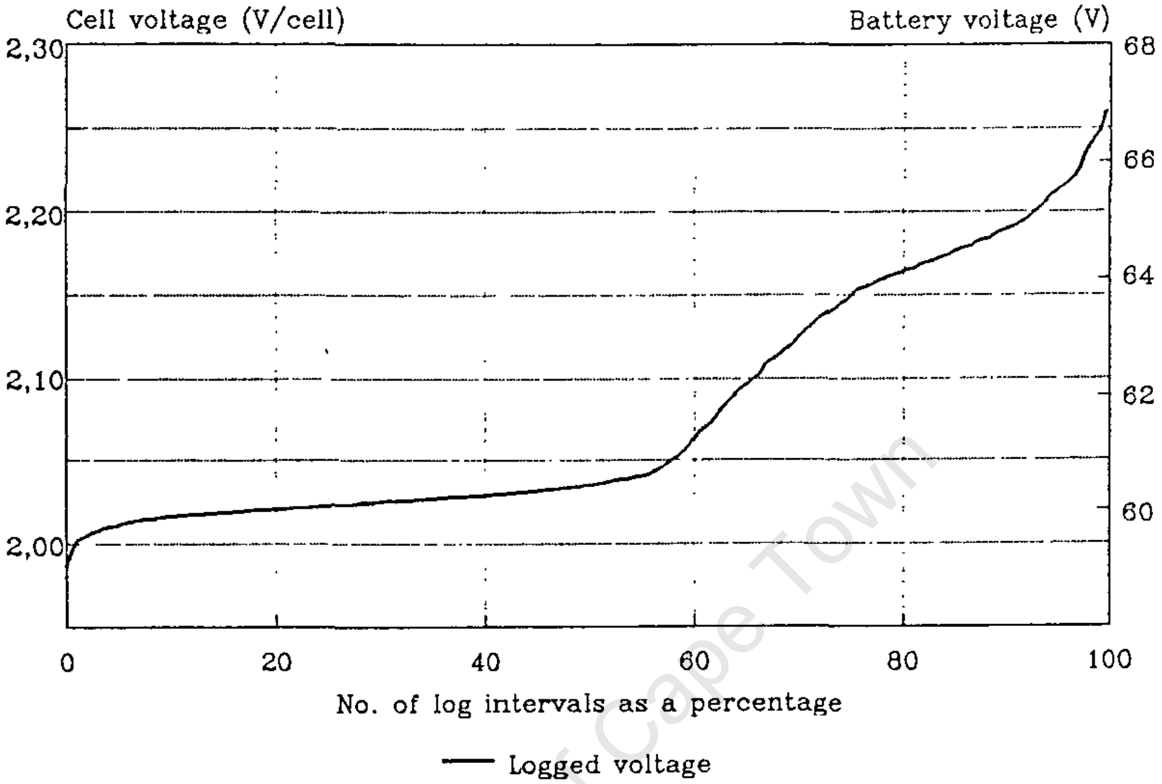

Figure 5.22 : Recorded battery voltage sorted into ascending order and plotted against the number of log intervals as a percentage

The minimum voltage was 59,5 V (1,98 V/cell) averaged for the log interval between 05h15 and 05h30 on 04/10/87 following two days of overcast weather during which the camp had been occupied by twelve tourists.

The continuous DC/DC converter power demand meant that battery voltage was not ever an open circuit voltage. Therefore no deductions could be drawn regarding the absolute state of charge of the battery at any point during the monitoring period.

Figure 5.23 shows the energy into and out of the battery during the monitoring period.

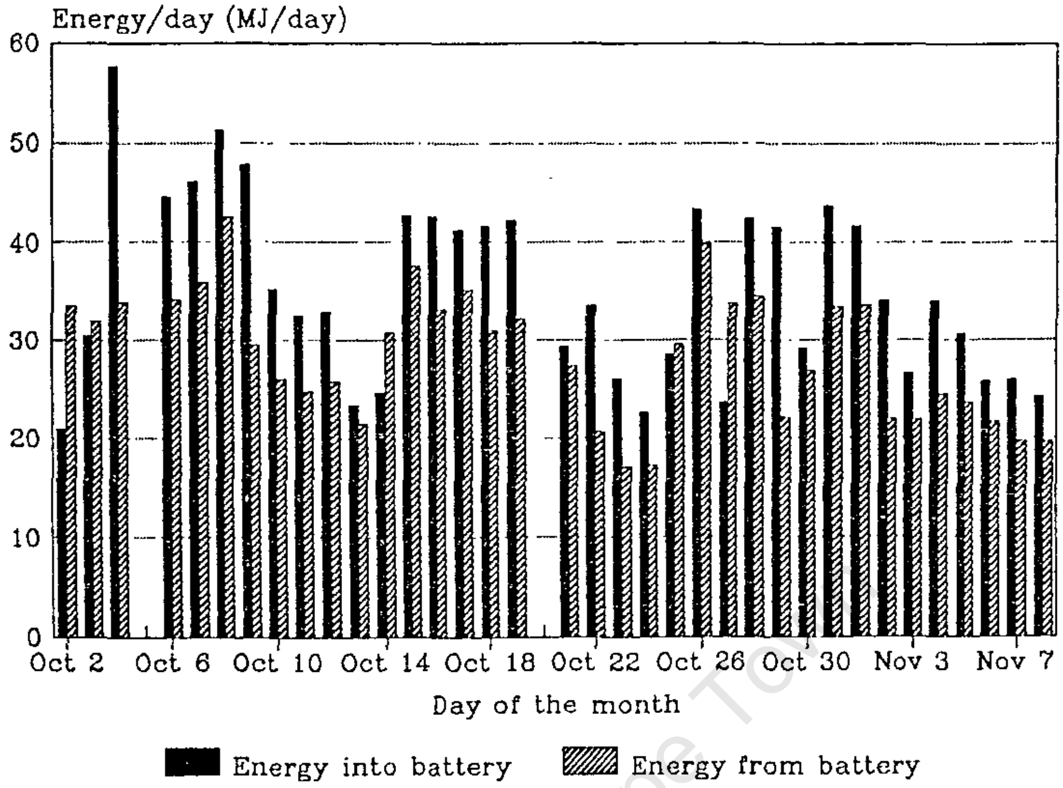

Figure 5.23 : Graph of energy into and out of the 880 Ah (nominal) battery at Boulders

A nett outflow of energy occurred over five days during the monitoring period, ie. on 02/10/87, 03/10/87, 14/10/87, 25/10/87 and 27/10/87. The energy deficits over these days varied between 1,11 MJ/day (5 Ah/day) to 12,73 MJ/day (57 Ah/day) corresponding to a depth of discharge of 1% and 10% respectively.

Based on the average recorded daily energy into the battery of 35,14 MJ/day (or 156 Ah/day), the battery would be fully charged from a 40% state of charge within four days.

The Wh efficiency of the battery evaluated over the overall monitoring period, without rigorous attention to the absolute state of charge at the beginning or end, was 81% and the Ah efficiency was 85%. These efficiencies are as high as could be expected for two year old batteries. No specific charge and discharge tests were conducted but from the recorded data the batteries appeared to be in good condition.

Although the system specification for the voltage regulator includes an over-ride facility for equalizing charges, no records or evidence of these were found. Similarly, apart from records logged during the commissioning, no records of the battery SG´s are available.

5.3.1.3.4 Voltage regulator

The 60 V 60 A voltage regulator is rated for a 7% greater power capability than the peak Array output of 3360 W_p.

The voltage regulator uses a power switching transistor and a voltage reference to switch eight relays in parallel, thereby disconnecting the battery from the array at the maximum charge voltage cut out setting. Eight blocking diodes prevent battery discharge through the panels during periods of low insolation.

The maximum charge voltage setting on the regulator was 69,5 V (2,32 V/cell). The regulator was adjusted to cut in at battery voltages below 65 V (2,17 V/cell). This hysteresis window is designed to avoid persistent "hunting" and excessive wear of the contact relays due to rapid switching of relatively high DC currents when the battery voltage rises to the maximum cut-out setting.

The equalizing charge setting on the regulator was 72 V (2,40 V/cell).

As illustrated in Figures 5.15 to 5.18, the charging current into the battery mimics the solar radiation within the bounds defined by the voltage regulator. The voltage regulator can be seen to have cut in at approximately 11h30 on 09/10/87, for a clear day when the camp was occupied, and 07/11/87 on an overcast day when the camp was vacant, and as early as 09h30 on 11/10/87, for a clear day when the camp was vacant. The charging current follows the solar radiation closely on 28/10/87, an overcast day when the camp was occupied, when the voltage regulator did not cut in.

The voltage regulator governs the overall output of the array, and hence the overall performance of the system, to match the load demand of the previous day. As shown in Figure 5.22, except for the five days during which the demand exceeded the energy supplied from the array, the excess energy in per day is approximately a consistent proportion of the total.

The maximum charging current recorded over the monitoring period was 43,6 A averaged over the log interval between 10h30 and 11h00 on 02/11/87. The average charging current over the monitoring period was 12,3 A.

The voltage regulator efficiency was not measured but would be approximately 97%, based on a voltage drop of 2 V across the diodes and relays and an average battery voltage under charge of 64 V.

5.3.1.3.5 PV array

The 3360 W_p array at Boulders comprises ninety-six 35 W_p M SETEK MS-101 modules connected in sixteen parallel sub-arrays of six modules in series. The array is mounted at 21° to the horizontal on a steel support structure on the roof of a ventilated battery room.

According to the manufacturer´s system specification, the array and voltage regulator were expected to provide "a total amperage of between thirty and forty amps for an average of six hours per day giving an average of 210 Ah/day at a nominal battery voltage of 60 V"; ie. 12,6 kWh/day. The average daily amount of energy supplied into the batteries from the array and regulator over the monitoring period was 156 Ah/day (or 10,04 kWh/day).

The peak DC power input to the battery from the array and voltage regulator during the monitoring period was 2906 W averaged between 10h30 and 11h00 on 02/11/87. The panel temperature averaged over this log interval was 47,9°C, the ambient temperature was 26,9°C and the incident solar radiation was 1102 W/m².

Figure 5.24 shows three I-V curves for the Boulders' array derived from the manufacturer's I-V curves for the M SETEK MS-101 modules. These curves represent the claimed output of the array for differing insolation levels at a constant cell temperature of 25°C. In practice the cell temperature is often in excess of 25°C and the output of the array is significantly less than might be expected.

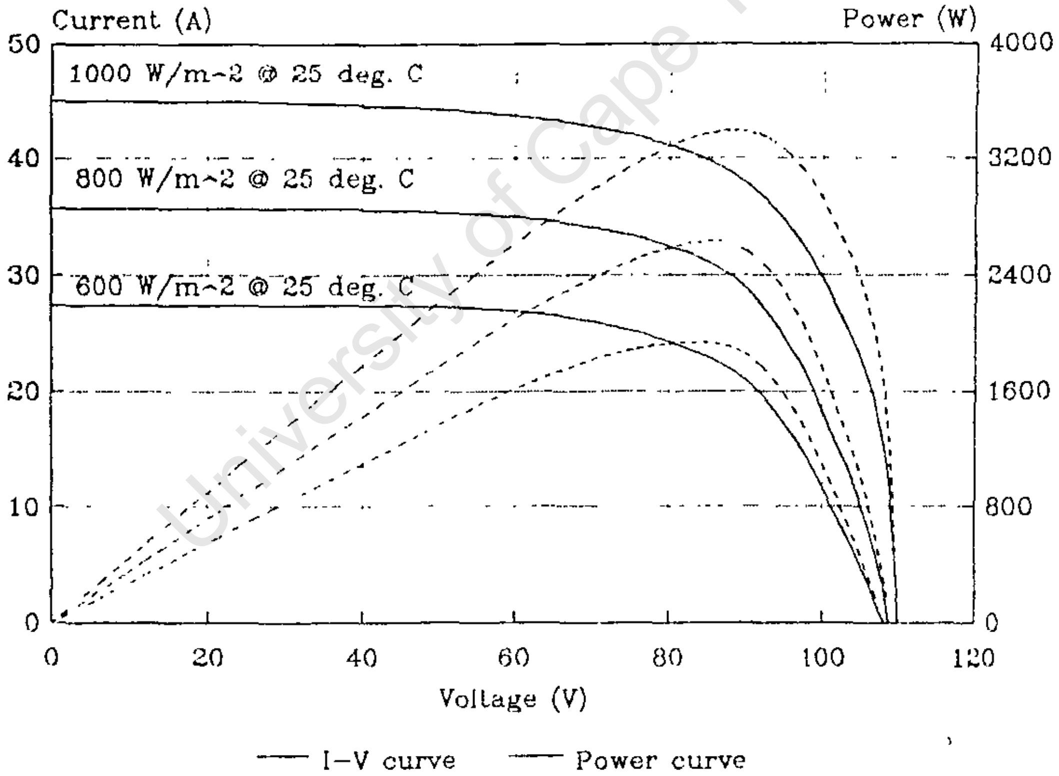

Figure 5.24 : Three I-V and array power curves for the Boulders M SETEK array as derived from the manufacturer's I-V curves

The average recorded battery charging I-V characteristic is plotted together with the array I-V curves in Figure 5.25 to gain an indication of the relative systems' match between the array and battery.

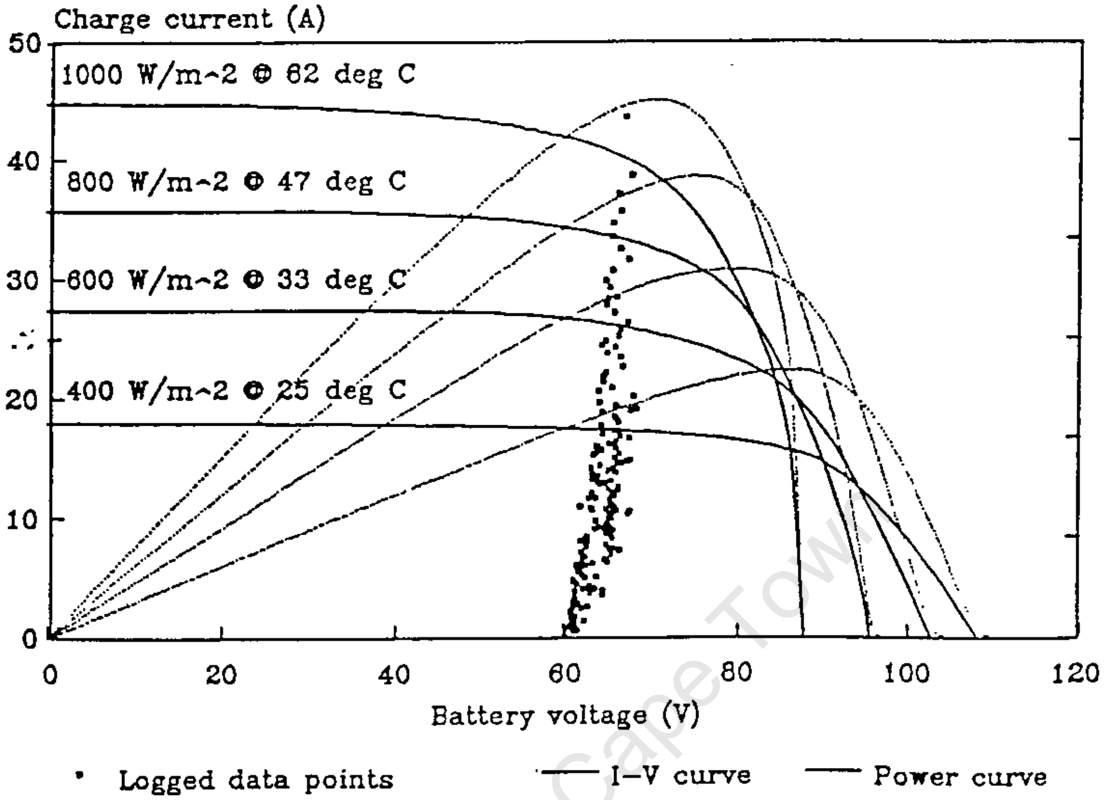

Figure 5.25 : Typical PV I-V curves and charging characteristics of the WILLARD FWA 17 batteries at Boulders

The optimum operating voltage for the array would be between 68 V (1000 W/m² @ 62°C) and 84 V (400 W/m² @ 25°C). The battery charge voltage would vary between 60 V and the maximum of 69,5 V set by the voltage regulator.

Allowing for an average combined voltage drop of 2 V across the transmission wires between the array and the battery and the voltage regulator, the array would have been operating at voltages varying between 62 V and 70 V.

The PV array optimum operating voltage and the battery charge voltage are matched best for high array temperatures. The open circuit voltage of the array, and hence the optimum operating voltage, decrease with increasing array temperature. In practice this characteristic improves the overall efficiency of the array as the bulk of the incident daily solar energy occurs over a period when the array temperature is elevated.

Power losses due to the relative mismatch of optimum operating voltages between the array and battery would vary between zero, for 1000 W/m² @ 62°C, and 330 W, or 35%, for 400 W/m² @ 25°C.

The efficiency of the array is a function of the cell and module conversion efficiencies within the array, the efficiency and operating characteristics of the voltage regulator, the panel temperature and on the load power demand in relation to the insolation.

The average combined overall array and voltage regulator efficiency over the monitoring period was 5,9% and the corresponding average efficiency for the boost mode of operation was 7,9%. The efficiency of the voltage regulator is implicit in the calculated combined efficiency for the PV array and regulator.

Based on an average voltage regulator efficiency of 95%, the average daily array efficiencies would be 6,2% and 8,3% respectively. The manufacturer´s quoted efficiency for new MS-101 modules under standard conditions of 1000 W/m² and 25°C is 9,9%.

Figures 5.26 to 5.29 illustrate the effects of global solar radiation, array temperature and the action of the voltage regulator on the combined array and voltage regulator efficiency for the four typical operating regimes discussed in Section 5.3.1.1.

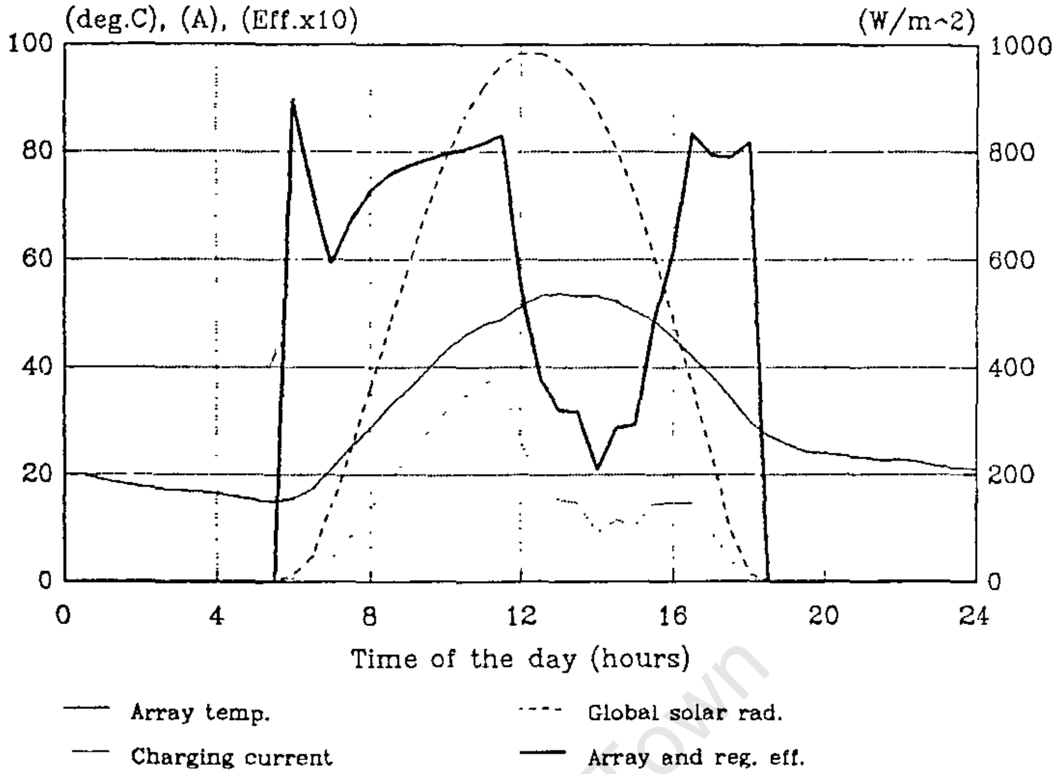

Figure 5.26 : Graph of combined array and voltage regulator efficiency as a function of global solar radiation, array temperature and voltage regulator action for a clear day with the camp occupied

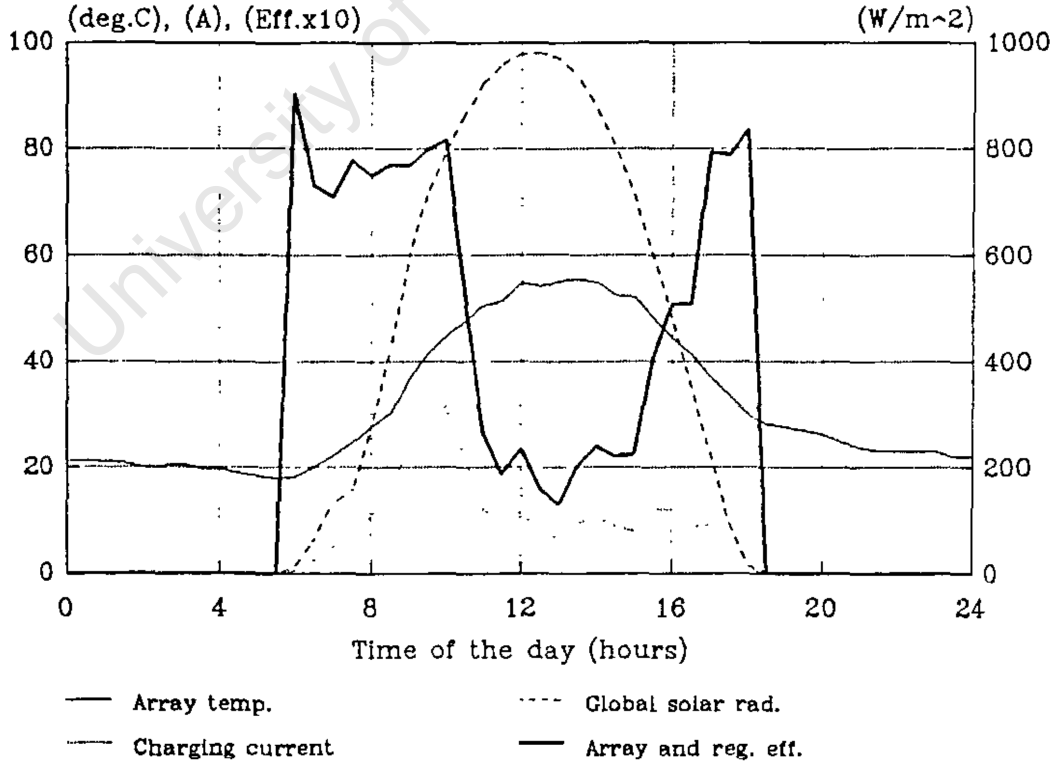

Figure 5.27 : Graph of combined array and voltage regulator efficiency as a function of global solar radiation, array temperature and voltage regulator action for a clear day with the camp vacant

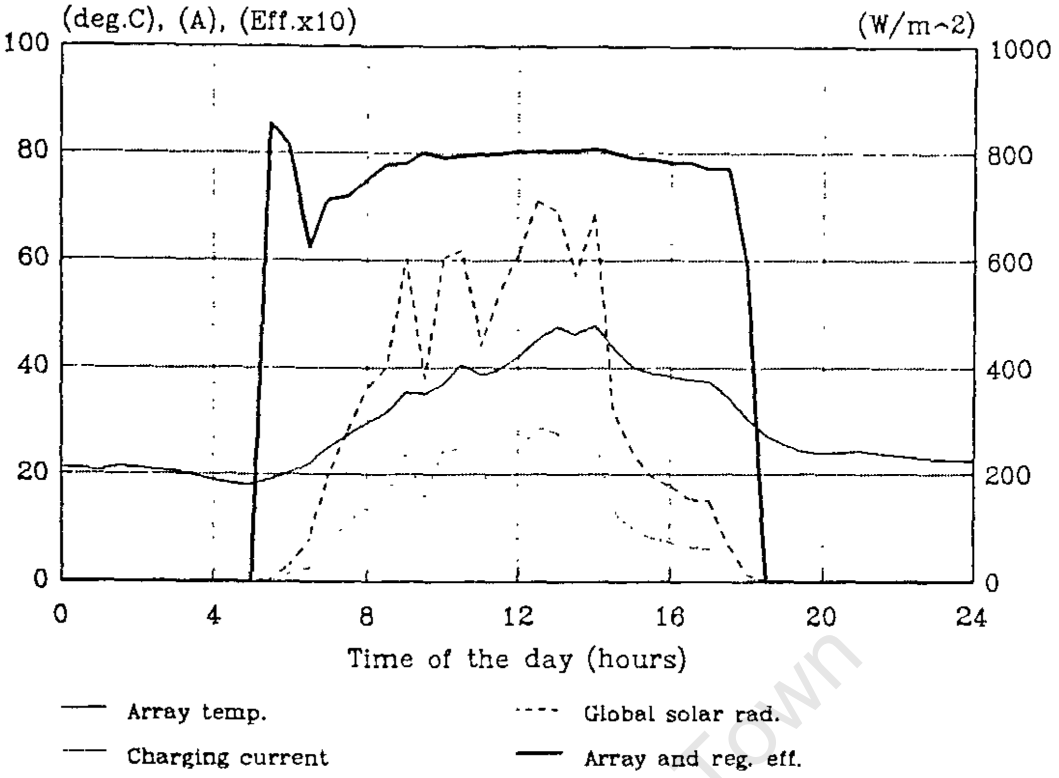

Figure 5.28 : Graph of combined array and voltage regulator efficiency as a function of global solar radiation, array temperature and voltage regulator action for an overcast day with the camp occupied

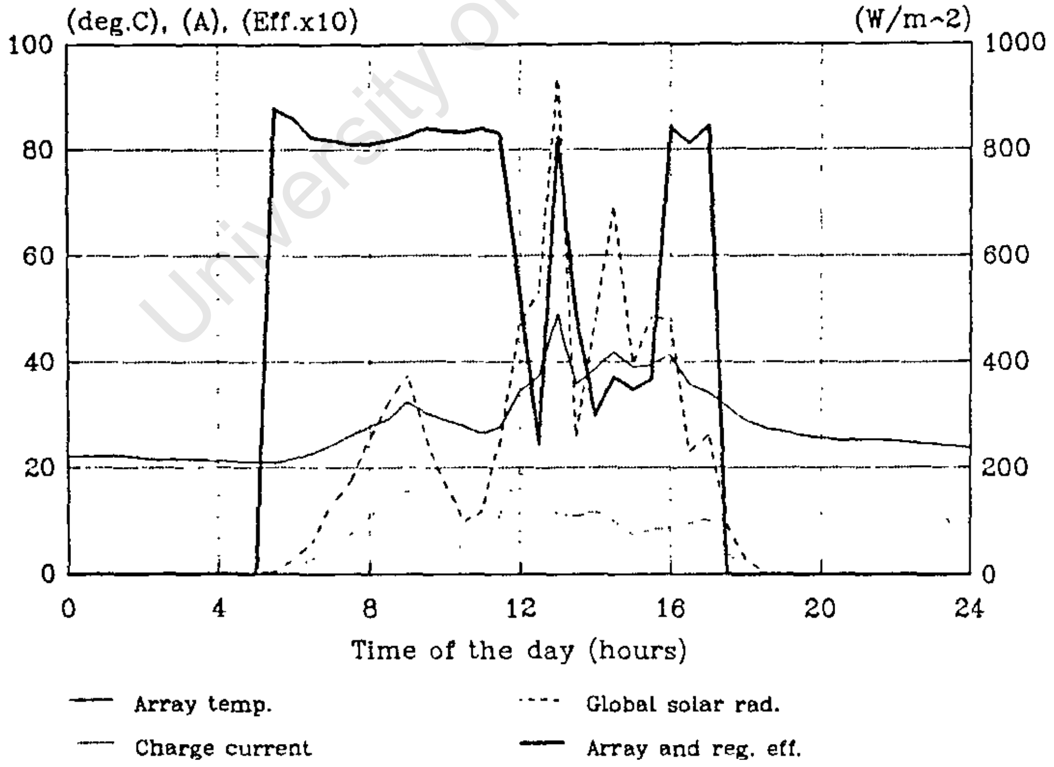

Figure 5.29 : Graph of combined array and voltage regulator efficiency as a function of global solar radiation, array temperature and voltage regulator action for an overcast day with the camp vacant

Generally the highest daily combined (array) efficiencies were between 8,0% (8,4%) and 8,3% (8,7%).

The panel temperature can be seen to fluctuate above and below the ambient temperature in Figures 5.15 to 5.18. It is a function of the ambient temperature, the prevailing wind and the incident solar radiation. The panel temperature rises above ambient after sunrise and increases with increasing incident solar radiation to follow a similar curve to that of the solar radiation but displaced by a lag time due to the thermal inertia of the array. At night the panel temperature falls below ambient due to convective cooling by the wind and radiative heat transfer with the night sky.

The overall average daytime panel temperature for the monitoring period was 33,1°C. The maximum panel temperature recorded during the monitoring period was 61,8°C averaged between 12h30 and 13h00 on 03/11/87. The ambient temperature and solar radiation averaged over the same log interval were 30,4°C and 961 W/m². The maximum average daytime panel temperature over the monitoring period was 46,2°C on 03/11/87 and the corresponding daily average ambient temperature was 29,5°C.

Figure 5.30 shows the correlation of the difference between array temperature and ambient temperature, and the incident global solar radiation.

The equation of the best fit linear regression for the particular configuration of the ambient and array temperature sensors at Boulders is :

$$T_{array} = 0{,}0265\ I_{gt} + T_{amb} - 2{,}206 \qquad (r^2 = 0{,}796)$$

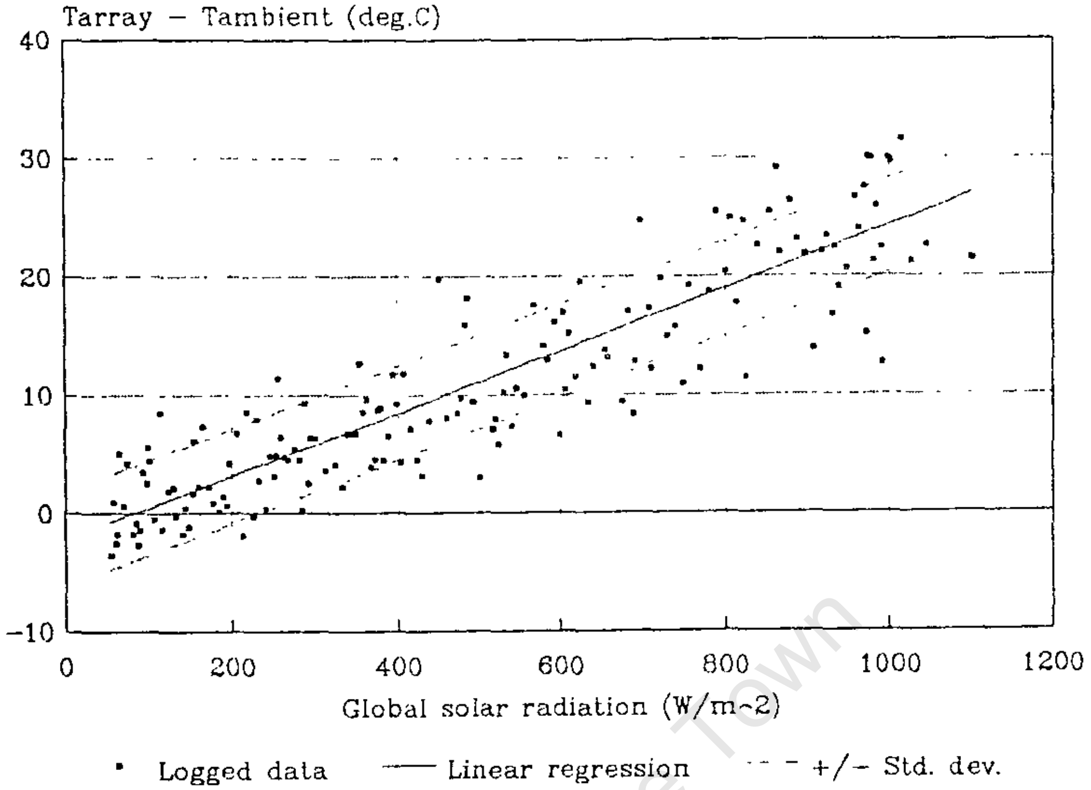

Figure 5.30 : Difference between array and ambient temperature data vs. global solar radiation and a best fit linear regression for Boulders

Overall, the effective or useful energy delivered into the battery during the monitoring period was 68,5% of that potentially available from the array. The data supports the on-site observation that the battery voltage is often in the hysteresis window, between 65 V under load and 69,5 V under charge, with the array in open circuit and that the available incident solar energy was under-utilised for the period under consideration.

5.3.1.4 System availability

As for the 220 V AC PV system at Jock of the Bushveld, no empirical data was found regarding the availability of supply from the 12 V DC PV system at Boulders.

The system configuration at Boulders is one with a high degree of inherent availability. There is an low probability of a total power failure due to the decentralized DC/DC converter arrangement.

Anecdotal observations offered by the former Electromechanical Engineer indicated that the Boulders installation had not suffered any major breakdowns or loss of supply in the two years of operation since commissioning in October 1985. The DC/DC converters have been prone to blow the light bulbs due to high voltage spikes. This intermittent problem has been solved by the supplier and, as suggested above, has only affected one of the huts at a time.

5.3.1.5 Operation and maintenance considerations

The day to day attention given to the system comprises a daily record of the ampere-hour meter reading and an occasional sweeping of the floor of the ventilated battery room. Long term operating considerations include switching off all the circuit breakers except those for the fridges and freezers when the camp is vacant, as recommended in the system specifications.

The recommended maintenance specified for the Boulders DC PV system includes :

i) maintaining the batteries according to the manufacturer's specification
ii) monthly washing of the array to remove dust
iii) monthly checks on the maximum charge voltage setting and cut in voltage setting on the voltage regulator
iv) monthly equalizing charges for the batteries at 72 V (2,40 V/cell) until the SG's stabilize
v) removal of dust from the ventilation holes on the DC/DC converters
vi) checks on the wiring and cables for damage

In practice the maintenance of the system is limited to a quarterly site visit by the supplier on the same contract basis as for the Jock of the Bushveld system. The annual cost to the National Parks Board is R 1 800,00.

No maintenance records of the equalizing charges or cell SG´s are available.

As for Jock of the Bushveld, minimal administrative overheads are incurred and no overheads for the processing of maintenance job cards or accounting or storage costs for operating consumables or spares are required.

The maintenance of the electrical appliances, fittings and wiring is performed by a National Parks Board electrician based at Letaba.

5.3.2 Economic evaluation

The economic evaluation of the DC PV system at Boulders is executed using a LOTUS 123 routine based on the annuity method recommended by Finck and Oelert (1985), as for the AC PV system at Jock of the Bushveld. All prices are based on January 1988 prices.

5.3.2.1 Assumptions on which the economic analysis is based

The assumptions on which the economic evaluation for the Boulders DC PV system is based are summarised overleaf in Table 5.15 :

Table 5.15 : Summary of assumptions for the economic evaluation of the Boulders DC PV system

System lifetime	20 years
Battery life	10 years
Discount rate	4 %
Escalation rate	0 %
GST	12 %
PV module costs	R 63 800 (19 R/Wp)
Voltage regulator cost	R 2 965 (0,82 R/W)
Battery cost	R 21 000 (400 R/kWh)
DC/DC converter cost	R 5 000 (2,60 R/W)
Residual batteries value	10 % of initial cost
Planning costs	0 % of installed system cost
Cost of land	R 0
Array support cost	R 1 100 (34 R/m^2 array area
Battery room cost	R 0 (70 R/kWh)
Wiring cost	R 320 (10 R/m^2 array area
Battery repl. labour cost	R 1 000 (20 R/kWh)
Transport to site	R 0
Installation cost	3 % of equipment cost
Commissioning cost	0% of equipment cost
Engineering fees	0 % of installed cost
Admin. infrastructure cost	200 R/year
Maint. and labour cost	1 800 R/year
Ave. daily energy output	7,60 kWh/day

As for Jock of the Bushveld, the projected operating lifetime of the DC PV system is twenty years.

The estimated battery life is based on a cycle life of 500 cycles and an annual total of 50 deep cycles per year.

The PV array cost is based on the manufacturer's quoted price ex-factory for ninety-six M SETEK MS-101 modules.

The battery cost is for thirty cells based on the manufacturer's quoted price of R 700,00 ex factory per WILLARD FWA 17 cell (inclusive of lead surcharge).

The DC/DC converter cost is based on the manufacturer's quoted price ex-factory for one 40 A and six 20 A 60 V/12 V units.

As for Jock of the Bushveld, the cost of land, battery room cost, planning costs, transport costs, commissioning costs and engineering fees were excluded.

The estimated costs of administrative overheads for the system (see Section 5.3.1.5), was 200 R/year and the estimated annual O&M cost of 1 800 R/year is based on four quarterly site visits by the system supplier at R 450,00 per visit. No cost has been included for the camp attendant's role in operating the system.

The annualised unit cost of energy is based on the estimated average daily system energy output of 7,60 kWh/day. This figure is the average system output based on the handwritten Ah log for the fifteen month period discussed in Section 5.3.1.2.

5.3.2.2 Capital costs

The initial capital cost of the system is calculated as :

PV module	: 63 800,00
Array support	: 1 100,00
Voltage regulator	: 2 965,00
Batteries	: 21 000,00
Inverter	: 5 000,00
Wiring	: 320,00
Sub total	: 94 185,00
GST	: 11 302,00
Installation	: 3 165,00
TOTAL	: 108 652,00

5.3.2.3 Operating and maintenance costs

No. of battery replacements	: 1
Battery replacement costs (NPV)	: 13 444,00
Residual value of batteries (NPV)	: (958,00) negative NPV
Admin. costs (NPV)	: 2 718,00
Maint. and labour costs (NPV)	: 24 463,00
Total O&M costs (NPV)	: 27 181,00

5.3.2.4 Lifecycle cost

Total installed cost	: 108 652,00
Battery replacement cost	: 13 444,00
Residual value	: (958,00)
Total O&M costs	: 27 181,00
NPV lifecycle cost	: 148 319,00

Annualized unit energy cost : 393 c/kWh

Figure 5.31 shows the cashflow for the project over the lifetime of twenty years and the annualized unit energy cost at the end of each year.

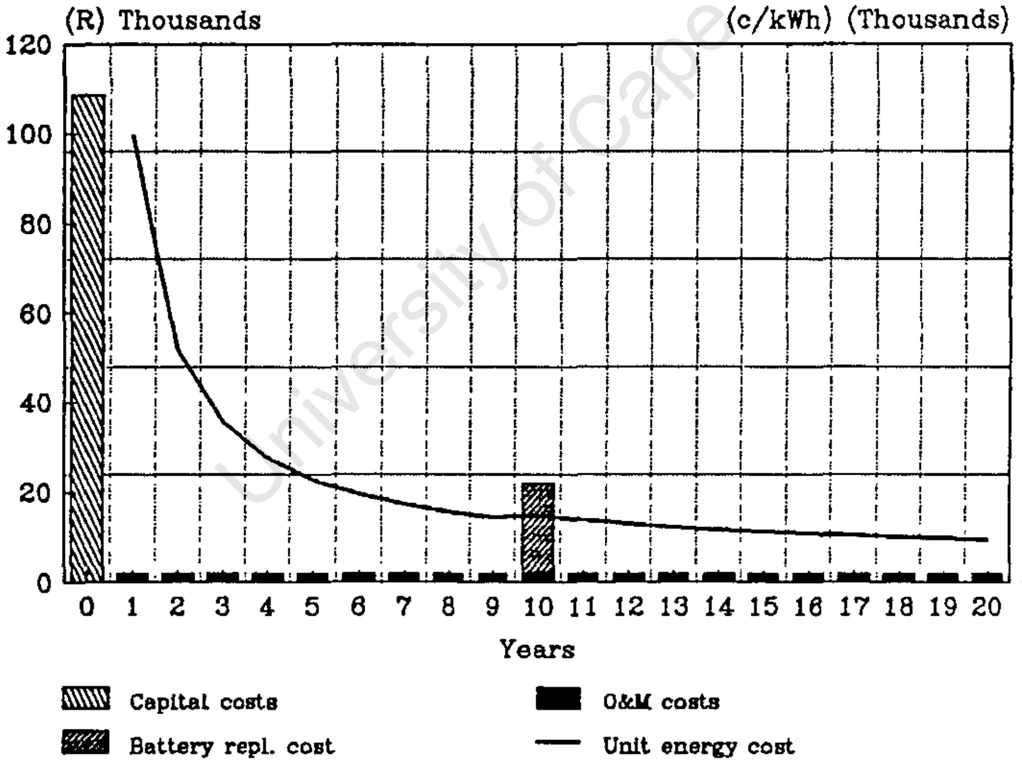

Figure 5.31 : The estimated cashflow and the estimated unit energy cost of kWh supplied for the Boulders DC PV system over a projected lifetime of twenty years

As for the AC PV system at Jock of the Bushveld, the graph illustrates the high initial costs in year zero for the

Boulders PV DC system. Similarly the subsequent annual O&M costs for years one to twenty are relatively small, and the battery replacement cost in the tenth year is the largest single operating cost during the system lifetime. The unit energy cost line represents the unit cost of electricity, calculated at the end of each year, based on the total number of units generated up until that time. As expected, the unit cost of electricity generated decreases asymptotically to the limit which is the quotient of the annual O&M costs divided by the annual number of units generated, ie. 72 c/kWh. In practice the operating lifetime of the system sets the unit cost limit which in this case is 393 c/kWh over the twenty year lifetime.

The cost components of the NPV life-cycle cost evaluated over twenty years are :

Investment costs	: 73 %
O&M costs	: 27 %

5.3.3 Summary

The key operating dynamics that determined the overall performance of the DC PV system at Boulders are the interactions between the array, the voltage regulator and the average daily load energy demand. A summary of the overall system performance is presented in Table 5.16.

The DC PV system at Boulders operates competently and is essentially a well designed system but the relative sizing of the PV array appears to be sub-optimal for minimum initial costs and overall life-cycle costs for the application.

The original design specification for the system was based on a maximum DC/DC converter demand of 165 Ah/day (10,3 kWh/day). Assuming a DC/DC conversion efficiency of 70%, this corresponds to an average load energy demand of 7,2 kWh/day. In practice the recorded average daily DC/DC converter demand was 7,95 kWh/day, ie. 23% less than the projected demand.

As a consequence of oversizing the array relative to the actual load energy requirement, the array was frequently shunted to open circuit by mid-morning as the battery voltage approached full charge and the upper limit of the voltage regulator was reached. The array was therefore not required to contribute to the overall load energy requirement for the bulk of the solar day. A direct result of this is a reduction in the overall system efficiency due to the potential PV array output effectively being wasted.

Table 5.16 : Summary of key indicators of the performance of the Boulders DC PV system

System description : 60 V DC/12 V DC PV system
Array rating : 3360 W_p (96 35 W_p M SETEK modules)
Voltage regulator : 60 V 60 A
Battery storage : 60 V 880 Ah (flat plate)
DC/DC conv. rating : 1,92 kW

Installed load : 1,92 kW 12 V DC (lights, fridges
Load per person : 160 W/person freezers, fans)
Peak load : 628 W
Ave. load : 232 W
Load factor : 0,37
Ave. LED : 7,60 kWh/day
LED per person : 633 Wh/day

Ave. array eff. : 8,3 %
Peak array eff. : 9,5 %
Peak array output : 2906 W
Ave. array temp. : 33,1 °C
Max. array temp. : 62,0 °C

Voltage reg. eff. : 95 % (assumed)
Battery Wh eff. : 81 %
Ave.depth of disch.: 18 %
DC/DC conv. eff. : 70 % (assumed)

Overall system eff.: 3,8 % (average)

Installed cost : R 108 652,00
Batt. repl. cost : R 13 444,00
O&M costs : R 27 183,00
NPV life-cycle cost: R 148 319,00

Unit energy cost : 393 c/kWh

The higher array efficiencies recorded for the M SETEK modules at Boulders, compared to the older ARCO modules at Jock of the Bushveld are a function of the improvements in solar cell technology rather than PV degradation.

Despite the long term economic disadvantages of a higher PV array power than necessary, the excess W_p rating meant that the battery was maintained at a high state of charge. As a result the 880 Ah battery bank was operating consistently well with high charge/discharge cycle efficiencies. The regular charging to the 69,5 V (2,32 V/cell) voltage regulator limit is healthy for the battery, but the lack of evidence of regular equalizing charges or records of the specific gravity could however lead to premature deterioration of the batteries.

The voltage regulator was functioning competently in all respects despite being rated for a 37% higher current than the peak array charging current. A boost/float mode of voltage regulation, as opposed to the boost/open circuit mode installed, would have been a refinement to control the charge current in a more efficient and smooth manner in a system where the array was more optimally sized.

No comment can be made on the performance of the DC/DC converters except that they have apparently functioned adequately after the initial component failures had been rectified. The seven independent units decrease the probability that the entire camp be* deprived of electricity at any one time in the event of a malfunction.

The declared satisfaction with the system by the Electo-mechanical Engineer, and the relatively low RAPS unit energy cost of 393 c/kWh reflect the overall benefits of an essentially well engineered, if slightly conservatively sized and unnecessarily expensive, system.

5.4 WOODLANDS

5.4.1 Technical evaluation

The technical evaluation of the 220 V AC 7,0 kVA, 1180 Ah genset-plus system installed at Woodlands is presented in the same fashion as those for Jock of the Bushveld and Boulders. The fact that only seven days' of data were considered acceptable, from the data recorded for the Woodlands system, reduces the reliability of the recorded data and the calculated findings deduced from the data. Nevertheless, the data does provide a valuable qualitative measure of the technical performance despite being a less than ideal basis for the more quantitative observations.

5.4.1.1 Overall results and daily operating characteristics

Table 5.17 presents a summary of the overall technical performance of the Woodlands genset-plus system based on the seven days' recorded data.

The average daily run time is the number of hours that the genset was operated per day. The genset load share is the proportion of the daily load energy provided directly by the genset, the balance being provided indirectly via the battery charger, battery and inverter. The overall system efficiency is the quotient of the useful energy delivered to the loads per day over the nett energy in the fuel per day expressed as a percentage.

Two days were selected to illustrate the typical daily operating characteristics of the system. 02/10/87 was selected as being representative of a day during which the ranger's house was not occupied. In contrast 06/10/87 was selected as being representative of a day during which the house was occupied. In practice the ranger's house is occupied for most of the year.

Table 5.17 : Overall technical performance of the Woodlands genset-plus system over the period from 01/10/87 to 09/10/87

Date	Daily run time (hours)	Ave. fuel cons. (l/hr)	Energy out of genset (MJ/d)	Energy into DC charger (MJ/d)	Energy out of invert (MJ/d)	Energy into loads (MJ/d)	Genset load share (%)	Overall system eff. (%)	Occup. (pers)
01-Oct	10,0	1,41	66,1	59,0	29,5	36,5	19,4	7,0	0
02-Oct	10,3	1,47	68,2	60,4	28,1	35,9	21,7	6,4	0
03-Oct	13,3	1,41	94,2	79,8	26,9	41,3	34,9	6,0	0
04-Oct									
05-Oct									
06-Oct	11,5	1,39	98,1	63,7	47,5	80,0	40,6	13,5	4
07-Oct	11,5	1,52	96,1	61,9	51,1	85,4	40,1	13,1	4
08-Oct	19,0	1,45	178,1	111,7	13,6	80,0	83,0	7,8	4
09-Oct	17,0	1,31	112,0	79,7	26,1	58,3	55,3	7,1	4
Ave.	13,2	1,42	101,6	73,7	31,8	59,6	42,2	8,7	2,4
Std.dev.	3,2	0,06	34,7	17,5	12,1	20,4	20,1	3,0	
Max.	19,0	1,5	178,1	111,7	51,1	85,4	83,0	13,5	4
Min.	10,0	1,3	66,1	59,0	13,6	35,9	19,4	6,0	0

Figures 5.32 and 5.33 show the recorded system parameters plotted against the time of day for the house vacant on 02/10/87. The technical performance of the system over this day is summarized in Table 5.18.

Figures 5.34 and 5.35, and Table 5.19 are the corresponding presentations of the system performance on 06/10/87 for the house occupied.

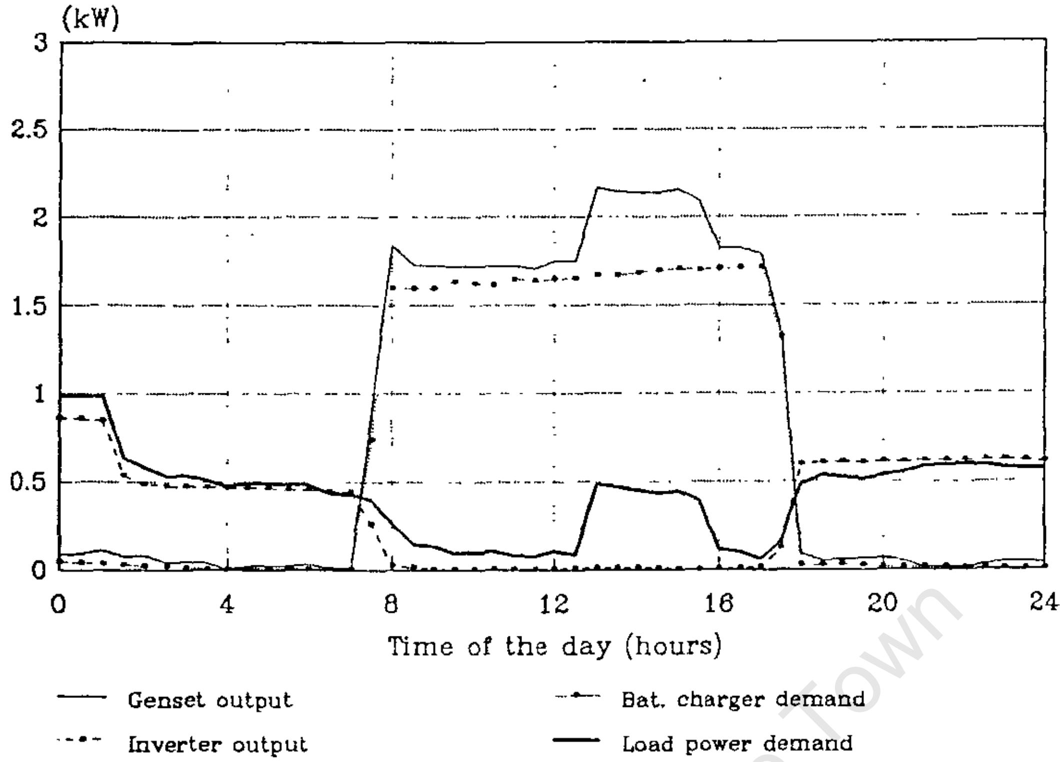

Figure 5.32 : Genset and inverter power output, battery charger power demand and load power demand for a vacant ranger's house at Woodlands, 02/10/87

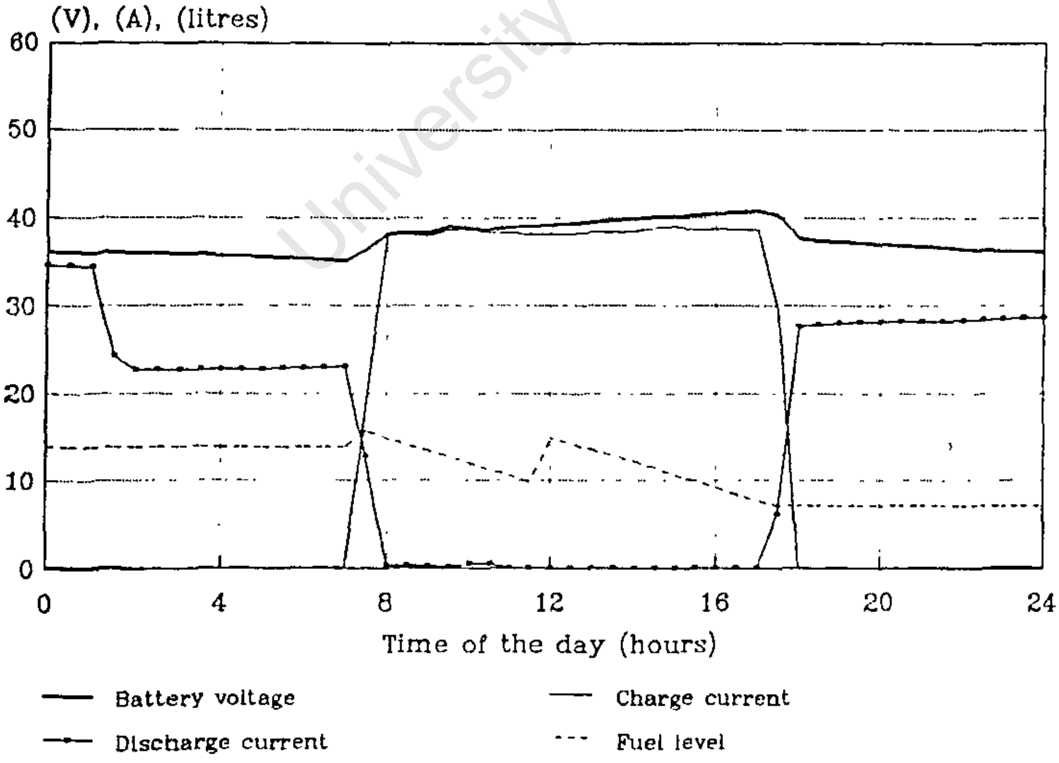

Figure 5.33 : Daily battery voltage, charge and discharge current and fuel level characteristics for a vacant ranger's house at Woodlands, 02/10/87

Table 5.18 : Daily system performance for a vacant ranger's house at Woodlands, 02/10/87

Daily run time	:	10,3 hours	
Ave. fuel consumption	:	1,47 l/hour	
Diesel consumed	:	15,1 l/day	
Energy in fuel	:	559,6 MJ/day	
Energy out of genset	:	68,2 MJ/day	19,0 kWh/day
Energy into charger	:	60,4 MJ/day	16,8 kWh/day
Energy into loads	:	35,9 MJ/day	10,0 kWh/day
Energy into battery	:	55,4 MJ/day	15,4 kWh/day
Energy out of battery	:	47,7 MJ/day	13,3 kWh/day
Energy out of inverter	:	28,1 MJ/day	7,8 kWh/day
Ave. genset eff.	:	12,0 %	
Ave. gen. capacity factor	:	32,6 %	
Ave. DC charger eff.	:	91,6 %	
Ave. inverter eff.	:	58,8 %	
Ave. inv.capacity factor	:	18,3 %	
Genset load share	:	21,7 %	
Inverter load share	:	78,3 %	
Ave. charge voltage	:	39,5 V	
Ave. discharge voltage	:	36,3 V	
Overall system eff.	:	6,4 %	

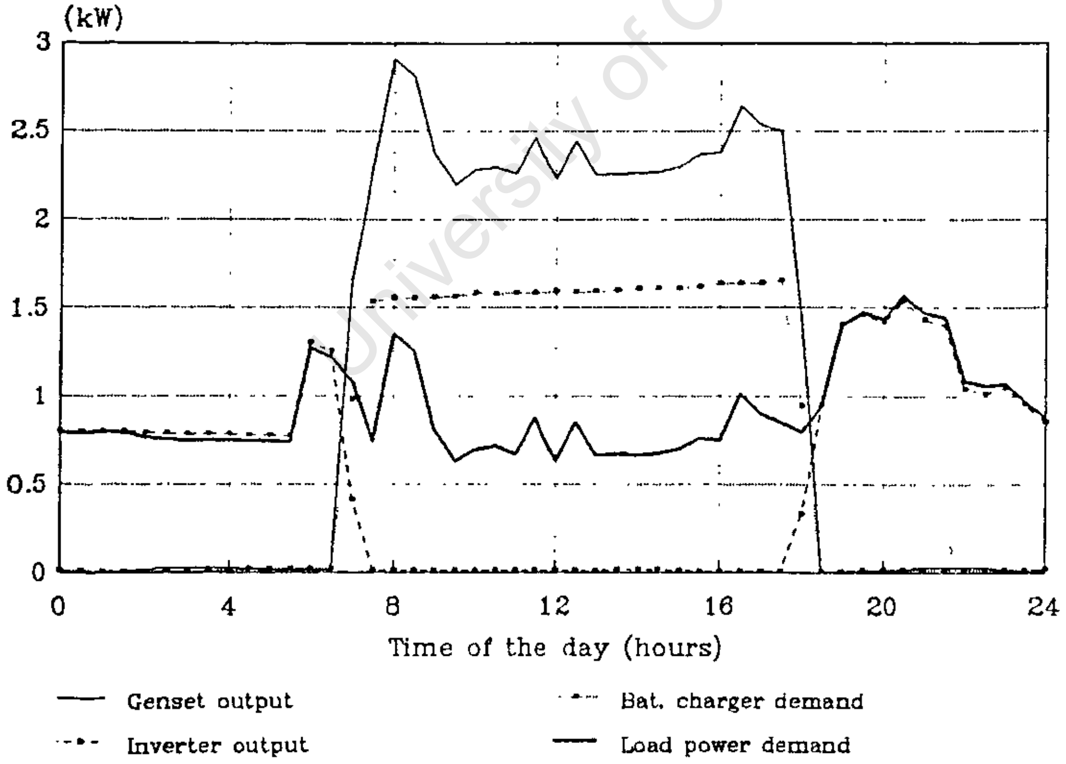

Figure 5.34 : Genset and inverter power output, battery charger power demand and load power demand for an occupied ranger's house at Woodlands, 06/10/87

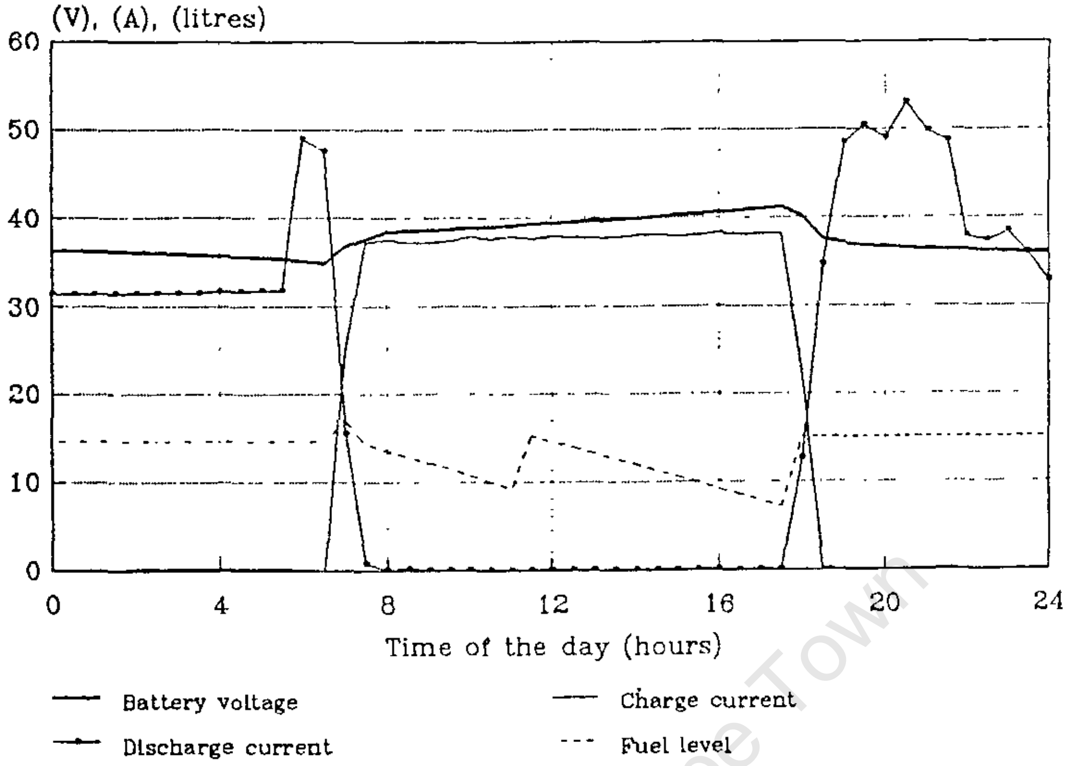

Figure 5.35 : **Daily battery voltage, charge and discharge current and fuel level characteristics for an occupied ranger's house at Woodlands, 06/10/87**

Table 5.19 : **Daily system performance for an occupied ranger's house at Woodlands, 06/10/87**

Daily run time	:	11,5 hours	
Ave. fuel consumption	:	1,39 l/hour	
Diesel consumed	:	16,0 l/day	
Energy in fuel	:	593,7 MJ/day	
Energy out of genset	:	96,1 MJ/day	26,7 kWh/day
Energy into charger	:	63,7 MJ/day	17,7 kWh/day
Energy into loads	:	80,0 MJ/day	22,2 kWh/day
Energy into battery	:	59,8 MJ/day	16,6 kWh/day
Energy out of battery	:	64,5 MJ/day	17,9 kWh/day
Energy out of inverter	:	47,5 MJ/day	13,2 kWh/day
Ave. genset eff.	:	16,2 %	
Ave. gen. capacity factor	:	38,1 %	
Ave. DC charger eff.	:	93,9 %	
Ave. inverter eff.	:	73,6 %	
Ave. inv. capacity factor	:	33,9 %	
Genset load share	:	40,6 %	
Inverter load share	:	59,4 %	
Ave. charge voltage	:	39,5 V	
Ave. discharge voltage	:	36,1 V	
Overall system eff.	:	13,5 %	

In general the genset is started at about 07h00 by the ranger and operated until sunset at about 18h00. The inverter supplies the loads during the night. The inverter output falls to zero when the genset is started and remains at zero until the genset is switched off in the evening. The genset output and the battery charger power demand both increase from zero on startup. The battery charger AC power demand is determined by the manually adjusted charge current setting and the state of charge of the batteries. The genset output is determined by the combined AC power demand of the battery charger and the domestic loads in the household. The load power demand is the difference between the instantaneous sum of the genset and inverter output and the instantaneous battery charger power demand.

The battery voltage decreases slowly under discharge during the night and undergoes a step increase on startup when the batteries start being charged. A marked drop in battery voltage occurs as the genset is switched off when the batteries immediately cease to be charged and are simultaneously required to provide power for the inverter. The discharge and charge currents also reflect the cycling of the battery. The discharge current is variable, being dependent on the DC power demand of the inverter and therefore indirectly a function of the variable AC load power demand of the household. The charge current is generally constant, for the duration of the genset run time, at the battery charger charge current setting.

The average proportions of the load energy demand supplied from the inverter and genset over the monitoring period were 57,9% and 42,1% respectively. These proportions are slightly skewed from the expected annual averages due to the high vacancy/occupancy ratio and the 36,5 hour genset run time on 08/10/87 and 09/10/87. The figures in Table 5.19 are more representative of the system performance for an occupied house.

5.4.1.2 Load energy demand and load curve

The data monitoring system for Woodlands did not account for the power and energy requirements from the genset for the float switch controlled 2,0 hp (1,47 kW) submersible AC borehole pump supplying water to the household, garden and the compound. The fact that the power cables to the pump were connected "upstream" of the data logging AC power measurement was only revealed late in the monitoring program. However, the average uncertainty in the daily energy demand introduced by the omission of the energy requirement of the pump is calculated to be less than 1% of the average daily load energy demand of 16,56 kWh/day, on the basis of a daily water pumping requirement of :

- 100 litre/day/person
- 10 people
- 25,0 m total head
- ave. pump efficiency of 60%

The average system load curves for the monitoring period are shown in Figure 5.36. Curves of the averages of the recorded load power demand averaged over the individual log intervals for the overall monitoring period as well as for a vacant and an occupied ranger's house are presented.

The system load curves show a base load of approximately 600 - 800 W due to lighting during the night with load peaks at 08h30, 13h00 and 19h00 for breakfast, lunch and supper respectively. These peaks are particularly pronounced for the load curve corresponding to the house when occupied. The difference between the load power demand for the house vacant and occupied is roughly 400 - 600 W. Peak average load power demands of 970 W and 980 W occurred over log intervals between 18h30 and 19h00 and 21h30 and 22h00 respectively. The minimum average load power demand of 380 W occurred over the log interval between 10h30 and 11h00.

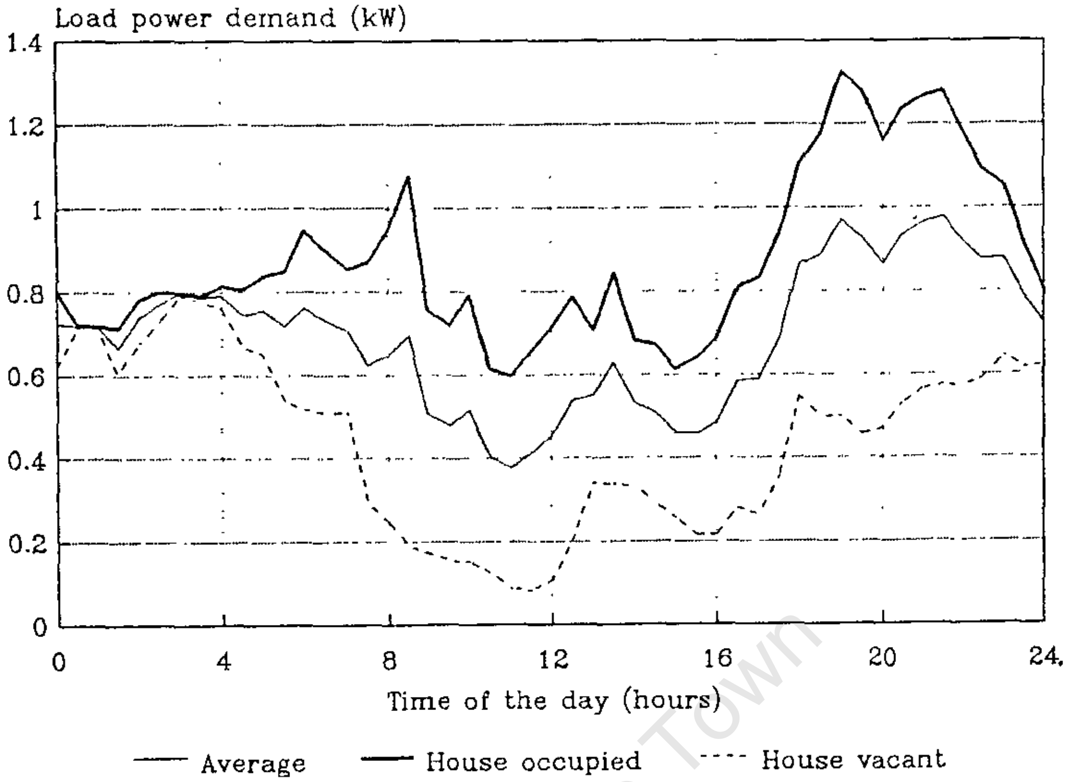

Figure 5.36 : Average system load curves for Woodlands for the overall monitoring period between 01/10/87 to 09/10/87, and for a vacant and occupied ranger's house

The overall average daily load energy demand for the monitoring period was 16,56 kWh/day and the average load power demand was 685 W.

The maximum daily load energy demand was 23,7 kWh/day on 07/10/87. The average daily load energy demand during the period of occupation was 21,1 kWh/day with an average load of 879 W corresponding to a load factor of 0,48. The average load energy demand during the period of no occupation was approximately halved, being 10,5 kWh/day with an average load of 439 W and a peak load of 1000 W averaged between 02h30 and 02h45 on 03/10/87 resulting in a load factor of 0,44. Based on the maximum load power demand of 1850 W averaged over the log interval between 18h30 and 19h00 on 07/10/87, the average system load factor for the overall monitoring period was 0,37.

The load power demand curve for 02/10/87 in Figure 5.33 shows a base load of approximately 600 W at night due to lighting and daytime base load of approximately 100 W together with a recurrent periodic load of approximately 500 W lasting for 3 hours which recurs at 8 to 12 hourly intervals. This load can be seen to end at 01h30 and come on between 12h30 and 15h00.

The recurrent 500 W load is probably due to the thermostatically controlled large GEC Coldspace freezer cycling on a 20-38% duty cycle.

Similarly, the load power demand curve for 06/10/87 in Figure 5.34 shows an increased base load of approximately 800 W at night due to lighting, an increased daytime load of approximately 700 W and the superimposed loads due to breakfast, lunch and supper. The recurrent 500 W load is also apparent between 05h30 and 08h30 and again between 19h00 and 21h30.

5.4.1.3 System component performance

5.4.1.3.1 Inverter

The 3 kW 36 V/ 220 V sine wave inverter AC output is determined by the load energy demand and the operating regime of the diesel genset. The inverter output falls to zero during the day when the genset meets the combined load demand of the household loads and battery charger. At night the inverter output was directly determined by the load demand during the time that the genset was off.

The average load demand on the inverter over the monitoring period was 730 W. The peak load demand on the inverter averaged over one log interval was 1,85 kW between 18h30 and 19h00 on 07/10/87. This corresponded to the maximum DC inverter power demand of 2,30 kW drawing 63,4 A from the battery at 36,3 V.

The average inverter efficiency for the monitoring period was 63,6% corresponding to the average load demand of 730 W, with a maximum efficiency of 80,6% averaged over one log period corresponding to the peak load demand of 1,85 kW between 18h30 and 19h00 on 07/10/87.

The relationship between inverter efficiency and AC power output is illustrated in Figure 5.37 and a frequency distribution of the inverter efficiency over the monitoring period is shown in Figure 5.38.

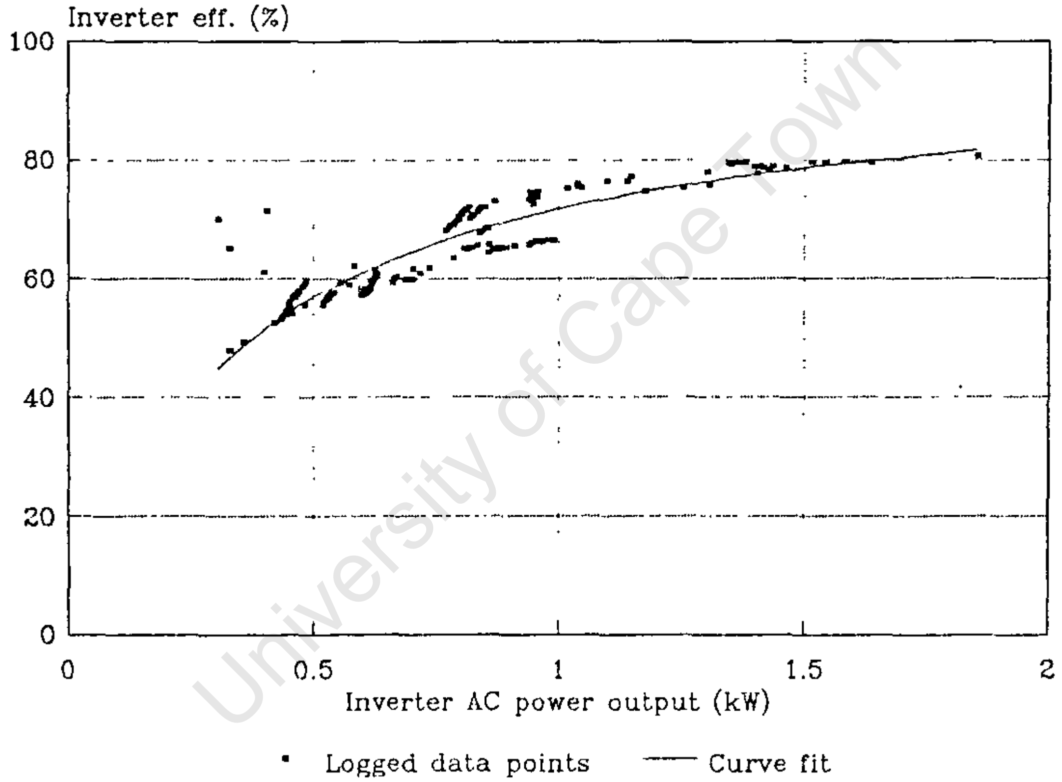

Figure 5.37 : Graph of the inverter efficiency as a function of the AC power output for the 3 kW sine wave inverter at Woodlands

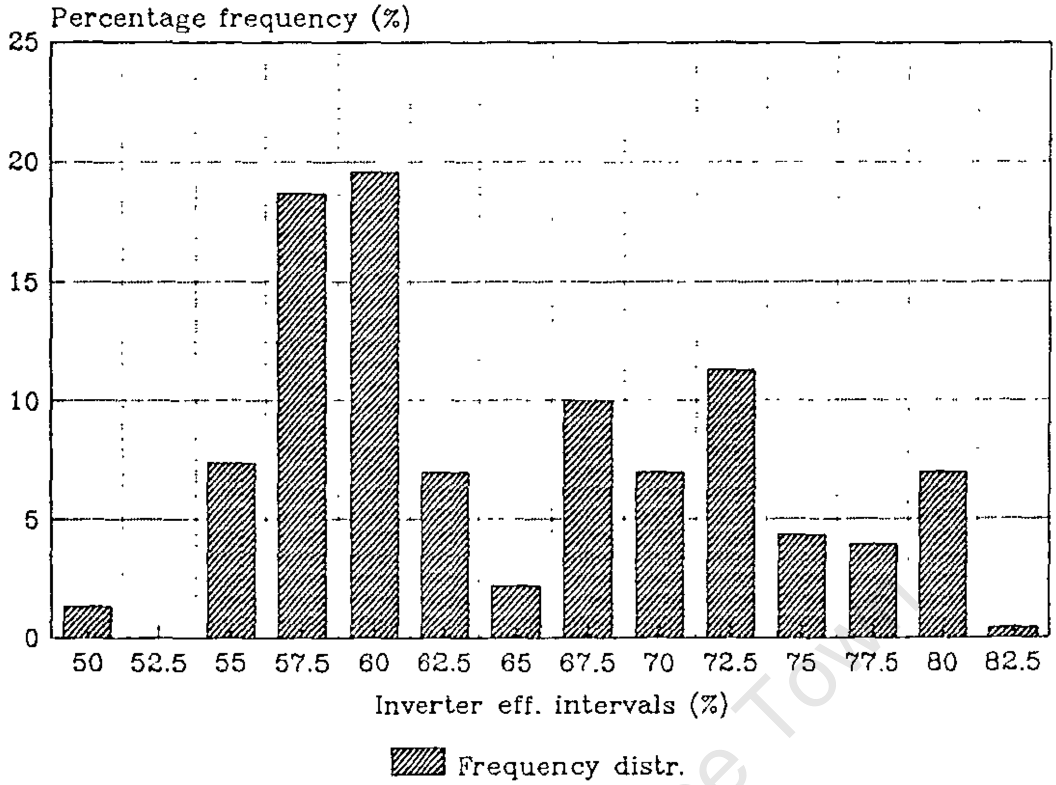

Figure 5.38 : Frequency distribution of inverter efficiency for the 3 kW sine wave inverter at Woodlands

The curve fit was derived from the linear relationship between DC power demand and AC power output of the inverter as illustrated in Figure 5.39. A linear regression for the recorded data points yields the following expression for the relation between DC power demand and AC power output, as for the Jock of the Bushveld square-wave inverter :

$$P_{DC} = 1{,}027\ P_{AC} + 0{,}367 \quad (r^2 = 0{,}967)$$

The calculated inverter efficiency at the rated output of 3 kW is 87%

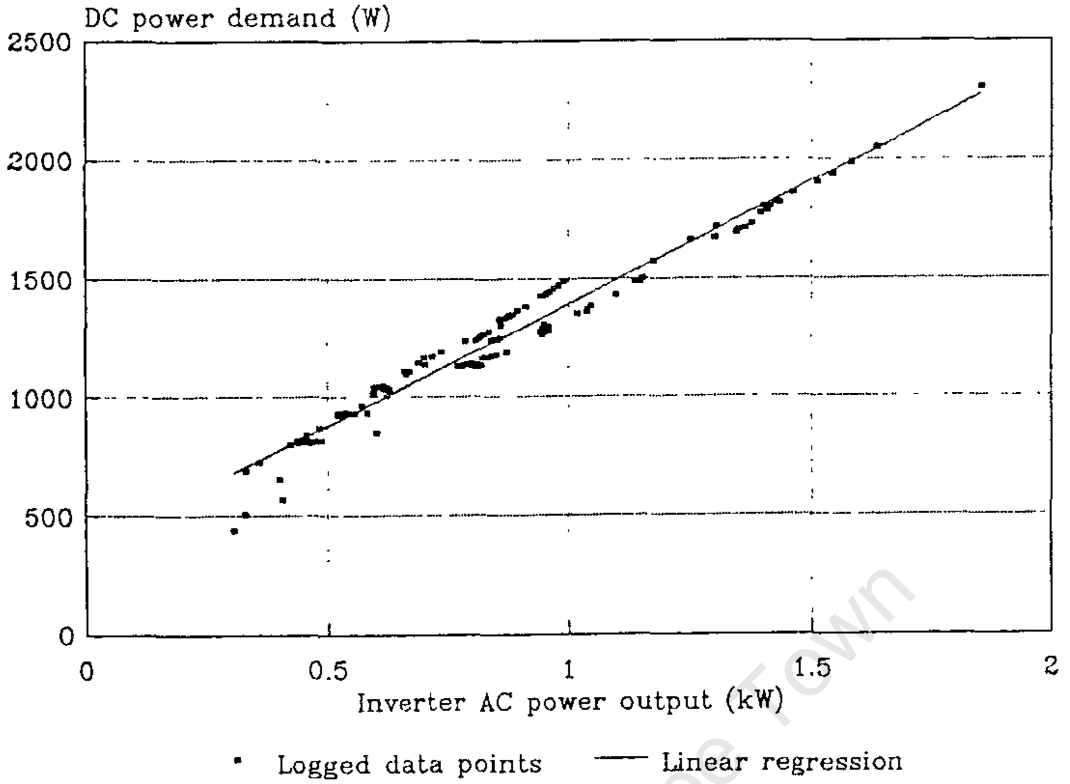

Figure 5.39 : Graph of the DC power demand as a function of the AC power output of the 3 kW sine wave inverter at Woodlands

The no load DC power demand is approximately 0,37 kW. The load sensing facility of the inverter did not appear to have been required during the monitoring period. Sketches of the current and voltage waveforms for the inverter are reproduced in Appendix E. The corresponding power factor is approximately 0,85.

5.4.1.3.2 Storage battery

The function of the battery in the Woodlands genset-plus system is as an energy storage reservoir which serves to improve the capacity factor of the genset by allowing the genset theoretically to be operated at close to its optimum rated output. The battery is required to meet the load energy demand on a cyclical basis. The period of the charge/discharge cycle is ultimately determined by the available battery capacity and the average daily load energy demand. The operating regime at Woodlands is dictated by factors other than the energy flows, such as switching off the genset at sunset to avoid the noise throughout the night.

The battery installed at Woodlands comprises two parallel strings of nine 4 V RAYLITE 2IMR tubular plate lead acid batteries in series. These batteries are identical to those installed at Jock of the Bushveld. Their nominal capacity is 590 Ah each at the 8 hour rate to a final voltage of 1,75 V/cell @ 20°C. The SG is 1,250. The battery configuration at Woodlands provides a 36 V 1180 Ah (nominal) DC energy storage reservoir for the genset-plus system.

The battery bank is charged by the battery charger at a manually selected maximum DC current subject to charge current limitation when a maximum battery voltage of 43,3 V (2,40 V/cell) is reached. The discharge current of the battery is not constant, being dependent on the DC power demand of the inverter.

The average charging period per day corresponds to the daily run time of the diesel genset ie. an average of 13,2 hr/day over the monitoring period or 11,15 hr/day over a 411 day Kruger National Park log period, (see Section 5.4.1.3.4).

The average daily charge energy was 68,6 MJ/day or 476 Ah/day. The average daily discharge energy was 46,8 MJ/day or 360 Ah/day corresponding to an average depth of discharge of 30% of the initial capacity of the battery. The overall ampere-hour efficiency of the batteries was 78% and the average watt-hour efficiency was 71%. These battery efficiencies were evaluated over the seven day monitoring period based on similar battery voltages under a constant charge rate, (ie. similar state of charge), at the beginning or at the end of the interval over which the efficiencies were calculated. The extended battery charging period was excluded in the efficiency calculations to avoid skewing of the results.

Nevertheless, the efficiencies are low compared to the accepted Ah efficiency of 90% and Wh efficiency of 75-80% for sound batteries, which implies deterioration of the cells and a loss of capacity, as well as less than optimum charging routines.

Figure 5.40 shows the energy flows into and out of the battery for the monitoring period.

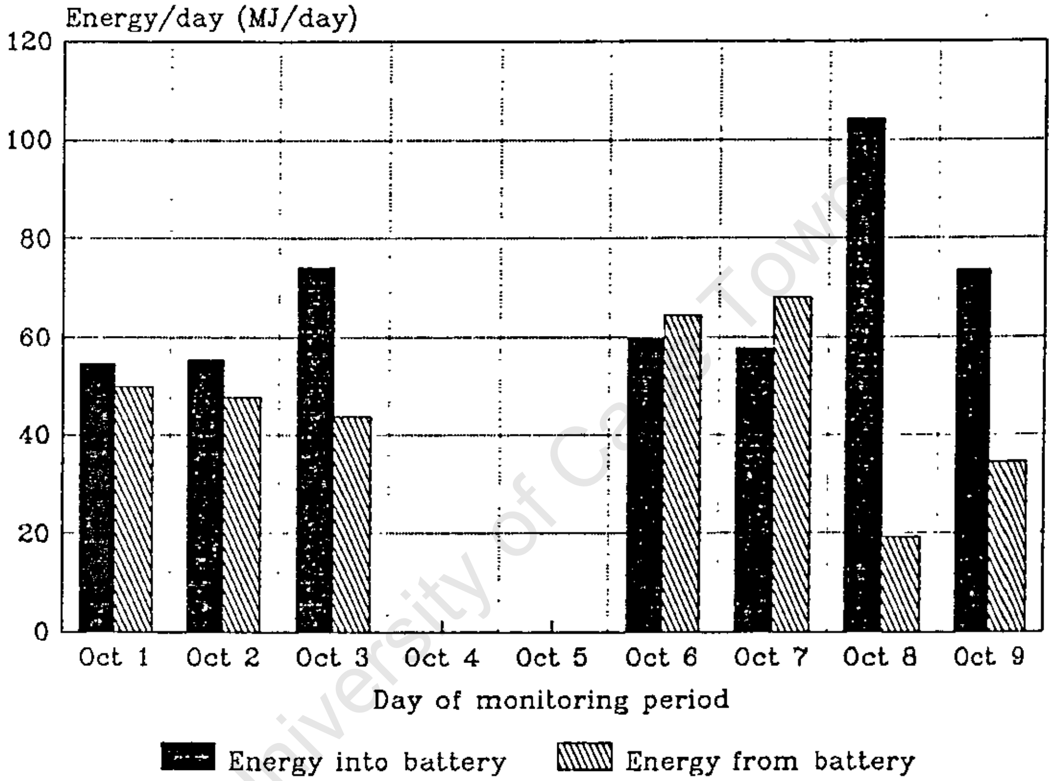

Figure 5.40 : Graph of the daily energy flows into, and out of the 1180 Ah (nominal) battery at Woodlands

Based on a maximum allowable depth of discharge of 60% and the extremes of daily energy discharged from the batteries, the batteries would provide between 1,33 days and 2,10 days of autonomy before requiring charging from the genset via the battery charger.

Similarly, the time required to bring the batteries back up to charge from a state of charge of 40% would take approximately nineteen hours at a constant charge current of 38 A. The corresponding AC power required from the genset would be approximately 1,6 kW. The charging time could be more than halved by adjusting the charge current setting to the manufacturer's suggested maximum of 98 A which corresponds to a demand of approximately 4,2 kW on the genset. The genset rating of 5,6 kW would, in addition, still allow a margin of 1,4 kW for domestic loads.

The average battery charging current over the monitoring period was 36,2 A. The maximum was 39,5 A averaged over the log interval between 16h15 and 16h30 on 01/10/87 and the minimum was 24,8 A averaged between 06h30 and 07h00 on 09/10/87.

The maximum charge current setting during the monitoring period was approximately 38 A. The current into the battery bank remained at this maximum throughout the monitoring period up to 22h30 on 08/10/87, after 26 hours of continuous genset operation, when the charge current decreased to approximately 26 A over a period of seven hours. The current remained at 26 A for a further ten hours before the genset was switched off.

The current out of the battery is a function of the DC power requirements of the inverter, and hence the load power demand.

The average current out of the batteries during the monitoring period was 31,0 A and the maximum was 63,4 A, averaged over the log period corresponding to the maximum load demand on the inverter between 18h30 and 19h00 on 07/10/87.

The battery voltage is alternately a function of the load demand of the inverter, and hence the household, at night, and the output of the DC charger during the day.

The average battery voltage over the monitoring period was 38,2 V (2,12 V/cell). The maximum was 43,3 V

(2,40 V/cell), for the five hour period between 12h00 and 17h00 prior to switching off the genset after 26 hours of continuous operation. The minimum battery voltage was 33,7 V (1,87 V/cell), averaged over the log interval between 04h30 and 05h00 on 08/10/87 immediately prior to the extended genset operation referred to above.

The reason for this protracted genset operation was almost certainly due to drastically discharged batteries for which the battery voltage fell below the minimum voltage cut out setting of the inverter. The inverter ceased to provide the required load power demand and the genset was manually started to restore the supply and begin charging the batteries.

Figure 5.41 shows the charge current and battery voltage for this extended charging period as well as the preceding twenty-four hour charge/discharge cycle.

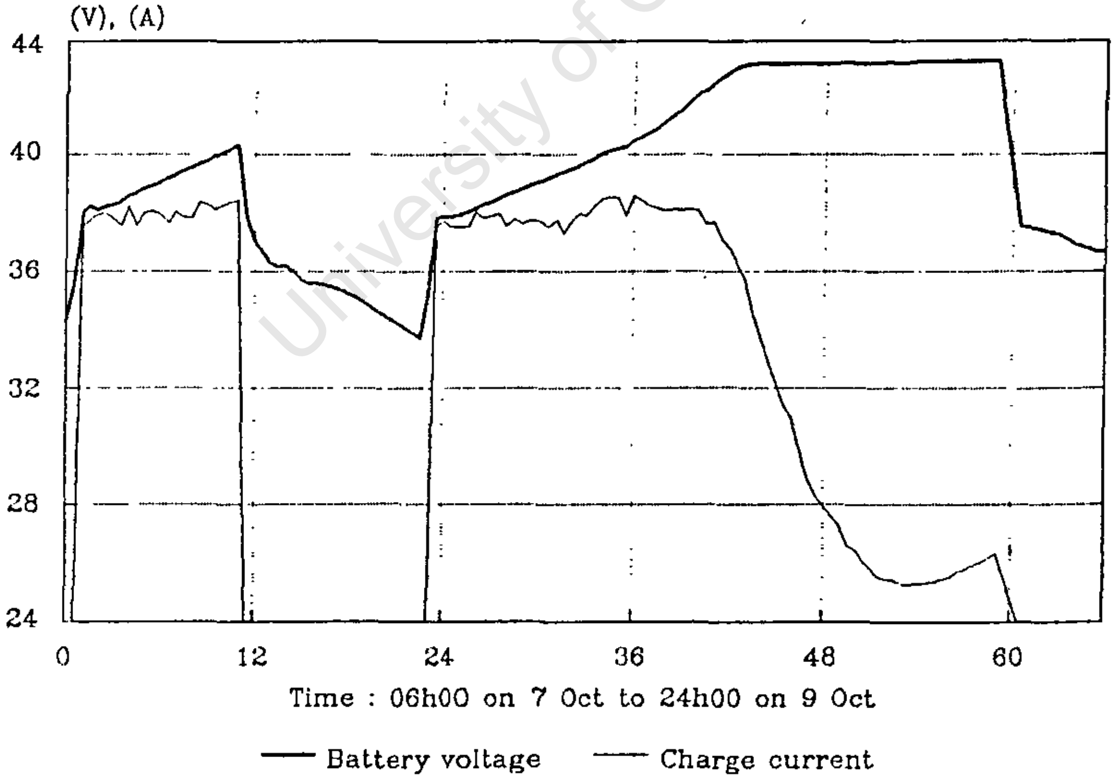

Figure 5.41 : Graph of charge current and battery voltage for the extended charging period and preceding twenty-four hour charge/discharge cycle, 07/10/87 to 09/10/87

The voltage drop of approximately six volts between the voltage at the end of the charge period and the subsequent discharge period is a function of the elevated voltage under charge (2,40 V/cell) compared to the nominal open circuit voltage (2,09 V/cell), and the drop in voltage due to the internal resistance of the battery under load.

5.4.1.3.3 Battery charger

The function of the battery charger is to restore the charge in the battery following a period of discharge during which the load power demand had been met by the inverter. The battery charger begins charging the battery bank automatically when the diesel genset is switched on. In Figures 5.32 and 5.34 the AC power demand of the battery charger can be seen to follow the operating regime of the diesel genset.

The AC power into the battery charger is determined by the manually adjusted maximum DC charging current setting and the state of charge of the battery bank. Thyristor controlled voltage regulation prevents overcharging and damage to the battery due to gassing and overheating. The battery charger is rated for a 100 A charging current, however the maximum DC charging current was set at approximately 38 A, as illustrated in Figures 5.33, 5.35 and 5.41.

In Figure 5.32 on 02/10/87, the AC power demand of the DC charger can be seen to rise linearly for the constant charge current of 38 A from 1,60 kW to 1,71 kW as the battery voltage rose from 38,2 V to 40,9 V, and in Figure 5.34 on 06/10/87, 1,55 kW to 1,65 kW for a voltage rise from 38,4 V to 41,3 V.

The average daily efficiency of the DC charger was 92,9% varying between a maximum of 93,9% and a minimum of 91,6%.

No direct correlations were derived between the efficiency of the DC charger and factors such as the battery voltage, maximum charge current setting, state of charge of the battery, battery and ambient temperature or nett energy into the battery.

The battery charger operated in the maximum battery voltage/current limit mode once during the monitoring period. (see Section 5.4.1.3.2)

5.4.1.3.4 Diesel genset

The function of the single phase 7 kVA LISTER ST2 genset in the genset-plus system at Woodlands is to provide the energy conversion of fuel energy into electrical energy for supplying the load energy demand of the Woodlands ranger´s compound. As mentioned earlier the genset was operated so as to meet the parallel AC power requirements of the battery charger and the household load power demand.

The genset output was measured directly as AC power and is determined by the nett effect of the maximum charging current setting of (i) the DC charger and the state of charge of the batteries; and (ii) the load power demand of the household.

In Figures 5.32 and 5.34, the genset power output can be seen to rise to meet the combined requirements of the DC charger and domestic loads at startup in the morning between 06h30 and 07h00 and fall to zero again at shut down in the evening between 17h30 and 18h00.

The average diesel genset run time for the monitoring period was 13,2 hr/day. This average is based on only seven days´ data during which the house was unoccupied for three days and is therefore not a true reflection of the long term average run time. Furthermore, this average should be interpreted with caution due to the fact that the genset was run continuously for approximately 36,5 hours from 05h00 on 08/10/87 to 17h30 on 09/10/87. The extended operation of the diesel genset is likely to have been required to charge depleted batteries and is discussed further in Section 5.4.1.3.2.

Based on the National Parks' Board fuel consumption log sheets for the period 22/12/85 to 20/04/87, as summarised in Table 5.20, the average run time per day was 11,15 hours.

Table 5.20 : Summary of National Parks Board fuel consumption log sheets for Woodlands genset-plus system for the period from 22/12/85 to 20/04/87

WOODLANDS 'MOTORVOERTUIGLOGSTAAT' RUN TIME AND FUEL CONSUMPTION

Log period from	to	No. days	Engine hours from	to	No. hours	Fuel (litres)	Oil (litres)	Ave. run time (hr/day)	Ave.fuel cons. (l/hr)	Ave.oil cons. (ml/hr)
22-dec	19-jan	28	5116	5463	347	390	0.5	12.39	1.12	1.44
20-jan	15-feb	27	5463	5794	331	390	1.5	12.26	1.18	4.53
16-feb	27-mar	41	5794	6113	319	360	0.0	7.78	1.13	0.00
28-mar	18-apr	22	6113	6342	229	330	0.5	10.41	1.44	2.18
19-apr	19-may	31	6342	6715	373	480	0.5	12.03	1.29	1.34
20-may	16-jun	28	6715	7027	312	435	0.0	11.14	1.39	0.00
17-jun	21-jul	35	7027	7413	386	465	1.0	11.03	1.20	2.59
22-jul	18-aug	28	7413	7686	273	435	0.5	9.75	1.59	1.83
19-aug	20-sep	33	7686	8068	382	495	0.5	11.58	1.30	1.31
21-sep	12-oct	22	8068	8320	252	300	0.5	11.45	1.19	1.98
13-oct	14-nov	33	8320	8683	363	465	1.0	11.00	1.28	2.75
15-nov	23-dec	39	8683	9125	442	600	1.0	11.33	1.36	2.26
24-dec	08-jan	15	9125	9333	208	210	0.0	13.87	1.01	0.00
28-mar	20-apr	24	9632	9875	243	345	0.0	10.13	1.42	0.00
Average :								11.15	1.28	1.59
Std.dev.:								1.37	0.15	1.26
Maximum :								13.87	1.59	4.53
Minimum :								7.78	1.01	0.00

From the constant slope of the plot of cumulative engine hours over time, as illustrated in Figure 5.42, the variation of the daily genset run time appears to have been negligible over this period. The corresponding average daily run times calculated for each fuel consumption log sheet period are plotted in Figure 5.42 as a bar chart. The average daily run time varies between 7,8 hrs/day to 13,9 hrs/day. The apparent contradiction between the constant slope of the cumulative engine hour line and the varying average daily run time bar chart is due to the variation in the fuel consumption log sheet intervals, as presented in Table 5.20.

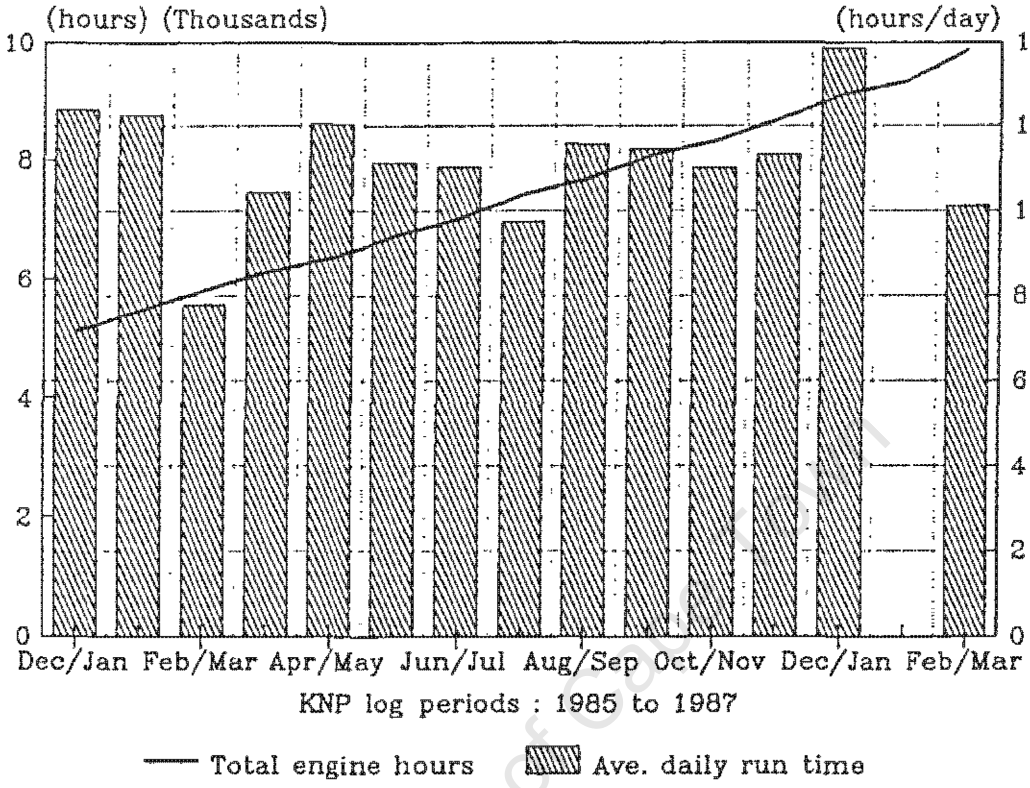

Figure 5.42 : Graph of cumulative engine hours against time and average daily run time for the 411 day period between 22/12/85 and 20/04/87

The average daily load share provided directly by the genset was 42,2%.

The overall average diesel genset output, while operating, for the monitoring period was 2,05 kW, corresponding to an average overall capacity factor of 0,30. The maximum genset output was 3,29 kW averaged over the log interval between 08h00 and 08h30 on 08/10/87. under the combined demand of the battery charger (1,57 kW) and the domestic loads (1,71 kW). This corresponds to a load factor, as seen by the genset, of 0,62.

Figure 5.43 illustrates the relationship between the genset efficiency and AC power output. The efficiency increases from 9,5% to the maximum of 19,4% with increasing AC power output. The scatter of the points on the graph reflect the influence of factors such as engine temperature, time since startup, state of tune and the fluctuations in the load power demand during the log intervals.

The data is directly comparable to the results of the tests performed by Kenna (1987) on a similar LISTER ST2 genset in Kenya, as shown in Figure 2.3.

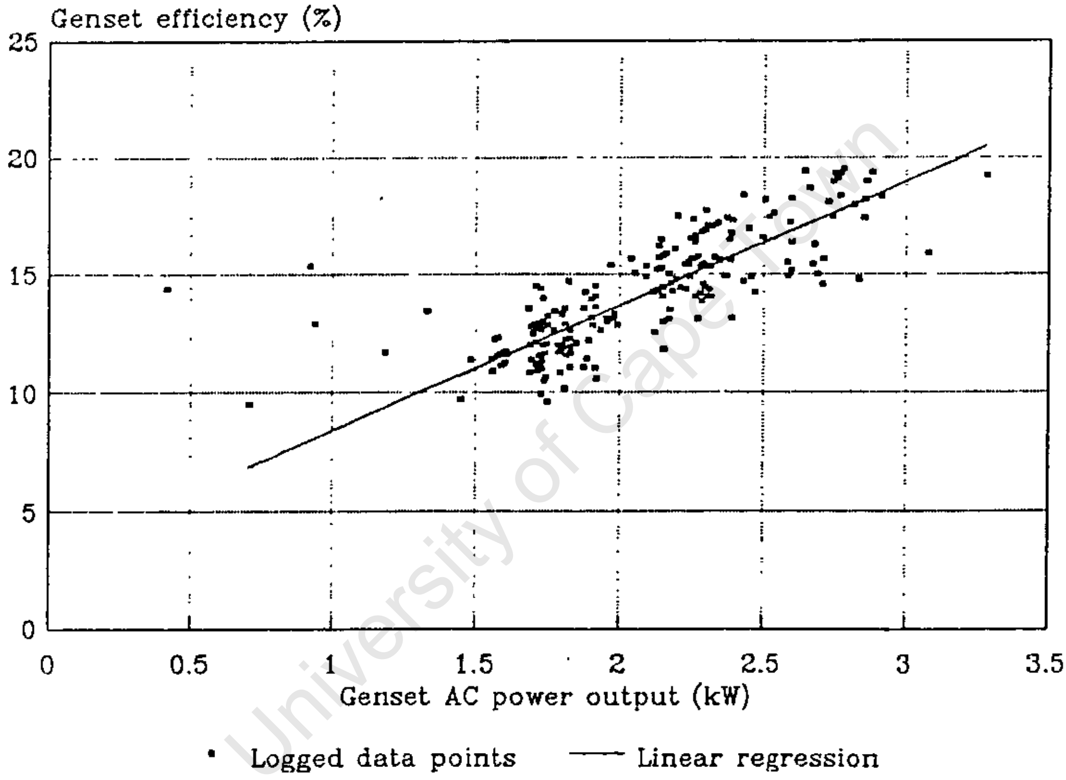

Figure 5.43 : Graph of the genset efficiency as a function of the AC power output for the Lister ST2 genset at Woodlands

The average genset efficiency was 14,3% corresponding to the average load power demand of 2,05 kW. The maximum genset efficiency was 19,5% averaged over the log interval between 21h00 and 21h30 on 08/10/87 at a genset output of 2,78 kW, battery charger power demand of 1,69 kW and a load power demand of 1,09 kW. Figure 5.44 shows the frequency distribution of the genset efficiency over the monitoring period. The efficiency was between 10% and 16% for the majority of the time.

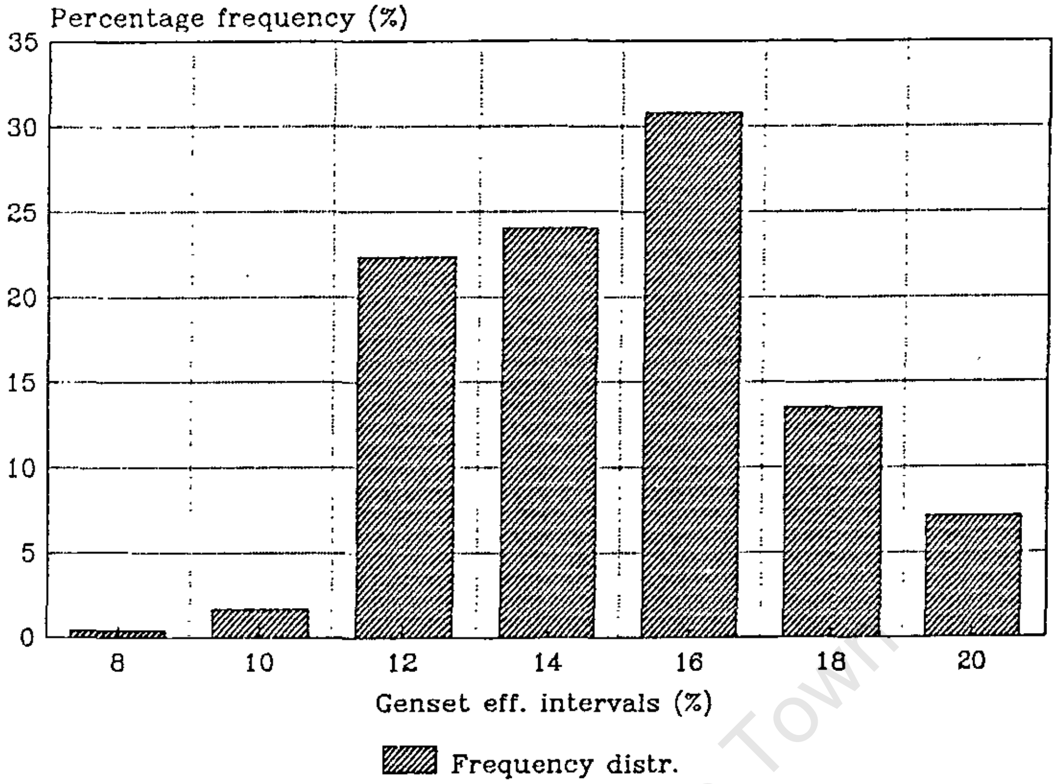

Figure 5.44 : Frequency distribution of genset efficiency for the Lister ST2 genset at Woodlands

In Figures 5.33 and 5.35 the fuel level in the diesel tank of the genset can be seen to fall uniformly over the periods during which the genset is running with sudden increases in fuel level corresponding to the intermittent topping up of the fuel tank. The fuel level remains unchanged over those periods during which the genset was off and the loads are supplied by the inverter ie. at night. The fuel consumption of the diesel genset is represented by the slope of the fuel level curve.

The average fuel consumption over the monitoring period was 1,42 l/hr, calculated from linear regression of the fuel level with respect to time. The minimum fuel consumption averaged over one day was 1,31 l/hr on 09/10/87 and the maximum was 1,52 l/hr on 07/10/87.

The average fuel consumption calculated for the 411 day period recorded on the National Parks' Board log sheets was 1,28 l/hr, ranging between a maximum of 1,59 l/hr and a minimum of 1,01 l/hr. The oil consumption was calculated as 1,59 ml/hr.

Based on the recorded AC power output the average specific fuel consumption of the genset was 620 g/kWh varying between 436 g/kWh and 893 g/kWh. The manufacturer's claimed fuel consumption at 1500 rpm ranges between 233 g/kWh and 245 g/kWh, based on the mechanical power output for the bare engine without transmissions, gearboxes and optional extras. Eskenazi et al (1986) quote a generalized specific fuel consumption of 0,4 l/kWh (350 g/kWh) for diesel gensets in the range between 3 kW and 25 kW. Figure 5.45 shows the specific fuel consumption as a function of the genset power output.

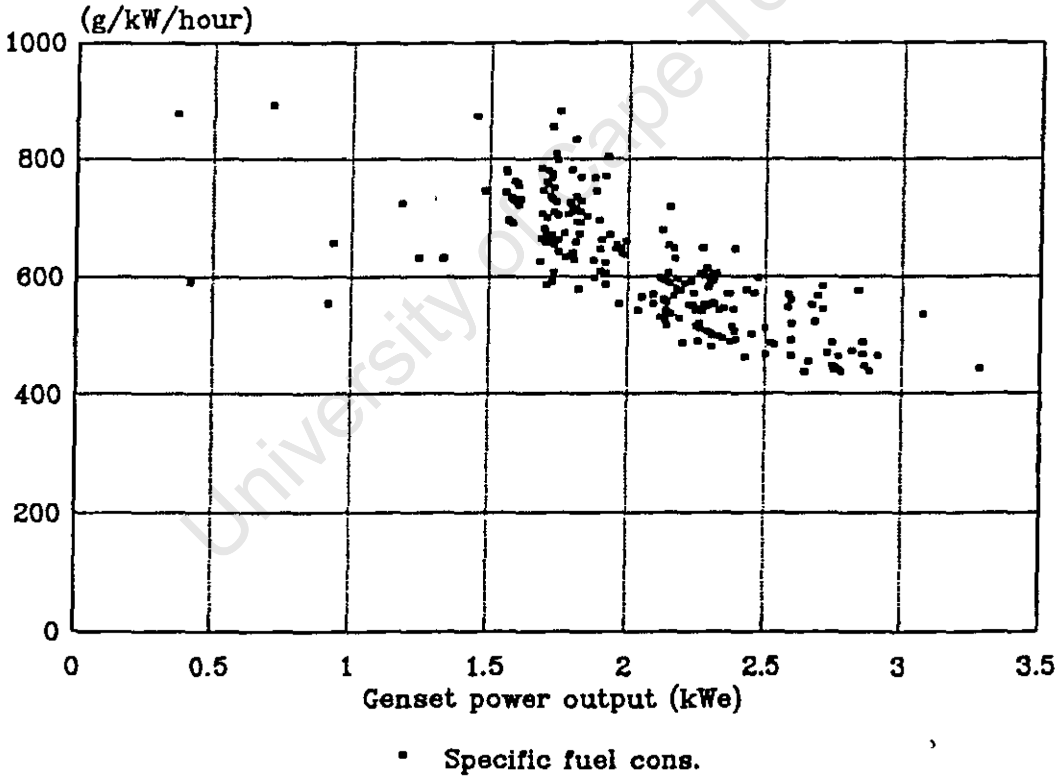

Figure 5.45 : Graph of the specific fuel consumption vs. the output power of the LISTER ST2 genset at Woodlands

The limited range of recorded capacity factors for the genset operation precludes a complete illustration of how the specific fuel consumption varies as a function of the capacity factor under the full range of steady state operating conditions. The graph shows the reduction in specific fuel consumption which would be expected to be a minimum for capacity factors between 70% and 80%.

The voltage and current waveforms of the Woodlands genset are reproduced in Appendix E.

5.4.3.1.4 System availability

No recorded data regarding the system availability was available from the National Parks Board administration.

The energy storage facility of the genset-plus configuration, combined with the rated capacity of the genset and parallel power supply options, increases the reserve capacity of the system in the event of down-time of components due to routine maintenance or breakdowns. There is effectively between 1-3 days of autonomy for the system depending on the state of charge of the batteries.

The versatility of the system was demonstrated on 08/10/87, when the genset was started manually following a temporary loss of supply after the inverter had kicked out due to a low battery voltage condition.

5.4.1.5 Operation and maintenance considerations

As discussed in Chapter Two, the operating and maintenance costs of diesel gensets have been the most difficult factor of the life-cycle cost to estimate and have in the past been assumed to be much lower than appears to be the case in practice.

Records of maintenance performed on the genset at Woodlands were obtained from the Electo-mechanical

Engineer in the form of job cards for the 604 day period between 18/03/86 and 12/11/87. The complete maintenance record is presented in Appendix G.1.

The engine had logged 6040 hours by 18/03/86 and 12210 hours by 12/11/87, a difference of 6170 hours at an average of 11,15 hrs/day.

The recorded cost of maintenance for this period was estimated to be R 6 260,00 which equates to 1,02 R/hr. The estimate is based on the following National Parks Board rates :

Diesel fitter labour rate	: 22 R/hr
Overtime rate	: 35 R/hr
Travelling costs	: 33 c/km

However, the genset should have been given twenty-five 250 hr services over this period although only nine were recorded on the job cards. Furthermore, the genset was removed to the Shingwedzi mechanical workshop between 05/12/86 and 27/02/87 for undisclosed maintenance. This could have been a 5000 hr major overhaul as recommended by Stewarts and Lloyds.

The maintenance cost calculated above would therefore appear to be deceptively low and could more realistically be estimated at R 10 600,00 or 1,72 R/hr if the additional sixteen 250 hr services @ R 208,40 each (R72,00 in spares, 5 hours of work and travelling time and 80 km travelling costs) and a major overhaul (R1 000,00) are included for the period under consideration.

The fuel costs for the average fuel consumption of 1,28 l/hr is 0,93 R/hr based on the current cost of diesel to the National Parks Board of 72,8 c/litre.

The oil consumption cost would be 0,3 c/hr based on oil cost of 2,00 R/litre and the recorded oil consumption of 1,59 ml/hr.

The total hourly O&M cost would be 1,95 R/hr based on the recorded O&M costs or 2,65 R/hr based on more probable assumptions.

The annual O&M cost for 365 days and an average run time of 11,15 hr/day (4070 hr/year) would be R 7 936,50. The annual O&M cost based on the more probable assumptions would be R 10 785,50.

The cost of an attendant to operate the genset and maintain the fuel tank level has not been included in the above costs.

5.4.2 Economic evaluation

The economic evaluation was performed as described in Section 4.7 based on January 1988 prices.

5.4.2.1 Assumptions on which the economic analysis is based

The assumptions on which the economic evaluation for the Woodlands genset-plus system is based are summarised overleaf in Table 5.21 :

Table 5.21 : Summary of assumptions for the economic evaluation of the Woodlands genset-plus system

System lifetime	7 years
Battery life	5 years
Discount rate	4 %
Escalation rate	0 %
GST	12 %
Genset costs	R 14 000
Fuel tank	R 150
Battery charger cost	R 1 930
Battery cost	R 11 600
Inverter cost	R 4 350
Residual batteries value	10 % of initial cost
Planning costs	0 % of installed system cost
Cost of land	R 0
Generator room	R 2 000
Battery room cost	R 0
Wiring and switchgear	R 150
Battery repl. labour cost	R 100
Transport to site	R 0
Installation cost	3 % of equipment cost
Commissioning cost	0% of equipment cost
Engineering fees	0 % of installed cost
Admin. infrastructure cost	2 000 R/year
Maint. and labour cost	10 800 R/year
Ave. daily energy output	16,56 kWh/day

The system lifetime is based on the projected useful lifetime of the genset. The useful operating lifetime of diesel gensets is highly variable, depending on such factors as duty cycle and maintenance. Estimates vary between 3 000 and 15 000 hours (Fraenkel, 1979; Williams, 1986; McNelis, 1986). Eskenazi et al (1986) have suggested that 20 000 hours is reasonable for most gensets. Based on a generous service life of 30 000 hours for a well maintained engine and an average daily run time of 11,15 hr/day, the system lifetime adopted for this analysis is seven years. The service life of 30 000 hours was considered attainable because the genset had already logged 13 000 hours and was in good working order.

The battery at Woodlands is cycled on a daily basis. The estimated battery life is based on a cycle life of 500 cycles and an annual total of 100 deep cycles per year.

A real discount rate of 4% was thought to be reasonable for the National Parks Board (see Section 5.2.2.1).

The escalation rate of 0% is a measure of the relative escalation of energy related costs and the general price index escalation due to inflation.

General sales tax is due on plant and equipment.

The cost of the genset is for a 7 kVA (electrical) single phase 220 V LISTER ST2 diesel genset complete with bedplate, remote stop/start, exhaust and control panel ex factory.

The fuel tank cost includes a 45 litre steel fuel tank complete with fuel lines and diesel filter.

The battery charger cost is the manufacturer's quoted price ex-factory for a 36 V 100 A DC charger with thyristor regulator.

The battery cost is based on manufacturer's quoted price for eighteen batteries at R 590,00 per RAYLITE 2 IMR 4 V battery (inclusive of lead surcharge) ex factory.

The planning was assumed to be done by the National Parks Board and these costs have been omitted.

The land was assumed not to have cost the National Parks Board anything.

The generator room cost is based on the estimated cost of a 9 m² ventilated brick generator room and concrete genset foundations.

As for Jock of the Bushveld and Boulders, the cost of the 8 m² ventilated battery room was omitted.

The wiring cost includes the estimated cost of the switchgear and wiring between the generator room and the battery room.

No cost has been included for transport

The estimated cost of installation is 3% based on the initial equipment cost inclusive of GST

No commissioning costs or engineering fees were included.

The estimated annual costs of administrative overheads for the system was R 2 000 (see Section 5.2.1.5) and the estimated annual O&M cost is based on the more probable O&M costs discussed in Section 5.4.1.5.

The estimated average daily energy output of the system on which the unit cost of energy calculation is based was 16,56 kWh/day. This figure is the measured average daily system output during the monitoring period.

5.4.2.2 Capital costs

The initial capital cost of the system is calculated as :

Diesel genset	: 14 000,00
Fuel tank	: 150,00
Generator room	: 2 000,00
Battery charger	: 1 930,00
Batteries	: 11 600,00
Inverter	: 4 350,00
Wiring	: 150,00
Sub total	: 33 180,00
GST	: 3 982,00
Installation	: 1 115,00
TOTAL	: 38 277,00

5.4.2.3 Operating and maintenance costs

No. of battery replacements : 1

Battery replacement costs (NPV) : 7 923,00

Residual value of batteries (NPV) : (806,00) negative NPV

Admin. costs (NPV) : 12 004,00

Maint. and labour costs (NPV) : 64 822,00

Overall O&M costs (NPV) : 76 826,00

5.4.2.4 Lifecycle cost

Total installed cost : 38 277,00

Battery replacement cost : 7 923,00

Residual value : (805,00)

Total O&M costs : 76 822,00

NPV lifecycle cost : 122 217,00

Annualized unit energy cost : 337 c/kWh

Figure 5.46 shows the cashflow for the project over the lifetime of seven years and the annualized unit energy cost at the end of each year.

In contrast to the PV systems at Jock of the Bushveld and Boulders, the graph illustrates the relatively lower initial costs in year zero for the Woodlands genset-plus system. Similarly the subsequent annual O&M costs for years one to seven are relatively high. The battery replacement cost in the fifth year is less than the individual annual O&M costs. The unit energy cost line represents the unit cost of electricity, calculated at the end of each year, based on the total number of units generated up until that time. Again, the unit cost of electricity generated decreases asymptotically to the limit which is the quotient of the annual O&M costs divided by the annual number of units generated, ie. 179 c/kWh. In practice the operating lifetime of the system sets the unit cost limit which in this case is 337 c/kWh over the seven year lifetime.

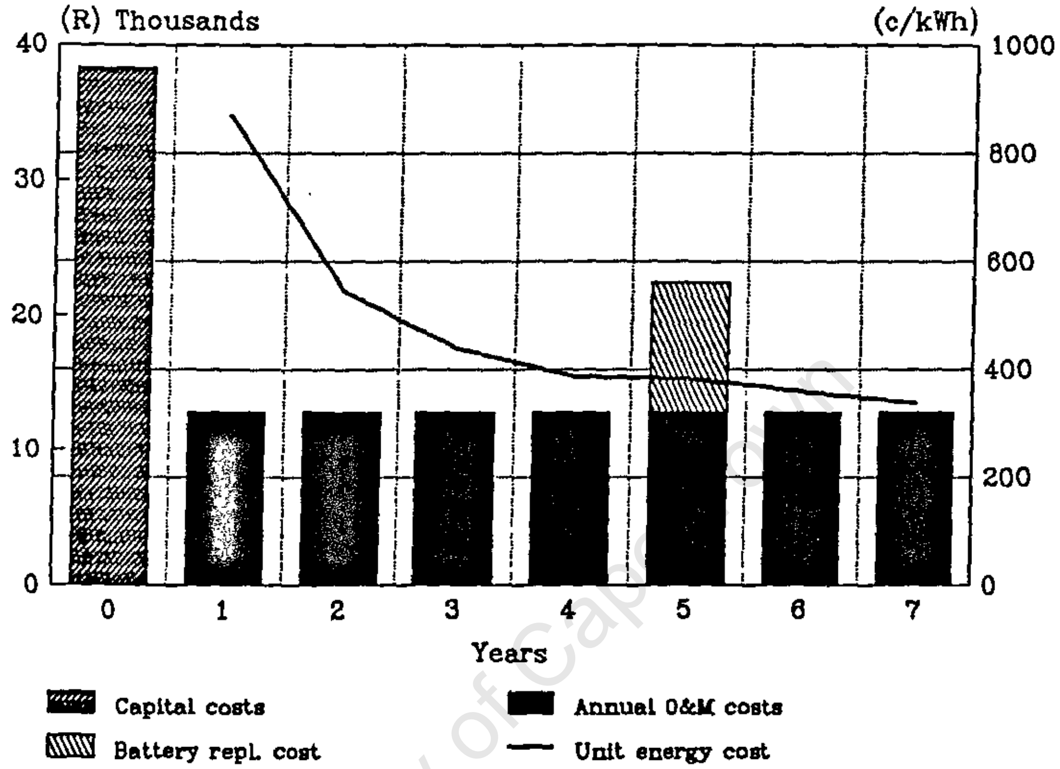

Figure 5.46 : The estimated cashflow and the estimated unit energy cost of kWh supplied for the diesel genset-plus system at Woodlands over a projected lifetime of seven years

The cost components of the NPV life-cycle cost evaluated over seven years are :

Investment costs	: 31 %
O&M costs	: 69 %

5.4.3 Summary

The single most important factor which determined the overall performance of the Woodlands genset-plus system was the operating regime. Table 5.22 briefly summarizes the recorded performance of the Woodlands genset-plus system.

Table 5.22 : Summary of key indicators of the performance of the Woodlands genset-plus system

System description	36V DC/220V AC genset-plus system
Genset rating	7,0 kVA (5,6 kW) LISTER genset
Battery charger	36 V 100 A thyristor regulated
Battery storage	36 V 1180 Ah (tubular plate)
Inverter rating	3 kW sine wave
Installed load	9,00 kW 220 V AC (lights, fridges stoves, A/C, etc.)
Load per person	3,0 kW
Peak load	1,85 kW
Ave. load	685 W
Load factor	0,37
Ave. LED	16,56 kWh/day
LED per person	5,52 kWh/day
Ave. genset eff.	14,3 %
Max. genset eff.	19,5 %
Ave. genset output	2,05 kW
Max. genset output	3,29 kW
Ave. cap. factor	0,30
Ave. run time	11,15 hours/day
Ave. fuel cons.	1,42 l/hour (620 g/kWh_e)
Batt. charger eff.	93 %
Ave. charge current	38 A
Ave.depth of disch.	30 %
Battery Wh eff.	71 %
Ave. inverter load	730 W
Max. inverter load	1,85 kW
Ave. inverter eff.	64 %
Overall system eff.	8,7 % (average)
Ave. O&M costs	1,72 R/hr
Ave. fuel costs	0,93 R/hr
Installed cost	R 38 277,00
Batt. repl. cost	R 7 923,00
O&M costs	R 76 822,00
NPV life-cycle cost	R 122 217,00
Unit energy cost	337 c/kWh

The underlying rationale on which the genset-plus concept is based is the reduction of running costs of the genset by increasing the average genset capacity factor by the introduction of an energy storage reservoir. The evidence accumulated over the brief period of recorded data indicates that the operating regime is based purely on the elimination of noise at night regardless of the operating efficiency of the overall system. The genset is started at dawn and switched off at dusk regardless of the energy flows across the battery.

Optimum operating efficiency would be achieved by increasing the manually adjustable battery charge current from 38 A to the maximum recommended charge current for the batteries, (98 A in the case of the RAYLITE batteries installed), and operating the genset for approximately five hours per day, at an average capacity factor of 90%, until the batteries are fully charged, before shutting down the genset. The whole cycle would be repeated as soon as the battery state of charge fell to approximately 40% ie. roughly 23 hours later.

The overall operating regime should therefore be determined by the charge/discharge cycle of the battery. Ideally the system should be controlled automatically (with a manual over-ride facility), on the basis of the battery voltage under charge and discharge.

Despite the inefficient operating regime, the system is essentially correctly sized and the system components are well matched.

The 3 kW sine wave inverter is appropriately sized to supply the average load power demand of 730 W and in addition provide sufficient capacity to start and run AC motors in the household appliances. The average inverter efficiency of 64% is tolerably good for this compromise. A more sophisticated multi-stage inverter would accommodate the awkward range of load power demands at a higher average efficiency but at a higher initial cost.

The 1180 Ah nominal capacity batteries are sized to provide between 0,8 and 1,5 days of autonomous operation based on a maximum depth of discharge of 60% and the variation in the load energy demand of between 10,5 kWh/day and 23,7 kwh/day. Based on the maximum recommended charge current of 98 A, to prevent overheating and excessive gassing, the average charge time would be approximately five hours. In practice the batteries appeared to have been abused and displayed signs of deterioration, (ie. a Wh efficiency of 71%). Anecdotal evidence indicated that they had stood unattended for over a year before being commissioned at Woodlands. The battery capacity would almost certainly have been reduced by such an extended period of disuse. In addition the lack of evidence of equalizing charges or battery maintenance implies a lack of basic care for this essential component in the genset-plus system.

The 100 A 36 V battery charger is ideally sized, but under-utilized, for the 98 A maximum charge current specified for the batteries. It operated at an average efficiency of 93% at an average charge current of 38 A and functioned well in the constant current/constant voltage mode, as demonstrated over the protracted 36 hour charging period. In practice the battery charger should have been operated at the optimal recommended maximum charge current of 98 A instead of at the less efficient rate of 38 A.

The 5,6 kW 7 kVA LISTER ST2 diesel genset is well sized for the combined power demand of the battery charger at full 100 A rated charge capacity and the load power demand of the household appliances. The unnecessarily long operating hours at a low capacity factor of 0,3 (due to the low charge current setting on the battery charger), contribute to the high average specific fuel consumption of 620 g/kWh and low average operating efficiency of 14,3%.

Overall, the system could meet the electricity requirements of the ranger´s camp for a lower unit cost than the current cost of 337 c/kWh, and accomplish it with less noise, if more efficient utilization were made of the existing plant.

5.5 Shingwedzi

The technical and economic evaluation of the two 380 V three phase 225 kVA and 250 kVA diesel gensets installed at Shingwedzi is based on :

- handwritten logbooks of the hourly instantaneous power output of the two gensets for the period 13/01/86 to 30/09/87.
- 'Motorvoertuiglogstaat' fuel and oil consumption logs for the period January 1986 to September 1987.
- Maintenance job cards for the work done to the gensets over the period January 1986 to November 1987.
- Accommodation data as recorded by the tourism administration at Shingwedzi.

5.5.1 Technical evaluation

5.5.1.1 System load curves and load energy demand

Based on the log of the hourly power output for the one year period between 01/09/86 and 01/10/87 the maximum, minimum, and the average hourly power output were calculated and are tabulated in Table 5.23.

The system load factor was 0,43 based on the average daily load power demand of 108,6 kW and the maximum recorded load power demand of 255 kW at 18h00 on Saturday 11/10/86. The minimum recorded load power demand was 40 kW at 03h00 and 04h00 on Friday 19/06/87. The total installed load power demand of the system loads is 454 kW which reflects an average load diversity factor of 23,9% and a maximum and minimum of 56,2% and 8,8% respectively.

Table 5.23 : Tabulated load power demand for Shingwedzi over the 365 day period between 01/09/86 and 01/10/87

Time (00h00)	Average power (kW)	Maximum power (kW)	Minimum power (kW)
01h00	74,36	140	45
02h00	71,62	135	45
03h00	70,00	120	40
04h00	70,12	125	40
05h00	74,59	135	45
06h00	105,73	200	55
07h00	130,31	195	80
08h00	131,37	200	85
09h00	124,84	195	80
10h00	116,20	185	75
11h00	115,44	195	75
12h00	120,77	185	75
13h00	120,56	200	75
14h00	118,43	230	70
15h00	117,13	215	65
16h00	118,73	215	65
17h00	124,99	225	70
18h00	147,86	255	80
19h00	147,16	240	90
20h00	132,11	240	75
21h00	115,98	210	55
22h00	96,04	180	55
23h00	82,51	150	50
24h00	77,55	145	45

Figure 5.47 shows the load curves for the annual average hourly load power demand as well as those of the monthly average hourly load power demand for summer, (December 1986), and winter, (June 1987).

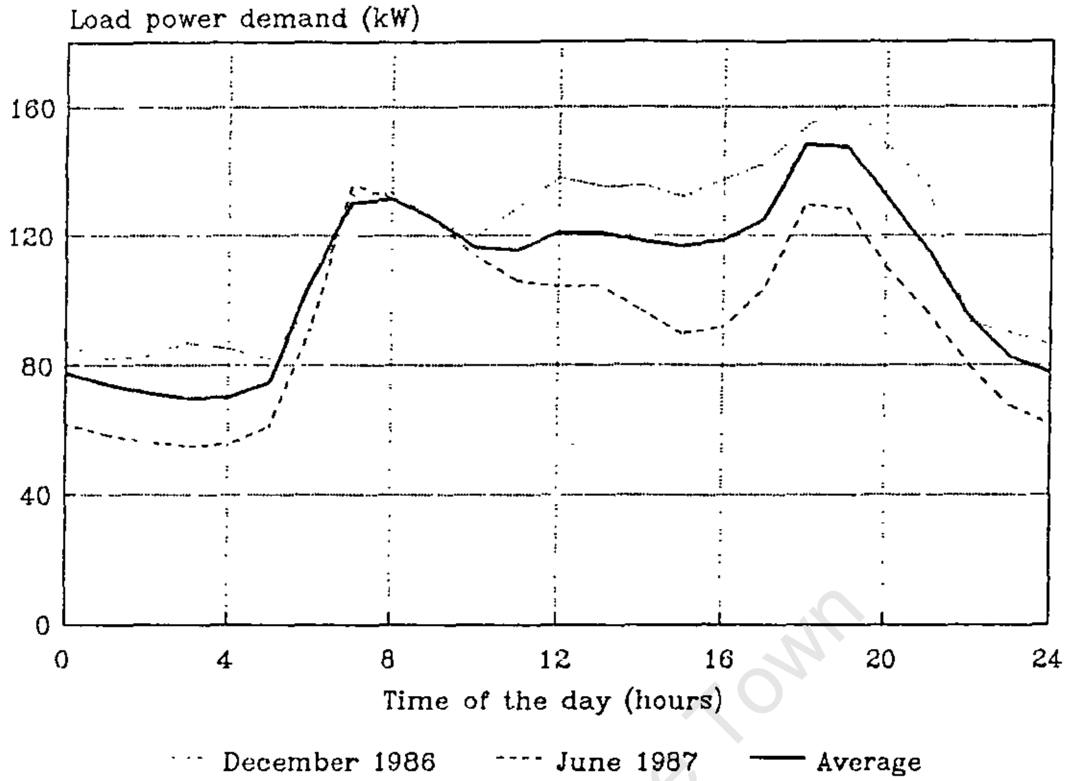

Figure 5.47 : Load curves of the annual average hourly load power demand and the monthly average hourly demand in summer and winter for Shingwedzi

The system load curves exhibit two peaks of about 135 kW between 07h00 and 08h00 and 130 kW to 160 kW between 18h00 and 19h00. The annual average base load is approximately 70 kW. A further characteristic of the load power demand illustrated by the curves in Figure 5.47 is the contrast between the summer and winter hourly average loads. The summer load curve exhibits a base load of approximately 85 kW as opposed to a winter base load of approximately 60 kW. The early morning peak of approximately 135 kW between 07h00 and 08h00 is similar in magnitude and timing, but the increased load power demand due to air-conditioning is clearly evident from 10h00 onwards and during the night. The evening peak of approximately 163 kW at 19h00 in December is 30 kW greater and displaced one hour later than the evening peak of 130 kW between 18h00 and 19h00.

The average daily load energy demand for December and June were 2844 kWh/day and 2257 kW/day respectively.

The monthly averages of the daily load energy demand and average capacity factor per single set are tabulated in Table 5.24.

Table 5.24 : Monthly averages of the daily load energy demand and monthly average capacity factor at Shingwedzi for the 365 day period between 01/09/86 and 01/10/87

Month	Average monthly LED (kWh/day)	Average capacity factor (%)
Oct 86	2638	0,58
Nov 86	2518	0,55
Dec 86	2844	0,62
Jan 87	2691	0,59
Feb 87	2837	0,62
Mar 87	2784	0,61
Apr 87	2999	0,66
May 87	2416	0,53
Jun 87	2257	0,49
Jul 87	2647	0,58
Aug 87	2529	0,55
Sep 87	2398	0,53

The average daily load energy demand was 2605 kWh/day varying between a maximum of 4130 kWh/day on Monday 08/06/87 and a minimum of 1995 kWh/day on Wednesday 29/10/86.

The average daily load energy demand for each month is plotted in Figure 5.48 for the year under consideration.

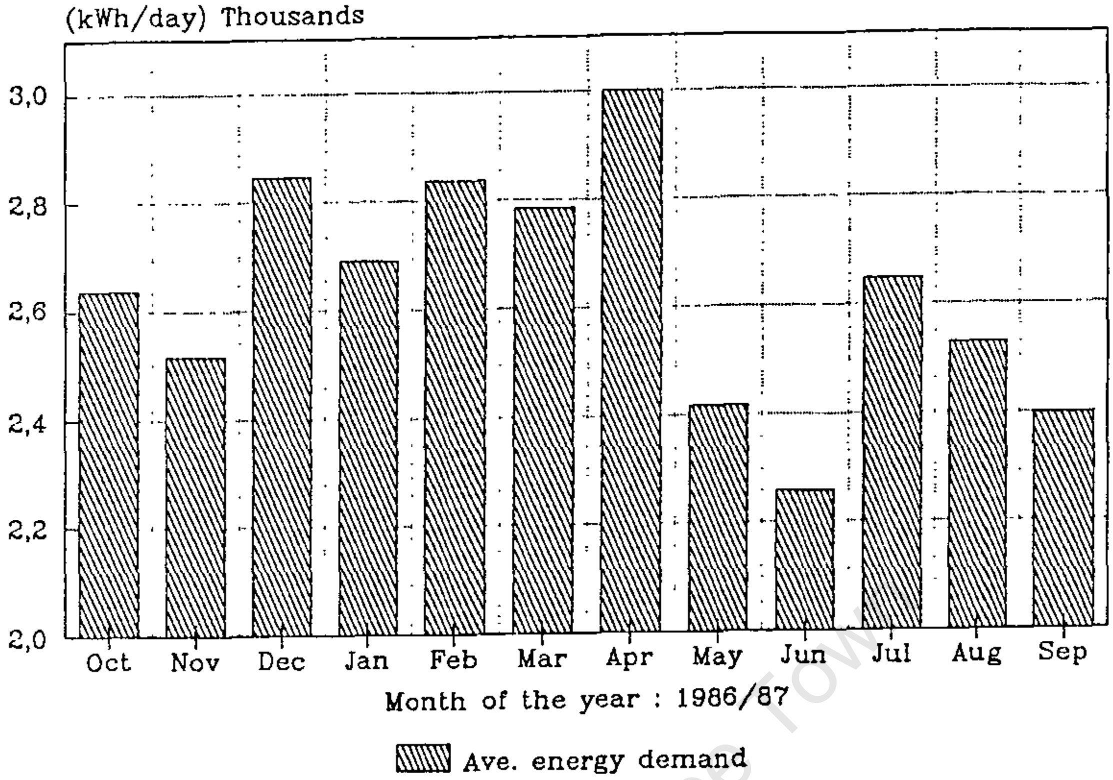

Figure 5.48 : Monthly average daily load energy demand for Shingwedzi for the 365 day period between 01/09/86 and 01/10/87

The annual variation in daily load energy demand is large and appears to be a function of the combined factors of occupancy of the camp and air-conditioning load, (and hence ambient temperature). This observation is supported by the lack of a direct correlation between camp occupancy, in terms of tourists or in terms of huts, and the daily load energy demand, as illustrated in Figures 5.49 and 5.50.

Based on the schedule of loads installed at Shingwedzi as listed in Appendix C.4, the calculated load energy demand for daily use patterns increases from 2376 kWh/day, for reasonable patterns of load usage, to 4240 kWh/day by increasing the air-conditioner usage from 5 hr/day to 18 hr/day.

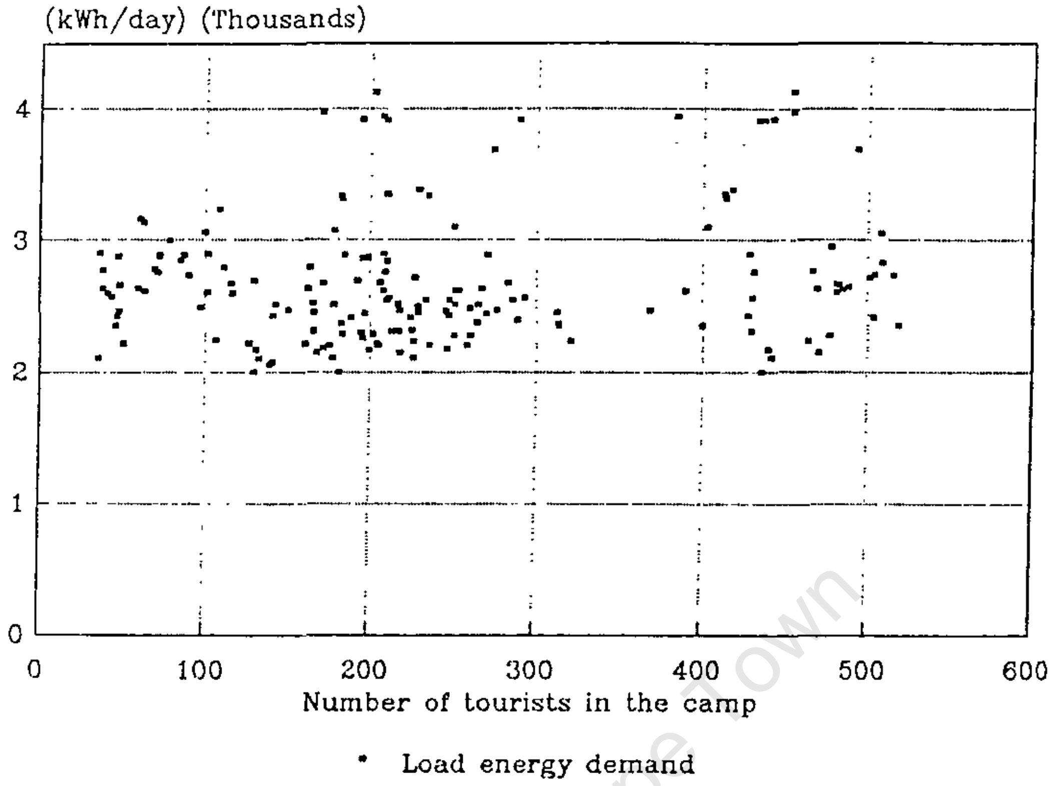

Figure 5.49 : **Graph of the daily load energy demand vs the number of tourists accommodated in the camp**

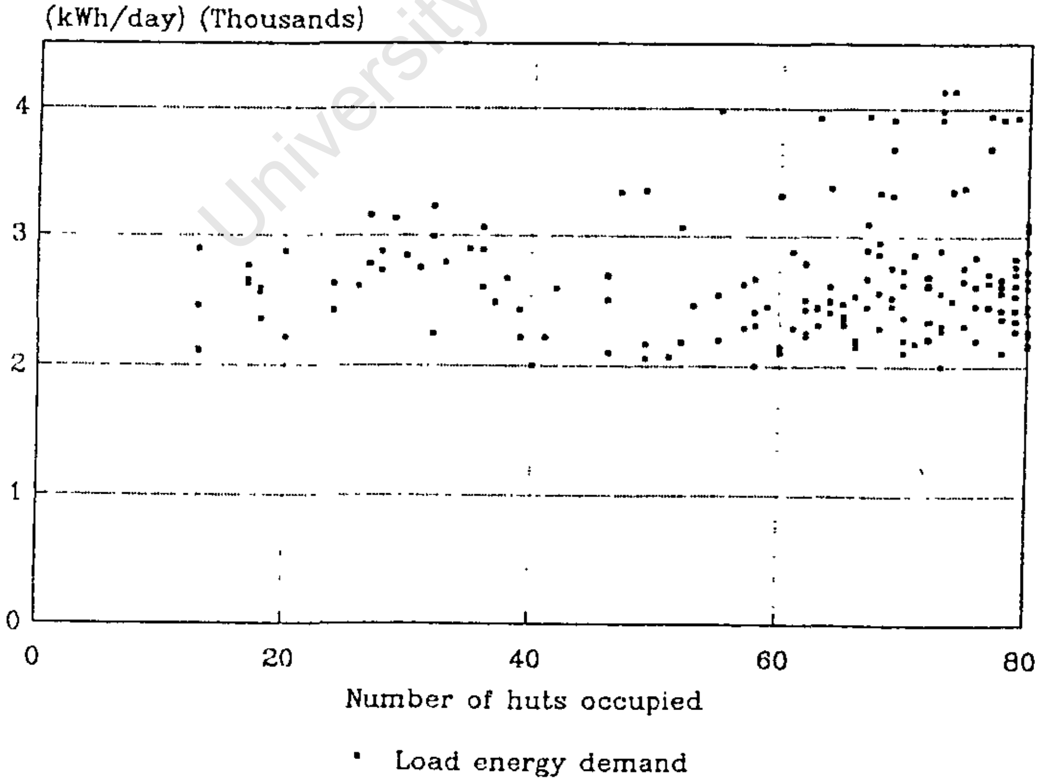

Figure 5.50 : **Graph of the daily load energy demand vs the number of huts occupied in the camp**

Figure 5.51 shows a frequency distribution of the daily load energy demand for the year.

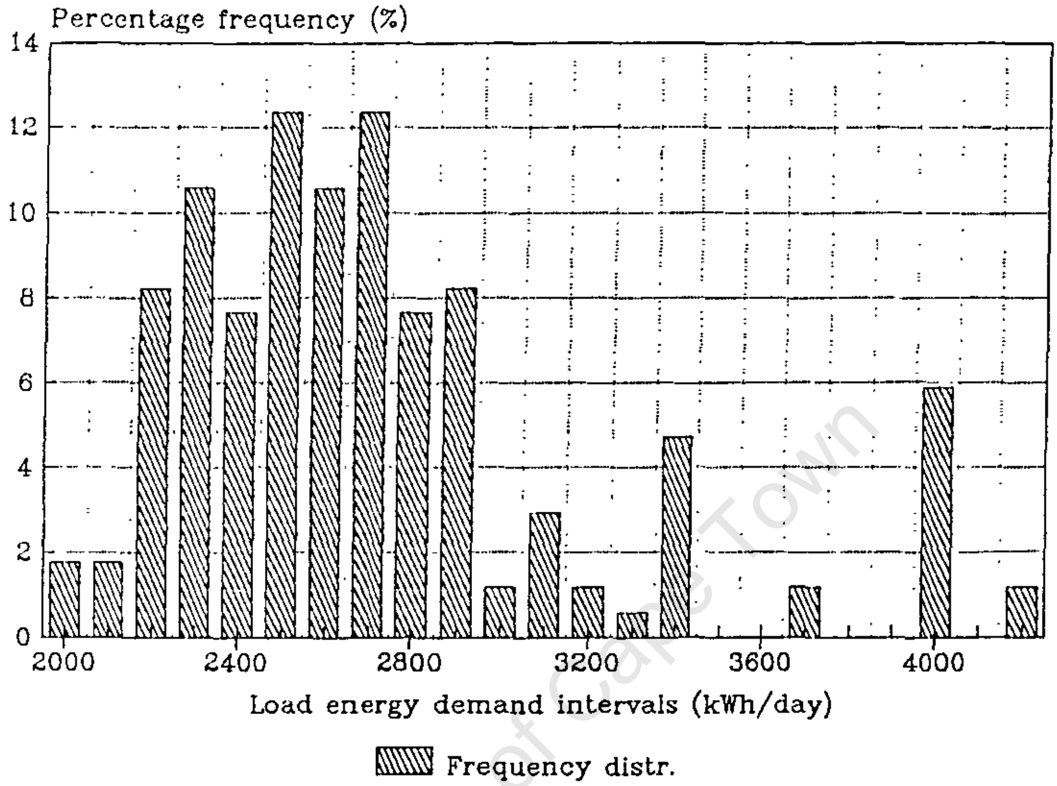

Figure 5.51 : Frequency distribution of the daily load energy demand over the 365 day period between 01/09/86 and 01/10/87 for Shingwedzi

5.5.1.2 Performance of the two Shingwedzi diesel gensets

5.5.1.2.1 Operating considerations

The two gensets installed in the Shingwedzi power station are CAT D3406 sets, one 225 kVA/180 kW turbocharged set and one 250 kVA/200 kW set with turbocharger and aftercooler. They are identified by their National Parks Board serial numbers, K16 and K125 respectively. The sets operate on alternate days, providing a duty and standby capacity. The sets have short term standby ratings of 200 kW and 240 kW for brief overload capacity.

In practice, the standby set is operated in parallel with the duty set for periods when the load power demand exceeds the continuous rated power output of the duty set ie. 180 kW and 200 kW respectively for K16 and K125. A full-time power station operator is employed to ensure the smooth operation of the plant and maintenance of the hourly power station log records.

Based on the figures recorded on the maintenance job cards over a periods of 642 and 668 days, the average daily run time for the sets was calculated to be 20,6 hr/day and 21,1 hr/day for K125 and K16 respectively. Based on the genset logbooks kept by the power station attendant, these figures appear to be an under-estimate. Each set runs for at least 24 hr/day and sometimes more if the load power demand of the camp exceeds the maximum continuous power rating of the duty set. The discrepancy between the calculated run time and the observed run time in the power log books would be accounted for by an uncertainty of ±5,0% in the engine hour meters resulting in an uncertainty in the calculated daily run time of 4,3 hr/day.

The gensets had operated for 23 550 ±1200 hours by 30/10/87 (K16) and 15 995 ±800 hours by 03/11/87 (K125) according to the job card records.

Based on the fuel and oil consumption logs for the 21 month period between January 1986 and October 1987, the fuel consumption for K16 and K125 was 35,6 ±2,1 l/hr and 35,1 ±2,2 l/hr respectively. Overall the average specific fuel consumption was 285 g/kWh. The oil consumption was 0,25 ±0,025 l/hr for K16 and 0,29 ±0,032 l/hr for K125.

The rated fuel consumption for K16 is 31,77 l/hr @ 50% load rising to 43,17 l/hr @ 75% load. The rated fuel consumption for K125 is 31,46 l/hr @ 50% load rising to 44,21 l/hr @ 75% load. By linear interpolation the fuel consumption at the average load of 58% of full rated capacity is 35,27 l/hr and 35,37 l/hr for K16 and K125 respectively.

The overall annual average efficiency of the Shingwedzi power station gensets was 34,4 ±3,9% based on the recorded daily run times, fuel consumptions and the average daily load energy demand of 2605 kWh/day.

5.5.1.2.2 Maintenance considerations

The complete record of maintenance performed on the Shingwedzi CAT sets is presented in Appendix G. The maintenance record is based on the job cards completed by the diesel fitter over the 642 and 668 day periods for K125 and K16 respectively.

The CAT agents, (Barlows Product Support Dept.), recommend 250 hour service intervals for lightly loaded engines but 125 hour service intervals are recommended for engines running at the duty required at Shingwedzi. In addition the engines require a major service at 1000 hour intervals. The maintenance schedule that appears to have been adopted at Shingwedzi, as borne out by the job card records, is based on service intervals of 125 hours, 250 hours, 500 hours and 1000 hours.

A 125 hour service would include change of oil and fuel filters and oil and checks on air cleaners, fluid levels, radiator, hoses etc. The 1000 hour service includes adjusting the tappet clearances in addition to the 125 hour service requirements.

The estimated maintenance cost in terms of labour and spares for the two gensets over the 21 month period between January 1986 and October 1987 was R 31 847,00 for K16 and R 24 757,00 for K125. These figures equate to 4,52 R/hr and 3,74 R/hr respectively and are based on the maintenance work recorded on job cards and labour cost of 22,00 R/hr.

The estimated fuel cost for the gensets is between 25,89 R/hr and 25,57 R/hr based on the cost of diesel to the National Parks Board of 72,8 c/litre and an average fuel consumption of 35,57 litre/hr for K16 and 35,12 litre/hr for K125. The estimated oil cost would be 0,55 R/hr based on a oil cost of 2,00 R/litre and an average oil consumption of 0,275 litre/hr.

The cost of two power station operators is estimated to cost the National Parks Board approximately R 24 000,00 per year, ie. 2,74 R/hr.

The overall average O&M cost would be between 33,70 R/hr for K16 and 32,60 R/hr for K125.

For a combined aggregate average daily run time of 24,3 hr/day the annual O&M cost for the Shingwedzi power station is R 294 024,00.

5.5.1.2.3 Availability

One major mechanical failure was recorded in the job cards. A cracked No.2 "piston chamber" on K16 on 07/03/86 resulted in water contamination of the crankcase oil and a loss of power. The set was shut down at 17h55 for repairs which put the set out of commission for two days. Power availability appeared not to have been affected thanks to the standby capacity of K125.

The configuration and sizing of the Shingwedzi diesel gensets contribute to an overall installation with an inherently high degree of reserve capacity and availability. The gensets are each capable of meeting the load power demand for 98% of the time, allowing a generous degree of flexibility for routine maintenance and breakdowns, as illustrated above.

There was one recorded power failure of 15 minutes duration between 20h00 and 21h00 on 04/04/87 when K16 was providing the load. The load was taken up by K125, on standby, and the fault on K16 was investigated. As no faults were detected on K16, the failure was attributed to operator error.

5.5.2 Economic evaluation

The economic evaluation was based on the annuity method described by Fink and Oelert (1985) as discussed in Section 4.7.

5.5.2.1 Assumptions on which the economic analysis is based

The assumptions on which the economic evaluation for the Shingwedzi twin genset system is based are summarised in Table 5.25 :

Table 5.25 : Summary of assumptions for the economic evaluation of the Shingwedzi twin genset system

System lifetime	: 15 years
Discount rate	: 4 %
Escalation rate	: 0 %
GST	: 12 %
Genset costs	: R 172 000
Exhaust costs	: R 3 600
Fuel tank	: R 4 000
Planning costs	: 0 % of installed system cost
Cost of land	: R 0
Generator room	: R 20 000
Wiring and switchgear	: R 1 000
Transport to site	: R 0
Installation cost	: 3 % of equipment cost
Commissioning cost	: 1 % of equipment cost
Engineering fees	: 4 % of installed cost
Admin. infrastructure cost	: 5 000 R/year
Maint. and fuel cost	: 294 000 R/year
Ave. daily energy output	: 2605 kWh/day

The system lifetime is based on the projected useful lifetimes of the gensets. Based on a service life of

60 000 hours and an average daily run time of 12,15 hr/day, the system lifetime adopted for this analysis is fifteen years. The sets had already clocked 16 000 and 24 000 hours respectively and were thought to be in sound operating condition. The estimated lifetime of 60 000 hours is generous but not unattainable for these large sets.

A real discount rate of 4% was thought to be reasonable for the National Parks Board (see Section 5.2.2.1).

The escalation rate is a measure of the relative escalation of energy related costs and the general price index escalation due to inflation.

General sales tax of 12% is due for plant and equipment.

The cost of the 225 kVA (electrical) three phase 380 V CAT D3406T and 250 kVA CAT D3406TA diesel gensets includes the CAT SR4 generators, bedplates and control panels ex factory.

The exhaust costs are for two exhaust stacks and silencers ex factory.

The cost of a 4500 litre steel fuel tank includes fuel lines and diesel filters.

The planning was assumed to be done by the National Parks Board and these costs have been omitted.

The land was assumed not to have cost the National Parks Board anything.

The estimated cost of the 60 m^2 ventilated brick generator room and concrete genset foundations is R 20 000.

The cost of the switchgear and wiring in the generator room was estimated at approximately R 1 000.

No cost has been included for transport of equipment to site.

Estimated cost of installation of 3% is based on the initial equipment cost inclusive of GST.

Estimated cost of commissioning a large system such as this is 1%, based on the initial equipment cost inclusive of GST.

Estimated cost of professional fees for engineering design and project management for a large project is 4%, based on the total installed project cost.

The estimated costs of administrative overheads and annual O&M cost for the system are discussed in Section 5.2.1.5.

The estimated average daily system energy output on which the unit cost of energy calculation is based is the calculated average daily system output based on the hourly data logs.

5.5.2.2 Capital costs

The initial capital cost of the system is calculated as :

Diesel gensets	:	172 000,00
Exhausts	:	3 600,00
Fuel tank	:	4 000,00
Generator room	:	20 000,00
Wiring	:	1 000,00
Sub total	:	200 600,00
GST	:	24 072,00
Installation	:	6 740,00
Commissioning	:	2 247,00
Engineering fees	:	8 987,00
TOTAL	:	242 646,00

5.5.2.3 Operating and maintenance costs

Admin. costs (NPV) : 55 592,00
Maint. and labour costs (NPV) : 3 268 806,00

Overall O&M costs (NPV) : 3 324 398,00

5.5.2.4 Lifecycle cost

Total installed cost : 242 646,00

Residual value : 0,00

Total O&M costs : 3 324 398,00

NPV lifecycle cost : 3 567 034,00

Annualized unit energy cost : 33,7 c/kWh

The cost components of the NPV life-cycle cost evaluated over fifteen years are :

Investment costs : 7 %
O&M costs : 93 %

Figure 5.52 shows the cashflow for the project over the lifetime of fifteen years and the annualized unit energy cost at the end of each year.

In contrast to the two PV systems at Jock of the Bushveld and Boulders and the genset-plus system at Woodlands, the graph shows that the annual O&M costs for the system is greater than the initial capital costs in year zero. The unit energy cost line represents the unit cost of electricity, calculated at the end of each year, based on the total number of units generated up until that time. Again, the unit cost of electricity generated decreases asymptotically to the limit which is the quotient of the annual O&M costs divided by the annual number of units generated, ie. 31,4 c/kWh.

In practice the operating lifetime of the system sets the unit cost limit which in this case is 33,7 c/kWh over the fifteen year lifetime.

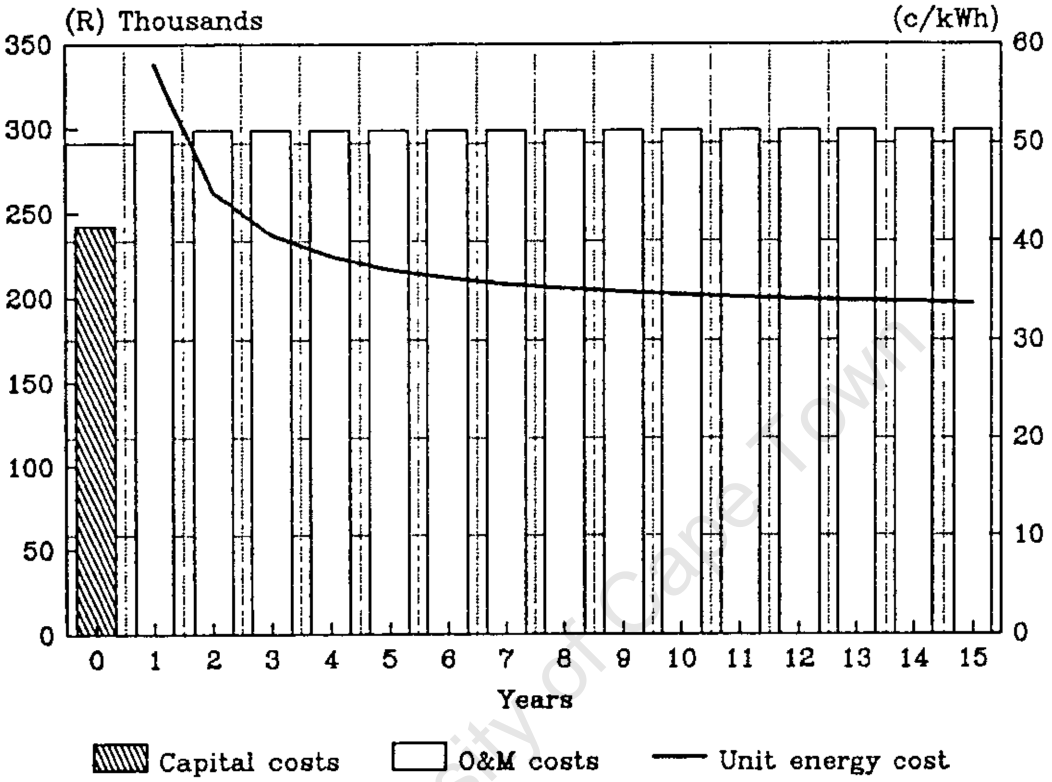

Figure 5.52 : The estimated cashflow and the estimated unit energy cost of kWh supplied for the twin diesel genset system at Shingwedzi over a projected lifetime of fifteen years

5.5.3 Summary

Table 5.26 overleaf, briefly summarizes the key performance characteristics of the Shingwedzi twin genset installation.

Table 5.26 : Summary of key indicators of the performance of the Shingwedzi twin genset system

System description : twin 225 kVA/250 kVA gensets
Genset rating : 180 kW/225 kVA and 200 kW/250 kVA

Installed load : 454 kW 220 V AC (lights, A/C, hot water, admin. etc)
Load per person : 760 W/person
Peak load : 255 kW
Ave. load : 109 kW
Load factor : 0,42
Ave. div. factor : 0,24
Ave. LED : 2605 kWh/day
Max. LED : 4130 kWh/day
LED per person : 11,3 kWh/day (average)
: 18,0 kWh/day (maximum)

Ave. genset eff. : 34,4 %
Ave. cap. factor : 0,49-0,66 (monthly averages)
Ave. run time : 24,3 hrs/day (duty set + standby)
Ave. fuel cons. : 35,4 l/hour (285 g/kWh$_e$)

Overall system eff.: 34,4 % (average)

Ave. O&M costs : 4,13 R/hr
Ave. fuel costs : 25,7 R/hr

Installed cost : R 242 646,00
O&M costs : R 3 324 398,00
NPV life-cycle cost: R 3 567 034,00

Unit energy cost : 33,7 c/kWh

The 225/250 kVA twin genset installation at Shingwedzi is a very well optimized system that is ideally matched to the electricity requirements of the tourist camp.

The relatively high load factor of 0,43 coupled to the load diversity and inertia in the instantaneous load power demand enable the twin genset system to operate at more optimal monthly average capacity factors of between 0,49 and 0,66.

The system achieves high capacity factors and a high degree of standby security by virtue of the alternating roles of the two gensets, which ultimately minimize the operating and maintenance costs at the relatively insignificant price of increased initial capital costs. Each genset is capable of meeting 98% of the typical daily load power demand while the other is on standby or undergoing maintenance.

The benefits of economies of scale for diesel gensets are demonstrated by the relatively low unit energy cost of 33,7 c/kWh for the Shingwedzi installation. Despite the running costs being a high proportion (93%) of the lifecycle costs, this well maintained system confirms the viability of diesel gensets for larger off-grid electricity requirements.

CHAPTER SIX

DISCUSSION

The purpose of the monitoring project described in this thesis, and the technical and economic evaluation of the four RAPS in the Kruger National Park, was to more fully understand the overall system performance, system dynamics, operating regimes, component matching and the actual system efficiencies of off-grid power systems.

The immediate benefits of this empirically based understanding would be improved design of off-grid power systems resulting in more economical systems and an increased awareness amongst engineers and institutional organizations of the relative merits of PV, gensets and genset-plus systems in the Southern African context.

Most design and sizing procedures for RAPS require some basic assumptions regarding a range of anticipated operating parameters such as PV module efficiency and operating temperature, battery efficiencies, voltage regulator, inverter and DC/DC converter effiencies, load factors etc. This project begins to provide an empirical basis, in the form of recorded operating parameters, summarized in Tables 5.8, 5.16, 5.22 and 5.26, for making these assumptions. In addition the realistic economic evaluation of these four systems begins to furnish a frame of reference for assesing the cost of off-grid electricity for a range of technologies and electricity demands.

The format of the discussion below is one which first comments on some general technical and economic implications of the configuration and design of off-grid electrical power supply systems, before discussing more specific aspects system design in the light of the analysis and findings for the PV, diesel and diesel genset-plus systems investigated in this project.

6.1 PHOTOVOLTAIC SYSTEMS

The 800 W_p AC PV system at Jock of the Bushveld and the 3360 W_p DC PV system at Boulders are two contrasting examples of an older, poorly optimized, (and consequently more expensive), AC PV design and a newer, better engineered DC PV system which was operating at 20% of the cost of the former system.

As highlighted in Section 5.3, the predominant source of system inefficiency in the Jock of the Busveld AC PV system is the gross oversizing of the 3 kW square wave inverter for the installed load rating of 420 W. In practice the load demand characteristics of the high efficiency AC light fittings are well defined and easily measured, (Appendix C.1; Section 5.2.1.2), and consequently the correct sizing of the inverter should not have been difficult.

Overall, an AC PV system for Jock of the Bushveld could be substantially smaller, more efficient and supply the required power at a lower delivered unit energy cost if it were sized and designed to incorporate a more efficient and better matched inverter.

The other salient feature of the overall performance of the Jock of the Bushveld AC PV system is the extent of the battery degradation, which was manifested in the low recorded watt-hour cycle efficiency of 66%. The systems' match between the PV array, voltage regulator and the battery would also be more optimal than the recorded 3-12% power loss if the battery were in a sound operating condition.

The essentially sound design but conservative sizing of the DC PV system at Boulders is highlighted in Section 5.3.3. The load demand characteristics are less well defined than for Jock of the Bushveld, (Appendix C.2, Section 5.3.1.2).

The main source of non-optimality in this system is the apparent mismatch of the array and the average daily load power demand from the battery recorded over the monitoring period. Both the sizing of the array with respect to the load energy demand, and the matching of the battery charging voltage and the optimum operating voltage of the array at elevated operating array temperatures, could be optimized to increase the overall efficiency of the system, (Section 5.3.1.3.5).

The specification of a smaller battery capacity and smaller array peak watt rating, and the configuration of the system as a 64 V (nominal) system, (to improve the system matching between the optimum operating voltage of the array and the average battery charge voltage), with 32 cells and 64 V/ 12 V DC/DC converters would seem to have been mechanisms for optimizing the system.

6.1.1 General comments on PV system components

A brief discussion of the basic components in PV off-grid power supply systems is offered in the light of the evaluation of the AC PV system at Jock of the Bushveld and the DC PV system at Boulders. Detailed discussions of these components are found elsewhere in standard texts.

6.1.1.1 PV modules

The average efficiencies of the PV arrays were between 60% and 80% of the quoted module efficiency depending on the temperature, insolation and primarily on the operation of the voltage regulator. The overall reduction in effective conversion effiency is due to module mismatch within the array due to manufacturing tolerances, inter-module connector losses and dust accumulation.

The module costs were approximately R 19/W_p. The array costs represent 53% and 60% of the installed costs and this high proportion of the installed costs emphasizes the need to reduce the peak watts required for the system.

No module failures had been recorded.

The matching between the PV array optimum operating voltage and the average battery charging voltage must be optimized for operating conditons ranging from 400 W/m^2 @ 25°C to 1000 W/m^2 @ 60°C. The power losses inferred from Figures 5.11 and 5.25 vary between 3% at high array temperatures and high levels of insolation to as much as 35% at low array temperatures and low levels of insolation.

The array should be angled so as to optimize the power output for the critical month(s). The implications of tracking array supports were not considered in this study.

The module temperatures varied from ambient to as high as 62°C. The average module temperatures were 29,2°C at Jock of the Bushveld and 33,1°C at Boulders. The generally higher module temperatures at Boulders are due to : i) the fact that the Boulders array is one large 7,0 m x 6,3 m heat transfer surface compared to the three smaller 1,2 m x 2,4 m sub-array surfaces at Jock of the Bushveld; ii) the Boulders array is mounted on a battery room and therefore has very little air circulation behind the array compared to the free-standing sub-arrays at Jock of the Bushveld; iii) the Boulders array is tilted at approximately 10° less to the horizontal than the array at Jock of the Bushveld which increases the effective area under the high summer sun; iv) the Boulders array was often in open circuit and therefore not dissipating any incident radiant energy into the battery, unlike the Jock of the Bushveld array which was never in open circuit due to the voltage regulator having been bridged out.

6.1.1.2 DC power conditioning equipment

The use of maximum power point controllers to optimize the array/battery voltage match was not considered in this study although it would appear that the added complexity and potential for reduced reliability outweigh the immediate benefits of reduced power loss due to poor matching for small systems. Careful selection of the array modules and the battery voltage could reduce potential power losses to a minimum and avoid the complexity of DC power conditioning equipment except for a voltage regulator.

The voltage regulator should operate as a boost/trickle charge device with an override for equalizing charges. The boost/open circuit type of voltage regulator at Boulders is not an optimal device.

6.1.1.3 Storage batteries

The sizing and selection of the batteries is vital because they represent a significant proportion of the initial costs, (20%), as well as the operating costs, (12-50%), over the system lifetime. Correct sizing would ensure the required degree of autonomy and rapid recharge rate combined with the maximum operating life of the cells.

The apparent loss of capacity and the associated reduction in the watt-hour efficiency from 85% to 66% of the battery bank at Jock of the Bushveld are proof of the need for effective battery protection by the voltage regulator and the inverter and the need for effective maintenance.

6.1.1.4 Inverters

The cost of poor inverter sizing has been shown in Sections 5.2.2 and 5.3.2. The sizing and specification of inverters must be based on the operating efficiency at the anticipated load power demand levels. The efficiency of the square-wave inverter at Jock of the Bushveld was 45% operating at an average capacity factor of 0,03 whereas the sine-wave inverter at Woodlands was operating at an efficiency of 64% for an average capacity factor of 0,24.

The quality of the AC waveform reqired by the loads impacts on the initial cost of the inverter and the complexity and efficiency of the inverter and the minimum load requirements should be established before specifying an inverter.

The problem of low inverter efficiencies can be mitigated by the use of multi-stage or multiple dedicated inverters.

6.1.1.5 DC/DC converters

DC/DC converters should only be considered for applications with low power, high efficiency 12 V (or 24 V) loads that are dispersed such as at Boulders. For most applications where transmission is required AC inverters are generally more cost effective.

6.1.1.6 Maintenance

The maintenance requirements of PV systyms are essentially battery maintenance in the form of monthly equalizing charges, electrolyte replenishment and recording of the specific gravity; inspections of the wiring and periodic cleaning of the array.

6.1.2 PV system design

Many design and sizing techniques for PV systems are available. Some sizing and design techniques for PV systems are briefly discussed in Appendix I.

In contrast to the the configuration and design of small PV systems by individuals or small companies, as described elsewhere in this thesis, the design of large MW_p PV systems, similar to that required for Shingwedzi, would typically be undertaken by consultants and research establishments in co-operation with PV manufacturers. Appendix I therefore includes some design considerations for large PV systems.

Ultimately any effective and realistic PV system design method should be based on a statistical analysis of the loss of power probability evaluated in terms of statistical weather data and component reliability data.

6.1.3 Optimal PV system designs for the Kruger National Park sites

For the purposes of investigating the technical and economic viability of PV systems for off-grid power supply for a range of applications, four optimal PV systems are sized using the Jet Propulsion Laboratories method proposed by Borden et al (1984), which is elaborated on by Müller (1987) and in Appendix I.

6.1.3.1 Jock of the Bushveld

Load energy demand and load curve

The daily load energy demand for a load comprised exclusively of lighting is expected to vary throughout the year as the number of daylight hours vary. The annual peak daily load energy demand would be expected in June/July due to an increased lighting demand and accordingly the average daily load energy demand of 1,15 kWh/day would increase by 10-15% ie. 1,27-1,32 kWh/day corresponding to an average load of 100 W for 13 hours per day between dusk and dawn.

System configuration

The PV system at Jock of the Bushveld need not necessarily have been an alternating current (AC) system. The lighting requirements of the camp, comprising 24 lights and a total load of 418 W, could be met with 12 V DC light fittings similar to those specified for Boulders. Paul (1981) suggests that 12 V DC equipment is optimal for installations such as this where the maximum demand does not exceed 1 kW and the daily load energy demand is less than 3 kWh/day.

However, the electrical transmission losses for a 12 V system introduced by the dispersed layout of the camp would be unacceptable and a higher voltage transmission line would be required. The additional use of small, dedicated inverters or DC/DC converters similar to those at Boulders would improve the overall average efficiency of conversion or inversion.

An alternative would be to have small dedicated 12 V DC PV systems for each hut. This option could be economically viable (Müller, 1987) and would also increase the diversity of the power supply and overall power availability to the users at the expense of flexibility and the benefits of reduced ADMD (after diversity maximum demand).

The night-time lighting loads at Jock of the Bushveld and the need for autonomy under overcast conditions require battery storage.

Theoretical system sizing and design

For comparison, a PV system was sized for Jock of the Bushveld, based on measured load and component performance data, to meet the maximum projected winter daily load energy demand of 1,32 kWh/day with daily global radiation in June of 20,0 MJ/m^2/day incident on an array tilted at 30°, (Table 5.2). A similar AC PV configuration was used for the comparison. The procedure adopted is using the JPL sizing methodology described by Borden, et al (1984) (Appendix I). The system specifications and lifecycle costs for the existing system are presented together with the more optimal design in Table 6.1. The basic assumptions in Section 5.2.2 are used throughout for the economic evaluation except that the annual O&M cost is estimated at 1% of the installed cost.

The 71% reduction in the annualized unit energy cost is a reflection of the cost associated with poor component sizing and low component operating efficiencies. The cost reduction is due to the 35% reduction in the peak PV power requirement, the 73% reduction in battery storage capacity and the 67% reduction in NPV maintenance and labour costs.

The same tubular plate type of batteries were considered in the optimized system as those installed at Jock of the Bushveld, ie. 250 R/kWh.

Table 6.1 : **Comparative table of existing and optimized AC PV system specifications for Jock of the Bushveld**

System specifications	Existing design	Optimized design
Load energy demand	1,32 kWh/day	
Design insolation	20,0 MJ/m^2/day	
Module efficiency	8,97	10,0 %
PV cell temperature	47,0	47,0 °C
Voltage reg. eff.	93	95 %
Battery efficiency	(66)[1]	85 %
Depth of discharge	12	60 %
Battery voltage	36	36 V
Inverter efficiency	45	70 %
Peak array power	792	503 W$_p$
Array area	8,82	5,31 m^2
Voltage reg.rating	30	17,5 A
Battery capacity	590	157 Ah
Inverter rating	3000	420 W
Days autonomy	(1)[2]	1,8 days
Battery charge time*	4,5[3]	1,7 days
Admin. costs	200	200 R
Maint.& labour	1 800	140 R
Installed system cost	28 870	13 950 R
Battery repl. cost	3 250	886 R
Battery residual value	(242)	(64) R
NPV O&M costs	27 183	4 613 R
NPV lifecycle costs	59 061	19 380 R
Unit energy cost	1 035	296 c/kWh

[1] actual recorded efficiency
[2] estimated actual autonomy for deteriorated batteries
[3] for nominal initial capacity
* based on a minimum state of charge of 40%

6.1.3.2 Boulders

Load energy demand and load curve

The fifteen month record of daily DC/DC converter ampere-hour energy demand at Boulders shows the annual variation of the daily load energy demand (see Figure 5.21). The peak demand is in summer between October and February. In practice the critical month for a PV array would be

November when the incident global solar radiation is 18,40 MJ/m^2/day on a surface tilted at the optimum angle of 20° to the horizontal, (Table 5.2), and the estimated load energy demand is 5,56 kWh/day for the 12 V DC loads.

System configuration

The configuration of the Boulders DC PV system was well conceived. Battery storage is necessary for autonomy on sunless days and for the refrigeration and ventilation loads which operate 24 hours per day and the lighting loads which operate at night. The use of a "high" voltage 60 V DC transmission line connected to seven dedicated, load sensing DC/DC converters which supply efficient 12 V DC appliances is an effective means of reducing transmission losses, increasing the overall DC/DC conversion efficiency (by operating individual units at high capacity factors), and minimizing the probability of a total blackout in the camp. In effect the system could equally well have had seven 60 V DC to 220 V AC dedicated inverters coupled to high efficiency 220 V AC appliances. The inverters would need to be sine wave or quasi-sine wave devices with overload capacity to start the fridge and freezer comppressor motors. The possible advantages of 220 V AC appliances being cheaper and more freely available have not been considered in the evaluation of the Boulders system.

The typical operating efficiencies of inverters and DC/DC converters are similar.

Theoretical system sizing and design

Similarly as for Jock of the Bushveld, a correspondingly optimized DC PV system was sized using the JPL method for comparison with the existing Boulders system.

The system was sized to meet the estimated average load energy demand of 5,56 kWh/day, (based on the recorded

DC/DC converter LED and a DC/DC converter efficiency of 70%), for November and based on an average incident solar radiation of 18,40 MJ/m²/day on a surface tilted at 20° to the horizontal.

The system specifications and lifecycle costs for the existing system are presented together with the JPL sized system in Table 6.2. The basic assumptions in Section 5.3.2 are used throughout for the economic evaluation. As for Jock of the Bushveld the annual O&M cost was estimated as 1% of the installed cost.

The 16% reduction in the annualized unit energy cost is due to the reduction in PV array costs (33%), the reduction in battery costs (48%) and O&M costs (52%). The JPL sizing method suggests a 31% smaller array rating and a 48% smaller battery storage capacity. The smaller array rating is consistent with the on-site observation and recorded evidence that the battery was fully charged by mid-morning and that the array would be shunted into open circuit mode for the bulk of the day by the voltage regulator. The low system efficiency of 3,8% recorded for the Boulders system is a direct result of the relative mismatch of the array and the recorded average daily load energy demand.

Table 6.2 : Comparative table of existing and optimized AC PV system specifications for Boulders

System specifications	Existing design	Optimized design	
Load energy demand	5,56 kWh/day		
Design insolation	18,40 MJ/m²/day		
Module efficiency	9,9	10,0	%
PV cell temperature	62,0	60,0	°C
Voltage reg. eff.	(93)	95	%
Battery efficiency	81	85	%
Depth of discharge	18	60	%
Battery voltage	60	60	V
DC/DC converter eff.	(70)	70	%
Peak array power	3306	2318	W_p
Array area	32,7	25,42	m²
Voltage reg.rating	60	48,3	A
Battery capacity	880	455	Ah
DC/DC conv. rating	1925	1925	W
Days autonomy	4,1	2,1	days
Battery charge time	3,0	1,9	days
Admin. costs	200	200	R
Maint.& labour	1 800	730	R
Installed system cost	108 652	72 647	R
Battery repl. cost	13 444	6 972	R
Battery residual value	(958)	(498)	R
NPV O&M costs	27 183	12 591	R
NPV lifecycle costs	148 319	91 712	R
Unit energy cost	393	332	c/kWh

* based on a minmum state of charge of 40%

6.1.3.3 Woodlands

As an exercise in the evaluation of the comparative costs of electricity generated by alternative off-grid power supply systems, an AC PV system was sized and costed for Woodlands.

Load energy demand and load curve

The load power requirements at Woodlands are for a 24 hour per day electricity supply for essential refrigeration and security lighting loads. The most representative recorded load energy demand for the Woodlands ranger's camp is 21,1 kWh/day corresponding to the load curve in Figure 5.37 for the period when the house was occupied. As for Boulders, the daily load energy demand would be expected to be greatest in the summer months due to increased refigeration loads. There are no space heating requirements in winter due to the warm Lowveld weather characteristics. Overall, the annual average daily load energy demand would be marginally less than 21,1 kWh/day due to the brief periods when the house is unoccupied. The long term load energy demand variation is more predictable than for the tourist camps due to the uniform occupancy of the site, but the daily variation in load energy demand is entirely a function of the domestic routines of the household.

System configuration

The most appropriate PV system configuration for the domestic household and assorted small workshop loads would be an AC PV system with a high efficiency, multi-stage, pulse width modulated, sine wave inverter. The peak load power demand for the system was 1850 W averaged over half an hour. The instantaneous peak load power demand could be as high as 4,4 kW based on a typical farm load factor of 0,2, (Williams, 1988). The total installed load power demand is approximately 9,8 kW.

Theoretical system sizing and design

For comparison a PV system capable of meeting the system load power and energy demand was designed according to the JPL procedure. The basis of the design is an average load energy demand of 21,1 kWh/day in the critical month of November when the incident global solar radiation on a surface tilted at 20° to the horizontal would be 18,4 MJ/m²/day. The system specifications and life-cycle costs for the existing genset-plus system and the JPL design are presented below in Table 6.3.

Table 6.3 : Comparative specifications and lifecycle costs for the existing genset-plus system and an optimized AC PV system for Woodlands

System specifications	Existing genset-plus design	Optimized AC PV design	
Load energy demand	21,1 kWh/day		
Design insolation	18,40 MJ/m^2/day		
Module efficiency	-	10,0	%
PV cell temperature	-	55,0	°C
Voltage reg. eff.	-	95	%
Battery efficiency	-	85	%
Depth of discharge	30	60	%
Battery voltage	36	120	V
Inverter efficiency	64	80	%
Peak array power	-	7698	W_p
Array area	-	83,15	m^2
Voltage reg.rating	-	80	A
Battery capacity	1180	755	Ah
Inverter rating	3000	5550	W
Days autonomy*	1,9	2,1	days
Battery charge time*	0,4	1,9	days
Admin. costs	2 000	200	R
Maint.& labour	10 800	2 310	R
Installed system cost	38 277	231 109	R
Battery repl. cost	7 923	23 303	R
Battery residual value	805	(1 654)	R
NPV O&M costs	76 822	34 127	R
NPV lifecycle costs	122 217[1]	286 965	R [2]
Unit energy cost	337	274	c/kWh

* based on a minimum state of charge of 40%
[1] based on an operating lifetime of seven years
[2] based on an operating lifetime of twenty years

The annualized unit energy cost for the AC PV system for Woodlands is 19% less than the current unit energy cost of 337 c/kWh for the genset-plus system.

The direct comparison is misleading because i) the genset-plus was operated sub-optimally, as discussed in Section 5.4.3, and could have produced the same quantity of electricity at a more competitive cost, (Section 6.3.3);

and ii) the systems are fundamentally different in their operating requirememts, lifetimes and maintenance requirements. Although the unit energy costs are in principle directly comparable in terms of the method of economic evaluation accomodating and accounting for the disparate cashflow and lifetime characteristics, the specific requirements of an off-grid power system might suit one or the other option equally well.

6.1.3.4 Shingwedzi

Similarly as for Woodlands, a first approximation for the sizing and costing of an AC PV system is presented for Shingwedzi for comparative purposes.

Load energy demand and load curve

The annual variation in daily load energy demand and the system load curve for Shingwedzi is not great. The daily load energy demand falls between 2200 kWh/day and 3000 kWh/day for 78% of the year. The average load power demand of 108,6 kW and maximum load power demand of 255 kW combined with the average load energy demand of 2605 kWh/day therefore form a reliable basis on which to size a power supply system.

System configuration

An AC PV system for a large off-grid electricity consumer such as Shingwedzi would be similar to the typical MW_p PV system configuration described and discussed in Appendix I with an array field of tracking sub-arrays, a partitioned 400 V battery, effective power conditioning and multi-stage inverters and a software based micro-computer control system.

Theoretical system sizing and design

An initial PV sizing and design of an AC PV system for Shingwedzi is presented merely for the purposes of an approximate comparison with the current unit energy cost of electricity produced by the present twin genset installation. The specifications and lifecycle costs are presented in Table 6.4.

Table 6.4 : Comparative specifications and lifecycle costs for the existing twin genset system and an optimized AC PV system for Shingwedzi

System specifications	Existing design	Optimized design	
Load energy demand	2605 kWh/day		
Design insolation	18,40 MJ/m^2/day		
Module efficiency	-	10,0	%
PV cell temperature	-	55,0	°C
Voltage reg. eff.	-	98	%
Battery efficiency	-	85	%
Depth of discharge	-	60	%
Battery voltage	-	400	V
Inverter efficiency	-	95	%
Peak array power	-	776	kW_p
Array area	-	8380	m^2
Voltage reg.rating	-	2424	A
Battery capacity	-	23,5	kAh
Inverter rating	-	255	kW
Days autonomy	-	2,1	days
Battery charge time*	-	1,9	days
Admin. costs	5 000	2 000	R
Maint.& labour	294 000	246 000	R
Installed system cost	242 700	24 700 000	R
Battery repl. cost	-	2 300 000	R
Battery residual value	-	(172 000)	R
NPV O&M costs	3 324 400	3 380 000	R
NPV lifecycle costs	3 567 000[1]	30 200 000	R [2]
Unit energy cost	34	234	c/kWh

* from a minimum state of charge of 40%

[1] based on an operating lifetime of fifteen years

[2] based on an operating lifetime of twenty years

Theoretical system sizing and design

An initial PV sizing and design of an AC PV system for Shingwedzi is presented merely for the purposes of an approximate comparison with the current unit energy cost of electricity produced by the present twin genset installation. The specifications and lifecycle costs are presented in Table 6.4.

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Battery efficiency	-	85 %
Depth of discharge	-	60 %
Battery voltage	-	400 V
Inverter efficiency	-	95 %
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Array area	-	8380 m^2
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Unit energy cost	34	234 c/kWh

* from a minimum state of charge of 40%
[1] based on an operating lifetime of fifteen years
[2] based on an operating lifetime of twenty years

Although the JPL sizing technique is not intended for large PV systems, it serves as a first approximation and the benefit of economies of scale for larger diesel genset systems is clearly demonstrated. PV systems are essentially modular and consequently the annualized unit energy cost remains almost an order of magnitude larger than that for large diesel genset installations despite the increase in system size.

6.2 DIESEL GENSET SYSTEMS

The evidence presented in Section 5.5 (and summarized in Table 5.26) of the performance of the twin 225 kVA/250 kVA genset system at Shingwedzi confirms and reinforces the recommendations of the appropriateness of diesel for larger off-grid electricity generation.

The key questions relating to the viability of diesel for off-grid power supply are those regarding the operation and cost of small sets for applications with low power requirements and/or which are isolated from fuel and maintenance infrastructures.

Although no data were recorded for a small diesel genset system, the data recorded on the LISTER ST2 genset of the genset-plus installation at Woodlands enables extrapolation to investigate the O&M costs and unit energy costs of the set if it were operating as a straight genset system.

6.2.1 Diesel genset system design techniques and operating considerations

Diesel gensets systems are sized on the basis of having to meet the peak instantaneous load power demand regardless of the average load power demand. A system sized on this basis would therefore automatically be capable of providing the daily load energy demand but often at very low capacity factors. Many off-grid genset systems, particularly those on farms, operate only at night to reduce the operating costs. The electricity usage patterns are modified where possible to accomodate these shortened genset run-times in an effort to optimize the costs and reduce the noise.

The extended operation of diesel gensets at low capacity factors is however mechanically detrimental to the engine due to bore glazing, carbonization problems and potential cool running and lubrication problems. Similarly, the associated low system efficiencies and accelerated degradation of the engine are economically undesirable. The lower limit of economically viable genset systems is a function of the fact that the smallest available diesel gensets are rated for approximately 3 kW.

This is particularly a problem for applications with peak load power demands greater than 3 kW and average daily load energy demands of less than 22 kWh/day, ie. a capacity factor of less than 0,3 (and load factor of less than 0,3). In practice diesel gensets are under-utilized for sites with average daily load energy demands of less than 30 kWh/day, ie. capacity factor of less than 0,4 for a 3 kW set.

As noted in Section 2.1.2 and illustrated in Section 5.5, multi-set diesel genset systems are a viable alternative to single set systems as a means of increasing the genset capacity factor for larger installations with low load factor and predictable load power demands. The gensets need not be the same size.

For single genset systems the load factor is by definition also the upper limit of the capacity factor. The primary benefit of multiple genset systems is the ability to overcome this limitation and to operate the gensets at average capacity factors that are greater than the system load factor. For example, the overall load factor of the

Shingwedzi camp for 1986/7 was 0,42 and yet the average monthly capacity factor varied between 0,49 and 0,66. A secondary benefit is the provision of standby capacity and the associated operating flexibility. A disadvantage of multiple genset installations is the additional complexity required in the controls and operation for synchronizing the phase(s) of the AC waveform for parallel operation.

In general, a multi-set genset system should only be considered for large off-grid power supply systems with continuous loads, an average daily load energy demand in excess of 1200 kWh/day and a load factor of less than 0,4 ie. peak load power demand of 125 kW.

6.2.2 Optimal diesel genset system designs for the Kruger National Park sites

Of the four sites investigated in this project, only the Shingwedzi main tourist camp would be optimally served by a straight diesel genset power supply system.

Figure 6.2 shows the costs of running a 5,6 kW (7kVA) LISTER ST2 genset at different capacity factors. This graph of the unit energy cost vs. capacity factor is based on the assumptions for fuel consumption and engine lifetime presented in Figure 6.1 and the sensitivity analysis matrix in Table 6.5.

The shape of the engine life curves is a function of reduced overall life at the two extremes of capacity factor. Cylinder bore glazing, carbonization and accelerated wear due to slow warm-up after start-up reduce overall engine life at low engine loads, whereas the reduction at peak engine loading is due to greater bearing loads, high cylinder loads and general wear.

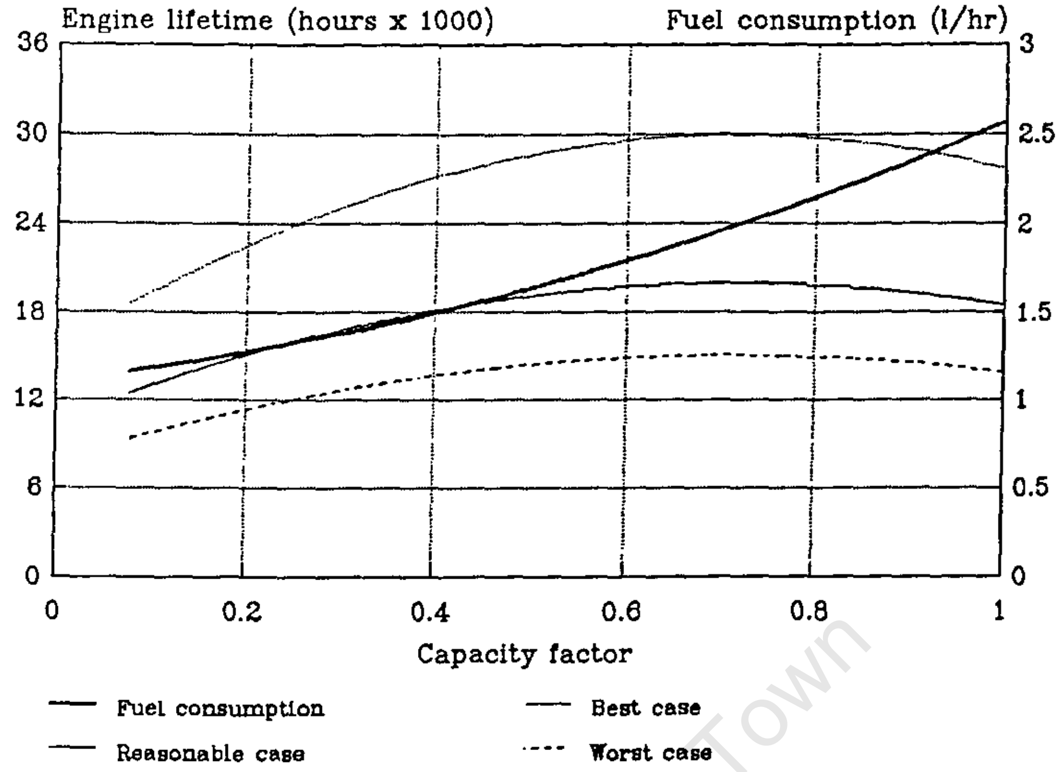

Figure 6.1 : Graph of the assumptions for fuel consumption and engine life as a function of the capacity factor for the LISTER ST2 genset

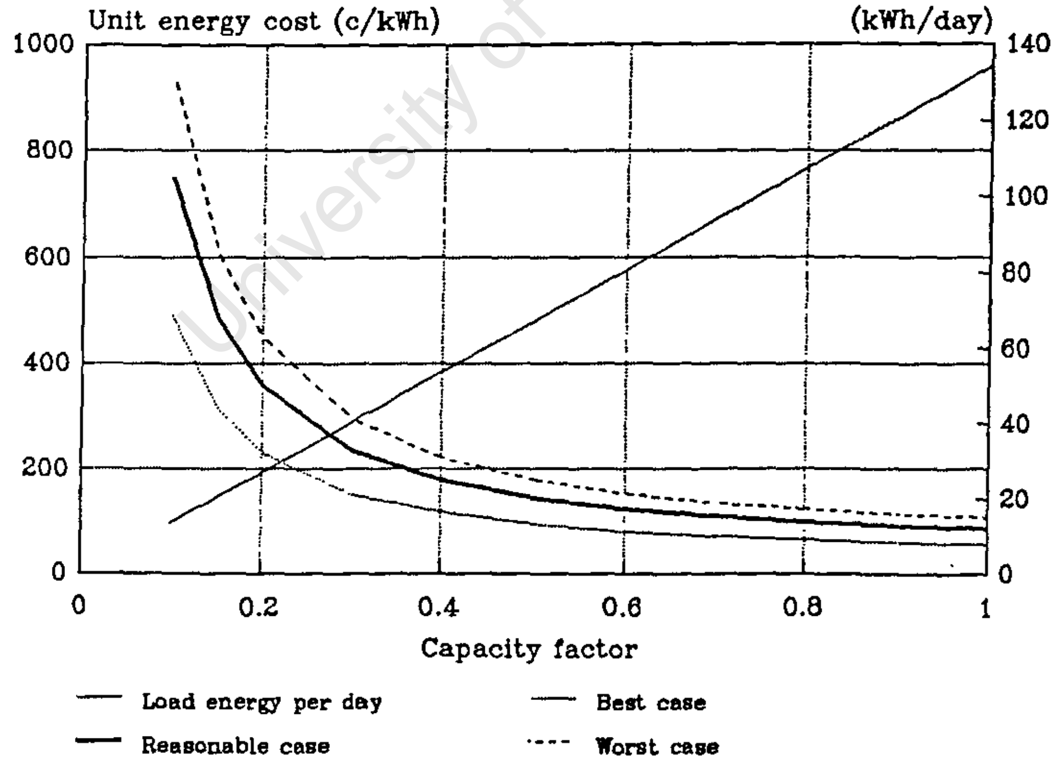

Figure 6.2 : Graph of the variation in the unit energy cost for a LISTER ST2 genset system as a function of the capacity factor for three cases of basic assumptions

The fuel consumption characteristic is based on interpolation of the quoted fuel consumptions for the LISTER ST2 at capacity factors of 0,25; 0,5; 0,75 and full capacity.

The unit energy cost is based on the annuity method of economic assessment discussed in Section 4.7.

Table 6.5 : Assumptions and results of the sensitivity analysis for the operating costs of the LISTER ST2 genset

Genset rating	7,00 kVA (LISTER ST2)
Power factor	0,8
Daily run time	24 hr/day
Genset cost	R 18 256
Installation	R 1 500

SENSITIVITY MATRIX		worst case	best case	reasonable case
Fuel cost	(R/hr)	1,00	0,50	0,75
Maint.cost	(R/hr)	2,50	1,00	1,75
Discount rate	(%)	2,0	10,0	4,0
Engine lifetime	(hrs)	15 000	30 000	20 000

capacity factor	genset output (kWh/day)	fuel cons, (l/hr)	UNIT ENERGY COST (c/kWh)		
0,10	13,44	1,18	937	490	749
0,15	20,16	1,22	610	317	488
0,20	26,88	1,27	450	232	359
0,30	40,32	1,37	295	150	235
0,40	53,76	1,49	221	117	179
0,50	67,20	1,63	179	94	145
0,60	80,64	1,78	152	79	123
0,70	94,08	1,95	134	70	108
0,80	107,52	2,13	122	63	98
0,90	120,96	2,33	113	59	91
1,00	134,40	2,55	107	56	85

The general shape of the empirically derived curves in Figure 6.2 echo that of the generalized curve presented by Paul (1981) in Figure 2.1.

The unit cost of energy supplied by a straight genset system for the electricity requirements at Woodlands would be 455 c/kWh at an average capacity factor of 0,16 compared to 337 c/kWh for the sub-optimally operated genset-plus system and 274 c/kWh estimated for an AC PV system.

6.3 DIESEL GENSET-PLUS SYSTEMS

As indicated in Section 5.4.3, the design and system sizing of the 7 kVA/1180 Ah genset-plus system at Woodlands is essentially sound but the operating regime is a major source of inefficency and unnecessary noise.

6.3.1 Genset-plus system design techniques and sizing considerations

Limited references to system sizing for genset-plus systems are available. Rules of thumb suggested by Paul (1981) for genset-plus systems are :

1. Minimum battery capacity for an independent power system is approximately two times the average daily load on the system.
2. Battery chargers should be sized to provide maximum charge rates of 15% to 25% of the 20-hour amp-hour capacity of the battery
3. The genset should be sized at minimum to match the single largest electrical device (usually the battery charger), but not larger than required to handle the peak load of the system with the battery off.

The battery is the heart of a genset-plus system. It must be sized to meet the load energy demand (via the inverter) over a reasonable discharge period before being charged as briskly as is practical within the charge current limits imposed by over-heating and gassing. The charge/discharge cycle period is a function of required load energy demand

and system factors such as the battery capacity, the allowable depth of discharge, the inverter efficiency, and the genset and battery charger rating.

The operating regime and the overall control of the genset-plus configuration should be based on a programmable logic controller driven by the cyclical state of charge of the battery.

6.3.2 Optimal genset-plus system designs for the Kruger National Park sites

Optimization of genset-plus systems is investigated in terms of the specific optimization of the genset-plus installation at Woodlands. The calculations are centred around the manually selected battery charge current and aim to establish the optimum charge current to minimize the genset run time and the overall unit energy cost.

The basic assumptions on which the calculations are based are listed in Table 6.6. The results of the optimization calculations and a sensitivity analysis are listed in Table 6.7 and illustrated in Figure 6.3.

Table 6.6 : Basic assumptions for the optimization of the operating regime for the LISTER ST2 genset at Woodlands

Genset rating	:	7,00 kVA
Power factor	:	0,8
Ave. LED	:	21 kWh
Battery cap.	:	1180 Ah
Depth of disch.	:	60%
Battery life	:	5 years
Inverter eff.	:	70%
Inv. run time	:	21,52 hours
Genset-plus IC	:	R 36 777
Bat. repl. cost	:	R 10 800
Installation	:	R 1 500

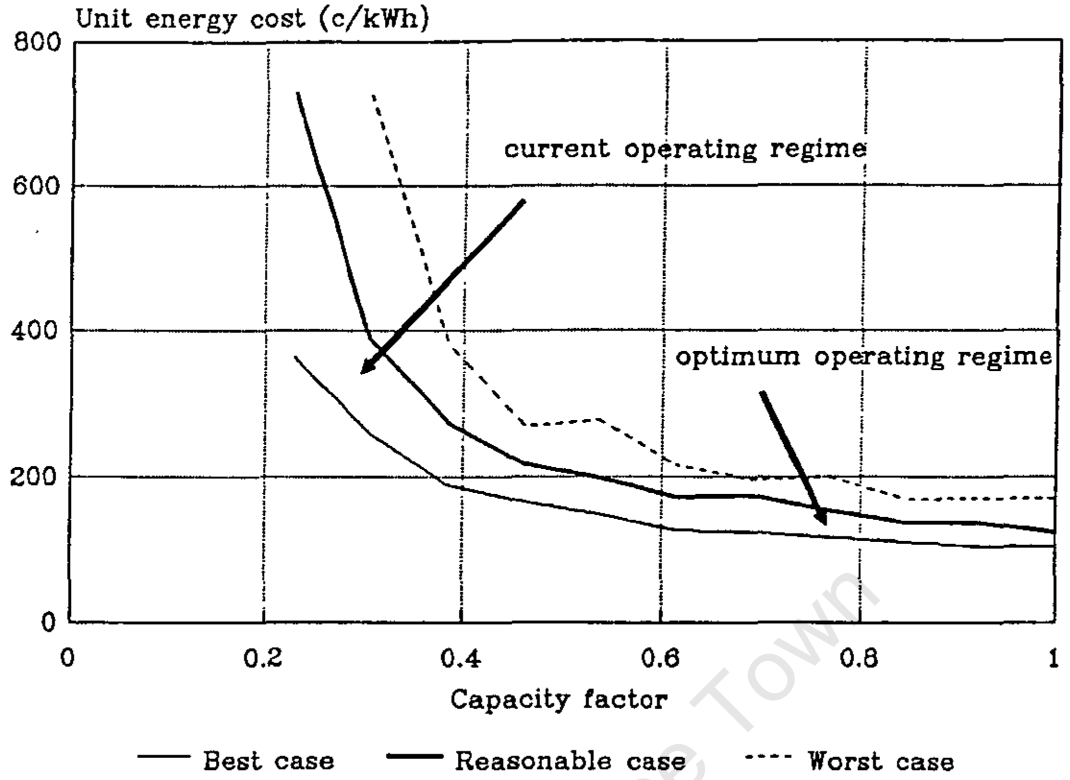

Figure 6.3 : Graph of the variation of unit energy cost for the genset-plus system as a function of the capacity factor for three cases of basic assumptions

The assumptions for the fuel consumption and effective operating lifetime of the genset are as described in Figure 6.1.

It can be seen from Table 6.7 and the graph in Figure 6.3 that the optimum charge current would be between 80 and 100 A, corresponding to load factors of between 0,6 and 0,8, to allow surplus some genset capacity for the instantaneous load power demand of the domestic appliances in the house. The system would be expected to supply the electricity requirement at an annualized unit energy cost of less than 172 c/kWh for approximately nine years during which time the batteries would have been replaced once.

Table 6.7 : **Assumptions for the sensitivity analysis and the results of the optimization of the operating regime for the LISTER ST2 genset at Woodlands**

SENSITIVITY MATRIX		worst case	best case	reasonable case
Fuel cost	: (R/hr)	1,00	0,50	0,75
Maint.cost	: (R/hr)	2,50	1,00	1,75
Discount rate	: (%)	2,0	10,0	4,0
Engine lifetime	: (hrs)	15 000	30 000	20 000

Charge rate (A)	Capacity factor	Daily runtime (h/day)	Fuel cons. (l/hr)	UNIT ENERGY COST (c/kWh)		
10	0,08	(71,4)	1,16	-	-	-
20	0,15	(35,7)	1,23	-	-	-
30	0,23	23,8	1,30	692	364	-
40	0,31	17,9	1,38	727	260	389
50	0,38	14,3	1,48	384	189	274
60	0,46	11,9	1,58	268	166	216
70	0,54	10,2	1,69	277	149	199
80	0,61	8,9	1,81	215	126	172
90	0,69	7,9	1,95	196	123	174
100	0,77	7,1	2,09	199	116	153
110	0,84	6,5	2,24	169	110	137
120	0,92	6,0	2,40	170	105	137
130	1,00	5,5	2,56	170	104	124

The current operating costs corresponding to 337 c/kWh are 95% greater than if the system were operated optimally.

Paul (1981) has suggested that a genset-plus system should provide electricity at a unit energy cost 74% less than that for a conventional genset system. The costs calculated for the Woodlands ranger's camp indicate that a 65% reduction in the unit energy costs could be expected, ie. from 488 c/kwh to 172 c/kWh.

6.3.3 Summary

A summary of the above-mentioned three considerations is presented overleaf in Table 6.8.

Table 6.8 : **Comparative specifications and lifecycle costs for the existing genset-plus system, a straight genset system and a genset-plus system for Woodlands based on an optimized operating regime**

System specifications	Existing genset-plus design	Genset system	Optimized genset-plus design	
Average daily load energy demand : 21,1 kWh/day				
Genset rating	7,0	7,0	7,0	kVA
Daily run-time	11,15	24,0	7,0	hr/d
System lifetime	7,0	3,4	12,0	yrs
Battery capacity	1180	-	1180	Ah
Charge current	38,0	-	98,0	A
Batt. charger eff.	93	-	93	%
Battery efficiency	85	-	85	%
Depth of discharge	30	-	55	%
Inverter rating	3000	-	3000	W
Inverter efficiency	64	-	64	%
Days autonomy*	1,9	-	1,9	days
Battery charge time*	0,3	-	0,9	days
Admin. costs	2 000	2 000	2 000	R
Maint.& labour	10 800	21 600	7 200	R
Installed cost	38 277	18 300	38 277	R
Battery repl. cost	7 923	-	7 923	R
Residual value	805	-	805	R
NPV O&M costs	76 822	37 318	54 205	R
NPV lcc costs	122 217	57 074	101 359	R
Unit energy cost	337	488	172	c/kWh

* based on a minimum state of charge of 40%

6.4 SUMMARY OF THE DISCUSSION OF OPTIMAL SYSTEM DESIGN FOR OFF-GRID SITES

The relative merits of PV, diesel genset and genset-plus installations for off-grid power systems are discussed in turn.

6.4.1 Photovoltaic systems

Figure 6.4 shows the graph of unit energy cost versus average daily load energy demand for the two monitored sites and the corresponding findings of Müller (1987), in addition to a curve of the estimated unit energy cost for more optimally designed PV systems. The optimal system cost curve is derived from the data in Tables 6.1 to 6.4.

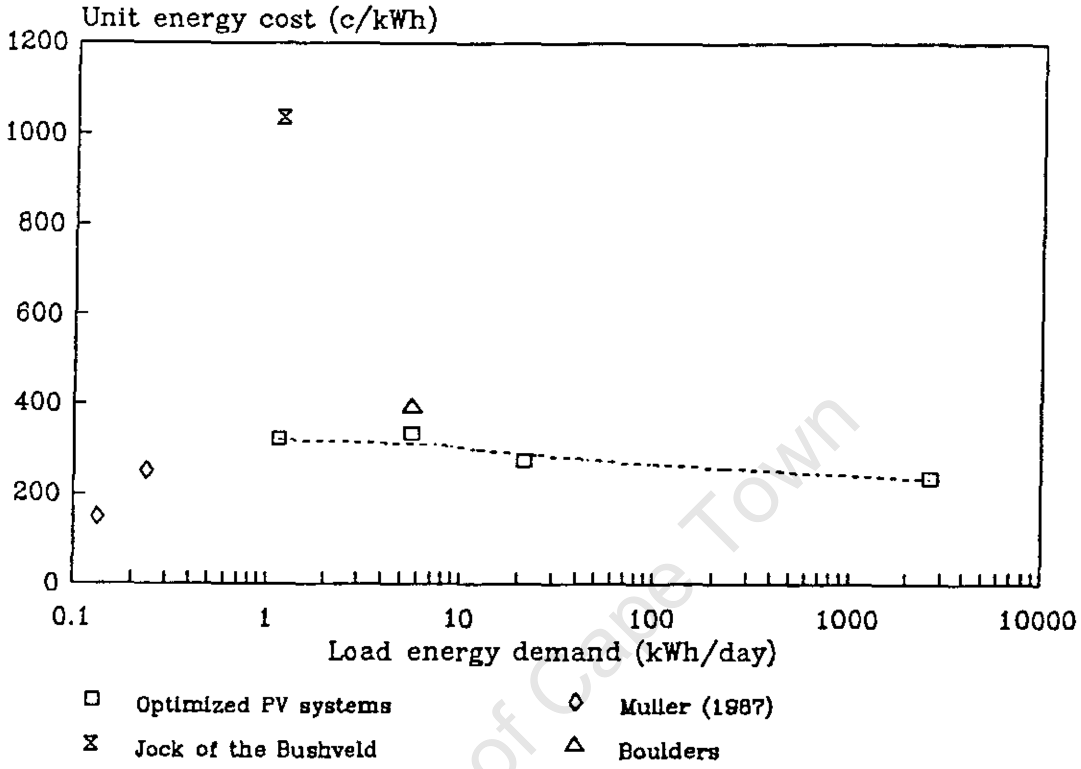

Figure 6.4 : Graph of the unit energy cost for the monitored DC and AC PV systems, Müller's data and the optimized unit energy costs for a range of average daily load energy demand

The two points calculated by Müller are based on different assumptions to Jock of the Bushveld and Boulders (see Table 2.6) and are for minimal home lighting systems, as opposed to so-called multi-use systems. They are included because they are relevant to the general case of off-grid energy supply in Southern Africa but should be interpreted within the context of Müller's study.

The unit energy cost of optimized PV systems is relatively insensitive to the average daily load energy demand. This is a function of the inherent modularity of PV systems. The marginal reduction in unit energy cost for increased average daily load energy demand is due to economies of scale in power conditioning and control systems and the benefits of array tracking.

6.4.2 Diesel genset systems

Diesel genset systems are a well entrenched technology. The unit cost of electrical energy generated by diesel gensets may vary widely as the delivered cost of fuel and the proximity to maintenance and support facilities vary.

Figure 6.5 shows the unit energy cost for the electricity supplied by the Shingwedzi twin genset system, that of the Woodlands genset-plus system and the data reported by Williams (1988) for the cost of electricity recorded on farms. In addition two points are included for the postulated cost of supplying the Woodlands ranger's camp with a straight LISTER ST2 genset system; and the cost of electricity supplied by the installed genset-plus system operating according to an optimized operating regime.

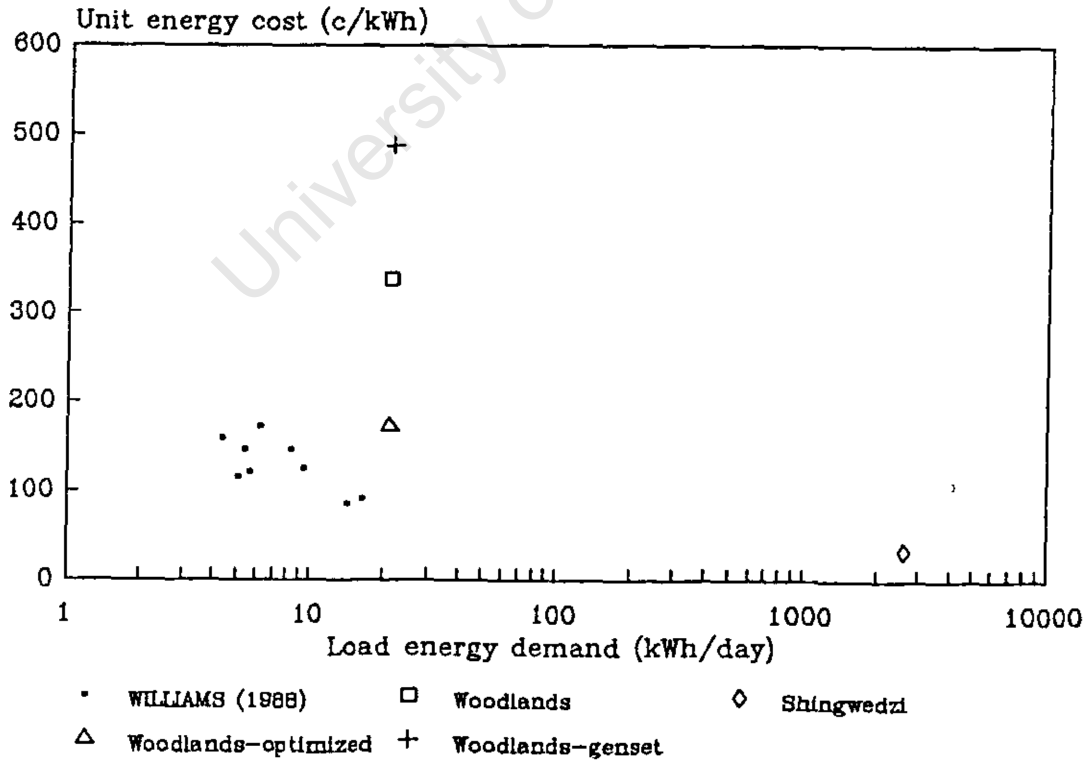

Figure 6.5 : Graph of the unit energy cost vs. load energy demand for the monitored genset and genset-plus systems, Williams' data and the unit energy costs for a Woodlands genset system and optimized Woodlands genset-plus system

Although the general characteristic curve is not shown, the massive reduction in the unit energy cost of electricity supplied by gensets as a function of increasing average daily load energy demand is clearly illustrated.

Williams' data is based on theoretically achieveable operating and maintenance costs and should therefore be regarded as best case costs. In practice it is estimated that these costs are likely to be 50% to 500% higher depending on the actual circumstances under which the sets are operated.

The sensitivity of the unit energy cost to the capacity factor and the load energy demand are graphically shown in Figure 6.3. As a result of the fact that diesel gensets are not available for rated capacities of less than 3 kW combined with the cost characteristics of operating genset systems at reduced capacity factors, the overall cost of operating a genset system for continuous loads with load energy demands of less than approximately 22 kWh/day is uneconomic compared to PV or genset-plus systems. A more precise determination of the crossover point from PV systems to diesel genset-plus or straight genset systems would require a study of wider scope than the one on which this thesis is based.

6.4.3 Genset-plus systems

Genset-plus systems are demonstrated to be viable for off-grid electrical power supply.

The key factor for the efficient and low cost operation of genset-plus systems is the operating regime.

The two data points plotted in Figure 6.5 for the 7 kVA/1180 Ah LISTER ST2 genset-plus installation at

Woodlands show the reduction in unit energy cost for an improved and optimized operating regime. The relative costs of operating a genset-plus and straight genset system to meet the Woodlands´ electricity requirements are also shown.

There appears to be large scope for the rationalization of diesel genset based off-grid power supply systems through the introduction of energy storage and the implementation of genset-plus systems.

CHAPTER SEVEN

CONCLUSIONS

The conclusions of this thesis are couched in terms of the three key questions raised in Section 1.2 as part of the objectives of the technical and economic evaluation of photovoltaic and diesel electricity supply systems in the Kruger National Park.

Firstly, the criteria on which the relative favourability of PV or diesel for particular off-grid electrical power requirements should be evaluated may be summarized as :

PV systems should be considered for off-grid applications in the Kruger National Park where :

- the average daily load energy demand is less than 30 kWh <u>and</u> the load factor is less than 0,4;
- the electrical power requirements warrant a projected power supply system lifetime in excess of ten years;
- low interest, long term capital financing is available;
- the access to the site is awkward;
- maintenance requirements and administrative overheads are to be minimized;
- the need for a full time system operator is to be avoided; or
- for sites where the environmental impact of noise, vibration, smells and air pollution are to be avoided.

The solar resource over the extent of the Kruger National Park exceeds 5 kWh/m^2 throughout the year, which is more than sufficient for viable PV systems on the basis of the abovementioned criteria, and no more specific qualifications regarding the levels of insolation are required.

Although the scope of the project did not include a range of diesel genset systems, some guidelines regarding their suitability for RAPS are suggested. Diesel genset systems should be considered for off-grid applications where :

- the average daily load energy demand is in excess of 30 kWh/day and the load factor exceeds 0,4, (diesel systems are particularly favourable in terms of economic performance for load energy demands of more than 100 kWh/day);
- the power supply system is not expected to have an operating lifetime of more than ten years;
- a compact power supply system with low visual impact is required;
- capital is scarce;
- regular 250 hour maintenance routines can be provided;
- a full-time operator is available; or
- for sites where environmental pollution, noise, smells and vibration are tolerated.

In terms of the criteria spelt out above and the technical and economic evaluation of the four sites in this study, photovoltaic systems would be technically viable and economically more cost effective than straight diesel genset systems for Jock of the Bushveld, Boulders and Woodlands but not for Shingwedzi, ie. sites with average daily load energy demands of less than 20 kWh/day and with load factors of less than 0,4.

Secondly with regard to PV system design, there is scope for optimization of the sizing and design of the both the

AC PV system at Jock of the Bushveld and the DC PV system at Boulders.

The Jock of the Bushveld system is an older PV system which is grossly inefficient as a consequence of the exceedingly poor match between the load power requirements and the inverter. Overall the system could be scaled down by approximately 30% if a more optimal inverter were installed. In addition the low battery cycle efficiency indicates impending failure of the batteries as a result of non existent battery maintenance. The unacceptably high unit energy cost of electricity supplied by this system is a direct consequence of the sub-optimal design.

The Boulders system is an essentially well engineered system, which benefitted from the experience of earlier PV systems, but which is conservatively sized in terms of the array peak watt rating. The system has operated adequately but a more optimal design could have supplied electricity at a unit energy cost of 15% less.

Thirdly, the relative merits of DC or AC for off-grid PV systems are determined by the type of loads and the electricity transmission requirements. In general DC PV systems would have a higher overall efficiency, (and hence a lower unit energy cost of electricity supplied), for small centralized 12 V or 24 V DC loads. DC electrical appliances are often more efficient than the equivalent AC counterpart but are generally more expensive and less freely available. There are no inherent advantages in DC PV systems when power transmission for dispersed loads is required. The requirement for higher voltages for efficient electrical power transmission introduces the additional requirement for DC/DC converters, which involve efficiency losses that are essentially similar to those due to inverters. AC PV systems are therefore the more optimal approach for these demand constraints, more particularly because the technology is more mature and better supported.

Finally, the introduction of energy storage in diesel genset systems, in the form of batteries, a battery charger and inverter, is demonstrated to be an excellent and viable mechanism for utilizing the compact dimensions and low initial cost of diesel genset technology. The so-called genset-plus system should be considered for off-grid power supply for sites at which the average daily load energy demand is between 20 - 100 kWh/day and the load factor is less than 0,4.

Overall the fundamental value of this study is the establishment of an additional four sets of recorded data against which other off-grid electrical power supply systems in Southern Africa can be compared, both in the design stage and in operation. The presentation of real observed system dynamics and component efficiencies for these four different systems would therefore serve to facilitate the implementation of cost effective and reliable power systems in rural and under-developed areas.

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APPENDIX A

Schedule of power requirements and generating plant in the Kruger National Park : September 1987

1. MAIN CAMPS

No.	NAME	PRIME MOVER		STANDBY		TYPE OF LOAD	ENGINE NO
		Type	Rating (kVA)	Type	Rating (kVA)		
1.1	Berg-en-dal	ESCOM	500	CAT	300	lights, A/C, fridges, etc	K126
1.2	Crocodile Bridge	ESCOM	100	-	-		
1.3	Lower Sabie	ESCOM	400	CAT 3306	175		K47
1.4	Skukuza	ESCOM	2000	CAT 3412	2000		K10, K17,K120
1.5	Pretorius Kop	ESCOM	400	CUMMINGS	200		K91
1.6	Satara	ESCOM	500	CUMMINGS	200		K90
1.7	Olifants	ESCOM	500	CAT D333	80		K62
1.8	Letaba	ESCOM	400	CAT D3304	80		K111
1.9	Punda Maria	CAT 3304T	100	CAT D3304	80		K14,K109
1.10	Pioneer	-	-	-	-		
1.11	Orpen	Lister	7	-	-		K115
1.12	Maroela caravan park	-	-	-	-		
1.13	Balule/Ngotsamond	CAT D3304	-	-	-		K74
1.14	Shingwedzi	CAT 3406T	250	CAT 3406T	225	lights, A/C, fridges, etc	K125,K16

2. PRIVATE CAMPS

No.	NAME	PRIME MOVER		STANDBY		TYPE OF LOAD	ENGINE NO
		Type	Rating (kVA)	Type	Rating (kVA)		
2.1	Nwanedzi	Deutz	7	-	-		K119
2.2	Boulders	PV (DC)	3.3	-	-		
2.3	Roodewal	PV (AC)	0.8				
2.4	Jock of the Bushveld	PV (AC)	0.8				
2.5	Malelane	ESCOM	500	CAT	300	lights, A/C, fridges, etc	

3. WILDERNESS BASE CAMPS

No.	NAME	PRIME MOVER		STANDBY		TYPE OF LOAD	ENGINE NO
		Type	Rating (kVA)	Type	Rating (kVA)		
3.1	Bushman	Petter	-	-	-	Water supply	K124
3.2	Wolhuter	diesel	-	-	-		
3.3	Olifants	Lister	-	-	-	Water supply	K21
3.4	Nayalaland	Lister	-	-	-	Water supply	K89

4. GATES

No.	NAME	PRIME MOVER		STANDBY		TYPE OF LOAD	ENGINE NO
		Type	Rating (kVA)	Type	Rating (kVA)		
4.1	Numbi	ESCOM	25				
4.2	Paul Kruger	ESCOM	25				
4.3	Malelane	ESCOM	25				
4.4	Crocodile Bridge	ESCOM	100				
4.5	Orpen	diesel	6	-	-		
4.6	Phalaborwa	ESCOM					Muncipal
4.7	Punda Maria	-	-	-	-		
4.8	Pafuri Gate	Lister	10	-	-		
4.9	Pafuri Customs Gate	-	-	-	-		

5. RANGERS' CAMPS AND HOUSES

No.	NAME	PRIME MOVER		STANDBY		TYPE OF LOAD	ENGINE NO
		Type	Rating (kVA)	Type	Rating (kVA)		
5.1	Kingfisherspruit	Deutz	7	Lister	7		K117,K24
5.2	Houtbosrand	Lister	7				K116
5.3	Pafuri	Petter					K136
5.4	Mooiplaas	Petter					K137
5.5	Mahlangene	Petter					K138
5.6	Shangoni	Petter					K139
5.7	Vlakteplaas	Petter					K45
5.8	Tshokwane	Lister					K76
5.9	Nwanedzi	Lister	7				K36
5.10	Stolznek	Deutz	7	Lister	7	gen/plus	K118,K48
5.11	Woodlands	Lister	7			gen/plus	K122

6. WATERHOLES

No.	NAME	PRIME MOVER		STANDBY		TYPE OF LOAD	ENGINE NO
		Type	Rating (kVA)	Type	Rating (kVA)		
6.1	Olifants ranger	Lister					K2
6.2	Pretoriuskop ranger	Lister					K3
6.3	Letaba	Lister					K4
6.4	Orpen gate	Lister					K5
6.5	Nwanedzi ranger	Lister					K6
6.6	Letaba ranger	Lister					K9
6.7	Tshokwane	Lister					K12
6.8	Tshokwane picnic area	Lister					K13
6.9	Hlangulene	Lister					K15
6.10	Punda Maria	Lister					K18
6.11	Satara ranger	Lister					K23
6.12	Numbi	Hatz					K25
6.13	Kingfisherspruit	Lister					K26
6.14	Orpen	Hatz					K28
6.15	Mahlangene	Lister					K29
6.16	Mlondozi	Lister					K30
6.17	Crocodile bridge ranger	Lister					K32
6.18	Crocodile bridge	Lister					K33
6.19	Pafuri	Lister					K34
6.20	Houtboschrand	Lister					K35
6.21	Shangoni ranger	Petter					K37
6.22	Nkhulu	Lister					K39
6.23	Tshokwane	Petrol Lister					K41
6.24	Satara fire pump	Lister					K46
6.25	Kingfisherspruit ranger	Lister					K50
6.26	Kingfisherspruit	Lister					K52
6.27	Kingfisherspruit	Lister					K53
6.28	Orpen	Lister					K55
6.29	Boulders	Lister					K60
6.30	Shangoni ranger	Lister					K63
6.31	Skukuza	Lister					K64
6.32	Mzanzene	Lister					K66
6.33	Timbavati	Lister					K68
6.34	Punda Maria	Lister					K69
6.35	Quarantine camp	Lister					K73
6.36	Vlakteplaas	Lister					K75
6.37	Malelane	Lister					K77
6.38	Nwanedzi ranger	Lister					K78
6.39	Mahlangene	Lister					K81
6.40	Tshokwane	Lister					K84
6.41	Mooiplaas	Lister					K85
6.42	Lower Sabie irrigation	Lister					K94
6.43	Mooiplaas	Lister					K96
6.44	Houtboschrand	Hatz					K97
6.45	Kingfisherspruit	Lister					K98
6.46	Malelane Gate	Hatz					K99
6.47	Pafuri ranger	Lister					K100
6.48	Pafuri	Lister					K101
6.49	Pafuri	Lister					K102
6.50	Park Engineer	Lister					K110
6.51	Skukuza	Deutz					K114
6.52	Lower Sabie ranger	Lister					K121
6.53	Jock of the Bushveld	Petter					K127
6.54	Afsaal picnic area	Petter					K128
6.55	Punda Maria Gate	Petter					K129
6.56	Shangoni	Petter					K130
6.57	Tshokwane	Lister					K131
6.58	Nwanedzi	Lister					K132
6.59	Orpen	Lister					K133
6.60	Stolznek	Lister					K134
6.61	Berg-en-dal fire pump	Lister					K140
6.62	Shingwedzi fire pump	Lister					K141
6.63	Skukuza emergency pump	Lister					K142
6.64	Pafuri Gate	Petter					K143
6.65	Pafuri picnic area	Petter					K144

7. UHF REPEATER STATIONS

No.	NAME	PRIME MOVER		STANDBY		TYPE OF LOAD	ENGINE NO
		Type	Rating (kVA)	Type	Rating (kVA)		

8. CONSTRUCTION AND ROADS

No.	NAME	PRIME MOVER		STANDBY		TYPE OF LOAD	ENGINE NO
		Type	Rating (kVA)	Type	Rating (kVA)		
8.1	-	Lister	7			building construction	K1
8.2	Park engineer	Hatz				-	K11
8.3	-	Hatz				road construction	K19
8.4	-	Hatz				road construction	K20
8.5	-	Hatz				road construction	K22
8.6	-	Hatz				road construction	K31
8.7	-	Lister				dam construction	K40
8.8		Lister				dam construction	K49
8.9	-	Lister				building construction	K56
8.10	Skukuza	CAT D3304				waste compacter	K61
8.11	Skukuza	CAT D3304				stone crusher	K82
8.12	Road construction	Lister				water pump	K87
8.13	-	CUMMINGS				NPD	K92
8.14	-	Lister				building construction	K105
8.15	Road construction	Lister				water pump	K106
8.16	Road construction	Lister				water pump	K107
8.17	-	Lister				building construction	K108
8.18	Building construction	Lister					K112
8.19	Building construction	Lister					K113
8.20	-	Lister				road construction	K135

8. CONSTRUCTION AND ROADS

No.	NAME	PRIME MOVER		STANDBY		TYPE OF LOAD	ENGINE NO
		Type	Rating (kVA)	Type	Rating (kVA)		
8.1	-	Lister	7			building construction	K1
8.2	Park engineer	Hatz				-	K11
8.3	-	Hatz				road construction	K19
8.4	-	Hatz				road construction	K20
8.5	-	Hatz				road construction	K22
8.6	-	Hatz				road construction	K31
8.7	-	Lister				dam construction	K40
8.8		Lister				dam construction	K49
8.9	-	Lister				building construction	K56
8.10	Skukuza	CAT D3304				waste compacter	K61
8.11	Skukuza	CAT D3304				stone crusher	K82
8.12	Road construction	Lister				water pump	K87
8.13	-	CUMMINGS				NPD	K92
8.14	-	Lister				building construction	K105
8.15	Road construction	Lister				water pump	K106
8.16	Road construction	Lister				water pump	K107
8.17	-	Lister				building construction	K108
8.18	Building construction	Lister					K112
8.19	Building construction	Lister					K113
8.20	-	Lister				road construction	K135

APPENDIX B : SYSTEM SPECIFICATIONS

B.1 Jock of the Bushveld

- Panel specifications

Type : Arco ASI-16-2000 (monocrystalline)
No. : 24 (3 sub-arrays, in series, of 8 panels in parallel)
Watts peak : 33 W (based on 1000 W/m^2 and cell temp of 28°C)
Volts peak : 16,1 V
Amps peak : 2,05 A
Open circuit volts : 20,3 V
Efficiency : 8,97 % (based on gross frontal area)
Volt. temp. coeff. : 2,5-3,0 mV/C/°C
Short circuit curr.: 2,3 A
Temp cell-temp air : 40°C
No. of cells : 35
Size : 4"
Panel dimensions : 47,9 x 11,9 x 1,5"
Front surface area : 570,01 in^2 (0,3677 m^2)
Cover material : glass
Weight : 11 lbs.
Ambient temp limit : -40°C to 90°C

Angle of tilt : 32°
Azimuth angle : 0° (ie. due North)

- Voltage regulator specifications

Rating : 30 A
Max.cut out voltage: 44 V (≈fully charged battery)

- Battery specifications

Type : Raylite 2 IMR 25L (tubular plate, lead acid)
Voltage : 4 V (nominal)
Capacity : 590 Ah @ 10 hr rate @ 20°C
SG : 1,250
Charge current : 98 A constant rate
49 A
No. : 9 in series
Nominal voltage : 36 V

- Inverter specifications

Type : Square wave
Rating : 32/36 V DC to 220 V AC @ 50 Hz
50 A DC to 5 A AC
Power : 3,0 kW
Min.voltage cut out: 34 V

B.2 Boulders

- Panel specifications

Type : M Setek MS-101 (monocrystalline)
No. : 96 (16 parallel sub-arrays of six panels in series)
Nominal operating conditions : 1000 W/m^2 @ 25°C
Open-circuit volts : 18,3 V
Opt.operating volts: 13,8 V
Short-circuit curr.: 2,80 A
Opt.operating curr.: 2,54 A
Max. power output : 35 W
Cell efficiency : 14,0 %
Length : 873 mm
Width : 390 mm
Thickness : 35 mm
Mass : 4,7 kg

Angle of tilt : 21,5°
Azimuth angle : 0° (ie. due North)
Panel support : angle section mild steel mounted on the battery room

- Voltage regulator

Manufacturer : K R Enterprises, P O Box 13079, Northmead, 1511
Nominal voltage : 60 V
Max. current : 60 A

- Battery specifications

Type : Willard FWA 17 (stationary type, flat plate lead acid)
No off : 30
Ampere hours : 880 Ah to 1,85 V/cell @ 10 hr rate
928 Ah to 1,75 V/cell @ 8 hr rate
length : 190 mm
width : 369 mm
height : 566 mm
mass : 88 kg
volume electolyte @ sg 1,220-1,250 : 18,1 l

- Distribution cabling

Main 60 V feeder : 25 mm^2 two core armour cable (with separate earth to each distribution board)
Length : ≈150 m
12 V wiring : 4 mm^2 four core armour cable

- DC to DC converters

Type : 60 V DC/12 V DC
Rating : 40 A (1 off); 20 A (6 off)
Manufacturer : K R Enterprises, P O Box 13079, Northmead, 1511

B.3 Woodlands

- Diesel engine specifications

Type : Lister air-cooled
Model no. : ST2
No. cylinders : 2
Bore : 95,25 mm
Stroke : 88,9 mm
Displacement : 1,266 litre
Speed : 1500 rpm
Power output : 8,9 kW (continuous BS649:1958)
Torque : 6,3 kgf.m
Fuel cons. : 2,6 l/hour @ full load

- Alternator specifications

Manufacturer : Boyd Brown - Leroy Somer AC Generator

Type : TA 1610S4 ACT No. : 56843/7 P : 23 S
kW : 5,6 cos ø : 0,8 Delta V : 220 A : 32
kVA : 7,0 eff.% : 82,5 Star V : - A : -
rpm : 1500 ph : 1 Hz : 50 cl : F Amb :40°C
Rating : S1 Excit. : Auto V : 20 A : 2
Regulator : - DE brg. : 6210
Date : 9-82 NDE brg.: 6208
Weight : 145 kg Grease every hrs. : -
Quantity : - Shel Alvania R3

- Battery charger specifications

Type : thyristor regulator
Rating : 100 A @ 36V (nominal)

- Battery specifications

Type : Raylite 2 IMR 25 TL (farm lighting type, tubular plate, lead acid)
No. : 18 (two parallel banks of nine batteries in series)
Rating : 590 Ah
SG : 1,250
Nominal voltage : 4 V

- Inverter specifications

Type : Ferro-resonant sine wave
Manufacturer : Semiconductor Services (PO Box 133 Mondeor 2110 Tvl.)
Volts : 36 V DC/220 V AC
Amps : 100 A DC/13 A AC
Serial no. : 860915
Model : SIN 36/3000
Install. date : 02/11/86

B.4 Shingwedzi

- Diesel genset specifications

- Genset No. : K16

Diesel engine : K16 CAT2 D3406 T
Type : water-cooled, 4 stroke, 6 cylinder, turbocharged
Displacement : 14,6 l
Rating : 225 kVA continuous
180 kW

Serial no. : 90U14001
AR no. : 6N4998 Dlr code : K16
Power : 265 kW High idle rpm : 1530
Full load rpm : 1500 Static fuel setting : 0,175
Max. altitude : 3000-N

Alternator type : three phase, brushless, revolving field
Rating : 225 kVA
180 kW
Voltage : 400 V ±10%
Current : 324 A
Excitation : 1,21 A
40 V
Serial No. : F 1117-2

- Genset No. : K125

Diesel engine : K125 CAT1 D3406 TA

Type : water-cooled, 4 stroke, 6 cylinder, turbocharged, after-cooled
Displacement : 14,6 l
Rating : 250 kVA continuous
200 kW

Serial no. : 75Z00328
AR no. : 1W9026
Power : 265 kW High idle rpm : 1530
Full load rpm : 1500 Static fuel setting : 0,170
Max. altitude : 3000-N

Alternator type : three phase, brushless, revolving field
Rating : 250 kVA
200 kW
Voltage : 400 V +5%, -10%
Current : 379 A
Excitation : 1,21 A
40 V
Serial No. : G 1271-1

APPENDIX C : SCHEDULES OF LOADS

C.1 Jock of the Bushveld

2 off wallmounted bedside lights per hut
1 off wall mounted double tube flourescent fitting per bathroom
2 off wall mounted lights in the lounge
1 off hanging light fitting in the dining room
2 off hanging light fitting in the kitchen
1 off flourescent fitting in the cloakroom

No. flourescent fittings : 7
Rating : 16 W

No. mercury vapour fittings : 17
Type : Phillips SL 18 18 W/ 900 lumen

Cooking, refrigeration and hot water heating by LPG
No fans

Total installed load : 418 W

C.2 Boulders

huts : 33 incandescent lights
6 flourescent lights
6 fans

main complex : 10 incandescent lights
9 flourescent lights
3 fans (Brevettato)
2 fridges (one 180 l and one 200 l capacity Alaska)
3 freezers (Polar bear 60 l capacity)

power rating of loads : incandescent lights : 20 W
flourescent lights : 15 W
fans : 60 W
freezer : 60 W
fridge : 60 W

total installed load : 1925 W

C.3 Woodlands

Fridges : Norge deep freeze : capacity 410 l
220 V 1,6 A
GEC Coldspace : 220 V 1,6 A
Kettle
Iron
Toaster
Hi Fi
Fans : small : 32,2 W
large : 50 W
TV : Sony : 85 W for 4hrs/day
Washing machine
Battery charger (for two way radio communications)
Lights : Kitchen : 2 off 65 W flourescent
Dining : 3 off 60 W incandecsent
Lounge : 3 off 60 W incandescent
TV room : 2 off 100 W incandescent
Main bed: 3 off 100 W incandescent
Front " : 2 off 100 W Incandescent
Kids " : 3 off 100 W
Bath " : 3 off 60 W
Passage : 1 off 100 W
Stoep : 2 off 65 W flourescent
Office : 2 off 65 W Flourescent

Total installed load : ≈ 8350 W

Planned extension to compound : Lights for 8 huts
1 double hut
kitchen
ablution block
2 plug points for irons

C.4 Shingwedzi

- List of loads and appliances and estimated usage

Item no.	Description	Volts	No.off	kW	Hrs/d
1.	lights outside in circles	220	6	.1	9
2.	lights in houses (5*21)	220	105	.1	3
3.	lights in flats (4*16)	220	64	.1	3
4.	lights in huts (79*4)	220	316	.1	3
5.	airconditioner in huts	220	79	1.6	6
6.	airconditioner in houses	220	5	1.6	5
7.	airconditioner in flats	220	4	1.6	5
8.	airconditioner guest house	220	3	1.5	5
9.	geysers in huts	220	79	1.0	3
10.	geysers in houses	220	5	2.0	5
11.	geysers in guest house	220	2	2.0	5
12.	geysers in flats	220	4	2.0	5
13.	heat pump in caravan park	380	1	3.3	6
14.	fridges in huts	220	79	.1	7
15.	fridges in houses	220	5	.3	7
16.	fridges in guest house	220	1	.3	4
17.	fridges in flats	220	4	.3	7
18.	compressor in workshop	380	1	2.0	3
19.	airconditioner in workshop	220	1	1.5	6
20.	clean water pump	380	1	3.0	9
21.	river water pump	380	1	3.0	7
22.	sewerage pump	380	1	3.0	6
23.	swimming pool pump	380	4	.75	17
24.	main complex				
24.1	flourescent lights	220	38	.06	5
24.2	incandescent lights	220	93	.1	6
24.3	airconditioners	220	4	2.3	6
24.4	heat pump in kitchen	380	1	2.0	9
24.5	geyser in toilets	220	1	2.0	4
24.6	fridge in restaurant	380	1	2.5	9
24.7	fridge in shop	380	1	.75	9
24.8	display fridge in shop	380	1	1.0	9
24.9	freezer in restaurant	380	1	4.0	9
24.10	display freezer in shop	380	1	5.0	9
24.11	Coca Cola coolers	380	4	.6	11
24.12	stove in restaurant	380	1	18.0	11
24.13	fish frier	380	1	9.0	2
24.14	tilting pan	380	1	12.0	4
24.15	dishwasher	380	1	12.0	4
24.16	mixer	220	1	.5	2
24.17	microwave oven	220	1	.5	3
24.18	toaster	220	1	6.0	3
24.19	urn	220	3	3.0	6
24.20	bainmarie	380	2	9.0	6
24.21	KIC heater	220	1	3.0	3
TOTAL				453.53 kW	

Estimated daily load energy demand : 2376 kWh/day

APPENDIX D

POWER MEASUREMENT ANALYSIS

Voltage = $V \sin \Omega t$

Current = $A \sin (\Omega t - \theta)$

Average power

$$P_{av} = 1/T \int_0^{T} [V \sin \Omega t]\, [A \sin (\Omega t - \theta)]\, dt$$

$$= \frac{1}{2\pi} \int_0^{2\pi} V \sin \alpha\, [A \sin (\alpha - \theta)]\, d\alpha$$

$$= \frac{1}{2\pi} V\, A \int_0^{2\pi} \sin \alpha\, [\sin \alpha \cos \theta - \cos \alpha \sin \theta]\, d\alpha$$

$$= \frac{1}{2\pi} V\, A \int_0^{2\pi} \sin^2\alpha \cos \theta - \sin \alpha \cos \alpha \sin \theta\, d\alpha$$

$$= \frac{1}{2\pi} V\, A \int_0^{2\pi} \frac{1}{2} [1-\cos 2\alpha] \cos \theta - \frac{1}{2} \sin 2\alpha \sin \theta\, d\alpha$$

$$= \frac{1}{4\pi} V\, A \cos \theta \int_0^{2\pi} 1-\cos 2\alpha\, d\alpha - \frac{1}{4\pi} V\, A \sin \theta \int_0^{2\pi} \sin 2\alpha\, d\alpha$$

$$= \frac{1}{4\pi} V\, A \cos \theta\, [\alpha - \frac{1}{2} \sin 2\alpha]_0^{2\pi} - \frac{1}{4\pi} V\, A \sin \theta\, [\frac{1}{2} \cos 2\alpha]_0^{2\pi}$$

$$= \frac{1}{4\pi} V\, A \cos \theta\, [2\pi] - \frac{1}{4\pi} V\, A \sin \theta\, [0]$$

$$= \frac{1}{2} V\, A \cos \theta$$

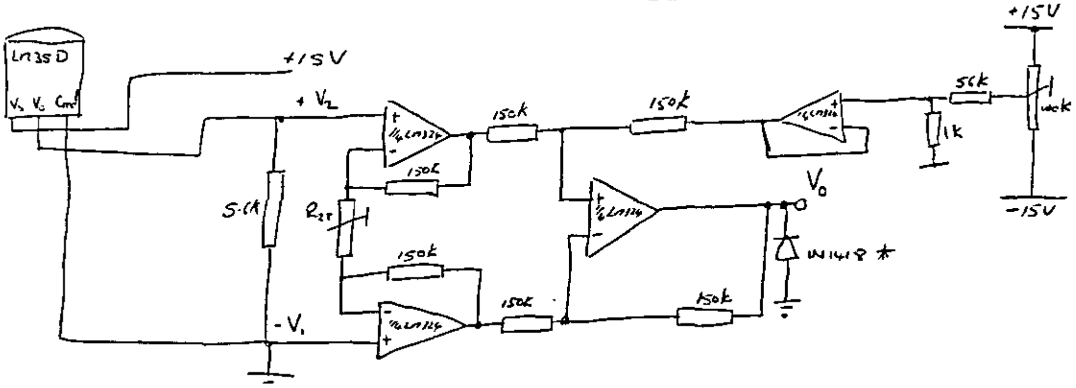
$$= \sqrt{\tfrac{1}{2}}\, V \sqrt{\tfrac{1}{2}}\, A \cos \theta$$

$$= V_{rms}\, A_{rms} \cos \theta$$

· 4 ELECTRONIC INTERFACE CIRCUITS.

4/10/87

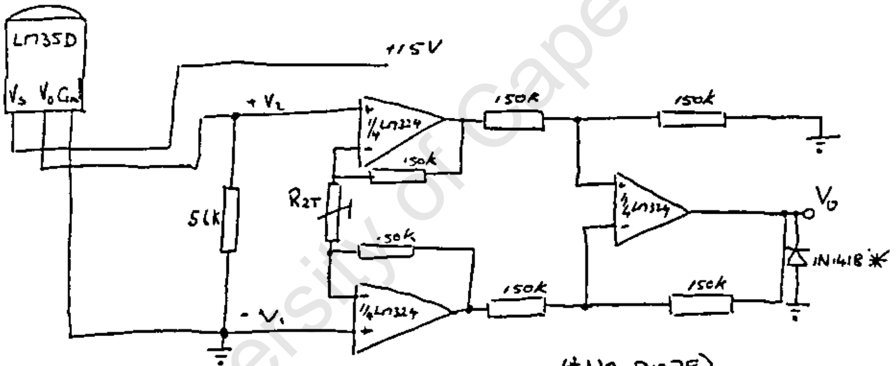
4.1] TEMP MEASUREMENT. — PANEL : MP



i)B JOCK - PANEL TEMP (*NO DIODE ON OUTPUT)

ii) BOULDERS - PANEL TEMP (*DIODE ON OUTPUT)

4·2] TEMP MEASUREMENT - AMBIENT TEMP.



i) JOCK - AMBIENT TEMP (*NO DIODE)

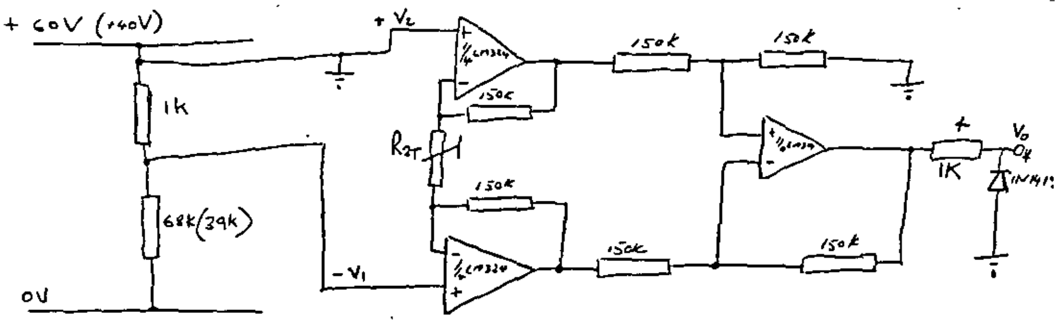
ii) BOULDERS - AMBIENT TEMP (" ")

iii) WOODLANDS - BATTERY TEMP (" ")

ELECTRONIC INTERFACE CIRCUITS.

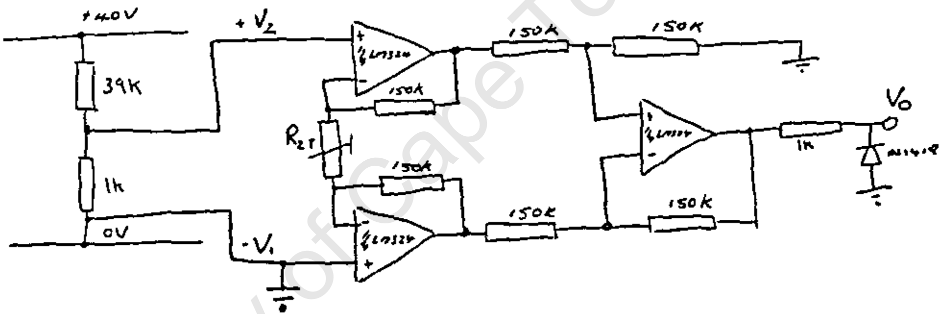
4/10/87

4·3] VOLTAGE MEASUREMENT -(i)



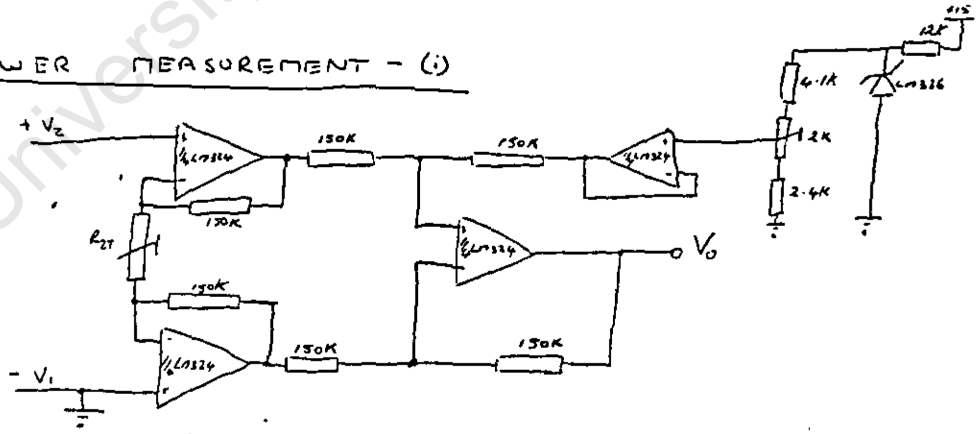
i) BOULDERS - VOLTAGE (Diode +1K Resistor) 60V
ii) WOODLANDS - VOLTAGE (No diode or 1K Resistor) 40V

4 4] VOLTAGE MEASUREMENT - (ii)



i) JOCK - VOLTAGE

4·5] POWER MEASUREMENT - (i)

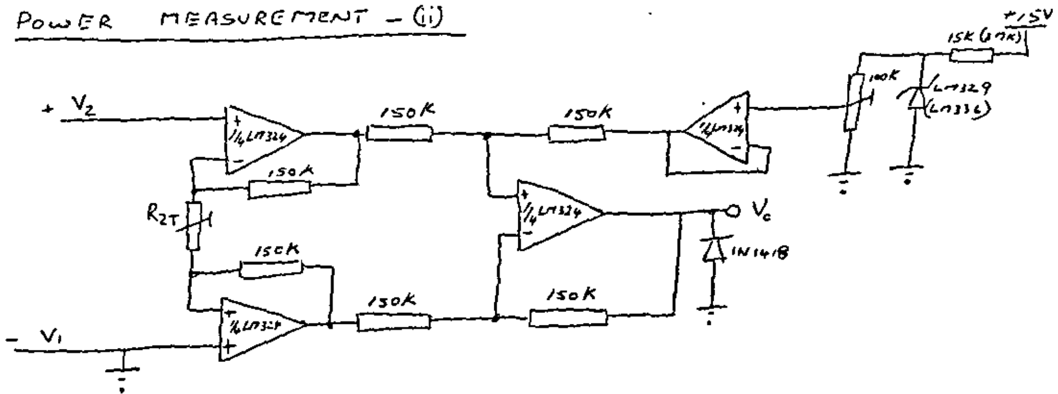


i) JOCK - POWER.

ELECTRONIC INTERFACE CIRCUITS

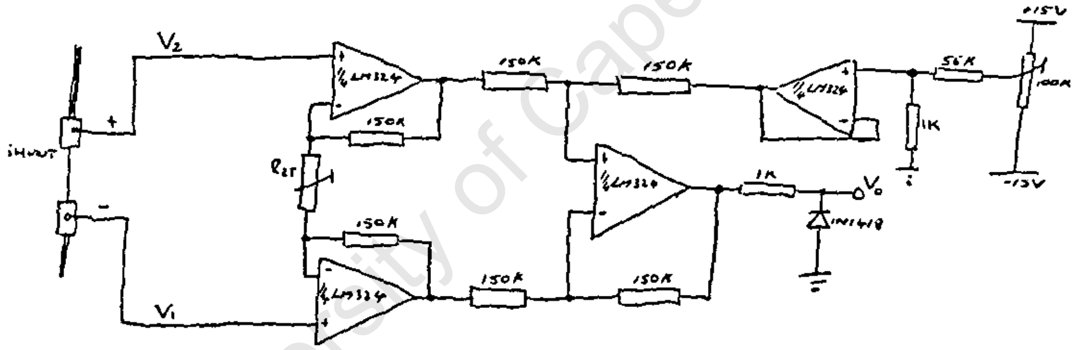
4/10/87

4·6] POWER MEASUREMENT – (ii)



i) WOODLANDS – POWER-1 (LM324 & 15K)
ii) WOODLANDS – POWER-2 (LM336 & 27K)
iii) WOODLANDS – POWER-3 (LM329 & 15K)

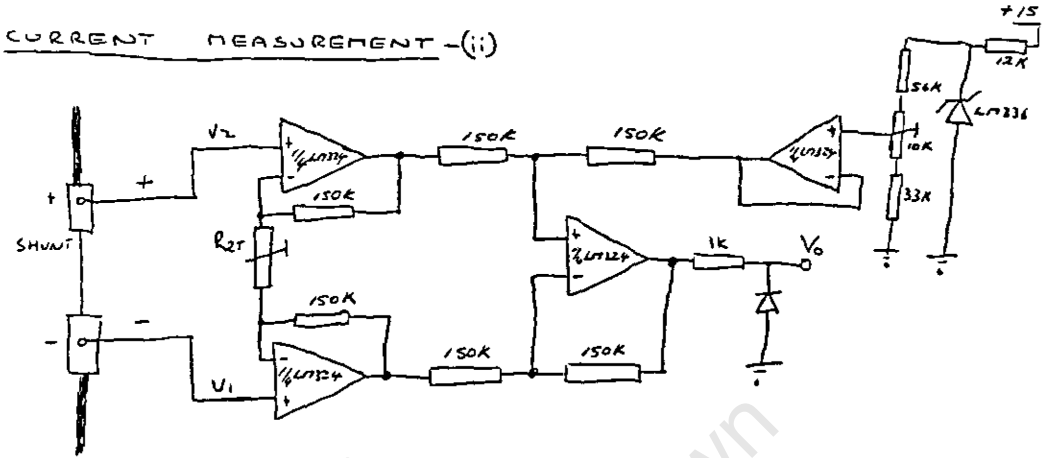
4·7] CURRENT MEASUREMENT – (i)



i) JOCK – CURRENT-1 (50A – 50mV SHUNT)
ii) JOCK – CURRENT-2 (50A – 50mV SHUNT)
iii) BOULDERS – CURRENT-1 (100A – 50mV SHUNT)
iv) WOODLANDS – CURRENT-1 (100A – 50mV SHUNT)
v) WOODLANDS – CURRENT-2 (100A – 50mV SHUNT)

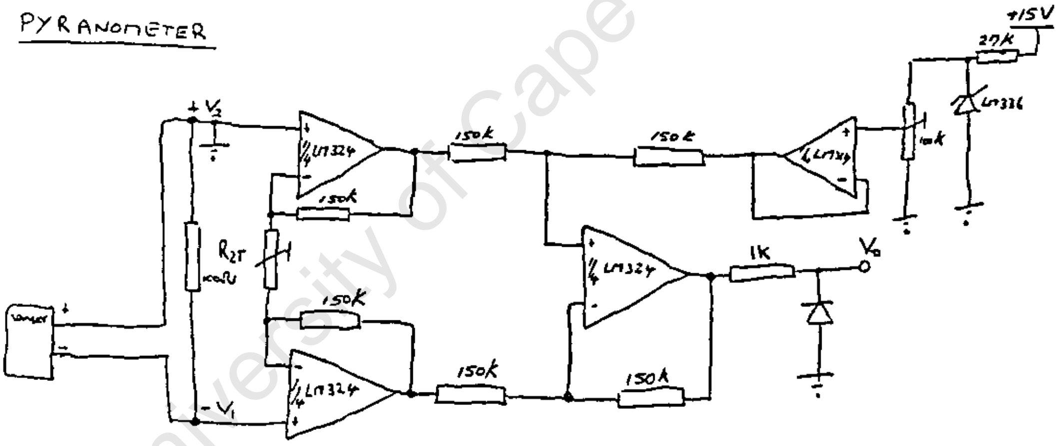
ELECTRONIC INTERFACE CIRCUITS 4/10/87

4.8] CURRENT MEASUREMENT -(ii)



i) BOULDERS - CURRENT-2 (10A - 50mV SHUNT)

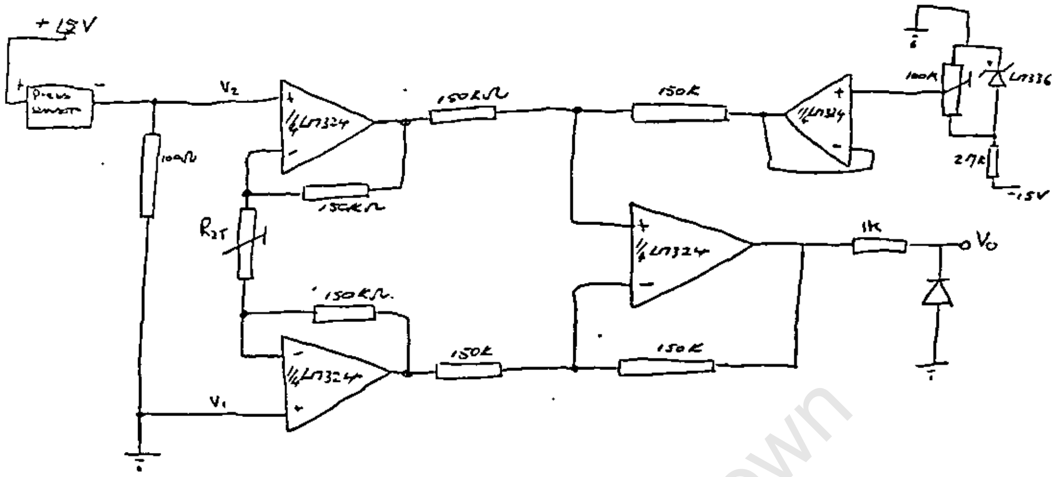
4.9] PYRANOMETER



i) JOCK - PYRANOMETER	PY7790
ii) BOULDERS - PYRANOMETER	PY7654

ELECTRONIC INTERFACE CIRCUITS. 4/10/87

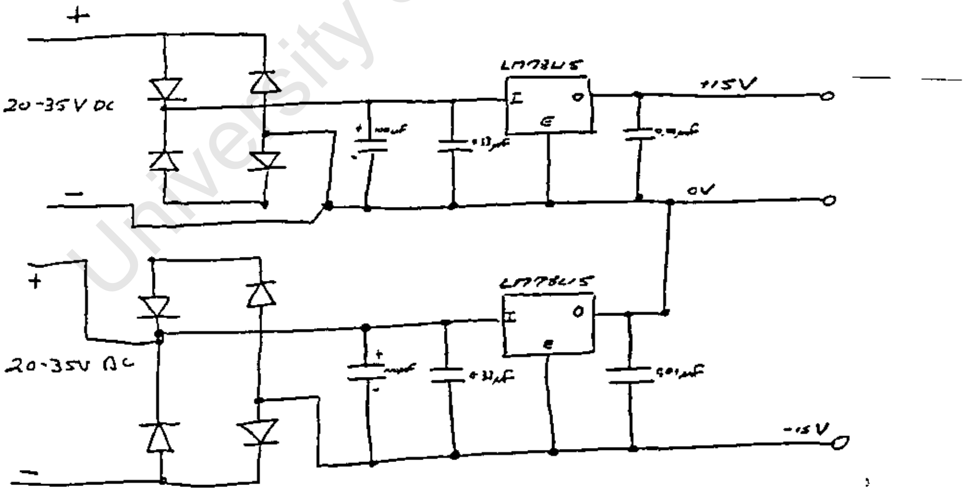
4.10) LEVEL MEASUREMENT



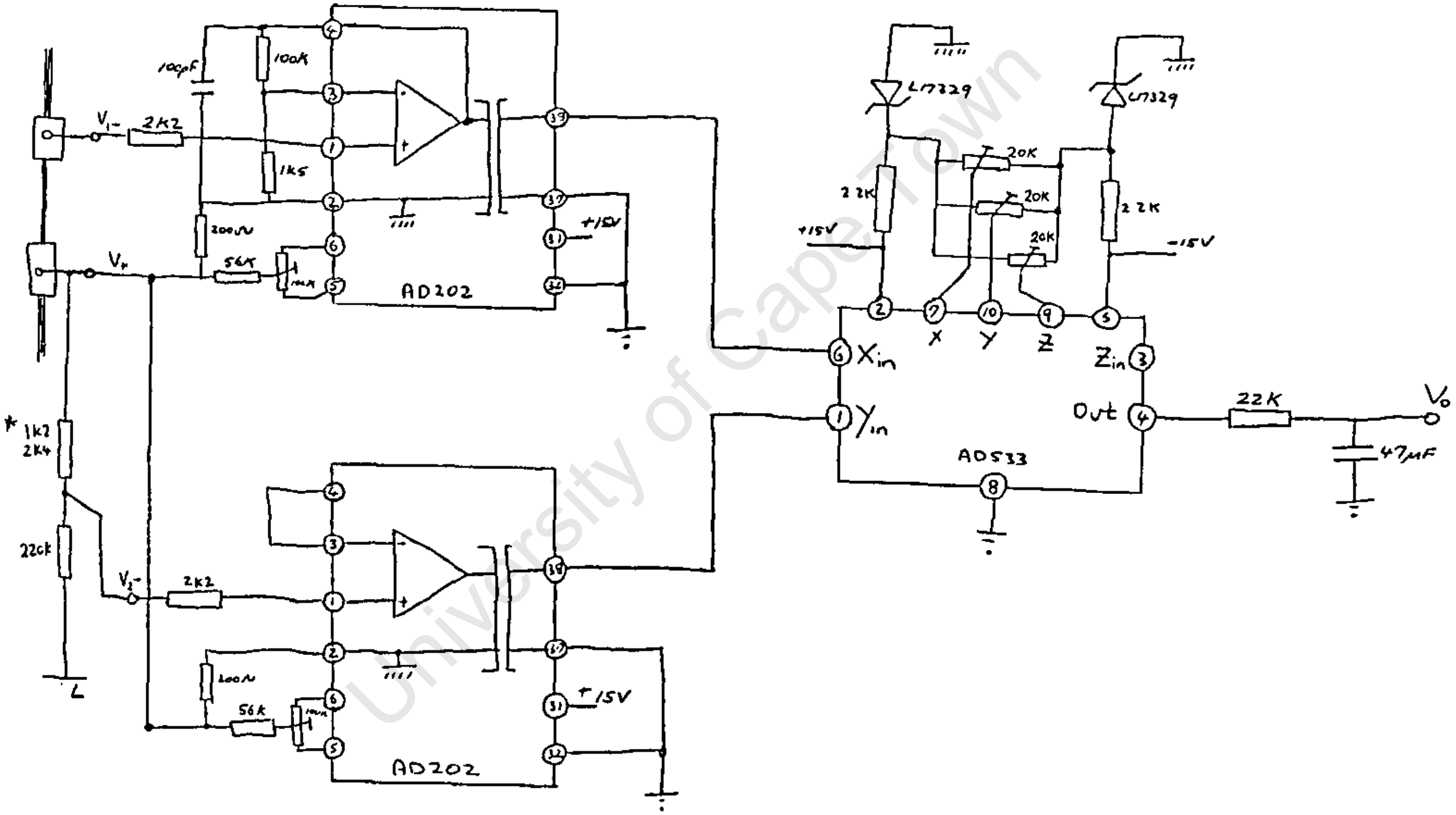
i) WOODLANDS - LEVEL MEASUREMENT

ELECTRONIC INTERFACE CIRCUITS 4/10/87

4.11] ±15V DC POWER SUPPLY



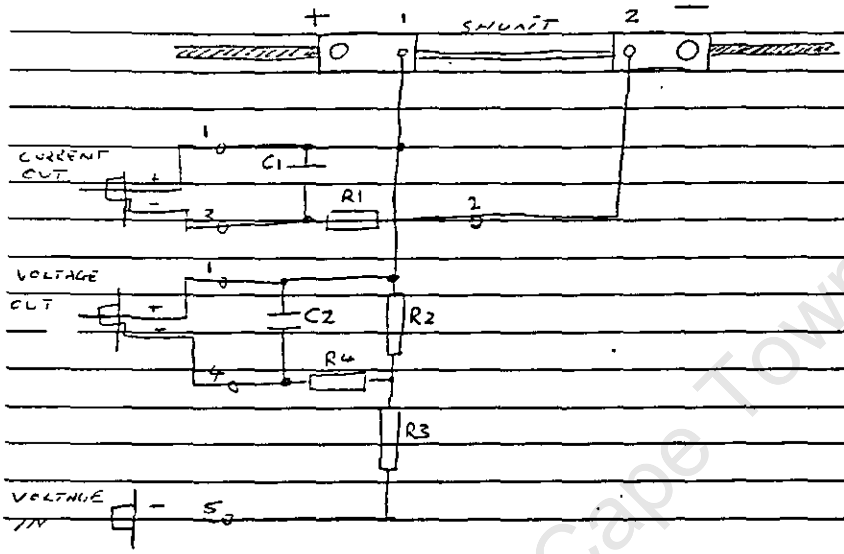
412) ELECTRONIC INTERFACE CIRCUITS.



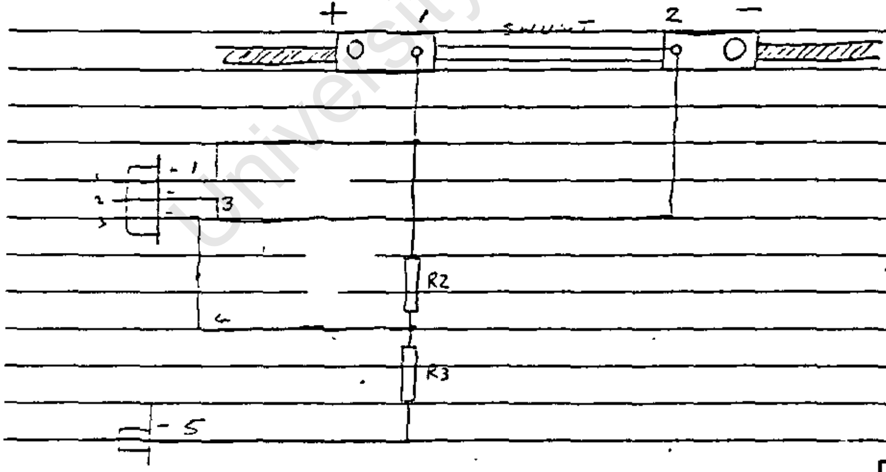
i) JOCK - (*2K4 RESISTOR)
ii) WOODLANDS - POWER-1 (*2K4 RESISTOR)
iii) WOODLANDS - POWER-2 (*1K2 RESISTOR)
iv) WOODLANDS - POWER-3 (*1K2 RESISTOR)

12] POWER MEASUREMENT

4.13 CURRENT SHUNT AND VOLTAGE SYSTEM



POWER MEASUREMENT SYSTEM



APPENDIX E

E.1 JOCK OF THE BUSHVELD

E.1.1 Input programs

Variable	Channel No.	Range	Offset	Multiplier
Panel temp	01	3	-10,00	0,0550
Ambient temp	02	3	0,000	0,0500
Bat. voltage	03	3	-0,3823	0,0215
Power	04	3	-730,6	0,7318
Bat. amps in	05	3	-0,5000	0,0253
Bat. amps out	06	3	-0,5000	0,0128
Solar rad.	07	3	-100,0	0,8000
skip	08	-	-	-

E.1.2 Output programs

Variable	Col. No.	Prog. No.	Channel No.
Panel temp	01	02	01
Ambient temp	02	02	02
Bat. voltage	03	02	03
Power	04	02	04
Bat. amps in	05	02	05
Bat. amps out	06	02	06
Solar rad.	07	02	07
skip	08	00	08

E.2 BOULDERS

E.2 1 Input programs

Variable	Channel No.	Range	Offset	Multiplier
Panel temp	01	3	-10,00	0,0550
Ambient temp	02	3	0,000	0,0500
Bat. voltage	03	3	0,000	0,0348
skip	04	-	-	-
Bat. amps in	05	3	-1,000	0,0505
Bat. amps out	06	3	-50,51	0,0505
Solar rad.	07	3	-100,0	0,8000
skip	08	-	-	-

E.2.2 Output programs

Variable	Col. No.	Prog. No.	Channel No.
Panel temp	01	02	01
Ambient temp	02	02	02
Bat. voltage	03	02	03
skip	04	00	04
Bat. amps in	05	02	05
Bat. amps out	06	02	06
Solar rad.	07	02	07
skip	08	00	08

E.3 WOODLANDS

E.3.1 Input programs

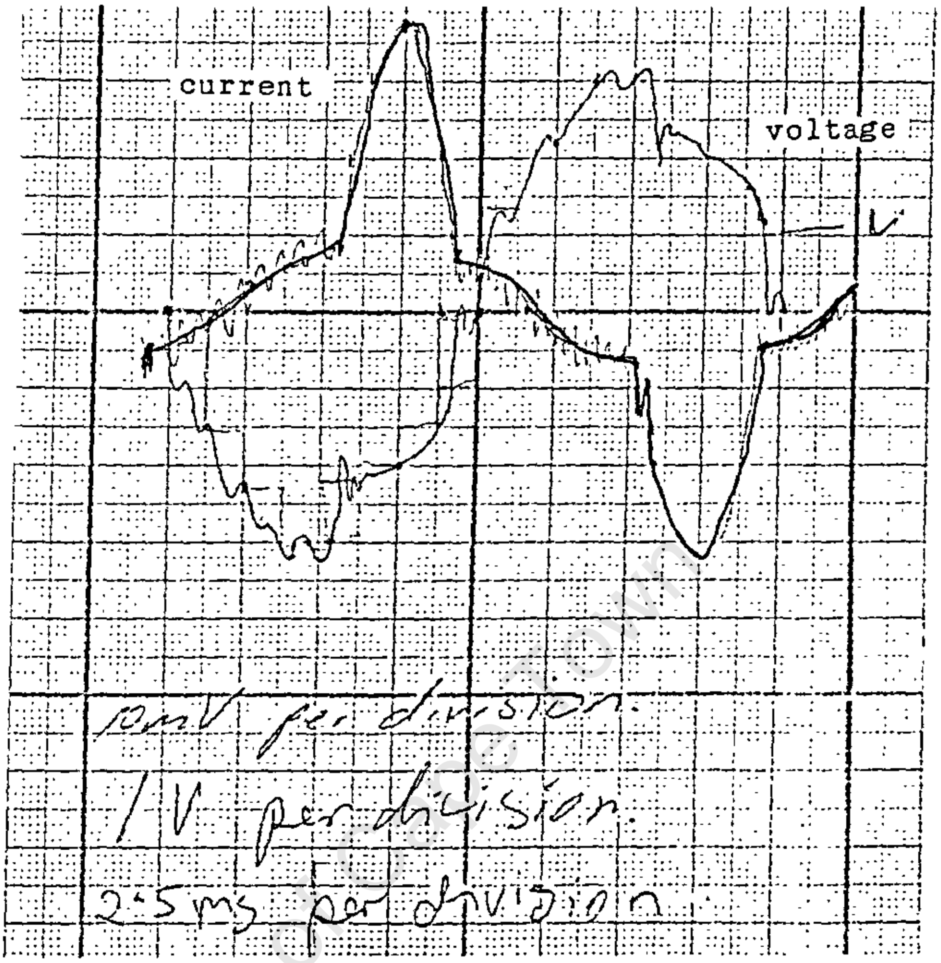
Variable	Channel No.	Range	Offset	Multiplier
Battery temp	06	3	0,000	0,0500
Bat. voltage	02	3	-2,000	0,0216
Alternator power	03	3	-6,500	0,0064
DC charger power	04	3	-4,490	0,0050
Inverter power	05	3	-5,082	0,0050
Bat. amps in	01	3	-1,000	0,0517
Bat. amps out	07	3	-1,000	0,0505
Fuel level	08	3	-1,012	0,0085

E.3.2 Output programs

Variable	Col. No.	Prog. No.	Channel No.
Battery temp	01	02	06
Bat. voltage	02	02	02
Alternator power	03	02	03
DC charger power	04	02	04
Inverter power	05	02	05
Bat. amps in	06	02	01
Bat. amps out	07	02	07
Fuel level	08	01	08

F.2

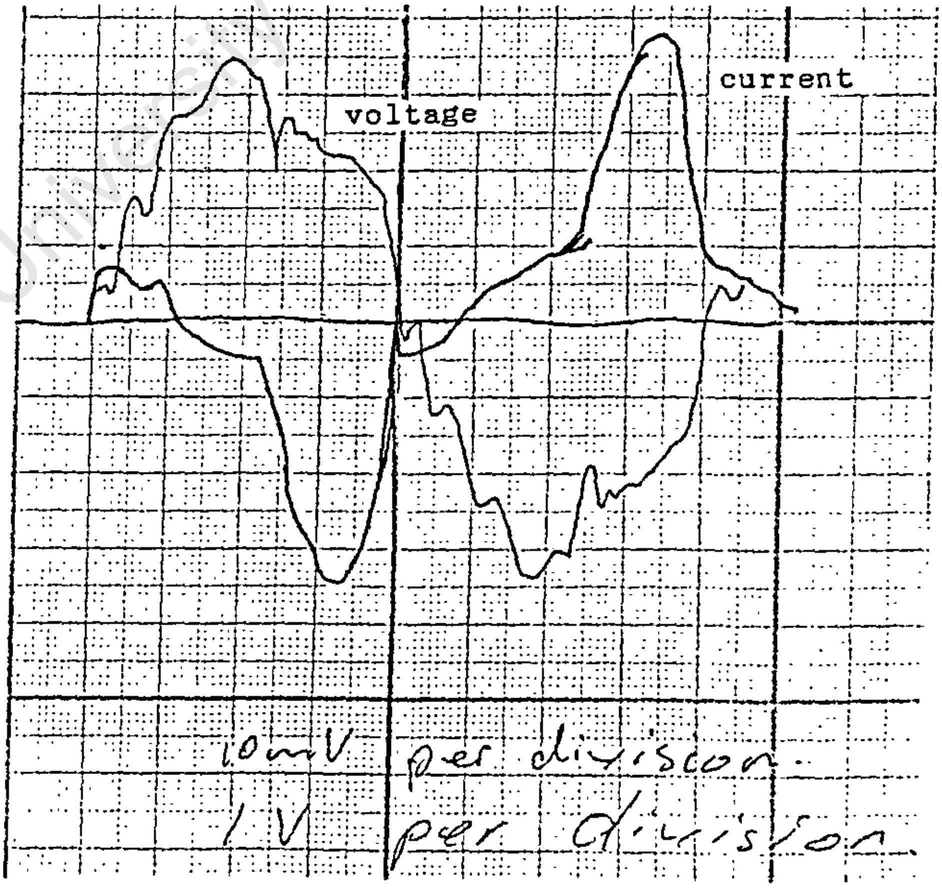
Woodlands : 5,6 kW Boyd Brown - Leroy somer AC genearator



10mV per division.

1V per division.

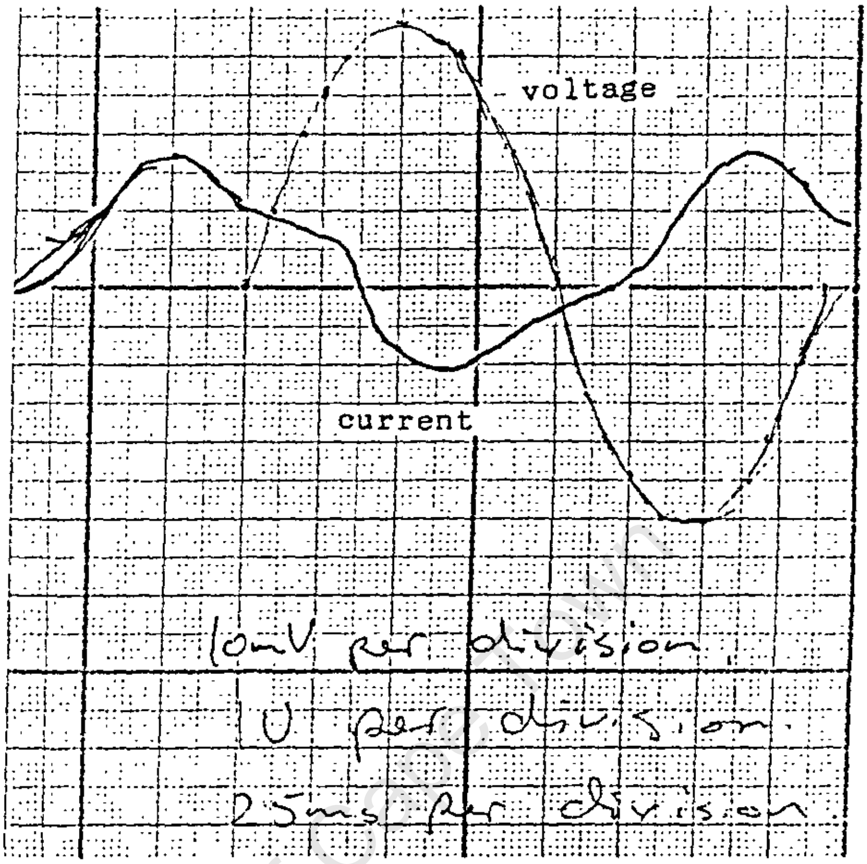
2·5ms per division.

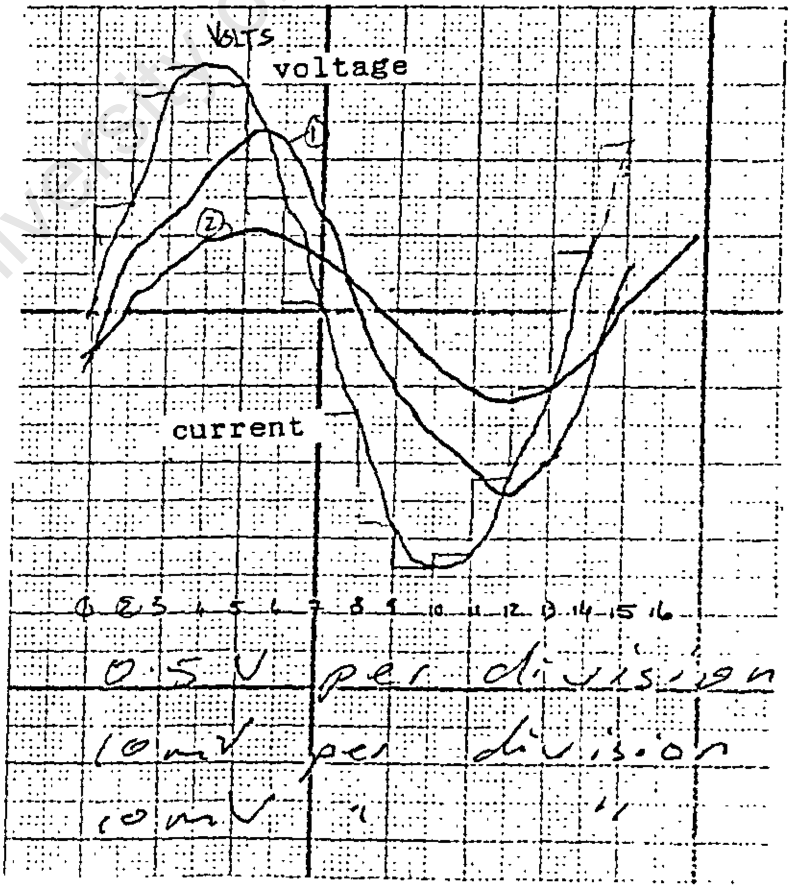


10mV per division.

1V per division.

Woodlands : 3 kW sine wave inverter





APPENDIX G : Genset operating and maintenance costs

WOODLANDS MAINTENANCE COSTS : 1986/87

Diesel fitter rate : 22 R/hour
" over-time : 35 R/hour
Travelling costs : 33 c/km
Ave. run time per day : 11.15 hr/day (based on fuel log : 22 Dec 1985 to 8 Jan 1987)

Item no.	Date (MM/DD/YY)	Engine hours	Service interval	Work done	Work time	Work over-time	Travel time	Travel distance	Spares req.	Spares cost	.abour cost	Travel cost	Total cost
1	03/18/86	6040	-	remove starter remove flywheel file teeth re assemble and test	3		1.5	80	-		99.00	26.40	125.40
2	05/05/86	6575	535	replace cylinder head gaskets and test	7		1.5	80	head gaskets	11.56	187.00	26.40	224.96
3	05/15/86	6687	112	clean battery terminals remove starter file pinion teeth re assemble and test	5		1.5	70	-		143.00	23.10	166.10
4	06/12/86	6999	312	250 hr service replace gaskets	5		1	60	250 hr service kit base gaskets	77.53	132.00	19.80	229.33
5	07/16/86	7378	379	inspection no repairs	4		1	60	-		110.00	19.80	129.80
6	08/04/86	7590	212	250 hr service braze fuel return pipe	4.5		0.75	30	250 hr service kit brazing rod, gas	87.00	115.50	9.90	212.40
7	09/10/86	8002	413	remove and strip starter clean, replace and test	1.5		1.5	80	-		66.00	26.40	92.40
8	09/18/86	8092	89	replace diodes polarize alternator	5	3	1.5	80	diodes	40.00	248.00	26.40	314.40
9	10/27/86	8526	435	remove starter install new starter remove flywheel install new ring gear	9		1	64	starter motor ring gear	1180.00	220.00	21.12	1421.12
10	10/28/86	8538	11	fabricate protective guard for drive shaft	4				steel brazing rod, gas	25.00	88.00		113.00
11	11/19/86	8783	245	250 hr service	4		1.5	64	250 hr service kit	72.00	121.00	21.12	214.12
12	12/05/86	8961	178	250 hr service service battery	1		1.5	80	250 hr service kit	72.00	55.00	26.40	153.40
13	02/27/87	9333	372	transport genset to site install genset bleed and start engine transport standby engine to Shingwedzi 500 hr service	7		2	86	500 hr service kit	72.00	198.00	28.38	298.38
14	03/02/87	9356	23	locate oil leak at filter replace filter	1		1.5	86	oil filter	15.00	55.00	28.38	98.38
15	03/24/87	9612	256	locate diesel leak replace diesel filter repair stator	3.5		1.5	80	diesel filter	15.00	110.00	26.40	151.40
16	03/31/87	9690	78	strip starter replace solenoid fix short circuit at brushes re assemble and test	2		1.5	80	solenoid	80.00	77.00	26.40	183.40
17	04/02/87	9712	22	locate short in diodes replace diodes and test install starter tow welder to site	6		1.5	80	diodes	40.00	165.00	26.40	231.40
18	04/02/87	9712	0	250 hr service	3		1.25	68	250 hr service kit	72.00	93.50	22.44	187.94
19	04/03/87	9723	11	tow welder to Shingwedzi check genset	2		1.5	80	-		77.00	26.40	103.40
20	04/03/87	9723	0	locate short in starter remove to Shingwedzi replace and test remote start	7	2	2.5	120	-		279.00	39.60	318.60
21	07/21/87	10939	1215	diagnose burnt out generato remove to Shingwedzi repair and re install rewire charging circuit and test	11		2	240	-		286.00	79.20	365.20
22	08/07/87	11128	190	250 hr service	2		1.5	60	250 hr service kit	72.00	77.00	19.80	168.80
23	08/28/87	11362	234	repair oil leaks clean diodes	6		1	60	-		154.00	19.80	173.80
24	09/02/87	11418	56	strip engine and repair oil leaks	7		1	70	-		176.00	23.10	199.10
25	10/16/87	11909	491	250 hr service	3		1.25	80	250 hr service kit	72.00	93.50	26.40	191.90
26	11/12/87	12210	301	250 hr service locate oil leak replace base gaskets	4		0.66	38	250 hr service kit base gaskets	77.53	102.52	12.54	192.59
	604				117.50	5.00	34.91	1976.00		2080.62	.528.02	652.08	6260.72

Ave. service interval: 247
Total no. of hours : 6170
No. 250 hr services : 25

SHINGWEDZI MAINTENANCE COSTS : 1985/86/87
Engine no. : k125

Diesel fitter rate : 22 R/hour
Ave. run time per day : 20.64 hr/day (based on hours/day x 2)
Ave. maintenance cost : 3.74 R/hour

Item no.	Date (MM/DD/YY)	Engine hours	Service interval	Work done	Work time	Spares req.	Spares cost	Labour cost	Total cost
1	01/30/86	9370	-	125 hr service	3	125 hr service kit	300.00	66.00	366.00
2	02/06/86	9436	66	replace oil seal and sleeve wash engine and radiator test engine	3	oil seal sleeve	25.00 200.00	66.00	291.00
3	02/12/86	9496	60	500 hr service	3	500 hr service kit	300.00	66.00	366.00
4	02/21/86	9638	142	125 hr service	2	125 hr service kit	300.00	44.00	344.00
5	03/24/86	9937	299	remove water pump replace oil seals test for oil leaks	2	oil seals	50.00	44.00	94.00
6	03/25/86	9940	3	1000 hr service	3	1000 hr service kit	1500.00	66.00	1566.00
7	04/14/86	10125	185	125 hr service	2	125 hr service kit	300.00	44.00	344.00
8	04/21/86	10227	102	remove and strip alternator diagnose faulty diodes dispatch alternator to Skukuza replace fan belts	3	fan belts	75.00	66.00	141.00
9	05/01/85	-	-	replace slip ring brushes replace diodes	2.5	slip ring brushes diodes	150.00	55.00	205.00
10	05/09/86	10409	182	125 hr service replace alternator and test	4	125 hr service kit	300.00	88.00	388.00
11	05/16/86	10480	71	500 hr service	1	500 hr service kit	300.00	22.00	322.00
12	05/23/86	10549	69	500 hr service wash engine and radiator	2	500 hr service kit	300.00	44.00	344.00
13	05/27/86	10589	40	repair diesel filter leak	2			44.00	44.00
14	06/02/86	10661	72	125 hr service grease service	3.5	125 hr service kit grease	300.00	77.00	377.00
15	06/13/86	10762	101	250 hr service wash radiator	3	250 hr service kit	300.00	66.00	366.00
16	06/16/86	10791	29	250 hr service	2	250 hr service kit	300.00	44.00	344.00
17	07/05/86	10995	204	1000 hr service wash engine and radiator	5	1000 hr service kit	1500.00	110.00	1610.00
18	07/10/86	11018	23	replace diesel filt. O-ring wash engine and radiator	1.5	O-ring for diesel filter	25.00	33.00	58.00
19	07/21/86	11142	124	strip and rebuild hourmeter	2			44.00	44.00
20	07/31/86	11250	108	250 hr service replace all fan belts	2	250 hr service kit fan belts	300.00 75.00	44.00	419.00
21	08/21/86	11462	212	500 hr service	2	500 hr service kit	300.00	44.00	344.00
22	09/18/86	11750	288	250 hr service wash engine and radiator	4	250 hr service kit	300.00	88.00	388.00
23	10/13/86	12028	278	fabricate fanbelt guard	5	steel and consummables	50.00	110.00	160.00
24	10/16/86	12060	32	1000 hr service wash engine and radiator replace fan belts	5	1000 hr service kit fan belts	1500.00 75.00	110.00	1685.00
25	11/07/86	12289	229	250 hr service	2	250 hr service kit	300.00	44.00	344.00
26	11/27/86	12493	204	500 hr service wash engine and radiator	3	500 hr service kit	300.00	66.00	366.00
27	12/03/86	12550	57	250 hr service wash engine and radiator	2	250 hr service kit	300.00	44.00	344.00

SHINGWEDZI MAINTENANCE COSTS : 1985/86/87
Engine no. : K16

Diesel fitter rate : 22 R/hour
Ave. run time per day : 21.09 hr/day (based on hours/day x 2)
Ave. maintenance cost : 4.52 R/hour

Item no.	Date (MM/DD/YY)	Engine hours	Service interval	Work done	Work time	Spares req.	Spares cost	Labour cost	Total cost
1	12/31/85	16506	-	500 hr service wash engine test operation	5	500 hr service kit	300.00	110.00	410.00
2	01/17/86	16697	191	125 hr service wash radiator core	3	125 hr service kit	300.00	66.00	366.00
3	01/23/86	16758	61	250 hr service	3	250 hr service kit	300.00	66.00	366.00
4	02/06/86	16900	142	125 hr service wash engine paint engine block	3	125 hr service kit 1 litre paint 500 ml thinners	300.00 15.00	66.00	381.00
5	02/13/86	16985	85	1000 hr service	3	1000 hr service kit	1500.00	66.00	1566.00
6	03/07/86	17125	140	250 hr service remove and check oil cooler remove tappet covers remove cylinder heads identify cracked no. 2 piston chamber	5	250 hr service kit	300.00	110.00	410.00
	03/08/86			de-coke combustion chambers travel to 621 for spares install combustion chambers install injector tips flush engine and radiator remove water pump and replace seals install water pump start engine drain oil	12.5	water pump seals head gaskets oil piston chamber	40.00 500.00 50.00 400.00	275.00	1265.00
	03/09/86			check for water in the sump fill crankcase with oil replace oil filter start and load engine	2	oil oil filter	50.00 100.00	44.00	194.00
7	03/24/86	17375	250	125 hr service wash radiator core	3	125 hr service kit	300.00	66.00	366.00
8	04/23/86	17696	321	125 hr service remove engine hour meter rebuild, replace and test	2	125 hr service kit	300.00	44.00	344.00
9	05/12/86	17895	199	125 hr service grease service	1.5	125 hr service kit grease	300.00	33.00	333.00
10	05/23/86	18003	108	1000 hr service wash radiator service batteries	4	1000 hr service kit distilled water	1500.00	88.00	1588.00
11	05/27/86	18044	41	remove battery alternator repair field winding short replace and test	4			88.00	88.00
12	06/03/86	18117	73	remove front pulley replace sleeve and seal replace pulley, check for oil leak	2.5	sleeve oil seal	200.00 50.00	55.00	305.00
13	06/05/86	18146	29	125 hr service replace fan belts	2	125 hr service kit fan belts	300.00 75.00	44.00	419.00
14	06/16/86	18247	101	250 hr service	2	250 hr service kit	300.00	44.00	344.00
15	06/19/86	18277	30	250 hr service replace tacho drive oil seals	2	250 hr service kit tacho drive oil seals	300.00 50.00	44.00	394.00
16	07/10/86	18478	201	wash radiator and engine replace tappet cover seals	1.5	tappet cover seals	100.00	33.00	133.00
17	07/22/86	18616	138	125 hr service remove and repair hour meter	2	125 hr service kit	300.00	44.00	344.00
18	08/21/86	18922	306	install new hour meter	2	engine hour meter	500.00	44.00	544.00

19	08/29/86	19005	83	1000 hr service wash engine and radiator	6	1000 hr service kit	1500.00	132.00	1632.00
20	09/11/86	19133	128	-	1	-			
21	09/15/86	19166	33	investigate alternator install new alternator and test	5	spare alternator		110.00	110.00
22	09/18/86	-	-	strip alternator replace rotor replace staor replace brushhes, diodes & capacitor install and test	2	rotor stator diodes capacitors	3000.00 2000.00 50.00 100.00	44.00	5194.00
23	09/24/86	19253	87	250 hr service wash radiator	2	250 hr service	300.00	44.00	344.00
24	10/16/86	19505	252	500 hr service	2	500 hr service kit	300.00	44.00	344.00
25	10/20/86	-	-	remove and strip starter replace armature replace field coils replace bendix install and test	2	armature field coils bendix	1000.00 1000.00 250.00	44.00	2294.00
26	11/03/86	-	-	remove and strip alternator replace capacitors replace regulator replace brushes install and test	2	capacitors regulator brushes	100.00 200.00 100.00	44.00	444.00
27	11/12/86	19780	275	250 hr service wash radiator	2	250 hr service	300.00	44.00	344.00
28	12/03/86	19999	219	1000 hr service wash engine and radiator	4	1000 hr service kit	1500.00	88.00	1588.00
29	12/08/86	20058	59	fabricate alternator drive-guard	2	steel sheet brazing consummables	30.00 20.00	44.00	94.00
30	01/19/87	20522	464	500 hr service	2	500 hr service kit	300.00	44.00	344.00
31	01/27/87	20604	82	125 hr service wash engine and radiator service fan belts	2.5	125 hr service kit	300.00	55.00	355.00
32	02/12/87	20771	167	250 hr service wash engine and radiator	2	250 hr service kit	300.00	44.00	344.00
33	02/17/87	20814	43	replace diesel filter	1	diesel filter	50.00	22.00	72.00
34	02/24/87	20894	80	1000 hr service set tappet clearances repair diesel pump leak wash radiator	3	1000 hr service kit	1500.00	66.00	1566.00
35	03/30/87	21248	354	250 hr service wash radiator	2	250 hr service	300.00	44.00	344.00
36	04/04/87	21296	48	15 min. power failure no repair operator error	2	-		44.00	44.00
37	04/09/87	21367	71	125 hr service wash engine and radiator	4	125 hr service kit	300.00	88.00	388.00
38	04/21/87	21511	144	500 hr service wash engine and radiator paint engine block	2	125 hr service kit 1 litre paint 500 ml thinners	300.00 15.00	44.00	359.00
39	05/15/87	21763	252	250 hr service replace water elements	2.5	250 hr service water elements	300.00 100.00	55.00	455.00
40	06/08/87	22011	248	1000 hr service adjust tappet clearances wash engine and radiator service batteries service starter	4	1000 hr service kit	1500.00	88.00	1588.00
41	07/02/87	22257	246	250 hr service wash engine and radiator	2	250 hr service kit	300.00	44.00	344.00
42	08/19/87	22753	496	250 hr service wash engine and radiator	2.5	250 hr service kit	300.00	55.00	355.00

43	08/28/87	22875	122	125 hr service wash engine and radiator	2.5	125 hr service kit	300.00	55.00	355.00
44	09/10/87	23006	131	1000 hr service adjust tappet clearances service starter service alternator	5	1000 hr service kit	1500.00	110.00	1610.00
45	10/08/87	23285	279	250 hr service wash engine and radiator	2	250 hr service kit	300.00	44.00	344.00
46	10/23/87	23491	206	500 hr service wash engine and radiator service battery	2	500 hr service kit	300.00	44.00	344.00
47	10/30/87	23550	59	remove water pump repair oil leak install and test	4			88.00	88.00
	668	7044			142		28745.00	3102.00	31847.00

APPENDIX H : Fuel consumption logs for Shingwedzi

SHINGWEDZI 'MOTORVOERTUIGLOGSTAAT' RUN TIME AND FUEL CONSUMPTION : 1985 -1987
Engine no. : K16

Log period from	to	No. days	Engine hours from	to	No. hours	Fuel (litres)	Oil (litres)	Ave. run time (hr/day)	Ave.fuel cons. (l/hr)	Ave.oil cons. (l/hr)
12/23/85	01/06/86	14	16400	16585	185	6750	79.0	26.43	36.49	0.43
01/14/86	02/10/86	27	16655	16943	288	9000	55.0	21.33	31.25	0.19
02/11/86	03/26/86	43	16943	17394	451	22500	100.0	20.98	49.89	0.22
03/27/86	04/21/86	25	17394	17677	283	9000	53.0	22.64	31.80	0.19
04/22/86	05/19/86	27	17677	17963	286	9000	67.0	21.19	31.47	0.23
05/20/86	06/16/86	27	17963	18247	284	9000	59.0	21.04	31.69	0.21
06/17/86	07/14/86	27	18247	18534	287	9000	95.0	21.26	31.36	0.33
07/21/86	08/17/86	27	18596	19881	285	11250	68.0	21.11	39.47	0.24
08/18/86	09/14/86	27	19891	19165	284	9000	74.0	21.04	31.69	0.26
09/16/86	10/19/86	33	19165	19535	370	15750	114.0	22.42	42.57	0.31
10/20/86	11/16/86	27	19535	19827	292	9000	67.0	21.63	30.82	0.23
11/17/86	12/20/86	33	19827	20182	355	13500	73.0	21.52	38.03	0.21
-	02/23/87	-	-	20873	351	15750	81.0		44.87	0.23
02/23/87	03/26/87	31	20973	21207	334	11250	57.0	21.55	33.68	0.17
03/27/87	04/18/87	22	21207	21489	282	11250	57.0	25.64	39.89	0.20
04/20/87	05/17/87	27	21489	21788	299	9000	98.00	22.15	30.10	0.33
05/18/87	06/14/87	27	21798	22072	284	9000	61.00	21.04	31.69	0.21
06/15/87	07/20/87	35	22072	22442	370	13500	91.00	21.14	36.49	0.25
07/21/87	08/20/87	30	22442	22757	315	11250	85.00	21.00	35.71	0.27
08/20/87	09/21/87	32	22757	23104	347	11250	136.00	21.69	32.42	0.39

Total no. days : 637
Total no. hours : 6704
Ave. run time : 21.05 hr/day
Total fuel cons.: 238456.8 litres
Total oil cons. : 1570 litres

	Ave. run time (hr/day)	Ave.fuel cons. (l/hr)	Ave.oil cons. (l/hr)
Average :	21.94	35.57	0.25
Std.dev.:	1.49	5.29	0.07
Maximum :	26.43	49.89	0.43
Minimum :	20.98	30.10	0.17

SHINGWEDZI 'MOTORVOERTUIGLOGSTAAT' RUN TIME AND FUEL CONSUMPTION : 1985 -1987
Engine no. : K125

Log period from	to	No. days	Engine hours from	to	No. hours	Fuel (litres)	Oil (litres)	Ave. run time (hr/day)	Ave.fuel cons. (l/hr)	Ave.oil cons. (l/hr)
-	01/06/86	-	-	9125	184	6750	63.0		36.68	0.34
02/10/86	03/27/86	45	9472	9968	496	15750	105.0	22.04	31.75	0.21
03/28/86	04/20/86	23	9968	10217	249	9000	38.0	21.65	36.14	0.15
04/21/86	05/18/86	27	10217	10499	282	9000	100.0	20.89	31.91	0.35
05/19/86	06/15/86	27	10499	10783	284	9000	71.0	21.04	31.69	0.25
06/16/86	07/13/86	27	10783	11064	281	9000	76.0	20.81	32.03	0.27
-	08/18/86	-	-	11431	289	11250	84.0		38.93	0.29
08/19/86	09/15/86	27	11431	11717	286	9000	97.0	21.19	31.47	0.30
09/17/86	10/20/86	33	11717	12099	382	16000	135.0	23.15	41.88	0.35
10/21/86	11/17/86	27	12099	12391	292	9000	92.0	21.63	30.82	0.32
11/18/86	12/20/86	32	12391	12727	336	13500	112.0	21.00	40.18	0.33
-	02/23/87	-	-	13436	379	15750	118.0		41.56	0.31
02/24/87	03/26/87	30	13436	13744	308	11250	151.0	20.53	36.53	0.49
03/26/87	04/20/87	25	13744	14038	294	11250	89.0	23.52	38.27	0.30
04/21/87	05/18/87	27	14038	14324	286	9000	90.0	21.19	31.47	0.31
05/19/87	06/15/87	27	14324	14609	285	9005	77.0	21.11	31.60	0.27
06/16/87	07/20/87	34	14609	14961	352	11250	74.0	20.71	31.96	0.21
07/21/87	08/20/87	30	14961	15275	314	9000	130.0	20.93	28.66	0.41
08/21/87	09/21/87	31	15275	15584	309	13500	93.0	19.94	43.69	0.30

Total no. days : 588
Total no. hours : 6112
Ave. run time : 20.79 hr/day
Total fuel cons.: 214635.1 litres
Total oil cons. : 1785 litres

	Ave. run time (hr/day)	Ave.fuel cons. (l/hr)	Ave.oil cons. (l/hr)
Average :	21.33	35.12	0.30
Std.dev.:	0.89	4.40	0.07
Maximum :	23.52	43.69	0.49
Minimum :	19.94	28.66	0.15

Appendix I

GENERAL COMMENTS ON OFF-GRID POWER SYSTEM DESIGN TECHNIQUES

Independent power systems require particularly rigorous design for optimal technical and economic performance due to the discrete nature of each application and the lack of large, cheap reserves of generating capacity afforded by the ESKOM grid for small grid-connected electricity consumers.

In general, the competence and optimality of an off-grid power supply system is a function circumstantial, probabilistic and design factors.

The circumstantial factors are those related to the specific requirements (or perceived requirements) of the user(s), the technical and economic means available for the purchase and subsequent maintenance of the system, the availability of the technology, either new or second hand, and environmental impact.

The probabilistic factors are those associated with the variability of the weather, (insolation, wind and temperature), the variability of the load usage patterns and the likelihood of random component failures within the system.

The design factors include the selection of and the specification of the system components, (component efficiencies etc.); the overall system sizing and the relative systems matching of components and sub-systems within the system, eg. array/battery ratio; and the operating philosophy and control of the system, eg. charge regulation, micro-computer based control systems etc.

In general all independent energy supply system design procedures for PV, diesel and genset-plus applications must address the following factors :

(i) Location : for PV the site specific characteristics of both the available daily global solar radiation and the diurnal and seasonal variations have a significant effect on the array size and energy storage requirements. For diesel gensets, derating due to altitude and the cost implications such as distance from fuel depots and maintenance infrastructures affect the viability and sizing of the system.

(ii) Required availability : the fraction of the year when the instantaneous load power demand is available from the power system. The directly related concepts of loss of energy probability, LOEP, and, perhaps more correctly, loss of power probability, LOPP, are applied to PV systems as a rational statistical basis on which to optimize the system sizing. LOEP (and LOPP) are equivalent to loss of availability. The level of availability inherent in a given system is ultimately determined by relative costs of loss of power to the load and the costs of increased technical sophistication or capacity. Lack of energy supply could be due to design, a poor combination of or under-sized array or battery storage capacity or under-sized genset, or due to component failures and system breakdowns. 100% availability could require a large over-sized system which would not be economically viable. In the case of diesel gensets 100% availability would require 100% back-up capacity for continuous loads. In practice downtime for routine maintenance and breakdowns on single diesel genset installations is approximately 2-4%, resulting in a monthly average availability of 96-98% (Borden et al, 1984).

(iii) Duty cycle : the cyclical pattern of instantaneous load power demand influences the system sizing. A system load curve that mimics the daily and seasonal variation of solar radiation would require minimal PV system storage capacity. Diesel engine fuel consumption, reliability and life are highly sensitive to the genset duty cycle. The related concepts of load factor and capacity factor describe the extent to which the load power demand profile or duty cycle affect the utilization of diesel gensets.

(iv) Energy demand : The daily energy demand, kWh/day, and annual variation in energy demand is a major design factor. The predictability of the load energy demand is a main constraint of the optimality of the system design. The load energy demand is defined as the objectively deduced load energy requirement as opposed to the perceived requirement by the user. It includes such considerations as AC or DC current, voltage requirements, frequency, AC wave form, and power factor. Many sizing procedures select system components based on the so-called "worst-month" energy demand. A more sophisticated approach would be a LOPP approach which considers the short to medium term energy flows across the system and which quantifies the component ratings based on an acceptable LOPP over the annual variation in load energy and power demand and energy source.

(v) Projected system life : The useful lifetimes of competing technical options relative to the required system lifetime are vital for both technical and economic optimization of a system. System components such as storage batteries are resilient to short term abuse at the expense of overall useful life. The differences in projected useful life of components relative to the overall system life allow for optimization of the overall life-cycle costs.

Most system design techniques assume a continuous range of off-the-shelf plant and equipment ratings. The system sizing would therefore typically be used as a first approximation in a dynamic engineering design process which would involve the user(s) and component suppliers.

PV system design techniques

Many differing design techniques for small and large PV systems are available. PV manufacturers such as ARCO SOLAR, MOTOROLA, PHOTOWATT, SOLAREX and others have developed proprietary design techniques. Numerous texts on PV systems include generalized design guidelines, (Komp, Buresch, Watts et al, Paul). A simplified "worst-month" design procedure for small stand-alone water pumping systems is described by Sir William Halcrow and Partners (1984).

The PV sizing technique favoured by the ERi for small PV systems, (<5 kWp), is one proposed by the Jet Propulsion Laboratory, Pasadena, CA, (Borden et al, 1984), which outlines a simple methodology to estimate "stand-alone" PV system size and a life-cycle costing methodology.

The JPL design methodology, as outlined, applies to stand-alone non-tracking flat-plate PV systems (including the array, voltage regulator, battery storage and inverter or DC/DC converter). The essence of this sizing procedure is summarised in the flow chart shown in Figure I.1.

The procedure is a "worst-month case" method based on an theoretically derived LOEP nomograph for suggested combinations of array and battery storage sizing factors for worst-month solar radiation values. The LOEP nomograph is based on a statistical condensation of meteorological data for the USA and the least cost curve for the array/battery ratio based on the relative array and storage battery costs in the USA in 1982.

Although the relative cost of PV modules in the USA has fallen with respect to battery costs, the effect of the devaluation of the Rand with respect to the Dollar and the additional effect of heavy (60%) import duties have been to maintain the relative costs of PV modules and batteries in Southern Africa.

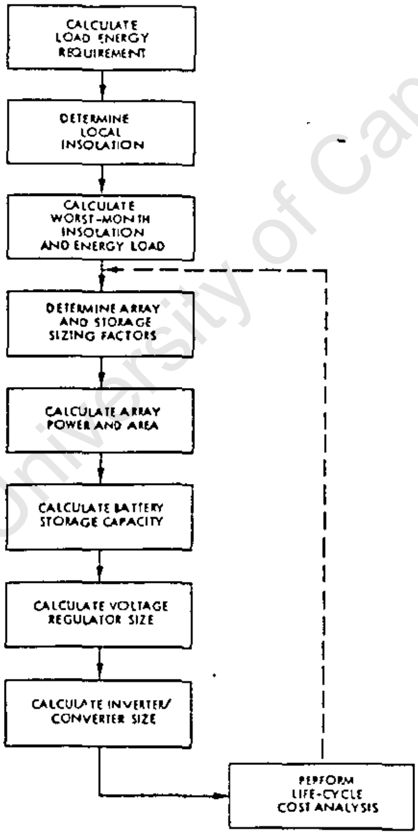


Figure I.1 : Design methodology for sizing a stand-alone flat-plate photovoltaic system (Borden et al, 1984)

The array and battery storage sizing factors from the nomograph are based on the lowest overall system cost and a "worst month" loss of energy probability (LOEP) of 0,1 which corresponds to an average monthly availability of 96-98%, or all but 11 days of the year.

This JPL method is claimed to have compared well to a NASA and a Solarex method described by Simon and a ROSSA method described by Rosenblum for a load of 4,2 kWh/day and worst-month insolation of 2,3 kWh/m^2/day, (Borden et al, 1984).

This method has been used to size two domestic PV systems for home lighting and TV in low income households in the winter rainfall area of the Western Cape and the more favourable North Western Cape (Müller, 1988). These 90 W_p systems were installed in October 1986 as part of an ERi domestic PV system evaluation project and have given satisfactory service.

Paul (1981) suggests several "rules of thumb" for component sizing in small off-grid power systems of which some relate to PV systems :

1. If the total load on an independent power system is frequently expected to exceed 1000 W, the system should be designed to provide AC electricity to the major loads. If the total load is rarely expected to exceed 1000 W and DC equipment of the type required is available, the system should be designed to provide DC electricity.
2. For a typical user the peak hour usage is likely to be 4 to 8 times the average hourly usage.
3. Peak minute loads can be estimated at 6 to 12 times the average hourly load and peak second (surge) loads at 12 to 24 times the average hourly loads.

4. The minimum voltages for DC components of an independent power system (battery bank, battery charging source and inverter) for various levels of electricity usage are as follows :

Daily usage (kWh/day)	Minimum DC voltage (V)
3 or under	12
6	24
9	32
12	36
16	48
over 16	120

Large PV systems require a more complex and sophisticated design approach. The design would typically be undertaken by consultants in collaboration with electricity utility companies and PV module manufacturers.

A typical system configuration for a MW_p system would comprise a PV array field of computer controlled tracking sub-arrays, a partitioned electrical storage battery (or hydro pumped-storage), multiple or a multi-stage 380 V three phase high efficiency inverter(s) connected to a 250 V to 400 V DC busbar system and a microcomputer based control system.

One of the problems encountered with large scale centralized PV systems of the order of 1 MW_p, is uneven charging and discharging of cells within the battery storage system. This is due to the resistance of the cell connecting busbars. Microprocessor control techniques have been proposed by H Kobayashi, et al (1987), to prevent unequal states of charge within a battery system.

Proper charge/discharge cycling of the battery would be regulated by the control system through switching the sub-arrays to segments of the battery and selective connection to the inverter(s) depending on solar radiation, state of charge and load demand. Deep-discharge, overcharging and gassing could be minimised. A catalyst based recombinator could recombine hydrogen and oxygen and return water to the electrolyte to reduce battery maintenance.

Microcomputer control is cosidered essential for larger PV systems for the following reasons : (McCarthy, 1985)

- using software the systems performance can be continually optimised to maximise the use of the solar enery generated
- the control can be tailored to specific local climates
- hardware changes are minimised by using software, resulting in reduced costs and higher system availability