# THE USE OF SMALL PHOTOVOLTAIC SYSTEMS FOR THE ELECTRIFICATION OF OFF-GRID HOMES

D H Müller

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I, Donovan Herbert Muller, submit this thesis in partial fulfilment of the requirements for the degree of Master of Science in Engineering. I claim that this is my original work and that it has not been submitted in this or in a similar form for a degree at any University.

Signed by candidate

D. H. Muller BSc(Chem.Eng)

# ABSTRACT

This thesis presents a study of the technical, economic and social appropriateness of small stand-alone photovoltaic (PV) systems for meeting minimal electrical requirements in low-income off-grid households.

A comprehensive review of the literature on photovoltaic technology was undertaken to identify key theoretical parameters and issues, and also to determine what the experience has been of similar applications in third world countries.

Two PV systems were installed as demonstration projects: one at Uitsig near Cape Town, and the other at Omdraaisvlei in the Northern Cape. In order to monitor and evaluate the technical performance of these systems, remote data capture units were installed for measuring appropriate parameters for analysis on typical daily, weekly and monthly bases. The degree of matching between the PV output characteristics and the battery and load demand was examined as well as the costs of system and component efficiencies under different operating conditions.

The economic evaluation aimed to compare small PV systems with these of alternative power systems, for example petrol generators. Using a life cycle costing methodology (discounted to present value) the least-cost option for small power systems was determined under a range of financial scenarios. The social evaluation aimed at determining the impact of PV power on peoples' lifestyles.

The results of the two demonstration projects have shown that photovoltaics can appropriately meet small domestic power needs in off-grid applications, providing clean, reliable, maintenance-free electricity which is far more convenient than other electricity producing technologies.

Photovoltaics proved to be very much more cost effective than petrol generators, and were also found to be cheaper than conventionally used energy sources such as paraffin, candles and batteries.

Both of the demonstration project households were extremely satisfied with the PV systems, which have resulted in significant improvement in quality of lifestyles.

However, based on the overall performance of the systems it was recommended that more research was needed, using local conditions, and data to develop better PV system design and sizing methodologies.

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# GLOSSARY

Autonomy: The number of consecutive sunless days the photovoltaic system must be able to supply the load

AC: Alternating current

BPU: Battery protection unit

Battery DOD: Battery depth of discharge

Battery gassing: The emission of hydrogen and oxygen from water in the battery eletrolyte fluid

Battery SOC: Battery state of charge

Boost charge: The battery is charged at the maximum rate

DC: Direct current

Divco: Divisional council

Electrical load: component of system which consumes electrical power

ESCOM: Electricity Supply Commission

Fill factor: The ratio of the peak power output of the array to the power calculated by multiplying the open-circuit voltage and the short-circuit current

$I_{sc}$: Short-circuit current

Insolation: Amount of solar radiation incident on Earth's surface

I-V curve: Current-voltage curve

Lcc: Life-cycle cost

LM battery: Low-maintenance battery

Load shedding: Disconnection of loads by a battery protection unit when the battery voltage drops dangerouslly low

LOEP: Loss of energy probability

Maximum power point: The point at which the PV power output is at a maximum, ie. the product of the PV voltage and PV current is a maximum

MF battery: Maintenance-free battery

Photovoltaic effect: The production of electricity from light

SLI battery: Starting, lighting and ignition battery

STC: Standard test conditions

Trickle charge: The battery is charged at a very low current

$V_{oc}$: Open-circuit voltage

# CHAPTER 1

# INTRODUCTION

## 1.1. OBJECTIVE

The objectives of this study are to determine the social, economic and technical appropriateness of using small stand-alone photovoltaic (PV) systems to power lights and television sets for low-income, off-grid households.

This subject is of interest for a number of reasons:

(1) the majority of people in South Africa do not have access to grid-supplied electricity and many households, particularly in peri-urban areas and closer settlements use costly alternatives such as paraffin for lighting, and batteries or petrol-driven generators for powering radios and/or television sets;

(2) photovoltaic systems are modular and can be designed to supply very small loads, or increased demand as household incomes increase;

(3) the international costs of photovoltaic modules are falling dramatically and the potential exists for photovoltaic systems to supply reliable, cost-effective power for particular off-grid applications; and

(4) relatively little work has been done on small stand-alone photovoltaic powered, low-voltage DC systems for low-income households. Most local PV suppliers rely on overseas design software, and very little local capability exists for the appropriate design of systems with acceptable loss of power probabilities.

The project aimed to evaluate small stand-alone PV systems by designing, procuring, installing, and monitoring the performance of two demonstration systems in low-income households. Real economic data were obtained, and the social impact and acceptability of these systems were analysed.

## 1.2. BACKGROUND RATIONALE

### 1.2.1. Limited access to electricity

ESCOM is one of the seven largest suppliers of electricity in the world. It generates 60 percent of all the electricity produced on the African continent, and because of our cheap coal, South Africa's electricity is inexpensive by world standards.

Yet despite the large amounts of electricity being produced at relatively low costs, 22 million of South Africa's total population of approximately 32 million (1984) do not have electricity. The majority of these households live in rural areas, but even in urban areas, 75 percent of black homes are not electrified.

While extending the electricity grid to remote rural areas is an expensive option, the same argument cannot be applied to black townships around metropolitan areas. Here there would appear to be no sound reasons for not connecting households to the national grid. The situation of closer and informal settlements, and peri-urban areas around the metropolitan centres and in the "homelands" is less clear. In these areas, grid electrification may be more difficult. With many families already using batteries or petrol-driven generators, PV power is becoming an increasingly attractive option. In the longer term, PV-power may also prove to be affordable for isolated rural households.

It is not envisaged that photovoltaics could in the short or medium term, substitute for cooking or heating fuels where the power requirements are much greater than, for example, lighting and where the number of PV panels required would be inhibitively costly. Nevertheless, convenient and affordable power for lighting and for other appliances is perceived as being important for quality of life expectations, and there would thus seem to be great potential for photovoltaics meeting minimal electrical requirements in poorer households in informal settlements. The need for such an initiative is further underlined by appreciating the problems associated with the lack of access to electricity.

### 1.2.2. The energy-related problems of non-electrified areas

A number of studies (Eberhard, 1984, and 1986; Rivet-Carnac, 1979) have shown that families without access to electricity can spend up to a fifth of their income on costly alternative fuels such as gas, candles, paraffin and batteries.

Apart from the economic costs of reliance on alternative fuels there are also social costs. A graphic account of the effects of not having electricity is given by a recent newspaper report (Evening Post,1986). It is quoted here to present a real and immediate picture of the social costs borne by many poor households in non-electrified areas.

Families in the "coloured" township of Helenvale, Port Elizabeth, are still waiting for electricity more than twenty years after moving into their homes. Although some of the poorest families live there, a recent survey by the Northern Areas Management Committee has shown that at least 20 households were able to afford electricity. They have petitioned the municipality twice, asking for speedy action to be taken: the first petition was drawn up and sent in 1982, and the latest was sent in 1985 when they became impatient about the delay. Members of most of the families concerned complained about the inconvenience the lack of electricity has caused since settling in their homes.

> 'Mrs Rebecca Classen, a widow, moved into her home in Martin Street 19 years ago. She bought a paraffin-operated fridge on an installment basis about two years ago. Now she has decided to

return it to the store because she prefers an electrically-operated model.

"It is frustrating working with paraffin all the time. It has a strong, unhealthy smell. My fridge cost more than R1000 and I'm not happy with its performance.

"I have to do my cooking on a small gas stove, although I can afford an electric one.

"It is about time that electricity was installed here," she said.

Mr Piet Coetzee, 71, of Martin Street has already returned his paraffin-operated fridge to the store where he bought it.

"My children and I do not like the smell of paraffin in the house. We also discovered paraffin was more expensive than we expected.

"And as far as our television is concerned, we are tired of operating it on batteries.

"The batteries must be recharged too often and reception quality is poor," he said.

Mrs Sarah Jansen, 75, lived in Schauderville for about 40 years before moving to Helenvale.

In Schauderville she always had electricity.

But soon after moving to Martin Street, because she wanted a smaller home, she had to leave her electric appliances with relatives.

"I would never have moved in here three year ago if I had known I would have no electricity for so long. I am accustomed to electricity," she said.

> Mrs Jansen also got rid of her paraffin-operated fridge and battery-operated television set last year because she was "fed up".
>
> "The TV battery got flat too often and we could seldom enjoy the programmes because the screen would flicker all the time," she said.
>
> Mrs Annie Samuels, a widow, who has been living in Gail Road for the past twelve years, also returned her portable television set to the store recently after experiencing battery problems.
>
> She said she could easily obtain the necessary electrical appliances and was just waiting for the big "switch on".'

The lack of electricity is felt to be a severe hardship, not only because of the consequent economic burden, but also because of the inconvenience and dangers associated with the alternative fuels being used.

Gas and paraffin lamps, and candles can, and have, caused fires; the smell and the smoke associated with paraffin is unpleasant and can result in health problems; candles and paraffin are messy to use; they provide poor light; and, gas cylinders and batteries are cumbersome to carry.

### 1.2.3. The potential of photovoltaics

Given the favoured demand for electricity over other fuels, and the cost and difficulties of extending the national grid to rural areas and closer, informal setlements, photovoltaics could be a viable option for meeting at least minimal electrical requirements for lights, television and other low-power appliances.

Photovoltaic systems should be seen as part of an integrated energy package, which would include better housing design to maximise passive solar gain for improving comfort levels and reducing space heating requirements; low-cost solar water heaters to reduce water heating energy bills; low-cost cooking fuels in efficient stoves; and awareness programmes of ways to use electricity more efficiently.

Photovoltaics provides an elegant and innovative means of producing electricity when compared with other electricity-generating technologies: they have the advantage of no working parts, no high temperature working fluids, and relatively maintenance-free electricity production. At present, rapid developments in photovoltaic technology are taking place which are aimed at minimizing material requirements and increasing efficiencies in order to further reduce costs. Photovoltaics are thus becoming increasingly competitive with conventional power supply systems.

## 1.3. PROJECT OUTLINE

### 1.3.1. Literature reviews

A comprehensive literature survey was undertaken of similar PV applications in developing countries. These are summarized in chapter two. Key theoretical parameters and issues in photovoltaic technology were identified and these are discussed in chapter three.

### 1.3.2. Designing, procuring, installing and monitoring the systems

Two PV systems were designed, procured and installed as demonstration projects:

(a) in the south-western Cape rainfall area in the township of Uitsig, near Elsies River on the Cape Flats; and,

(b) in a more favourable sunshine area, at Omdraaisvlei, near Prieska in the northern Cape.

In order to monitor and evaluate the technical performance of these systems, instrumentation was installed for measuring the following parameters:

(i) solar insolation,

(ii) solar module temperature,

(iii) ambient temperature,

(iv) amperage output from the photovoltaic array,

(v) amperage consumed by the appliances,

(vi) the voltage across the battery,

(vii) the voltage across the photovoltaic panels.

A remote data capture system recorded the data on interchangeable micro-chips which were collected at regular intervals. The data was then off-loaded into a micro-computer for storage, processing and analysis.

The experimental procedure is described in chapter four.

### 1.3.3. Technical evaluation

The technical evaluation of the monitored data for the two demonstration projects is presented in chapter five. The evaluation begins with a description of the observed system performance, and an analysis of the monitored data on typical daily, weekly and monthly bases.

The degree of matching between PV power output and the load energy demand, was investigated as well as the relationships between solar radiation, ambient temperature and cell temperature, and system and component efficiencies under different operating conditions.

This information is used as a basis for identifying further work which would refine and optimize PV system design procedures and so result in more appropriately sized (and thus more affordable) systems.

### 1.3.4. Economic evaluation of the system

The aim of the economic evaluation was to compare small PV systems with alternatives in order to determine the least-cost option for small power systems under different financial scenarios.

A Levelized Annual Cost analysis was undertaken and the sensitivity of the result was investigated for the following variables:

(i) the capital cost of PV modules,
(ii) the cost and life-time of different types of batteries,
(iii) the level of insolation, and
(iv) the discount rate.

The most commonly used alternative for this application is a petrol generator. An equivalent system was sized and costs determined for different fuel prices.

### 1.3.5. Social evaluation of the system

Interviews with the respective families were also carried out to determine their energy consumption patterns and the average expenditure per month prior to the installation of the PV systems. These results were compared with previous surveys carried out by ERI to derive a more generalized data base.

This study covers only the initial stages of a social assessment of these PV systems. The family life style before and after the PV system was installed was compared in terms of:

(i) the proportion of the monthly family income being spent on energy for lighting and television requirements;
(ii) the convenience/inconvenience of either system;
(iii) its effect on living standards and aspirations of the family;
(iv) its acceptability in the community; and
(v) the possibility of securing amortizing loans to cover the high capital costs of the PV system.

Finally, a concluding discussion is presented in chapter six.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1. INTRODUCTION

Photovoltaic power for home power systems is emerging as a significant technology in the Third World. For example, in French Polynesia more than 1000 of these systems were recently installed over a three-year period. These applications include one-to-two-module systems which are used in individual households for lighting, but they are also used to power radios, televisions, refrigerators, and/or water pumps. Area lighting is another application.

Lighting is used for evening activities such as cooking, reading, simple work and social activities. During the night, a lamp is often kept lit for security and safety reasons. Typically, lighting requirements in off-grid households in developing countries are met by candles, paraffin lamps or batteries. Lighting from these sources is often expensive and of a poor quality. For instance, a paraffin pressure lamp will provide only about 12 lux of light, while a 20 W fluorescent tube with reflectors, will provide approximately 100 lux (Maleva,1981).

This literature review covers PV-powered home power systems in developing countries, in particular, Papua New Guinea, Zimbabwe and French Polynesia. These systems were shown to be technically reliable, and many of the users found them to be cost competitive with the most often used alternative, namely, paraffin-fueled lamps.

## 2.2. PAPUA NEW GUINEA

A number of PV systems have been installed in Papua New Guinea for communication, lighting, water pumping and medical refrigeration. The total photovoltaic installed capacity in 1982 was approximately 50 kW. The potential for village house lighting systems over the next ten years was estimated at 500 000 single module units (35 Watts each, or 17.5 MW) (Maleva,1981).

In related work, the Appropriate Technology Development Institute of the University of Technology in Lae, PNG, has started testing fluorescent-tube "lanterns" powered by rechargeable Ni-Cad batteries. The lanterns are designed to look like the paraffin lamps, but are charged using PV power, and have been found to compete favourably with the paraffin lamps. In rural areas of developing countries, paraffin lamps are used both indoors and outdoors; hence, the portability of small light systems is an important design consideration (Kinnell,1982).

A survey was conducted among 30 village households to assess the costs of kerosene-fueled lighting as experienced in rural areas. The cost and performance of a comparable PV household system were analysed over a five year period.

The cost of operating a hurricane and a pressurized paraffin lamp was found to be 196 Kina (1 Kina = US$1.34) for the first year. A five-year expenditure of 817 Kina could be anticipated, using a 10 percent discount rate.

The photovoltaic-powered system consisted of a single ARCO panel (ASI 16-2000), a Delco 2000 battery, a regulator and two 20 W fluorescent lamps. The system was capable of delivering 160 Wh/day. The array was guaranteed for five years, and the batteries for three. The installed cost of the PV system in 1981 was 655 Kina.

However, it was felt that costs alone should not be used to determine the favourability of either of the lighting systems, and other comparative criteria were taken into account. For example, it was found that the quality of light was at least five times better with the PV system than with the kerosene light. Secondly, the PV system was also more convenient since light was immediately available at the flick of the switch, whereas for the kerosene pressure lamp, it was a time-consuming process, taking at least five minutes to refuel the tank, clean the glass and light it.

Hence, comparing the costs and benefits, it is clear that the benefits of the PV system out-weigh the costs, and therefore, from a national point of view, the replacement of kerosene light with the type described with the PV system, is worthwhile, although the high capital requirement for the PV system makes it difficult for many people to pursue this option. The survey suggested that the government should finance and encourage lending institutions in PNG to provide loan facilities to households willing to purchase PV systems.

## 2.3. ZIMBABWE

In 1983 PTA Consulting Services of Harare conducted a study into the viability of PV-powered water pumping and lighting in rural off-grid areas of Zimbabwe. The study focussed on two small PV-powered systems which had been installed by WS&G Hi Tech. (PTA Consulting Services,1983).

The first demonstration project was installed at Katsande in Mudzi District in November 1982, and the second at Siyahokwe in Takawira District in April 1983.

The equipment consisted of ARCO Solar 701 photovoltaic modules, each rated at 35 Wp, automotive batteries, and 40 watt fluorescent strip lights. The systems were installed in school classrooms and in individual homes.

Individual reaction to the lighting systems was positive with all users considering the systems to be "reliable and a welcome development in raising the standard of living in the rural areas" (ibid).

A comparison was made between the costs of lighting by candles, gas, or paraffin, and a small PV-powered system.

The cost to a family for conventional lighting was between Z$24 and Z$144 per year, depending on the affluence of the household. The capital cost for an equivalently sized PV system was calculated as Z$660, with an implied six- to seven-year payback period.

Another comparison was made between a 500 W petrol generator and PV system to supply equivalent amounts of lighting. The capital cost of Z$2000 for the PV system was compared with the initial cost of Z$550 and Z$975 annual running cost for a petrol generator. A payback period of less than two years was calculated.

Portability of the lamps, such that they may be used outside as well as inside, was stressed as an important design parameter for future work.

## 2.4. FRENCH POLYNESIA

Over 1000 PV home power systems have been installed to provide power for lighting, television and fans for individual households in French Polynesia. Studies from 1980 showed that it would be more cost effective to subsidize the introduction of PV power systems than to extend the grid (Malbranche,1985).

This programme is supported by the French Atomic Energy Commision (CEA), the French Agency for Energy Management (AFME) and the French Polynesian Government.

A typical system consists of three 13-watt lights, an 80-watt television, a fan and a small refrigerator. The cost of the system is approximately 17 600 Ff (US$2000), including taxes. The modules are 50 percent subsidized by the program. End-users can pay the balance all at once, or over a five-year period at 9 percent interest.

The conclusion of recent work is that the PV systems are economically justified in situations where the user is more than 200 metres from the grid. The South Pacific Commission was encouraged by this program and has proposed the development of similar rural electrification schemes throughout the South Pacific.

### 2.5. SPAIN

The Spanish photovoltaic market ranks second only to the USA and provides an interesting example of what can be accomplished in small stand-alone domestic PV-powered systems for lighting and television sets. Twenty percent of the Spanish market is for professional applications (telecommunications, remote signals, etc.), 40 percent for weekend houses and 35 percent for rural electrification (Lorenzo et al, 1985).

Many weekend houses belong to members of the lower-middle class and are built on non-serviced land. Photovoltaic systems are justified in these situations because their cost is significantly lower than the difference between the cost of utility serviced and non-serviced land. The typical PV system is 12 V DC and comprises a 30 to 35 Wp panel, a 100 to 150 Ah battery, and powers lighting and a black-and-white television set. In 1986 there were about 20 000 photovoltaic-powered weekend houses in Spain.

In the rural electrification sector, 99 percent of the applications currently serve domestic needs. There are approximately 6000 permanently inhabited rural PV-powered households in Spain, located mainly in Andalucia. The typical installation is 12 V DC, with 60 to 120 Wp PV modules, and a 200 to 300 Ah battery. The system provides power for lighting, radio, and black-and-white television sets, while many of these households also have butane gas refrigerators.

According to Lorenzo, the Spanish photovoltaic market will continue to grow provided that: the systems are simple and reliable; the cost is lowered to permit more loads; PVs are used in other applications which increase income, for example, agricultural activities; and an increase in government support occurs.

## 2.6. FINANCIAL OVERVIEW OF EXISTING PV-POWERED SYSTEMS

A financial analysis was carried out by Eskenazi in which the life-cycle cost of a PV-powered domestic system is compared with the most likely conventional alternative system, namely, paraffin lamps and batteries (Eskenazi et al,1987:8.1).

The costs are compared on two levels, the first case being a detailed net present value (NPV) life-cycle cost analysis over a twenty-year cash flow period, comparing the PV-powered system to the conventional alternative using specific base-case assumptions and, in the second case, a sensitivity analysis is carried out. In this situation certain base-case assumptions are varied to ascertain the economic implications on the respective systems.

It should be noted that the financial analysis was chosen to incorporate the decision-making perspective of a development bank scheme, as opposed to those for commercial loans.

The base-case analysis concentrates on domestic-power systems, the major component considered here being lighting. The unit of comparison used in this evaluation is the NPV levelized annual cost in dollars per lumen (1 lux = 1 lumen/sq.m), where, typically, 100 to 200 lux is the required light intensity for reading or working. In order to accomodate a mixture of conventional power sources, for example, a household may use paraffin for lighting and a 12 volt car battery for radio or television, the associated costs of conventional home power systems are compared with three PV-powered systems, namely, small, medium and large systems, which may be used to replace the conventional system.

The PV-powered system components and operating conditions are given as follows:

(i) small - one 10 W fluorescent light, operating for 12 hours per day;
(ii) medium - one 20 W and one 10 W fluorescent light operating 6 and 12 hours per day, respectively; and
(iii) large - one 20 W fluorescent light operating for 9 hours per day, one 10 W fluorescent light operating for 12 hours per day, and a 12 W continuous electrical load, eg., a radio, operating for 9 hours per day.

Each of the PV-powered systems comprises a PV array, battery storage and 12 V DC loads. The batteries are assumed to be deep-discharge types which are replaced every five years. Battery storage is sized for two days autonomy, and the lowest-month daily insolation on the array is taken as 4 kWh/sq.m-day.

The conventional home-power systems are specified as follows:
(i) small - one pressurized paraffin lamp;
(ii) medium - small + one paraffin hurricane lamp; and
(iii) large - medium + a 12-V car battery.

The usage patterns were based on the results of a study conducted in Papua New Guinea (Maleva,1981).

The costs for the the three base-case PV-powered systems are given in TABLE 2.1. These costs are based on informal surveys of manufacturers conducted by Eskenazi in 1985-86.

The PV array costs were set at US$8/Wp, the charge controller at US$50, and the fluorescent lights at US$40 each. Deep-discharge batteries were chosen and their costs were determined at US$66/kWh. The maintenance and repair costs include the replacement of bulbs and the ballast. Battery, controller and light replacements are assumed to occur every five years.

The costs for the three conventional home-power systems are based on a study conducted in Papua New Guinea (Maleva,1981). In this study, the initial costs of the hurricane and pressurized lamp are reported as US$5 and US$40 each, respectively. Average spare parts costs for the hurricane and the pressurized lamps are US$20 and US$40 per year, respectively.

Fuel consumption figures are based on typical usage figures in PNG and determined as 40 litres per year for the hurricane lamp and 115 litres per year for the pressurized lamp. The lifetime of these lamps is three years. The large system includes a 12-volt car battery with an initial cost of US$65. Annual recharging costs are equivalent to 10 percent of the initial cost, ie., US$6.5 per year. These costs are summarized in TABLE 2.2.

TABLE 2.1: Base-case PV-powered home power system costs

Small System

| SPECIFICATION | COSTS |
|---|---|
| Initial Capital Costs (FOB Manufacturer) | |
| - PV Array (39 Wp) | $310 |
| - Battery Storage (0.3 kWh) | 20 |
| - Charge Controller | 50 |
| - Fluorescent Light (1 @ 10 W) | 40 |
| Total Capital Cost | $420 |
| Recurring Capital Costs (FOB Manufacturer) | |
| - Battery/Controller/Light Replacement | $110 every 5 years* |
| Other Recurring Costs (% Initial Capital Costs) | |
| - Maintenance & Repair | 4%/year* |

Medium System

| SPECIFICATION | COSTS |
|---|---|
| Initial Capital Costs (FOB Manufacturer) | |
| - PV Array (78 Wp) | $620 |
| - Battery Storage (0.6 kWh) | 40 |
| - Charge Controller | 50 |
| - Fluorescent Lights (1 @ 20W; 1 @ 10W) | 80 |
| Total Capital Cost | $790 |
| Recurring Capital Costs (FOB Manufacturer) | |
| - Battery/Controller/Light Replacement | $170 every 5 years* |
| Other Recurring Costs (% Initial Capital Costs) | |
| - Maintenance & Repair | 4%/year* |

Large System

| SPECIFICATION | COSTS |
|---|---|
| Initial Capital Costs (FOB Manufacturer) | |
| - PV Array (132 Wp) | $1054 |
| - Battery Storage (1.02 kWh) | 67 |
| - Charge Controller | 50 |
| - Fluorescent Lights (1 @ 20W; 1 @ 10W) | 80 |
| Total Capital Cost | $1,252 |
| Recurring Capital Costs (FOB Manufacturer) | |
| - Battery/Controller/Light Replacement | $197 every 5 years* |
| Other Recurring Costs (% Initial Capital Costs) | |
| - Maintenance & Repair | 4%/year* |

* Plus appropriate escalation due to general inflation.

TABLE 2.2: Base-case conventional home power system costs

Small System

| SPECIFICATION | COSTS |
|---|---|
| Initial Capital Costs (FOB Manufacturer) | |
| - Pressurized Kerosene Lamp | $40 |
| Recurring Capital Costs (FOB Manufacturer) | |
| - Lamp Replacement | $40 every 3 years* |
| Other Recurring Costs | |
| - Maintenance & Repair | $40/year* |
| - Kerosene Fuel (115 liters @ $0.70/liter) | $81/year* |

Medium System

| SPECIFICATION | COSTS |
|---|---|
| Initial Capital Costs (FOB Manufacturer) | |
| - Pressurized Kerosene Lamp | $40 |
| - Kerosene Hurricane Lamp | 5 |
| Total Capital Cost | $45 |
| Recurring Capital Costs (FOB Manufacturer) | |
| - Lamp Replacement | $45 every 3 years* |
| Other Recurring Costs | |
| - Maintenance & Repair | $60/year* |
| - Kerosene Fuel (155 liters @ $0.70/liter) | $109/year* |

Large System

| SPECIFICATION | COSTS |
|---|---|
| Initial Capital Cost (FOB Manufacturer) | |
| - Pressurized Kerosene Lamp | $40 |
| - Kerosene Hurricane Lamp | 5 |
| - Battery | 65 |
| Total Capital Cost | $110 |
| Recurring Capital Costs (FOB Manufacturer) | |
| - Lamp Replacement | $45 every 3 years* |
| - Battery Replacement | $65 every 2 years* |
| Other Recurring Costs | |
| - Maintenance & Repair | |
| o Lamps | $60/year* |
| o Battery | $7/year* |
| - Kerosene Fuel (155 liters @ $0.70/liter) | $109/year* |

* Plus appropriate escalation due to general inflation.

Using the base-case assumptions, 20-year cash flows were developed for the three cases described previously, for both the PV-powered and the conventional-powered systems. The results were expressed as NPV life-cycle costs in and are summarized in TABLE 2.3.

TABLE 2.3: Summary of base-case life-cycle cost analysis

| SYSTEM | Twenty-Year NPV COST ($) | | |
|---|---|---|---|
| | SMALL | MEDIUM | LARGE |
| PV | 1,002 | 1,796 | 2,674 |
| Conventional | 1,797 | 2,447 | 3,087 |

Source: Eskenazi etal (1986)

Finally, sensitivity analyses were conducted to determine the effect of varying capital cost, discount and interest rates, paraffin fuel costs and insolation values. In the ranges and parameters selected, the PV-powered systems are always more cost-effective for small systems. Medium size conventional systems would be least costly at discount and interest rates of 17.7 percent and higher, or at insolation levels of 2.5 Kwh/sq.m-day and lower. Large PV-powered systems were found to be more cost-effective up to discount and interest rates of 13.5 percent at fuel costs of more than US$0.48 per litre, and for insolation levels above 3.3 kWh/sq.m-day.

This procedure has shown the extreme conditions of operation under which conventional systems will have a cost advantage, and the results are tabulated in TABLE 2.4.

TABLE 2.4: Assumptions necessary for conventional home power system cost-effectiveness

| PARAMETER | SMALL | MEDIUM | LARGE |
|---|---|---|---|
| Discount and Interest Rate (%) | 27 | 17.7 | 13.5 |
| Kerosene Cost ($/liter) | 0.15 | ** | 0.48 |
| Insolation (kWh/$m^2$-day) | 1.6 | 2.5 | 3.3 |

*Any single assumption will result in conventional system cost-effectiveness

**NPV cost ratio leveled out before conventional systems showed financial attractiveness.

Source: Eskenazi etal (1986)

FIGURES 2.1 and 2.2 show the sensitivity of home power costs to the capital costs of PV-powered and conventional-powered systems, respectively.

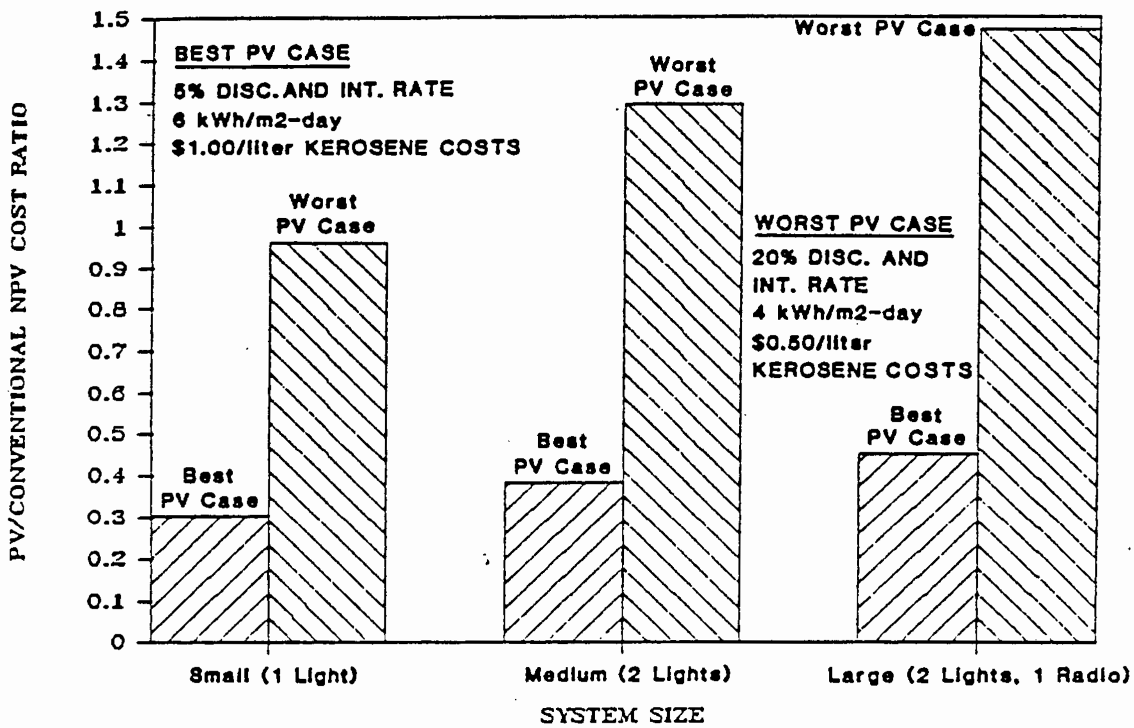


FIGURE 2.1: Sensitivity of PV-powered home power costs to capital cost

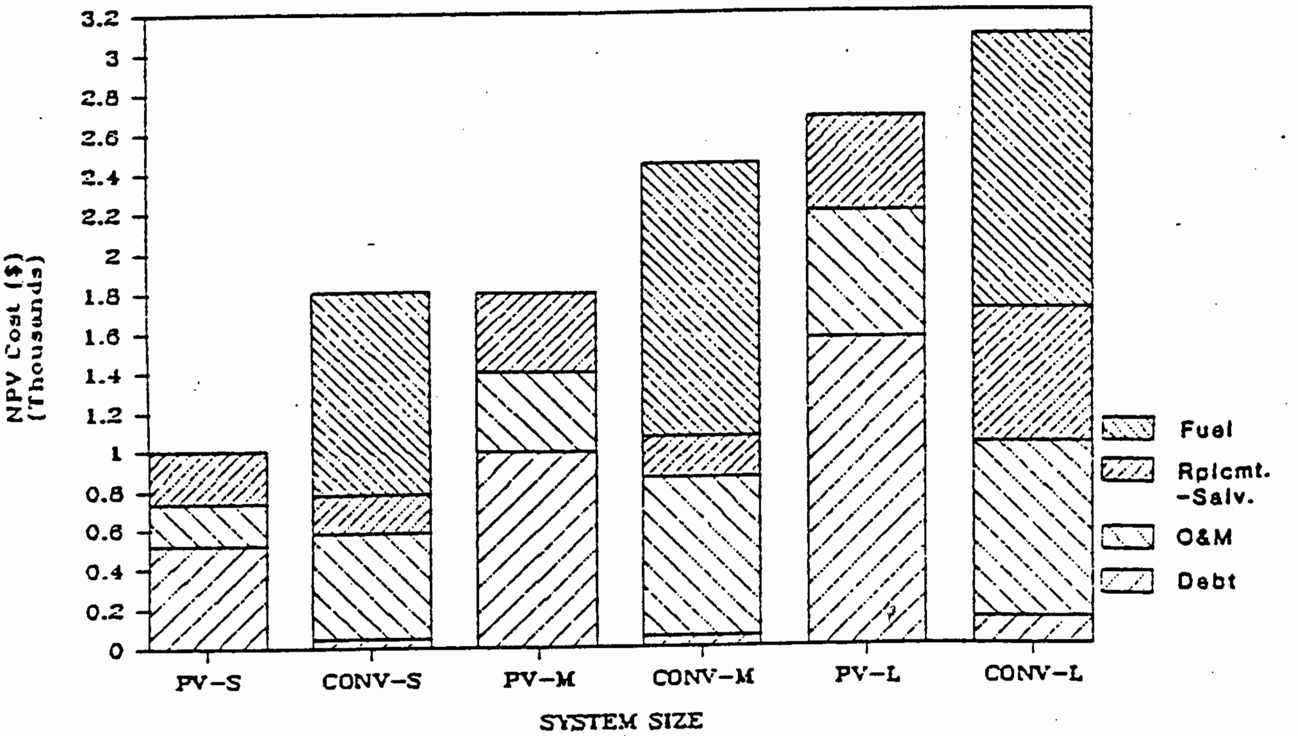


FIGURE 2.2: Sensitivity of conventional home power costs to capital cost

Source: Eskenazi et al (1986)

## 2.7. CONCLUSIONS

A review of existing PV projects in developing areas has shown that certain factors are critical to the implementation of successful projects (Eskenazi etal,1986). The main problems have arisen around:

(i) reliable charge controllers;
(ii) available spare parts and distribution system; and
(iii) customer financing policy.

Experience has shown that charge controllers are often the weak link in the system performance. These units are often the cheapest components of the system and it would be prudent to select reliable, high efficiency units to prolong battery life.

Ensuring that there is an adequate supply of spare lamps and ballasts has proven essential to the successful implementation of PV-powered lighting systems. Conventional paraffin units generally have an extensive spare parts and distribution system, and the widespread application of PV systems will be dependent on a similar infrastructure.

Like other renewable energy technologies, the use of photovoltaics implies a high initial capital cost and a very low running cost. This creates particular problems for poorer households unless innovative and appropriate financing schemes are implemented.

From the surveys conducted by Eskenazi, it was found that small PV-powered lighting systems are financially more attractive , even under worst-case conditions. For medium and large configurations, PV-powered systems may be more attractive, depending on the specific technical and financial project parameters.

Eskenazi argues that the strong financial viability of PV-powered systems suggests that shorter loan agreements applicable to individual private households would still show PV-powered system attractiveness. For example, in French Polynesia, five-year loan agreements to finance PV systems have resulted in a substantial expansion of the PV home power market.

In conclusion then, it appears that extensive experience in many Third World countries has shown that photovoltaics offer a viable and reliable alternative to conventional off-grid power supply options for households provided that reliable sub-system components (such as charge controllers and batteries) are chosen, an adequate infrastructure exists (for spare parts and distribution) and an appropriate financing policy is initiated.

# CHAPTER 3

## THEORETICAL CONSIDERATIONS

Before describing the two demonstration projects which were set up in this study and analysing monitored results, it is useful to outline the key design and performance features of photovoltaic systems and their components.

Domestic stand-alone photovoltaic systems for powering lights and other appliances, such as television sets, typically include a photovoltaic array, comprising photovoltaic modules or panels, batteries for energy storage, and power regulation and conditioning equipment. These components are shown schematically in FIGURE 3.1.

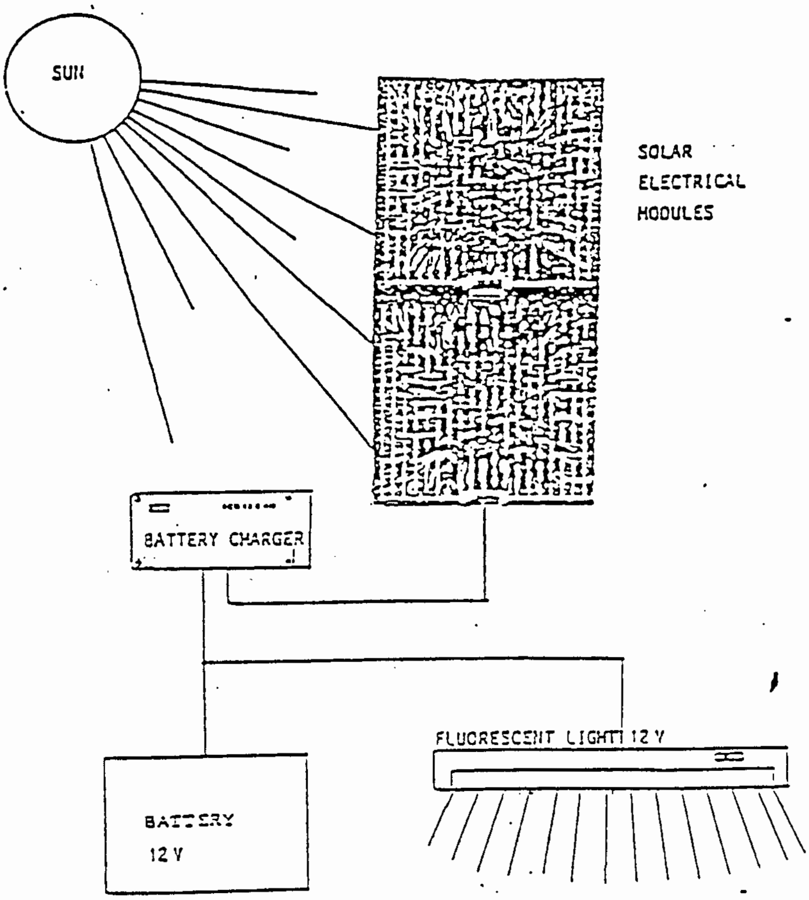


FIGURE 3.1: The major components of a stand-alone PV system

## 3.1. PHOTOVOLTAIC OUTPUT CHARACTERISTICS

The basic building block of a photovoltaic module is the photovoltaic cell which may be thought of as a semi-conductor device for converting solar energy directly into electrical energy through the photovoltaic effect[1].

Within a module, the cell arrangement may consist of either one string of series-connected cells or two or more series-strings of cells connected in parallel. Modules are electrically connected into a mechanically integrated assembly to form an array which provides the desired system power and voltage output.

The electrical terminal characteristics of a solar cell are described by a current-voltage (I-V) curve. A typical curve is shown in FIGURE 3.2.

The current-voltage characteristics of a module are the combined characteristics of the collection of cells which are connected in series or parallel. The power delivered to the load at any point on the I-V curve is the product of I and V at that point. The power output falls to zero at both open-circuit voltage ($V_{oc}$), and short-circuit current ($I_{sc}$) conditions. Between these two points, the power output reaches a maximum, $P_{max}$, near the "knee" of the I-V curve. The ratio of $P_{max}$ to the product of $V_{oc}$ and $I_{sc}$ is called the fill factor and is an important characteristic in evaluating module performance.

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[1] Discussion of photovoltaics in this study will be restricted to system performance characteristics and not to details of molecular activity within individual solar cells. Many publications are available which describe how solar cells operate (SERI, 1984).

The efficiency, n, of a solar cell is defined as:

$$n = P_{out} / (P_{in} . A_c)$$

where $P_{out}$ is the electrical power output of the cell,
$P_{in}$ is the solar illumination per unit area, and
$A_c$ is the active solar cell area.

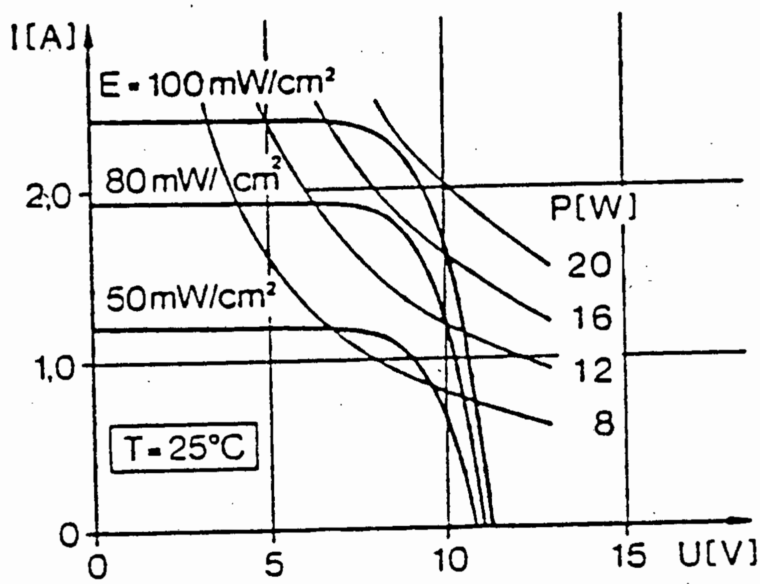



FIGURE 3.2: A typical I-V curve for a solar cell

Module efficiency at a given cell temperature is the module maximum power divided by the gross area and solar irradiance. A cell operates at its maximum efficiency ($n_{max}$) when its maximum power output capability is utilized by an optimized load at a particular illumination intensity and cell operating temperature.

The photovoltaic module power output and efficiency are therefore significantly affected by the intensity of sun light, solar cell temperature, and the type of electrical load.

### 3.1.1. Effect of sunlight

FIGURE 3.3 shows the effect of light irradiance on $V_{oc}$ and $I_{sc}$. Short circuit current is directly proportional to irradiance, while the open circuit voltage increases exponentially with irradiance at low intensities, rapidly reaching a saturation value. Thus, over the irradiance range of practical interest $V_{oc}$ is nearly constant.

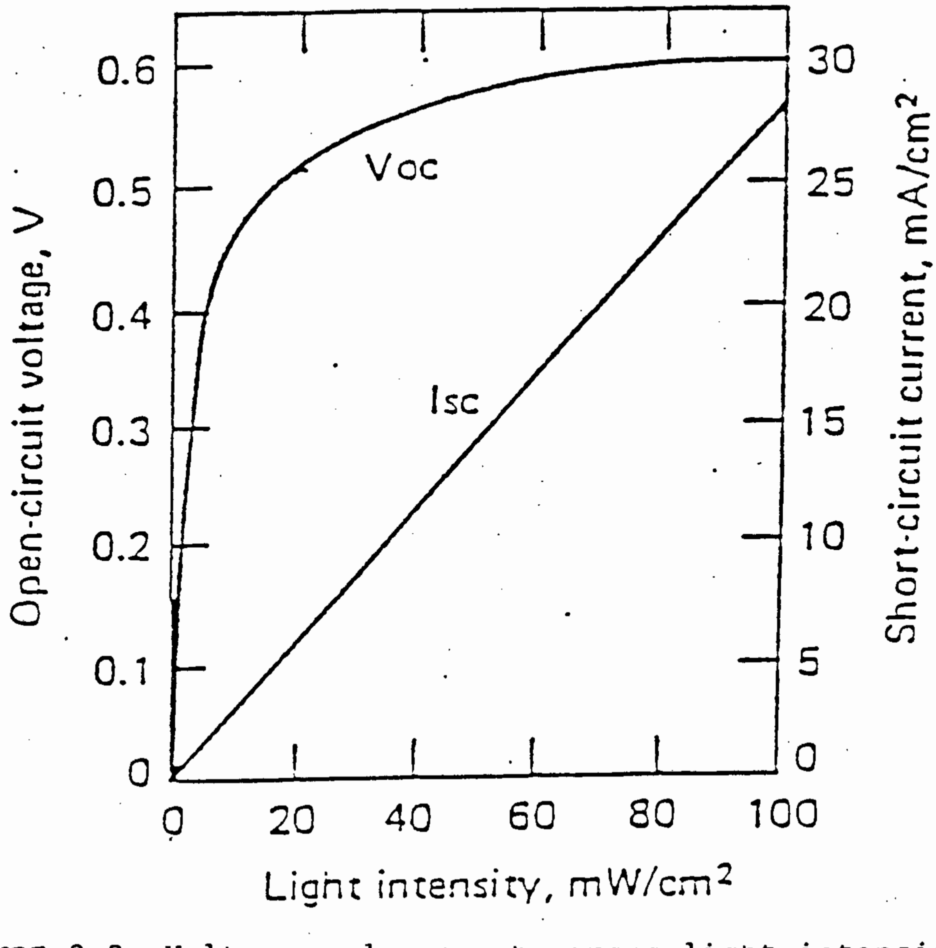



FIGURE 3.3: Voltage and current versus light intensity for a silicon solar cell.

Source: Buresch (1983)

FIGURE 3.4 displays the I-V curves for a typical commercial cell at different light intensities. At night the curve is on the zero point; however, as the sun rises, so does the I-V curve. The curve expands to its highest point around noon, then gradually falls as light intensity decreases towards sunset. $P_{max}$ at each irradiance level is indicated by a mark on the respective curve.

Most photovoltaic applications make use of sunlight or solar radiation which has both a temporal (duirnal and seasonal) and spatial variation. The amount of solar radiation received is also dependent on the angle of tilt of the photovoltaic modules.

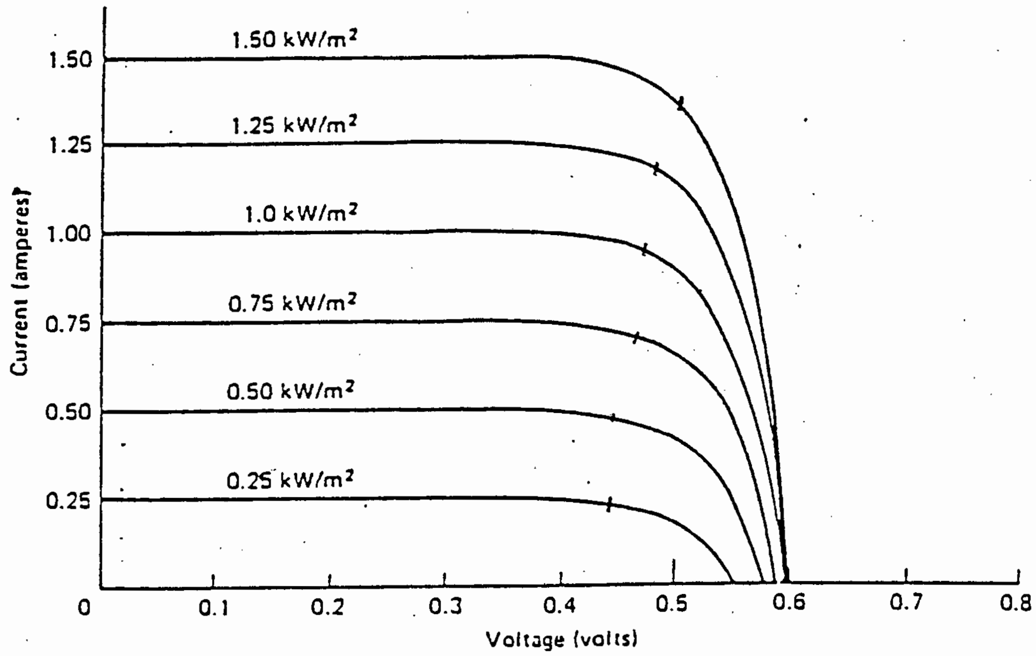



FIGURE 3.4: I-V curves at different light intensities.

Source: Buresch (1983)

### 3.1.2. Effect of temperature

During the day a solar cell operates hotter than the ambient temperature by a factor that depends on insolation and the cells' packaging and mounting.

The relationship between solar cell temperature and insolation is generally linear, depending on the degree of corrective cooling from the wind. This relationship is shown in EQUATION 3.1.

$$T_c = T_a + kS \tag{3.1}$$

Where $T_c$ = cell temperature under no wind or load conditions, deg.C

$T_a$ = ambient temperature, deg.C

$k$ = solar-cell temperature coefficient, $T_c/S$

$S$ = solar insolation, W/sq.m

The k value is typically between Ø.2 and Ø.4.

The actual operating cell temperature under full load will be lower than the cell temperature predicted by the above equation by about three deg.C since some of the sun's energy that would normally heat the cell has been transferred to electrical energy.

The effect of cell temperature on a typical commercial cell is shown in FIGURE 3.5. Changes in temperature throughout the day or from season to season affect the relatively vertical portion of the curve, for example, an increasing temperature causes the voltage to drop and the vertical part of the I-V curve to move leftwards, while decreasing temperature produces the opposite effect.

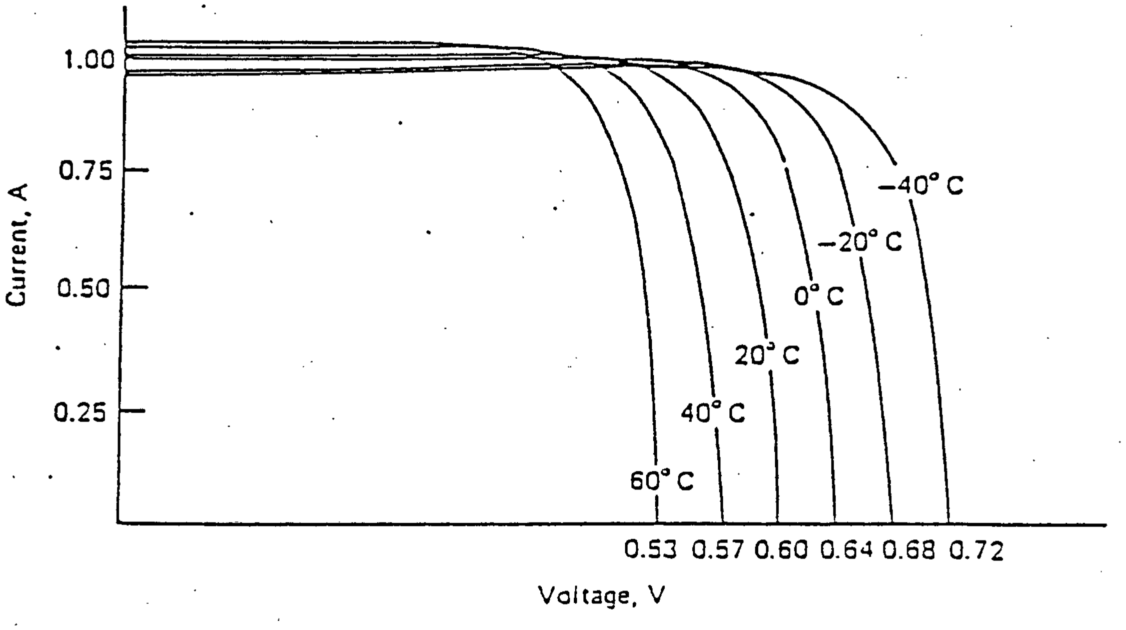



FIGURE 3.5: Current-voltage characteristics at different temperatures for a typical commercial solar cell.

Source: Buresch (1983)

Research has shown that short circuit current is relatively insensitive to temperature variations, increasing less than Ø.1 percent per deg.C, while open circuit voltage shows a greater effect, namely, decreasing Ø.3 percent per deg.C. Cell voltage is thus inversely proportional to temperature. FIGURE 3.6 demonstrates this principle graphically.

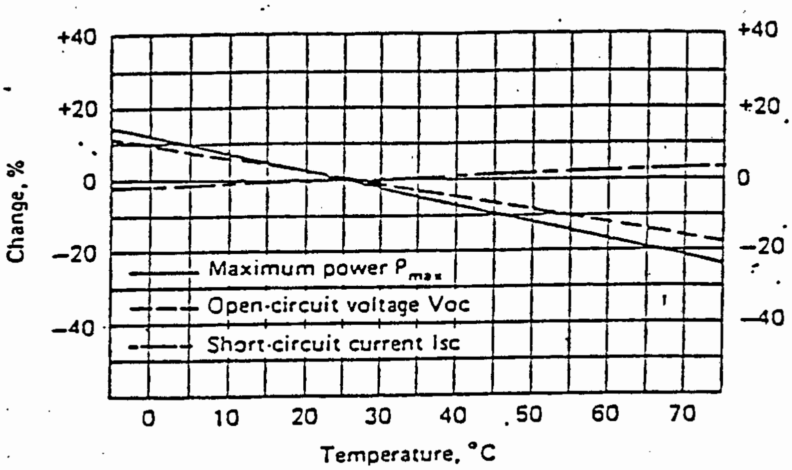



FIGURE 3.6: Voltage, current and power versus temperature for a silicon solar cell.

Source: Buresch (1983)

Since the product of current and voltage is power, it may be deduced that the solar-cell power output and thus cell efficiency also decreases with an increase in cell temperature. This is also shown in FIGURE 3.7.

Generally photovoltaic power and voltage are rated at the reference temperature - 25 deg.C. It is possible to predict adjustments in power and voltage at different temperatures through the following EQUATIONS, (3.2) and (3.3).

$$V_a = V_{ref} \times (1 + a(T_{ref} - T_a)) \qquad (3.2)$$

where $V_a$ = adjusted solar-cell voltage, V

$V_{ref}$ = reference solar-cell voltage, V

$a$ = solar-cell output versus temperature coefficient, /deg.C

$T_{ref}$ = reference cell temperature, deg.C
$T_a$ = adjusted cell temperature, deg.C

$$P_a = P_{ref} \times (1 + a(T_{ref} - T_a)) \qquad (3.3)$$

where $P_a$ = adjusted solar-cell power, W
$P_{ref}$ = reference solar-cell power, W

The solar-cell temperature coefficient is dimensionless and depends on the type of cell, but normally is in the range 0.004 and 0.006 per degree Celsius.

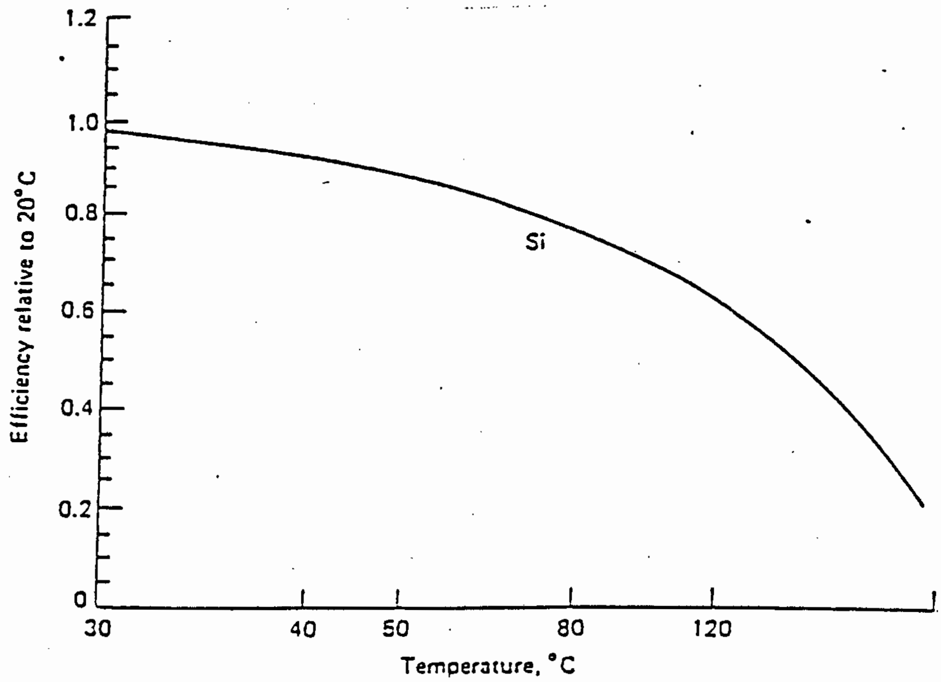



FIGURE 3.7: Silicon solar-cell efficiency versus temperature.

Source: Buresch (1983)

### 3.1.3. The load

The power output of the solar cell is also directly determined by the nature of the electrical load to which it is connected. The current-voltage curve will indicate how a solar cell will respond to any possible electrical loads under a particular set of light and temperature conditions. For example, when a resistive load is connected to a photovoltaic array, it represents a point somewhere on this curve. As the resistance decreases, the operating point moves along the curve to the left, as is shown in FIGURE 3.8. An increase in resistance causes the operating point to move to the right along the curve.

For maximum efficiencies, the load operating point should coincide with the maximum-power point, but this is often not possible.

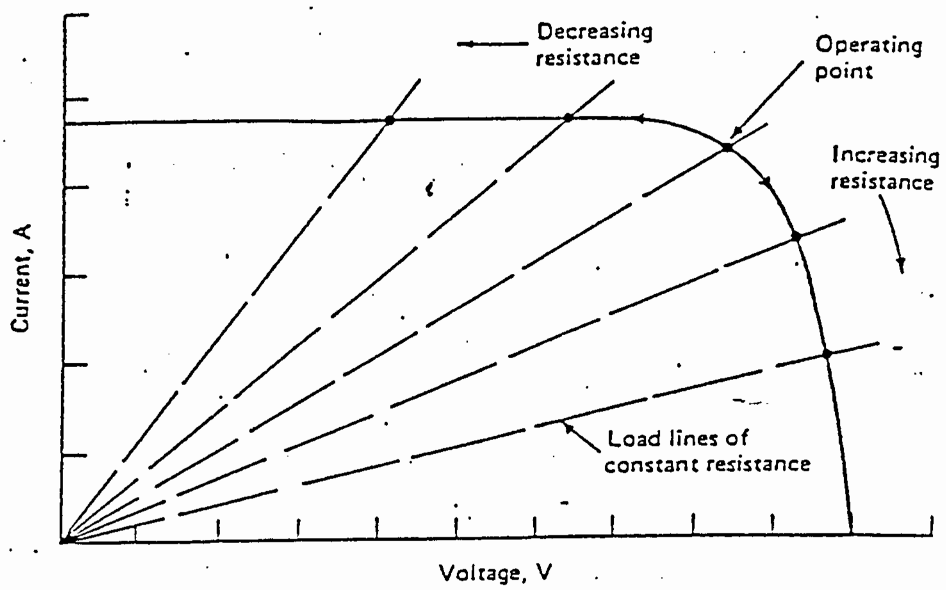



FIGURE 3.8: The load's operating point on a solar-cell I/V curve.

Source: Buresch (1983)

With a constant resistive load, for example, the operating and maximum-power points may be aligned at noon, but will be separated in the morning and late afternoon at lower solar radiation levels. This is shown in FIGURE 3.9.

A solar cell's maximum-power point is relatively insensitive to voltage.

Different types of loads have different characteristics. FIGURE 3.10a shows the load curve of a 20 ohm resistor, representative of a heating element. FIGURE 3.10b shows an inductive load (DC motor-driven air blower) curve.

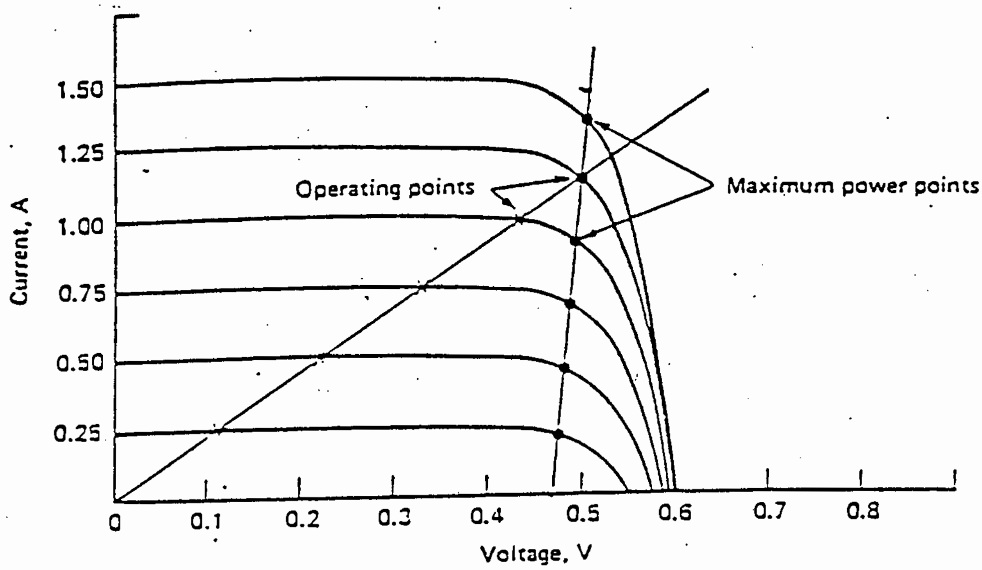



FIGURE 3.9: The resistive load's operating point and the PV cell's maximum-power point travel divergent paths as insolation changes.

Source: Buresch (1983)

FIGURE 3.10c shows the input curve for a utility-interactive inverter with fixed-input-voltage operation, and finally, FIGURE 3.10d shows the input characteristics of a lead-acid storage battery. A battery's response depends on its state of charge and its temperature, hence the range of curves to account for these various operating conditions.

Photovoltaic I-V properties, however, change during different times of the year as solar radiation and temperature fluctuate. A plot of the PV array's I-V curve under the extreme conditions of sunlight and temperature will demonstrate how much the maximum-power voltage varies over an entire year; the effect of ambient temperature on cell temperature and voltage can then be predicted, and estimated I-V plots for different times of the year can be made.

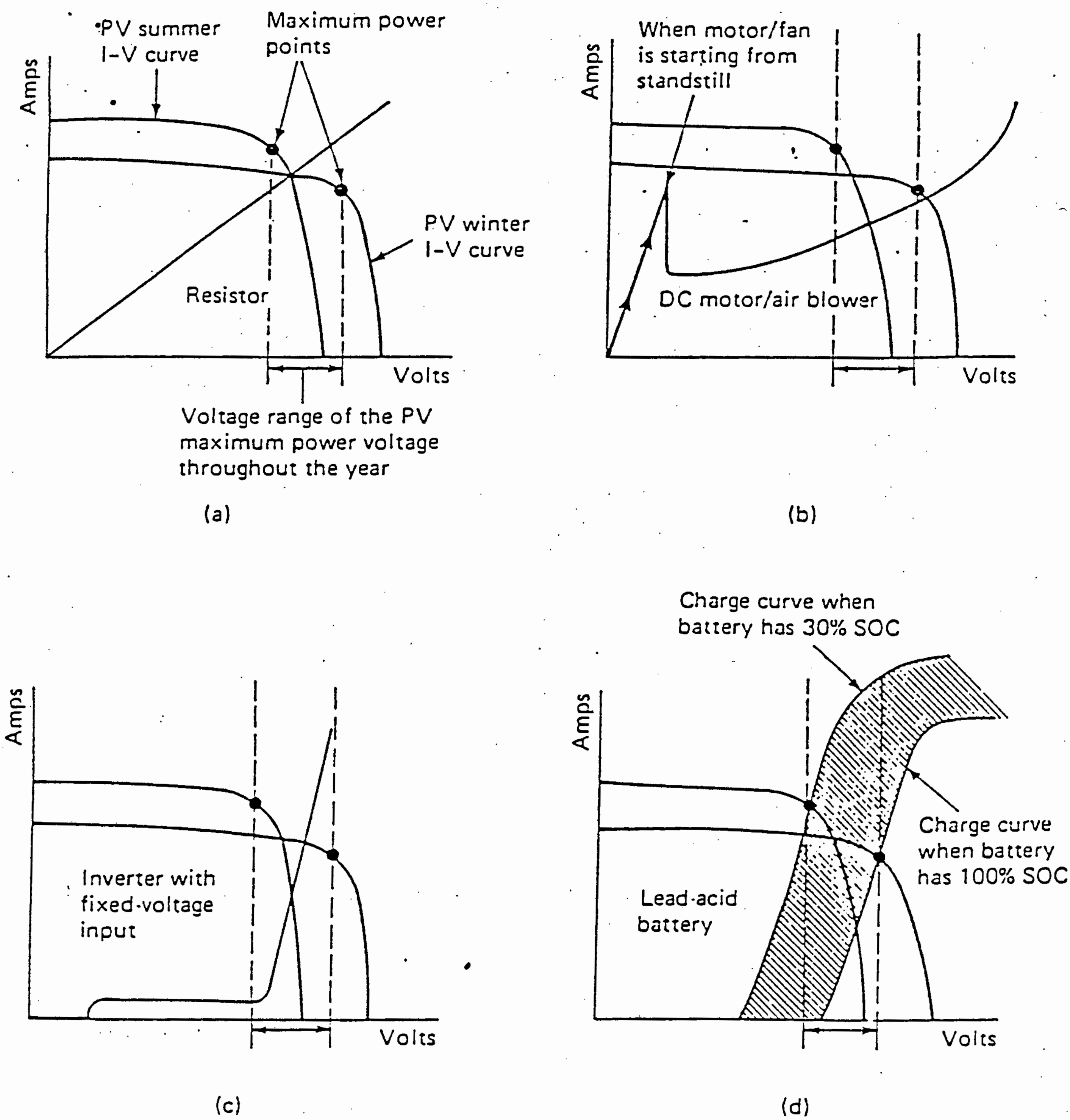



FIGURE 3.10: Photovoltaic output and load or storage input current versus voltage curves: (a) PV output and resistor input I-V curves. (b) PV output and DC motor-driven fan input I-V curves. (c) PV output and inverter with fixed voltage input I-V curves. (d) PV output and lead-acid battery input I-V curves.

Source: Buresch (1983)

### 3.1.4. Conclusion

The above analysis has indicated that the performance of specific photovoltaic modules varies with light intensity, cell temperature and the characteristics of electrical loads to which they are connected. These parameters need to be monitored in the evaluation of any photovoltaic system.

Commercial modules are available in a wide range of operating currents and voltages. The most common designs, however, are those with a maximum voltage output of around 15 V (at STC). Under most operating conditions this voltage output will match the voltage required to fully recharge a 12 V storage battery, namely, about 14.4 V.

Modules are typically rated in peak power expressed in peak watts (Wp). Peak power is loosely defined as the amount of power produced by the module at noon on a clear day with the collector facing directly towards the sun. More precisely, it is the amount of power produced at standard test conditions (STC): namely, a cell temperature of 25 deg.C and a solar radiation intensity of 1000 W/sq.m.

A wide selection of module power outputs is also offered, ranging from 1 to 80 Wp (at STC).

Module efficiencies range up to 15 percent (at STC). The higher efficiency modules are invariably those using square or rectangular solar cells, which allow for a higher packing efficiencies.

## 3.2. BATTERY STORAGE

Actual loads seldom match the pattern of power output from photovoltaic modules which are dependent on the vagaries of climate. Batteries are thus often used to store photovoltaic energy on a short-term basis.

A battery used in domestic PV-powered systems performs two essential functions, namely:

(i) it acts as a power buffer between the array and the loads; and,

(ii) it is an energy storage bank.

### 3.2.1. The power buffer

The PV array is not capable of supplying a constant current or constant voltage. The maximum power output of the array varies with changes in solar radiation, temperature conditions, and the size of the load that can be powered by the array.

A battery, however, can provide a relatively constant voltage; therefore, when it is used in a PV-powered system, the battery acts as a buffer between the array output and variable load demands by forcing the array to operate within a narrow voltage range which may be close to its maximum power output.

### 3.2.2. Energy storage

Solar radiation varies both daily (diurnally) and seasonally. To allow uninterrupted operation of the loads during all seasons and at all times, a storage battery is used to compensate for the absence of reserve energy capacity in the array. An appropriately-sized battery can store excess electrical energy during periods of high insolation and release it as needed during periods of low, or no, insolation.

### 3.2.3. Commercial battery types

The type of batteries which are commonly used for PV-powered application are lead-acid and nickel-cadmium types, with the former being more attractive for photovoltaic-energy storage because of their lower cost per unit of storage capacity, and the greater range of possible operating temperatures.

The following equation describes the reactions in lead-acid batteries:

$$PbO_2 + Pb + 2H_2SO_4 \underset{\text{charge}}{\overset{\text{discharge}}{=\!=\!=\!=\!=\!=}} 2PbSO_4 + 2H_2O$$

The active material of the positive (lead oxide) and negative (sponge lead) plates are usually supported on a lead grid structure. In some cells a small amount of antimony or calcium is alloyed with the lead to strengthen the grid and increase life. The plates are immersed in dilute sulphuric acid electrolyte and contained in a rubber or plastic case.

Lead-calcium batteries have a lower battery self-discharge rate than the less expensive lead-antimony batteries. The latter also require an overvoltage (equalizing charge) to assume that all cells in a battery bank are recharged to the same voltage level. Lead-calcium batteries do not require an equalizing charge and usually require less maintenance - the presence of calcium reduces gassing and loss of water. However they have a poor charge acceptance after deep depth of discharges (DODs). Battery life is shortened if deep-discharged repeatedly (usually a 15-25 percent DOD is recommended). On the other hand lead-antimony batteries can be repeatedly deep discharged to 50-80 percent of their capacity. They are capable of accepting fast charge rates and delivering fast discharge rates with high charge/discharge efficiencies. Lead-antimony grids adhere better to the $PbO_2$ resulting in less shedding of active material, but battery life is generally shorter than lead-calcium batteries.

Several types of commercial lead-acid batteries have been perfected to perform under the specialized duty requirements of various applications. These batteries are detailed below (McNicol & Rand, 1984).

### 3.2.3.1. Automotive (SLI) batteries

Automotive or SLI (starting, lighting and ignition) batteries are usually used for cranking a motor car engine, for ignition in internal-combustion-engines, and for small lighting requirements.

Automotive batteries are designed for high discharge rates and shallow cycling. They have thin plates allowing a great number to fit into a small space. The resulting large surface area allows currents of 200 amps or more to be drawn for a few seconds at a time without damage to the battery. They are the cheapest of the lead-acid battery types and are designed for shallow depths of discharge. They have a poor life if cycled deeply and are therefore generally not suitable for photovoltaic applications unless load shedding devices are employed which prevent deep discharge. Normal automotive batteries are capable of approximately 20 deep discharge cycles before battery life expires.

A typical 12 V car battery has an energy capacity of approximately 0.8 kWh, delivers 300 amps for a few seconds corresponding to a depth of discharge (DOD) of less than 3 percent of rated capacity.

### 3.2.3.2. Maintenance-free batteries

SLI batteries suffer certain drawbacks, namely, the shelf-life at open-circuit conditions is relatively short due to self-discharge processes, and secondly, water is decomposed during both charge and open-circuit conditions, necessitating periodic addition to maintain the electrolyte concentration at the required level.

These shortcomings are mainly due to the presence of antimony in the grid metal. Antimony decreases both the hydrogen and the oxygen over-voltages, and thus enhances the electrolysis of water. Water is lost also by evaporation when battery usage is carried out at high temperatures.

As a result of extensive metallurgical investigations, low antimony content alloys (1-3 percent Sb) have been developed which retain the mechanical properties required by the battery. Small amounts of silver, copper, tin and arsenic are added for grid strength and resistance to anodic corrosion. Batteries using these alloys may need periodic addition of water during the second half of their service life. These batteries, having low antimony concentrations, are termed "low maintenance" batteries.

On the other hand, SLI batteries having Pb-Sn-Ca grids require no addition of water for up to four years. These batteries have become known as "maintenance free" (MF-SLI) batteries.

Tests have shown that MF batteries require the highest voltage to start the electrolysis process. If the charge voltage is kept at 2.35 V per cell, or 14.4 V for a 6-cell battery, the gassing current is negligible.

The overcharging current is strongly affected by temperature. Under constant-voltage charging, the gassing current increases sharply at elevated temperatures in the low-antimony or LM batteries, but not in the case of MF batteries.

MF batteries also have their shortcomings, namely, the rapid deterioration in battery performance under deep-discharge conditions, which is attributed to the formation of lead sulfate in the grid corrosion layer and which leads to the impedence of the current flow between the grid and the positive active mass.

Other types of maintenance-free batteries include gelled electrolyte types which are manufactured in sealed units and employ lead-calcium grids. The sulphuric electrolyte solution is immobilized by the use of additives. There is no need for water addition.

In the last several years, batteries have been made available commercially that are designed to meet the specific requirements of terrestial, stand-alone photovoltaic power systems. They are optimized to provide the low rate operation typical of those systems and are available with lead-calcium grids to minimize self-discharge and maintenance requirements.

3.2.3.3. Traction batteries

Traction batteries are used essentially to provide the required energy and power for an electric vehicle (EV); and hence this battery must be able to operate under deep discharge conditions (typically 50-80 percent of their capacity). According to the type of usage pattern, traction batteries may be classified into three main catagories, namely,

(i) modern in-plant EV batteries which have a typical cycle life of 1500 to 1800 cycles at 80 percent utilization of the capacity. They are commonly known as "industrial" batteries.

(ii) the limited-range EV battery has properties and characteristics which lie between those of SLI and industrial batteries.

(iii) on-the-road EV batteries typically have a cycle life of 500 to 600 charge/discharge cycles and a specific energy of 22 to 32 Wh/kg.

These batteries are built with thick lead plates and greater electrolyte capacity to make them more reliable under difficult operating conditions. Most suffer from self-discharge problems. Those with lead-antimony grids can be expected to provide about 5 to 15 years of service in the absence of deep discharge while lead-calcium batteries yield a slightly longer service life.

Traction batteries are manufactured with two designs of positive plate, namely, tubular and flat pasted configurations.

Tubular design offers several advantages, the principal one being that shedding does not occur during the service life because the active material is held in the tube. Thus a lower density of active material can be used. In addition, the increased porosity of the tubular plates improves the utilization coefficient of the active mass. Another advantage is that the spine is coated with a layer of active mass which protects it from fast corrosion.

However, tubular plates also exhibit some disadvantages. Their production is more expensive, and pollution hazards are increased in comparison to the pasted technology. Furthermore, the contact area between the lead current-collector and the active mass is reduced when spines are used. Thus, under continuous heavy current drains, the increased current density at the spine/active-mass interface is high and local heating may crack part of the corrosion layer.

Comparison of the contribution of tubular and pasted traction batteries to the overall world production shows clearly that tubular batteries are steadily increasing their share of the market.

#### 3.2.3.4. Stationary batteries

Stationary batteries are designed essentially as standby energy and power sources, and are kept continuously in a state of charge. These batteries generally have capacities between 50 and 15 000 Ah, with the most common types having capacities between 50 and 1 500 Ah, and the service life is quoted between 15 and 20 years.

The battery is kept under float-charge conditions at a voltage of 2.20 to 2.25 V per cell. At this voltage the battery is completely charged while gassing is kept at a low rate. Annual charge/discharge cycles depend on the frequency and duration of the mains failures.

The electrolyte level must be kept constant and this is the most difficult maintenance problem with these batteries.

They commonly use pure lead grids with low strength though they are also available with lead-antimony or lead-calcium plates. They have a low self-discharge rate and are designed for float service. Their cycling performance is thus poor but they are capable of occasional deep discharges. Their initial cost is generally high.

Very few batteries have been developed specifically for photovoltaic applications and few are available commercially. System designers have often to select available batteries on primarily economic grounds taking into account the specific advantages and disadvantages of different types.

### 3.2.4. Lead-acid battery characteristics

There are a number of battery characteristics and concerns that must be taken into consideration in order to use a battery properly with a photovoltaic array. These may be summarized as follows:

(i) storage capacity
(ii) cycle life
(iii) storage efficiency
(iv) state of charge
(v) specific gravity
(vi) operation procedures
(vii) maintenance

#### 3.2.4.1. Battery storage capacity

A lead-acid battery's storage capacity can be rated in either ampere-hours or watt-hours. The watt-hour capacity denotes the amount of energy a battery can store and is equal to the time integral of the product of the discharge current and voltage from full charge to cutoff voltage. In practice, the full capacity of a battery is seldom used and the average depth of discharge is typically around 60 percent.

Thus

WC = AH x V x BF

where WC = usable watt-hour capacity, Wh

AH = ampere-hour capacity, Ah

BF = fraction of the battery that is available for use, Ø to 1

The amp-hour specification indicates how much current, in amp-hours, can be obtained from a new fully-charged battery during a constant current discharge over a specified period before the voltage falls to a specified end-point.

The amp-hour rating of a battery is valid only at a specific discharge rate, which usually ranges between five and 3Ø hours, and at temperatures within approximately 2Ø deg.C of room temperature. A battery has a larger ampere-hour capacity at longer discharge rates because more time is available for the acid in the elctrolyte to penetrate deeper into the battery plates (which also results in shortened battery life), eg. a 1ØØ Ah battery with a 2Ø hour rating will provide 5 Amps continuously for 2Ø hours equivalent to 12ØØ Wh. At a 5-hour discharge rate, the same battery will deliver a maximum of 7Ø Ah equivalent to 8ØØ Wh. Available battery capacity as a function of discharge rate for different types of batteries is shown in FIGURE 3.11.

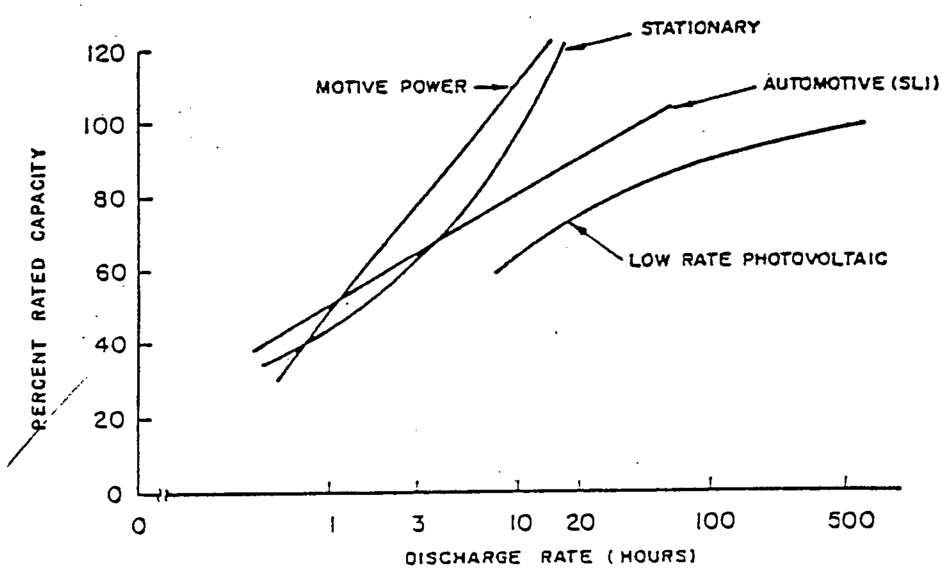



FIGURE 3.11: Battery capacity as a function of discharge rate.

Source: Lasnier et al (1987)

Lower temperatures result in less available capacity due to slower chemical reactions and this effect is more marked at higher discharge rates. This effect is shown in FIGURE 3.12. A lead-acid battery's storage capacity decreases about 1 percent for every 1 deg.C drop in temperature.

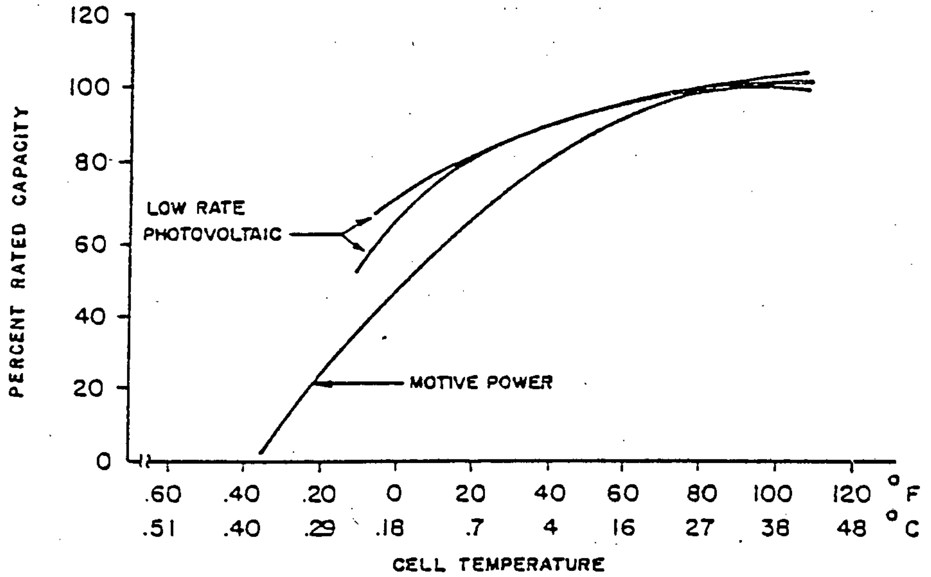



FIGURE 3.12: Lead-acid battery capacity as a function of temperature.

Source: Lasnier et al (1987)

### 3.2.4.2. Cycle life

The cycle life is defined as the number of cycles the battery undergoes to a specified depth of discharge, at a specified temperature and at a specified discharge rate until battery "end of life" is reached. Batteries are typically said to have ended their useful life when the storage capacity has dropped below 8Ø percent of the normal capacity.

Depth of discharge (DOD) and rate of discharge affect battery life. Deeper DODs shorten battery life due to larger internal stresses resulting from a more complete utilization of active materials. Longer discharge rates, though increasing battery storage capacity, shorten battery life due to the deeper penetration of acid into the plates. The industrial standard for shallow cycle batteries is based on the 8-hour discharge rate and the 6-hour rate for deep cycle batteries.

Shortened battery life may also be caused by stratification which results from very slow charging rates and where the state of charge is never high enough to cause gassing and resultant mixing of electrolyte. On the other hand excessive gassing causes loss of electrolyte and plate damage.

#### 3.2.4.3. Battery efficiency

There are two ways of measuring the battery's efficiency: on a watt-hour or amp-hour basis. The watt-hour efficieny is the battery's maximum energy output divided by the maximum energy input. The amp-hour efficiency is the battery's total current output divided by the total current input for a full charge/discharge cycle. Since the charging voltage is appreciably higher than the discharge voltage, the amp-hour efficiency value will always be higher than the watt-hour efficiency under the same conditions.

A new lead-acid battery's amp-hour efficiency typically is around 95 percent, while the usual watt-hour efficiency is about 85 percent, measured at the ambient temperature and the specified discharge rate (Buresch,1983:146).

The operating temperature of a battery and the energy storage time have similar effects on both the storage capacity and the efficiency. A decrease in temperature and an increase in the length of time a particular quantity of energy is stored will have an adverse effect on the battery's performance. Battery efficiency and storage capacity decrease with time because of a self-discharging current within the battery, but drop off significantly only after a month or more. Furthermore, a decrease in a battery's temperature below room temperature produces a conditional decrease in efficiency and storage capacity. At lower temperatures, the battery's discharge voltage is decreased, and therefore power output is reduced. When the temperature returns to a normal range, efficiency and storage are restored to their original values. Extreme operating temperatures will permanently damage the battery.

3.2.4.4. Battery state of charge

It is important to know the level of energy or state of charge (SOC) that exists in a battery at any point in time in order to tell how much energy is available. A battery's state of charge may be monitored periodically or continuously using one of several techniques. The voltage of a discharging lead-acid battery fluctuates almost linearly with state of charge over the higher SOCs and therefore is a good indicator when in this range. If the charge across the two plates of a lead-acid cell is at its maximum, the open-circuit voltage is about 2.35 V. When the state of charge is at a minimum, the voltage drops to about 1.75 V. A graph of the state of charge versus the cell voltage is shown in FIGURE 3.13.

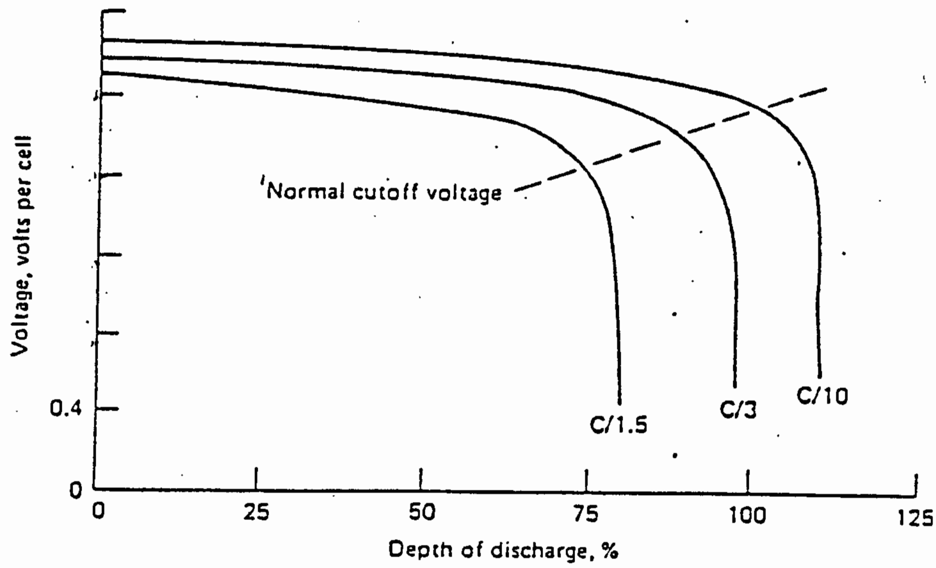



FIGURE 3.13: Lead-acid battery voltage versus state of charge; C/x is the discharge rate, where C = total amp-hour capacity, and x = hour rate.

Source: Buresch (1983)

The cutoff voltage and depth of discharge limitation is highly significant when sizing a battery for use in a PV system. The useful watt-hour storage capacity can be determined by multiplying the battery's amp-hour rating by its average discharge voltage (at about 60 percent state of discharge) and by the fraction of the battery's capacity that is available for use.

The current and voltage during discharge can be described in terms of the state of charge of the cell (SOC, ranging from 0 to 1.0) by EQUATION 3.4. (Macomber et al, 1981: 4.31).

$$V = V_r - I/AH(0.189/SOC + IR) \qquad (3.4)$$

where SOC = the ratio of the charge at the time of interest to the maximum charge, as measured for the specific discharge rate

$V_r$ = rest voltage = 2.094(1.0 - 0.001(T - 25 deg.C))

V = terminal voltage, volts

I = current, amps

AH = the amp-hour rating of the battery for the discharge rate

IR = internal resistance of the cell = 0.15(1.0 - 0.02(T-25))

The 0.189 factor represents the internal resistance due to polarization. During the charging period, the current and voltage are given by EQUATION 3.5 below (ibid).

$$V = V_r + I/AH(0.189/(1.142-SOC)+IR)+\underline{(SOC-0.9)\ln((300xI)/AH+1.0)} \qquad (3.5)$$

The underlined term is included only if the sum of the first two terms is more than 2.28 volts. During the idle period (neither charging nor discharging), the state of charge for a lead-calcium battery decreases according to EQUATION 3.6 (ibid).

$$SOC = SOC_o \times \exp(-kt) \qquad (3.6)$$

where k = 300 x exp(-4400/T)

T = temperature, deg.K

t = time, hours

K = 0.0001 $hour^{-1}$ at room temperature

3.2.4.5. Specific gravity

The specific gravity of a lead-acid battery when it is fully charged depends on the design of the battery. Typical values of the full-charge gravities most frequently used (usually expressed as a range of plus or minus 10 (0.010) points) and their corresponding applications are quoted as follows:

1.290 - heavily worked or "cycled" batteries
1.260 - automotive service
1.245 - partially cycled batteries
1.215 - batteries in stationary standby or emergency services

The specific gravity measured at any particular instant is an approximate indication of the state of charge of the battery. For example, if the specific gravity of a cell reads 1.195, corrected for temperature and electrolyte level, and the average full charge gravity is 1.245, the cell is now 50 points below full charge. Assuming that a 125 points drop in specific gravity corresponds to a fully discharged state (8 hour rate), the battery will therefore be 50/125 or 40 percent discharged.

The specific gravity of a battery, recorded at different times, temperatures and electrolyte levels, has to be "corrected" to a reference temperature, viz, 25 deg.C, and the normal electrolyte level. As a rough guide:

(i) 3 points of gravity are usually added for each 5 deg.C below 25 deg.C or 3 points of gravity are subtracted for each 5 deg.C above 25 deg.C.
(ii) 15 points of gravity are subtracted for each 12 mm below normal level, or 15 points are added for each 12 mm above normal level.

The specific gravity of a battery decreases with age due to loss of acid. This decrease is small, usually of the order of a few points per year.

#### 3.2.4.6. Operation procedures

Proper battery operation requires voltage regulating protection circuitry to prevent overcharging or excessive discharging.

Permanent damage of the battery can result if it is charged too fast and too long. Low-level trickle charging can be performed indefinitely, since it only off sets the self-discharging current of the battery. However, forcing higher charging currents into the battery when it is fully charged will cause the battery to gas, ie., give off hydrogen and oxygen from the water in the electrolyte fluid. The voltage at which gassing begins is a function of temperature so that the maximum acceptable charge voltage, during normal charging, must be adjusted to reflect the actual temperature of the cell (see FIGURE 3.14). Gassing decreases the fluid level of the electrolyte and thereby exposes and damages the battery's plates (Buresch,1983:143).

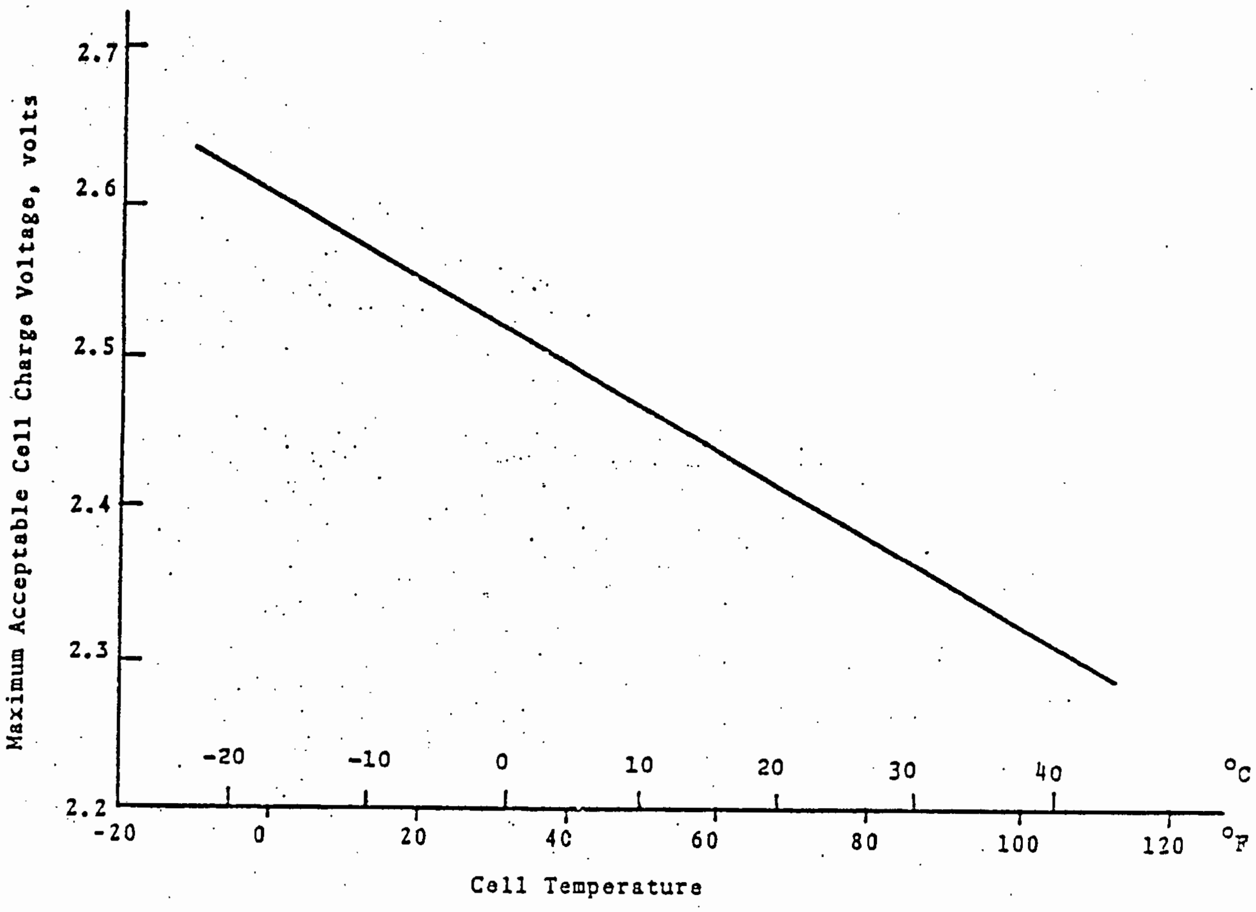



FIGURE 3.14: Maximum acceptable cell charge voltage vs. Temperature.

Source: Rosenblum, 1983, p4-13.

Excessive discharging over a long period is detrimental to the life of the battery, causing the plates to disintegrate. During the discharge process, as shown in the chemical equation earlier, lead sulphate is formed. This product occupies more space than the lead sponge of the negative plate; hence the plate material expands slightly. If the battery is too deeply discharged, the material may expand to the point where portions of it separate and lose proper contact with the grid, and thus with the electrical circuit. If the battery is left in a discharged state for a long time before being recharged, the lead sulphate may form crystals which are difficult to reconvert to its original state. These crystals may be washed from the surface of the plate and settle on the base of the cell as sediment.

Since excessive charging causes the battery voltage to rise prohibitively high, and conversely excessive discharging pulls the battery voltage too low, the battery should be protected using one of many different types of voltage regulating circuits that maintain the battery voltage within an acceptable range.

Charging curves demonstrating battery charge voltage as a function of state-of-charge (SOC) for three charge rates are shown in FIGURE 3.15. It is seen that at a high (C/2.5) rate of charge, the gassing voltage is reached when the battery has recovered to only about 60 percent SOC. To prevent excessive gassing, it is necessary at this point to drop to a lower charge rate. Dropping to a lower charge rate will allow higher states of charge to be reached without gassing.

#### 3.2.4.7. Battery maintenance

Battery maintenance is essential to ensure the longest possible battery life: the two basic tasks are checking the fluid level and battery equalization. Most lead-acid batteries are composed of a liquid electrolyte that diminishes as a result of evaporation and gassing. The fluid level must not be allowed to drop to a level that exposes the battery plates to air. Consequently, the fluid level in each cell must be checked and periodically 'topped up' with distilled water. Under normal operation, some cells in a battery will tend to discharge more quickly than others and, conversely, will not reach the uniform level of charge. Battery equalization involves a carefully monitored overcharge cycle that will bring these weaker cells up to the normal capacity. Failure to equalize will cause the weaker cells to further degrade and thereby decrease the battery's efficiency and storage capacity.

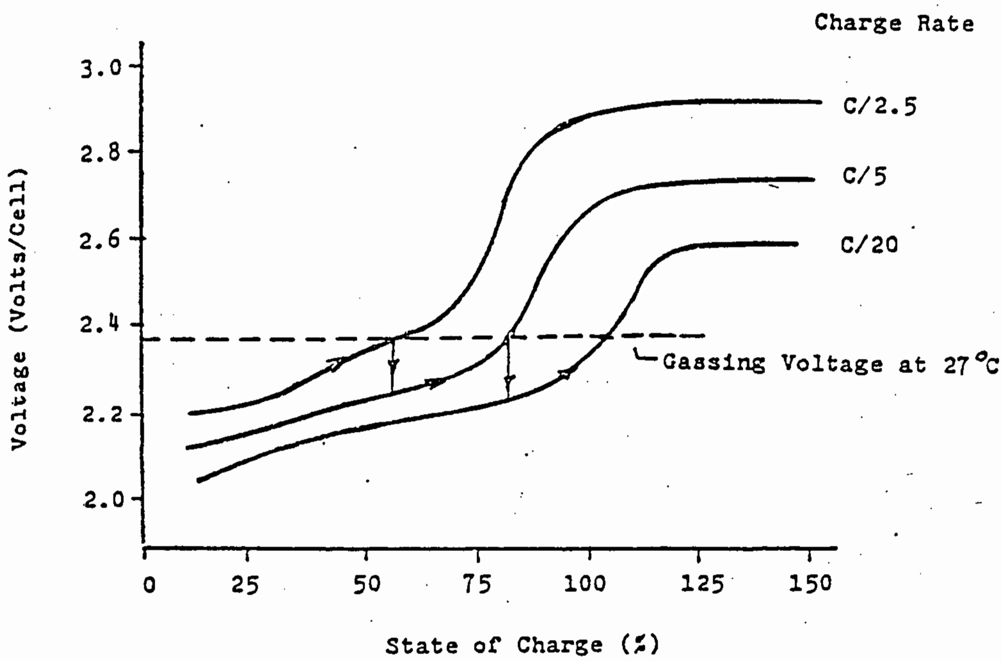



FIGURE 3.15: Lead-acid battery (Pb-Sb grids) charging voltage as a function of state of charge.

Source: Rosenblum (1982)

There are certain safety precautions that must be strictly observed when using lead-acid batteries. The hydrogen and oxygen gas produced during gassing is highly explosive and must be evacuated and diluted with some type of ventilation system. Battery acid is highly corrosive, and steps should be taken to prevent this acid from spilling (Buresch, 1983:150).

## 3.3. REGULATORS AND CONTROLLERS

The size and stability of the photovoltaic system's operating voltage are critical factors for the photovoltaic array, the storage battery and the load.

Most importantly the battery's charge and discharge cycles need to be regulated within the specified limits. In order to prolong the life time of the battery, over-voltage and under-voltage protection is necessary. A second concern is to maximize the energy transfer from photovoltaic arrays by matching the optimum operating voltage with specified loads. This may be accomplished through direct connection to constant voltage loads or through maximum power point tracking devices.

### 3.3.1. Battery protection

Battery protection is an important feature of the system design, since it prevents the battery from being overcharged during high insolation periods and being excessively discharged during periods of low insolation or extended usage.

Since excessive charging causes the battery voltage to rise prohibitively high, and conversely, excessive discharging pulls the battery voltage too low, battery protection can be achieved by using one of many different types of voltage-regulating circuits which maintains the battery voltage within an acceptable range.

Common system designs for a combined photovoltaic array with battery storage are shown in FIGURE 3.16(a and b).

FIGURE 3.16(a) shows the battery protecting regulator device in series with the photovoltaic array and the load. When the battery voltage becomes too high, the overvoltage regulator sheds part or all of the array to reduce or stop the charging current. Conversely, when the battery voltage and charge drop to a relatively low level, this regulator adds part or all of the array to the system circuit. The under voltage regulator disconnects the load, ie., load shedding, when the battery charge and voltage are below a minimum acceptable level. In the event of a load cut off, the array is also disconnected from the load and is only allowed to charge the battery. When the voltage level returns to a permissible level, the undervoltage regulator reconnects the load.

The photovoltaic system with battery storage shown in FIGURE 3.16(b) has the battery protection unit arranged in such a way that there is a permanent and direct connection between the array and the load.

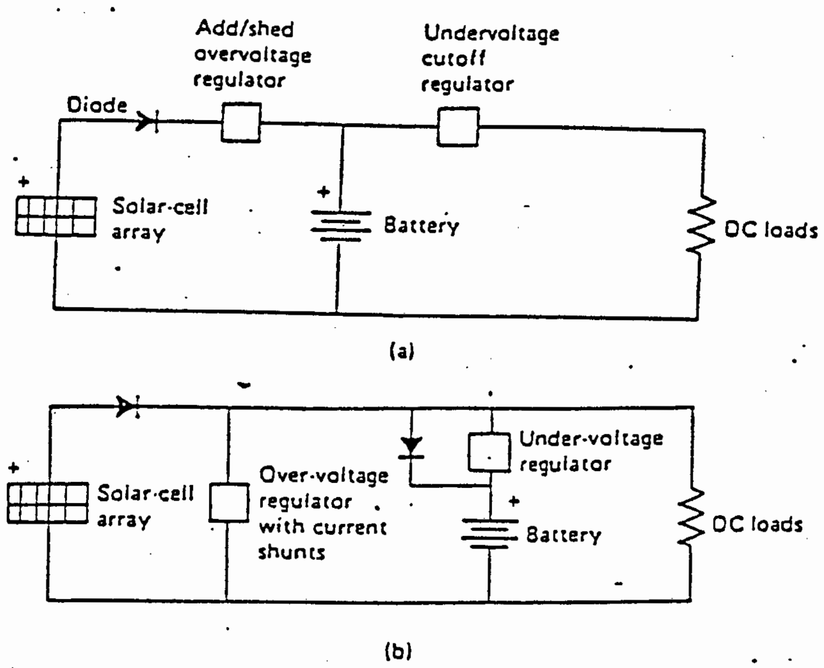



FIGURE 3.16: Photovoltaic system designs with and without battery storage: (a) battery storage with add/shed overvoltage regulator; (b) battery storage with current-shunting overvoltage regulator.

Source: Buresch (1983), p148.

The undervoltage cut off regulator is placed in the battery leg of the circuit. When a low battery voltage causes the regulator to disconnect the load from the battery, the diode wired across the regulator will allow the array to charge the battery. The over-voltage regulator shunts the current away from the battery when its voltage rises too high.

In both these battery-charging designs, excess array power is either disconnected or dumped into a bank of resistors. Large amounts of solar energy can be wasted if such a design is used.

### 3.3.2. Voltage regulation

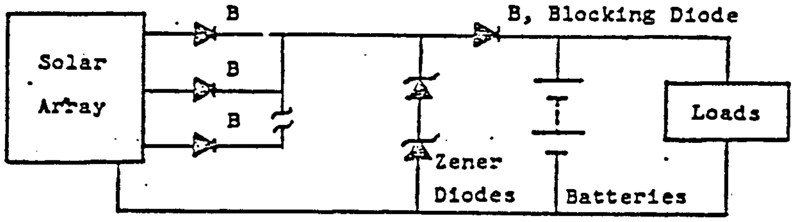
Voltage variations caused by changing solar radiation and temperature (and degradation due to aging) can be compensated by controlling the array voltage by means of a voltage regulator. Ideally a PV battery charging regulator should be capable of adjusting the amount of charging current to maintain the highest possible rate of charge, constant under array output and load demand, while avoiding excessive battery gassing.

Regulators for PV systems often involve "two-step" or "boost-float" charging whereby batteries are charged at the maximum rate until a specified voltage, and then trickle charged at a very low current. Permanent damage can be inflicted on the battery if it is charged too fast and too long. Low-level trickle charging can be performed indefinitely, since it only offsets the self-discharging current of the battery.

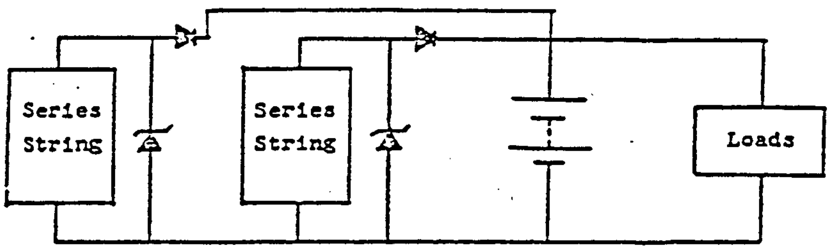
There are numerous different controllers available for PV system battery charge regulation. These are characterized by three major features, namely,

(i) the method of power dissipation (series or shunt);
(ii) the control method of the regulator (active or passive); and,
(iii) portion of the array output that is regulated (whole array or part).

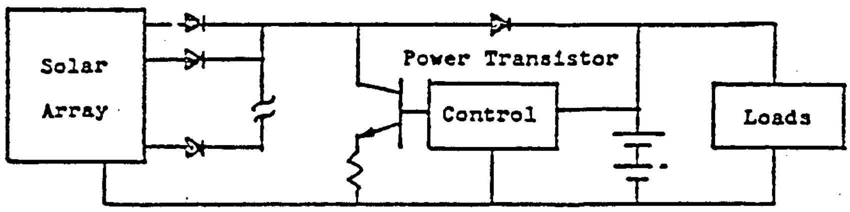
Shunt-type charge regulators usually have one of the following elements which shunts excess array current to ground, namely, Zener diodes, transistors, contactors, or solid-state relays (FIGURE 3.17a to c). Series-type regulators, on the other hand, use transistors, contactors, or solid-state relay elements to switch off or reduce the flow of current from the array to the battery (FIGURE 3.17d and e).



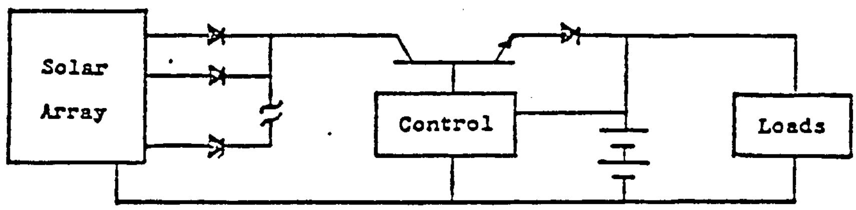

(a) Array,Passive, Shunt Regulation



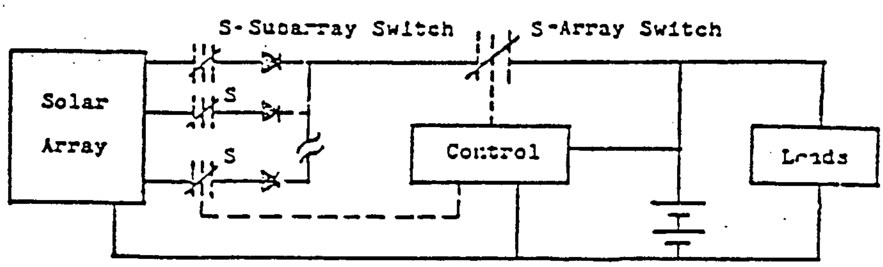

(b) String (or Subarray),Passive,Shunt Regulation




(c) Array, Active, Shunt Regulation




(d) Array, Active, Series Regulation




(e) Array (or Subarray), Active, Series Regulation

FIGURE 3.17: Methods of power regulation

Source: Rosenblum (1982)

Passive charge regulation uses a Zener diode, which will permit current flow once a particular voltage level is exceeded. These diodes can operate in a range from a few watts to 50 watts, and up to 200 volts. Passive charge regulation is characterized by a wide voltage cutoff band due to the I-V characteristics of the Zener diode.

Active charge regulation methods are characterized by a more precise voltage regulation, proportional current control, and the adjustment of the voltage control level to accomodate variations in battery temperature. Power transistors (eg. Darlington or bipolar junction diode) shunt and series elements with active control are shown in FIGURE 3.17c and d respectively.

The portion of the array output that is regulated is effected through taps (connections) to subsections of the array. These taps can activate current shunting or controlling elements for all the array output, or for a portion thereof. Controllers may incorporate a time modulated on-off control signal. For example, a duty cycle regulator has an integrated circuit which changes the ratio of the on to off time response to system voltage, thereby regulating the current flow to the battery.

Although there may be numerous factors influencing the choice of a PV system regulator, three essential considerations are discussed below.

(i) Power loss and heat dissipation

Charge regulating components of a charge regulator have an associated voltage drop which results in power loss and heat dissipation to an appropiately sized heat sink when current flows through the component. Under normal operating conditions the voltage drop across transistors and solid-state relays may be as much as 2 volts; therefore, their use in low voltage output systems may not be desirable.

(ii) Tolerance of environmental stress

There are serious environmental factors, such as high ambient temperatures, dust and moisture, which may affect the performance of the regulator or result in its failure. In areas with high ambient temperatures, transistors or diodes should not be used as linear elements in a control system. Contactors should be kept dust- and moisture-free by being stored in a weather-proof container to ensure satisfactory operation.

(iii) Reliability

To improve the reliability of a regulator system, the components are usually derated to accomodate increased environmental stress margins and stored in weather-proof containers.

### 3.3.3. System power optimisation

There are three fundamental ways of maximizing PV power output (Buresch,1983):

(i) direct connection with proper PV array sizing
(ii) fixed-voltage operation
(iii) maximum-power tracking

The suitability of each of these techniques must be examined on a case by case basis to ascertain whether the increased power output warrants the increased cost or decreased efficiency.

#### 3.3.3.1. Direct connection

Certain load and storage devices have input voltage characteristics that remain relatively stable throughout most levels of operation. If a PV array is placed in a location where the ambient temperature does not vary dramatically, the PV maximum-power voltage will also remain fairly constant. In such cases, an adequate match can be made by directly connecting a PV array to its load or storage.

A typical energy storage device is a lead-acid battery which operates under reasonably stable voltage conditions.

If a PV array is to be directly connected to a battery, it is important to know the battery's charge voltage range as well as the output voltage range of the PV array. Knowing these parameters, the array can be sized such that its maximum-power voltage equals the battery's average charging voltage, taking into consideration the effect of PV cell temperature on the array output. If the PV array's I-V curve fill factor[2] is less than Ø.6, insolation levels may also have an effect on the PV voltage.

In order to optimize the PV array's power output and to ensure that the battery operates at the array's maximum-power voltage, the PV array's maximum-power voltage should be equal or slightly greater than the battery's minimum charge voltage. In general, the PV array's lowest maximum-power voltage should equal the battery's charge voltage when it is at its lowest allowed state of charge. In this way, it ensures that the PV array will be operating at its maximum power voltage when the battery needs energy the most, and alternatively, the PV array current and voltage decreases naturally as the battery becomes fully charged.

#### 3.3.3.2. Fixed voltage operation

Certain power conditioning devices have flexibility in their input circuitry design that allows for fixed-voltage operation. This feature can force the PV to operate continuously near one voltage which should be sized to equal the annual average maximum-power voltage. The advantage of the fixed-voltage feature is its simplicity and low cost. The drawback is that it will force the array to operate at a voltage other than its maximum-power voltage during some times

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[2] The fill factor is defined as the ratio of the peak power output of the array to the power calculated by multiplying the open-circuit voltage and the short-circuit current. It is an indication of how much series resistance and how little shunt resistance there is in a PV module.

of the year. If the array is located at a site which causes the PV maximum-power voltage to make wide variations, a two-position "summer/winter" fixed-voltage option can be included.

### 3.3.3.3. Maximum-power tracking

Certain loads have operating voltages that can be quite erratic and would do a poor job of tracking a PV array's maximum-power voltage. A PV array can sometimes be placed in a location that will expose it to very wide temperature fluctuations; as a result, the PV maximum-power voltage will vary greatly, and significant power losses will be suffered when the direct-connection or fixed-voltage techniques are used.

A maximum-power tracker is placed between the PV array and its load, and is based on a design that samples the PV output and changes the apparent impedance of the load until the PV power is maximized.

A maximum-power tracker can be treated as a black box; only basic specifications need be known. Its input/output efficiency should be no less than 90 to 95 percent. The device has a voltage operating range and maximum power and current capability that must be sized for each application. A maximum-power tracker can be designed to obtain its operating power either from an external source or from the direct current provided from the photovoltaic array.

## 3.4. ELECTRICAL LOADS

The prefered tendency for small stand-alone photovoltaic power system is to use direct current (DC) loads. The advantage of using DC loads is that an inverter is not required, thus saving both the cost of the inverter equipment and of the added array capacity which would be required to supply the power lost from the inverter inefficiency. The decision to convert the DC array output to AC should be examined in terms of the overall system efficiency. Inverter efficiencies generally range from about 90 percent, for operation at 100 percent of the rated power capacity, to lower values at partial load operation. Addionally, a tare loss of 5 to 10 percent of the rated capacity is experienced while the inverter is in operation. Lastly, when inductive loads, eg. motors, are used, the inverter must be sized to accomodate the large, short-duration power demand on startup. Thus the use of a larger capacity inverter than would be needed to satisfy the steady-state load demand results in further losses. In the aggregate, these various inefficiencies can become intolerably high for small systems, for systems with a high percentage of inductive loads, or for systems with relatively small power demands for extended periods.

A disadvantage of using DC is that there is very little flexibility to choose a higher voltage distribution system than that of the load in order to minimize the losses in the distribution system.

One of the main advantages of an AC power system is the ease of matching system power output with commonly available load equipment.

Load efficiency is an important criterion in the selection of appliances. Load efficiency has a very great influence on PV system cost. The higher the efficiency of the loads, the less energy will be required to perform the service and the smaller and less costly the PV system.

Although more efficient load appliances may be more expensive, the additional costs are more than off set through savings in the cost of the PV system.

### 3.4.1. DC lights

In this study, the standard loads to be powered by photovoltaic systems for home use are lights and TV.

A DC light consists of three major components:

(i) a luminaire (or bulb, or tube);
(ii) a ballast; and
(iii) a fixture

Lighting applications use gas-vapour lamps, eg., fluorescent, low-pressure sodium, mercury vapour, and metal halides. A fluorescent light is a capacitive type load. Initially the lamps require a high-voltage electrical charge to excite the gas molecules to produce the light, but once initiated, lighting can be maintained with low voltages.

The charge is sparked, and the operating frequency is regulated by a ballast, ie., a high-frequency inverter and transformer which controls the current flow into the lamp. The ballast and the lamp are mounted in a fixture. The only difference between an AC and a DC light is the ballast design.

Fluorescent tubes are replaced as they burn out, whilst the ballast is replaced approximately every three years.

Incandescant DC lamps may also be used; however, the main disadvantage is that they provide less illumination when compared with a fluorescent lamp of the same power requirement.

## 3.5. SYSTEM DESIGN

The design of power supply systems, based on renewable energy sources such as solar energy, is essentially different from conventional power systems based on fossil or nuclear fuels, in that the availibility of the energy source is highly variable. Solar insolation is affected by cloud cover, a stochastic (or random) phenomenon. The main PV system sizing procedures described below recognize the stochastic nature of insolation; however, each deals with the problem in a different way.

(i) Arbitrary design margin:
In this approach, values of average daily insolation are used to calculate optimum tilt angle, array and battery size, and module performance for a specified load. Then the array size is arbitrarily increased by X percent and the battery size increased by Y percent to account for "no sun" days or a "bad sunshine" year. This approach is to be found in the system sizing procedures used by many of the commercial module suppliers. Often an arbitrary number of days of system autonomy will be specified - ie., the number of days that the system will work with no sunshine (assuming fully charged batteries at the start).

(ii) Arbitrary weather variability factor:
The design method is similar to that described previously, except that a random weather cycle variable is introduced to modify the array output. NASA has used this procedure with a simulated 4-day weather cycle (Martz and Ratajczak, 1982).

(iii) Insolation probability function:
With this method an insolation probability function is used to determine the probability of the occurrence of certain daily average insolation levels. Programmes for calculators are available which calculate monthly loss of energy probability (LOEP) for systems with a given array and battery size (Macomber et al, 1981). A set of

rapid sizing graphs, based on this method, are also available (Rosenblum, 1982, and Borden, 1984).

(iv) Typical meteorological year data:
In recent years, effort has gone into developing micro-computer based photovoltaic system simulation models which combine typical meteorological year data in order to determine loss of energy probabilities for specific designs. This is probably the most accurate design methodology but no programmes are available for South African conditions, and existing programmes still incorporate simplifying assumptions regarding PV maximum-power point operation and also for battery performance.

### 3.5.1. Sizing methodology

The sizing methodology used in this study is that described by Borden et al (1984) of the Jet Propulsion Laboratory, California Institute of Technology, Pasadena and sections 3.5 and 3.6 are derived largely from this report. This methodology is designed to estimate the photovoltaic system size and life-cycle costs for stand-alone applications for a specified load requirement, a given site and a desired level of system availability. It applies only to stand-alone fixed flat-plate photovoltaic systems, and permits a comparison of the economic viability of photovoltaics with that of the possible alternatives, thereby facilitating final selection of the preferred generating option.

FIGURE 3.18 schematically depicts the photovoltaic system serving a load. This representation illustrates the key factors involved in system sizing.

Solar radiant energy (I) is converted to DC electrical energy by the photovoltaic array which has an average conversion efficiency $e_a$. Part of the energy required by the load, $f_a$, may be used from the array, passing it through an inverter if the load is AC, or directly if the load is DC. The remaining load energy demand, $f_b$, may be obtained from an energy storage device, eg., a battery,which is recharged at regular intervals by the array. A DC-DC converter is used to change the voltage output from the array to that of a DC load if it operates at a different voltage level.

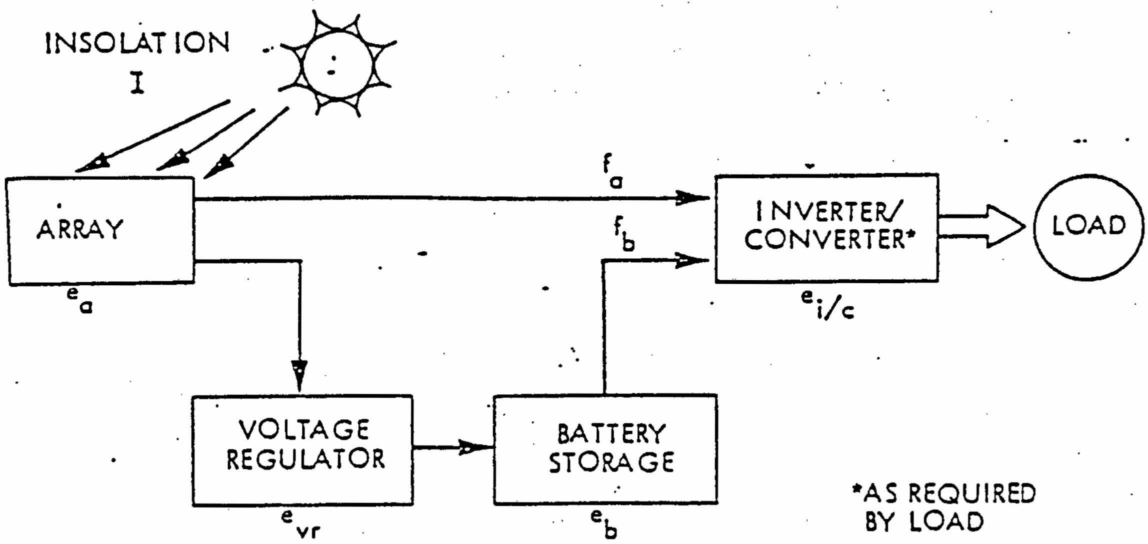


FIGURE 3.18: A photovoltaic system model showing the key system sizing parameters.

Source: Borden et al (1984)

Conversion efficiences for the voltage regulator (or, BPU), battery, and inverter or converter are $e_{vr}$, $e_b$, and $e_{i/c}$, respectively.

### 3.5.2. Photovoltaic system sizing procedure

This section describes the sizing procedure in detail, following the steps identified in FIGURE 3.19. Initially the average daily energy load is calculated for each site for each month of the year. The next step is to determine the local insolation level available for various tilt angles of the array. Thirdly, the month with the lowest ratio of available solar energy to load energy requirement (ie., the "worst" month) is determined. Based on this month's insolation, the array and storage required are sized using previously determined "sizing factors" in order to scale the system to achieve a desired level of autonomy (availability). Finally, the array power output and area, and the required battery storage are calculated. Provision is also made to include the sizing of a voltage regulator and an inverter/converter if they are required by the system.

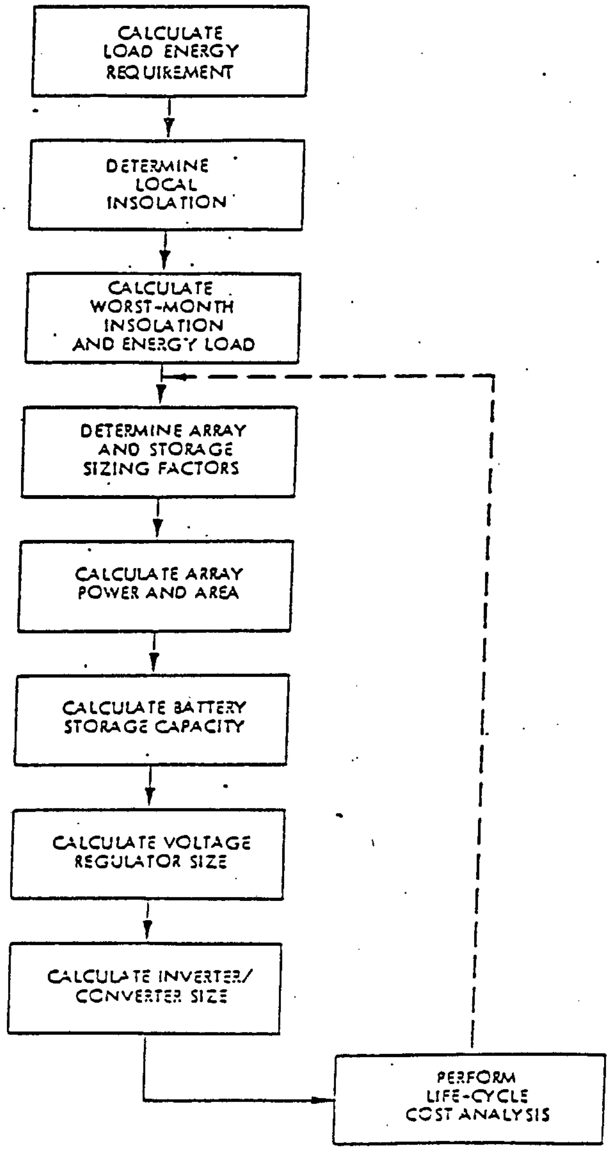


FIGURE 3.19: The sequence of steps in sizing a remote, stand-alone photovoltaic system.

Source: Borden et al (1984)

Two worked examples of this sizing procedure, along with the sample data used for the Omdraaisvlei and Uitsig demonstration projects, are shown in APPENDIX A.

### 3.5.2.1. Calculating the load

The first step in sizing the photovoltaic system requires the estimation of the average daily load energy demand for each month of the year. This is done by calculating the energy consumed by each load element in a 24-hour period, in Watt-hours, and summing these values to get the total. This procedure is shown mathematically in EQUATION 3.7.

$$L_{td} = \sum_{i=1}^{n} P_i D_i / 1000 \qquad (3.7)$$

Where

$L_{td}$ = total daily energy load (kilowatt-hours per day)

$P_i$ = power drawn by load element i while it is in service, in watts

$D_i$ = amount of time per day in hours that the load element i is in service

n = number of separate load elements

If the load energy demand for a particular element varies from day to day, an average load demand is calculated for each month of the year. This value is the sum of all the daily loads over the monthly period divided by the number of days in the month. However, if the load demand variation is appreciably large, or the load demand peaks appear on consecutive days, it may be necessary to use the peak load levels instead of monthly averages, else the system may be inadequately sized to accomodate cloudy periods coinciding with these high load periods. If the load consists of both AC and DC elements, the load calculations and the subsequent system sizing procedures should be applied separately to the AC and the DC loads. The final array and battery sizes are then obtained by summing the separate array and battery sizes calculated for the AC and DC load elements.

In this methodology, it assumes that the system and load are situated reasonably close to each other. However, if the distance from a PV array to DC loads is more than a few metres, resistive wiring losses become significant. These losses will necessitate a compensating increase in the required system size. If the wiring losses are considered to be significant, DC wiring losses may be included by increasing the calculated load size served by the photovoltaic system by incorporating $I^2R$ power losses calculated for the DC run.

3.5.2.2. Determine local insolation

Photovoltaic arrays are generally tilted so as to maximize solar gains, but as solar radiation data is generally only available for horizontal surfaces, average monthly data for various tilted surfaces must be calculated. For this purpose, a FORTRAN computer program was written and compiled by the author, and a listing of the program is included in APPENDIX B. The program calculates the total daily solar radiation on an inclined surface for a specific day of each month of the year, using mean daily direct and diffuse radiation values for horizontal surfaces.

The results of this simplified approach have been compared with results obtained using hourly data in a previous work and the error was found to be less than 3 percent on annual values (Bennett,1978:6.1).

The following parameters for each month are required inputs to the programme:

(i) the mid-month Julian day number
(ii) the mean daily direct solar radiation on a horizontal surface
(iii) the mean daily diffuse solar radiation on a horizontal surface

After computing the sunrise hour angle, and dividing the morning into sunshine hour angles, the programme computes the ratio of direct solar radiation on a tilted surface versus that on a horizontal surface. A correction factor, R, is included to account for the difference in the thickness of the atmosphere at different positions of the sun during the day.

Diffuse solar radiation on a tilted surface is then calculated whereafter total daily solar radiation may be derived. These calculations are repeated for each month of the year. This procedure is repeated for various tilt angles until an optimum is found in terms of maximizing annual global radiation.

The calculating procedures for converting direct and diffuse components of global radiation from horizontal to tilted surfaces are described below.

#### 3.5.2.2.1. Determination of the direct radiation component on a tilted surface

Consider the two plates shown in FIGURE 3.20, the one being horizontal, while the other is tilted at an angle $\Theta$ to the horizontal.

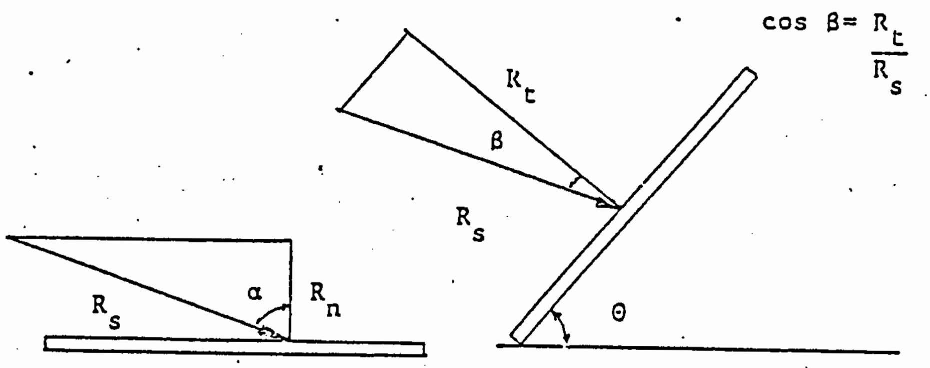


FIGURE 3.20: Horizontal and tilted surface radiation.

Source: Bennett (1978)

In both cases, $R_s$ represents the intensity of the sun's rays, while $R_n$ and $R_t$ represent the components normal to the two surfaces. The ratio of these components, Z, is given by EQUATION 3.8, as follows:

$$\begin{aligned} Z &= R_t/R_n \\ &= R_s \cos \beta / R_s \cos \alpha \\ &= \cos \beta / \cos \alpha \end{aligned} \qquad (3.8)$$

Hence, at any point in time, if the direct radiation on a horizontal surface is known, the direct radiation on a tilted surface may be determined.

However, the value of the angles ` and a depend on the latitude, the Julian day, and the time of the day. It has been shown that the ratio of the incident angles, ` and a, can be calculated using EQUATION 3.9, as follows[3] (Bennett,1978):

$$\frac{\cos\beta}{\cos\alpha} = \frac{\sin\theta_1\ \sin(\phi - \theta) + \cos\theta_1\ \cos(\phi - \theta)\ \cos\theta_2}{\sin\theta_1\ \sin\phi + \cos\theta_1\ \cos\phi\ \cos\theta_2} \qquad (3.9)$$

Where $\theta_1$ is the declination angle and is given by EQUATION 3.10, as follows:

$$\theta_1 = -23.45\ (\sin(360 \times (284 + \text{Julian day})/365) \qquad (3.10)$$

where $\phi$ = the latitude of the location (-ve for the S hemisphere)

$\theta$ = the angle of tilt of the collector, using the same sign as $\phi$

$\theta_2$ = the hour angle. 12 noon local time is equivalent to 0.0, while 9.00 am is equivalent to $\theta_2 = 3 \times 15 = 45$

Hence, for any time of the day, during any day of the year, it is possible to determine the instantaneious ratio of the radiation falling on a tilted plate to that falling on a horizontal plate.

If one has hourly data available, it is then possible to repeat this calculation at hourly intervals, by multiplying the ratio by the radiation data and summing the results to obtain the total direct radiation over the day. However, if these data are not available, an alternative approach can be adopted. Since the cosine of the incident angle is proportional to the normal radiation falling on the collector,

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[3] Adapted from Bennett (1978)

the summation of these cosines calculated at regular intervals will be proportional to the direct daily radiation falling on the plate; therefore, the total direct radiation over the day is obtained by multiplying the direct radiation on a horizontal plate by the cosine ratios corrected for atmospheric effects.

An empirical equation has been developed to simulate the reduced radiation obtained due to the effect of the thickness of the atmosphere (Bennett, 1978). The calculation is shown in EQUATION 3.11, as follows:

$$\text{Radiation loss, } R = (\ln(90 - \alpha)/4.5 \qquad (3.11)$$

Each time the cosine of an incident angle is calculated, it should be multiplied by the radiation-loss factor to account for atmospheric effects.

For calculation purposes, it is convenient to divide the time between sunrise and local noon into a set number of divisions, requiring a knowledge of the local sunrise hour angle. This is calculated by EQUATION 3.12, as follows:

$$\text{Sunrise hour angle, } S = \text{arc tan } (-\tan\theta_1 \ \tan\phi) \qquad (3.12)$$

It was assumed that the radiation captured from sunrise to local noon was similar to that obtained from noon until sunset. Hence, only the morning radiation values were calculated and doubled to get the values for the whole day.

The accuracy of these calculations may be improved by dividing the calculated sunrise hour angle into smaller intervals.

#### 3.5.2.2.2. Determination of the diffuse radiation component

The calculation to determine the diffuse radiation on a tilted solar array (Lui et al,1960), is given in EQUATION 3.13, as follows:

$$\text{Diffuse radiation} = 0.5(1 + \cos\theta) \times I_{dh} + 0.5(1 - \cos\theta)\sigma \times I_{gh} \quad (3.13)$$

Where $\theta$ = the angle of tilt of the collector

$I_{dh}$ = mean daily diffuse radiation obtained from weather data for a flat plate

$I_{gh}$ = mean daily global radiation obtained from weather data for a flat plate

$\sigma$ = the ground reflectivity.

= 0.70-0.87 for snow

= 0.31-0.33 for concrete

= 0.12-0.15 for tar, gravel and roofs

= 0.10-0.20 for asphalt-paved roads

While it is possible to perform the calculations for every day of the year, one normally only requires monthly totals of radiation, and therefore it is only necessary to calculate the declination for the mean day of the month, and then assume this angle to be constant for the month in question.

Finally, the total global radiation on the tilted surface is found by adding the diffuse radiation as calculated in EQUATION 3.13 to the direct radiation for a tilted surface as calculated previously.

These values are then used in the next step of the sizing methodology.

#### 3.5.2.3. Calculate "worst-month" insolation and load

In this sizing methodology, the, stand-alone photovoltaic system is designed to meet the load energy demand during the "worst" month of the year, ie., the month which has the smallest ratio of solar radiation on the array to the load energy demand. If the system is sized to meet the load during the "worst" month, it will automatically be able to meet the load energy requirement for all other months. It should be noted that this methodology provides a somewhat conservative size estimate of the PV system, particularly in situations where there is an appreciable difference between the "worst" month ratio and that for the other months of the year.

The worst-month insolation and load values (ie. the values for which the insolation-load ratio is the smallest) are most conveniently identified by tabulating daily average insolation data for each month of the year along with daily average load energy demand. This procedure is carried out at various tilt angles to determine the optimum PV array orientation required to best match the load energy demand, whether the load is constant year round, winter peaking, or summer peaking.

### 3.5.2.4. Determine array and battery storage sizing factors

The next step is to determine the sizing factors for the PV array and battery storage to be used in subsequent calculations of the actual array size and battery storage capacity. These sizing factors are used in the design methodology to ensure that there will always be sufficient energy available in the power system to meet the load energy demand. These factors have been derived from prior analyses of how the photovoltaic system loss of energy probability (LOEP) depends on array and battery size for a range of possible worst-month insolation levels. The LOEP provides an estimate of the number of days per month when there will be no solar energy available for charging the battery.

Computational procedures are available for determining LOEP values (Macomber et al, 1981). Firstly, the LOEP is calculated for one day. This involves three factors, viz, the probability that the system will fail in a single day, the probability that the load will be lost when the solar radiation is approximately zero on the following day, and thirdly, the probability of losing the load when the level of insolation is relatively high on the following day. The total LOEP is computed by determining the sum of the probabilities for several hundred individual days to determine a reasonable estimate.

In this sizing procedure, this probability value is the "worst-month LOEP", ie., the probability that the system will be unable to meet load requirements during the month having the smallest insolation-load ratio, and is based on a worst-month LOEP of 0.1, ie., 10 percent or approximately three days in the "worst" month of the year the photovoltaic system will not be able to meet the load energy requirement. This value corresponds to a monthly average LOEP of approximately 0.02-0.04, ie., for an average month during the year, the probability of system failure is between 0.6 and 1.2 days.

Borden suggests that this value is used because it will provide a service availibility roughly equivalent to that of conventional competitor power systems such as diesel generators. It should be noted that the LOEP is based on the characteristics of insolation only and does not take into account photovoltaic equipment reliability.

If a smaller LOEP was used, either the array and/or battery storage would have to be increased, or an emergency power back-up system would need to be used during PV system failure.

By determining the required size of array and battery storage per unit of load, dependent on the worst-month insolation, the proper array and battery sizes can then be calculated using the previously determined insolation and load values.

The sizing factors for the array and battery storage appear in FIGURE 3.21 in the form of a nomograph. The nomograph consists of solid curves which slope slightly from right to left, each corresponding to a level of solar radiation. These curves represent a relationship between the array sizing factor, $S_a$, and the battery sizing factor, $S_b$, which corresponds to the economically optimum combination of PV module size and battery storage capacity for a specific level of solar radiation and LOEP. At this stage of the sizing procedure, the "worst" month solar radiation is compared with the values of the solid curves of the nomograph, and the curve equalling the "worst" month value is used to determine $S_a$ and $S_b$ to be used in subsequent system sizing calculations. Interpolation may be necessary to obtain more accurate results.

The point of intersection of the lowest PV system capital cost curve (ie. the dashed curve) and the solid curve chosen as the initial solar radiation estimate, is used to determine $S_a$ and $S_b$. The array sizing factor, $S_a$, is found by drawing a horizontal line from the point of intersection to the Y-axis, while the battery sizing factor, $S_b$, is determined by drawing a vertical line to the X-axis. By using different array and storage sizing factors, the system's capital cost will vary; however, the point of intersection between the solid curve and the dashed curve gives the sizing factors which yield the lowest PV system capital cost for the required level of solar radiation. These curves were determined from the experiences gained in previous PV system costing procedures for remote, stand-alone applications.

It should be recognized, however, that the use of this dashed curved will not necessarily result in the lowest life-cycle cost estimate since it is based only on initial system capital costs. Other life-cycle costs such as operation, maintenance, and various financial parameters, have not been incorporated into the nomograph.

A photovoltaic system may have to be sized under the condition that the PV-powered system must be able to supply the load for a specified number of consecutive sunless days (ie. days of autonomy). The nomograph in FIGURE 3.21 may also be applied in these circumstances, but its use is considerably different.

(a) Determining sizing factors for a specified number of sunless days.

In this situation, the number of consecutive sunless days is used as the battery sizing factor, $S_b$. This value should be equal to, or larger than, the $S_b$ value determined from the "worst" month insolation to ensure an adequate PV power supply to the load and to recharge the battery for a given level of reliability (LOEP). From this point on the X-axis of the nomograph, a vertical line is drawn to intersect the solid curve representing the nearest approximation to the "worst" month solar radiation. From this point, a horizontal line is drawn to intersect the Y-axis at the appropriate $S_a$ value. This approach will generally not yield the lowest PV system capital cost for a given LOEP, but it is a more accurate method of ensuring a continuous power supply by the system.

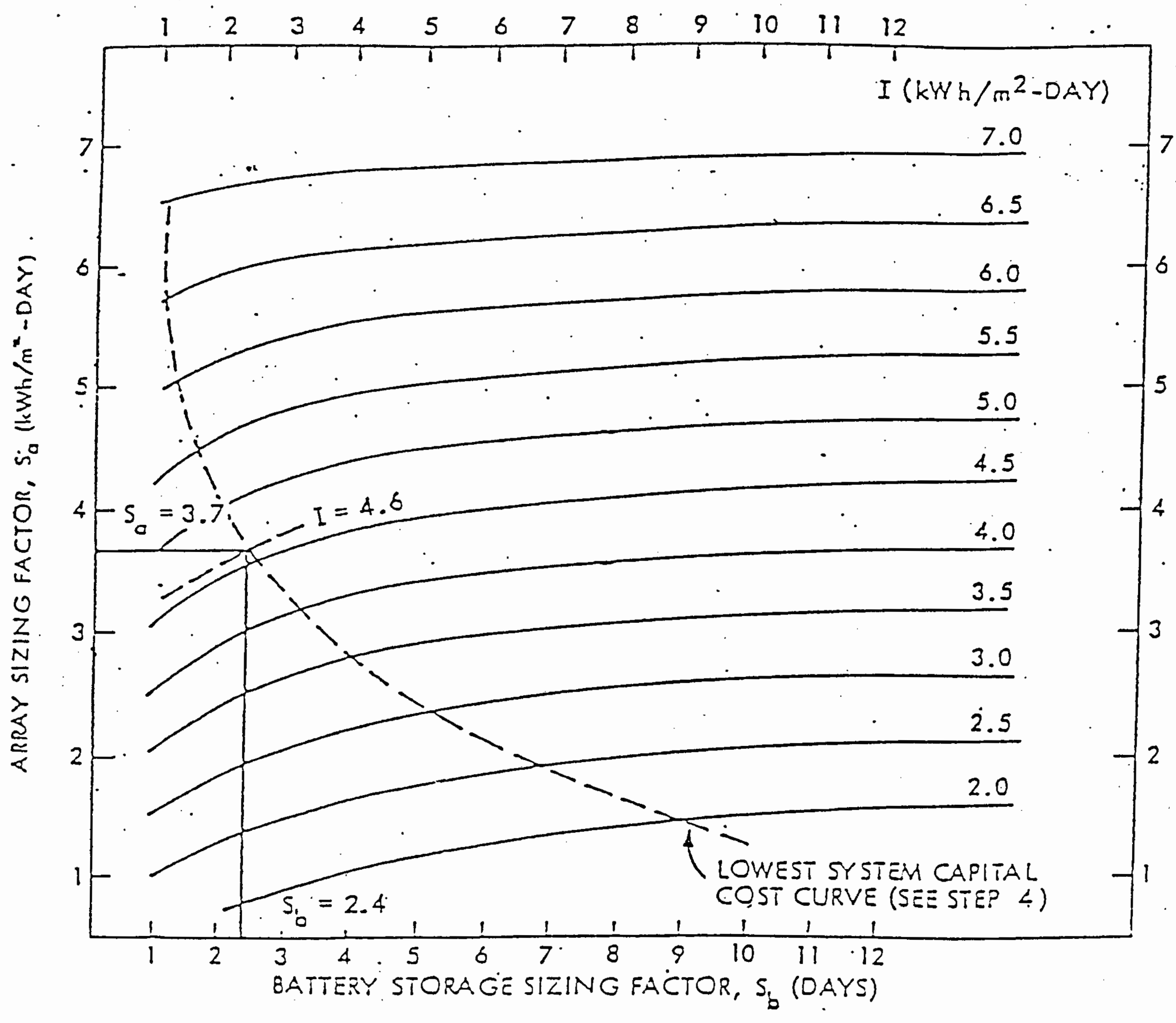



FIGURE 3.21: Determining the PV array sizing factors.

Source: Borden et al (1984)

(b) Estimate load fractions supplied by the array and storage.

In this case, the load energy demand is divided into two fractions, namely, $f_a$ and $f_b$, where $f_a$ is that fraction of the load energy demand supplied directly by the PV array, via an inverter or converter if one is used, and $f_b$ is the fraction of the load energy demand supplied from battery storage. By definition, $f_a + f_b = 1$.

Since there are greater power losses if the energy from the array passes through battery storage, than that passing directly from the array to the load, the relative sizes of $f_a$ and $f_b$ will influence the required PV array size, and therefore the cost. At the same time, precise determination of the load energy demand fractions is complicated due to changes in the PV power output over a 24-hour period, and this can be further complicated by complex or irregular load profiles. It may be simpler to assume that all of the array energy passes through battery storage before passing to the load, ie. letting $f_a=0$ and $f_b=1$. However, this is a conservative approach which results in an over-estimation of the PV system size, since in many applications part of the load is usually supplied directly from the array, thereby preventing battery storage losses.

For the Uitsig and Omdraaisvlei demonstration projects the loads are generally used at night and thus all the array energy passes through battery storage before passing to the load. Hence, $f_a = 0$ and $f_b = 1$.

### 3.5.2.5. Calculate array power and area

The following stage in the sizing procedure is to determine the PV array size by calculating both its peak power output in watts and its area in square metres. These results are used later to determine the cost of the system.

Using the "worst-month" load energy demand value, $L_{td}$ (determined in step 3), the array sizing factor, $S_a$ (found from FIGURE 3.21), and the load energy demand fractions, $f_a$ and $f_b$, as well as the efficiences of the storage batteries, the voltage regulator, and inverter or converter, the necessary array power is calculated as shown in EQUATION 3.14. A factor, F, is included in the array calculation to account for array degradation over the lifetime of the system. This factor initially oversizes the PV array to ensure that the system will meet load energy demand requirements until the end of its design life despite gradual photovoltiac array power output degradation.

$$P_a = \frac{L_{td} \times 1000}{S_a \times F \times e_{1/c}\ (f_b(e_{vr} \times e_b) + f_a)} \qquad (3.14)$$

Where

$P_a$ = array power in watts

$L_{td}$ = energy load value in kilowatt-hours per day

$S_a$ = array sizing factor in kilowatt-hours per sq.m per day

$e_{i/c}$ = inverter or converter efficiency at maximum steady state load, if used; otherwise, $e_{i/c}$=1.0

F = factor to account for array degradation over the system lifetime

$e_{vr}$ = efficiency of voltage regulator, if used; otherwise $e_{vr}$ = 1.0

$e_b$ = battery efficiency

$f_a$ = fraction of the load energy supplied directly by the array

$f_b$ = fraction of the load energy supplied from battery storage

1000 = 1000 W/sq.m; a term to convert $S_a$ into an equivalent number of hours per day that 1000 W/sq.m insolation would be received by the array

This equation is also applicable for systems not using battery storage, since as in the case with storage, the PV array power output on an average daily basis must match the average daily load energy requirements. The array area is based on the design array power output level determined in EQUATION 3.14 and is shown in EQUATION 3.15 below:

$$A_a = \frac{P_a}{e_m(1+P_{tc}(T_{op}-28)) \times 1000} \qquad (3.15)$$

Where

$A_a$ = array area in square metres
$P_a$ = array power in watts obtained from EQUATION 3.14
$e_m$ = module efficiency at standard test conditions (STC)
$P_{tc}$ = module temperature coefficient; typically=-0.005/deg.C
$T_{op}$ = actual module operating temperature in deg.C. For temperate climates, use the nominal operating cell temperature (NOCT). For hot climates, use NOCT + 10 deg.C.
1000 = 1000 $W/m^2$ at standard test conditions (STC).

### 3.5.2.6. Calculate battery storage size

The next step in the sizing procedure, is to determine the required size of the battery storage in kilowatt-hours. Battery storage size is based on $S_b$, either from FIGURE 3.21, or may have been specified previously as the number of sunless days, and a maximum permissible depth of discharge limit as specified for the battery. Operating within this limit prolongs battery life.

Calculation of the required battery energy storage capacity is also based on the "worst-month" load energy demand value, $L_{td}$, previously used in the PV array sizing equations, as well as the efficiencies of an inverter or converter (this must be the same value as was used in the PV array sizing calculation), and the procedure is shown in EQUATION 3.16.

$$E_b = \frac{L_{td} \times S_b}{d \times e_{i/c}} \qquad (3.16)$$

Where

$E_b$ = rated battery energy storage in kilowatt-hours
$L_{td}$ = worst-month average load value in kWh/day
$S_b$ = battery sizing factor in days
d = maximum allowable depth of discharge, fraction

$e_{i/c}$ = efficiency of the inverter or converter. If neither is used, $e_{i/c}=1$

3.5.2.7. Determine voltage regulator size

The battery voltage regulator is sized to handle the maximum PV array power output which is available for charging the batteries. For conservatism, the regulator, or battery protector as it is known for small systems (less than 3kW), is designed to handle the array power output at noon on a cold, clear day with the load disconnected (ie. the voltage regulator is sized to match the PV array power output at standard test conditions (STC), ie. 1 $kW/m^2$, and 25 deg.C cell temperature).

3.5.2.8. Determine inverter or converter size

The inverter or converter is usually sized according to the maximum steady-state load power demand in watts, ac or dc, respectively. However, if the photovoltaic system is to be used to power an inductive load, the inverter must be able to supply the full surge current required by the load. For example, in the case of an induction motor, the starting current can be as large as four or five times the rated motor capacity.

## 3.6. SYSTEM COST ANALYSIS

### 3.6.1. Introduction

Cost effectiveness is the primary criterion for the evaluation of photovoltaic system applications. This section discusses the life-cycle costing methodology which was used to compare the cost effectiveness of PV-powered systems with alternative power systems.

### 3.6.2. Cost analysis methodology

The life-cycle cost of the photovoltaic system is compared to the life-cycle cost of alternative power systems, such as petrol or diesel generators, utility grid connections, or other renewable energy technologies. Life cycle costs include the initial capital cost plus all future expenditures on equipment replacements, and operating and maintenance, discounted to present values. Thus systems like PVs and petrol generators, which have widely different initial and running costs, are compared on the same present value basis. It is assumed that, for the purpose of this comparison, all the power systems being compared are capable of providing sufficient power to satisfy a specific load energy demand. The sizing methodology which was used to design the photovoltaic system previously, ensures that there is an adequate power supply to satisfy the specified load.

### 3.6.3. Photovoltaic system life-cycle cost

The photovoltaic power system life-cycle cost is calculated from the initial cost of the system installed at the project site, and the net present value of all the recurrent costs associated with system operation. Photovoltaic systems are typically capital intensive, ie. they require a large initial capital expenditure, but have low operating costs. The sum of current and recurrent expenditures represents the equivalent amount of money required at the time of system installation to completely cover all costs associated with the photovoltaic system, including a return on the investment, over its operating lifetime. Life-cycle cost of the alternative power source similarly combines the associated initial capital cost and operating cost for comparison with the photovoltaic power system.

#### 3.6.3.1. Initial cost calculation

The initial cost of a photovoltaic system is based on the cost of the PV array; power-related balance-of-system cost; area-related balance-of-system cost; system installation and testing cost, and any indirect costs as a percentage of the equipment capital cost. EQUATION 3.17a describes the analytical relationships and EQUATION 3.17b is the detailed calculation procedure for estimating the initial installed photovoltaic system cost (IC).

$$\text{Initial cost} = (1 + \text{indirect }(\%) + \text{installation }(\%)) \times (\text{delivered equipment cost }(R)) \qquad (3.17a)$$

$$IC = (1+IND+INST) \times ((MOD \times P_a) + (ABOS \times A_a) + (CONV \times W_{dc}) + (INV \times W_{ac}) + (REG \times W) + (BAT \times BWh)) \qquad (3.17b)$$

Where

- IND = fractional indirect costs on equipment including engineering, management and contingency fees
- INST = fractional cost on equipment for installation, site preparation, testing, and checkout cost of the system
- MOD = module cost in Rand per peak watt of array
- $P_a$ = peak watts of solar array (DC)
- ABOS = area-related balance-of-system cost per square metre of array including the cost of array structure, land, wiring, connectors, etc.
- $A_a$ = array area in square metres
- CONV = converter cost per peak watt (DC)
- $W_{dc}$ = rated size of converter in peak watts (DC)
- INV = inverter cost per peak watt (AC)
- $W_{ac}$ = rated size of the inverter in peak watts (AC). If more than one inverter is used, sum th- peak watts of each.

REG = voltage regulator cost per peak watt (DC) of maximum regulator input power.

$W^*$ = maximum voltage regulator input power

BAT = battery cost per kilowatt-hour of energy storage

BWh = battery storage size in kilowatt-hours

It is assumed that the equipment cost estimates include delivery to the project site. All currency amounts are expressed in the same base year, namely, 1986, for consistency.

3.6.3.2. Recurrent cost calculation

In addition to the initial installed system cost described above, recurrent costs associated with photovoltaic system operations are to be included in the estimation of the life-cycle costs. These costs include estimates of operation, maintenance, and replacement costs, and are based on hardware performance characteristics and system operating strategy. Recurrent costs are primarily for battery replacement, if battery storage is included in the system design, and array, inverter or converter, and battery operation and maintenance. The photovoltaic system operating strategy, for example, the system may or may not be required to operate autonomously for a prolonged period of time, will affect both the initial and the recurrent costs.

3.6.3.2.1. Battery replacement costs

Battery lifetimes are typically quoted at between five and ten years, depending on the type of battery, number of discharge cycles, design depth of discharge, and operating temperature. In contrast, the anticipated life of a photovoltaic array is estimated to be about 25 years. Battery replacements at regular intervals are, therefore, required throughout the operating lifetime of the photovoltaic array. The cost for each replacement of storage batteries (BR) is shown in EQUATION 3.18.

$$BR = (BAT \times BWh) \times (1 - SV) + LREP \quad (3.18)$$

Where

BAT X BWh = delivered cost of batteries from EQUATION 11b

SV = fractional salvage value of batteries at time of replacement

LREP = labour cost of battery replacement in base-year Rands

Salvage value of the batteries is typically based on prices in the scrap metal market at the time of replacement. The present value of the sum of all battery replacements (RPV) over the photovoltaic system lifetime, escalated and discounted to account for the timing of the expenditure, is estimated as follows:

$$RPV = \sum_{j=1}^{n_{rep}} BR \times \left(\frac{1 + e_{scb}}{1 + dr}\right)^{jxk} \qquad (3.19)$$

Where

j = counter for number of battery replacements

k = battery lifetime in years

BR = single time battery replacement cost from EQUATION 3.12 in base-year rands

$e_{scb}$ = real (above inflation) annual escalation rate for storage batteries (fraction)

dr = discount rate (cost of money to system owner)

Expenditures for replacement of capital equipment other than batteries, with lifetimes shorter than the assumed photovoltaic system lifetime can also be determined using EQUATION 3.19, appropriately modified to reflect their cost and timing.

3.6.3.2.2. Operation and maintenance costs

Regular operation and maintenance costs can be estimated on an annual costs basis. These cost include expenditures for activities such as array, battery, and inverter maintenance; component replacements other than batteries; and grounds, structural and electrical upkeep. Annual operation and maintenance costs (OM) can be estimated on the basis of the number of required visits to the site per year times the cost per year in base-year rands.

To simplify matters, it is often assumed that annual expenses are a fixed percentage of the initial cost of the equipment. The present value of the cost of operation and maintenance procedures is the derived annual amount summed over the system lifetime, including any real escalation and discounting of expenditures over time. Annual expenditures are, therefore, growing in rand amounts at the constant rate of real escalation, if any. The present value of operation and maintenace costs (OMPV) is presented in EQUATION 3.2Ø as follows:

$$OMPV = OM \times \frac{(1 + e_{scom})}{(dr - e_{scom})} \times \left\{1 - \frac{(1 + e_{scom})^N}{(1 + dr)}\right\} \quad \text{if } dr \neq e_{scom} \qquad (3.20)$$

or

$$OMPV = OM \times N, \text{ if } dr = esc_{om}$$

Where

$OM$ = annual operation and maintenance costs in base-year rands

$esc_{om}$ = real (above inflation) annual escalation rate for operation and maintenance activites (fraction), typically Ø%

$dr$ = real discount rate (fraction); typically 1Ø%

$N$ = system lifetime (years)

### 3.6.3.3. Photovoltaic life-cycle cost

The photovoltaic life-cycle cost (LCC) can now be determined from its constituent parts described previously. Life-cycle cost is calculated in EQUATION 3.21 as the sum of the initial system cost, EQUATION 3.17, and the present value of recurrent costs, EQUATION 3.19 and operating and maintenance costs, EQUATION 3.2Ø.

$$LCC = IC + PRV + OMP^{*}$$ (3.21)

All costs are in base-year rands.

### 3.6.4. Alternative power system life-cycle cost

Small stand-alone photovoltaic systems are potentially competitive with a number of alternatives, such as petrol or diesel generators, or extension to a distant utility grid. The life-cycle cost for each alternative is evaluated in the same way as described above.

### 3.6.5. Determination of the levelized annual cost

This techniques takes the initial estimate of the project's life-cycle cost and converts it to an average annual charge, or annuity, and is given by EQUATION 3.22.

$$A = C / a_{ni}$$ (3.22)

Where

$A$ = average annual cost

$C$ = present value of the costs

$a_{ni} = (1-(1+i)^{-n})/i$

$n$ = number of interest periods taken over the expected life

$i$ = interest rate per period

This technique is recommended for comparing two or more energy alternatives offering the same service, but with different life times. Power costs may be calculated by dividing the average annual cost by the annual power produced to arrive at a c/kWh cost.

## 3.7. CONCLUSION

In summary, this chapter has presented a theoretical overview of the factors which are important in the design of remote stand-alone PV systems.

Some understanding has been obtained of some of the key parameters which affect PV power output. Balance of systems design is just as important and different types of batteries and regulators were discussed as an aid in the selection and specification of appropriate equipment. Any analysis of system data also requires an understanding of the parameters which determine the performance of batteries and regulators.

Finally the chapter spelt out in some detail the design methodology and financial appraisal techniques used in the project.

# CHAPTER 4

# EXPERIMENTAL PROCEDURE

The focus of this project is the assessment of photovoltaic applications for low-income households which do not have access to ESCOM power. Two demonstration projects were set up. Key parameters were fully monitored and data was analysed to evaluate system performance.

## 4.1. SELECTION OF SITES

Initially it was decided to install two small photovoltaic-powered domestic systems, one in an informal settlement in the Western Cape, and the second in an area with more favourable climatic conditions.

Problems were encountered with the authorities with our proposal to install PV-powered systems in informal settlements. They argued that these systems would give the recipients a sense of permanence in their dwellings. After prolonged negotiations, the Divisional Council of the Cape (Divco), agreed that a system could be installed at Uitsig in the Western Cape, which lies within a winter rainfall area, while the second site was a farm labourer's house at Omdraaisvlei in the Northern Cape.

Uitsig is a so-called "coloured" sub-economic township near Elsies River on the Cape Flats. It is situated approximately 18 km east of Cape Town (34 deg.S and 18 deg.E). The area, administered by the Divisional Council of Cape Town, was started as a transit settlement for low-income families moving from informal settlements to improved township accomodation. In some cases, however, residents have been living here for over ten years.

Omdraaisvlei is a farm and is situated in the Upper Karoo in the Prieska farming district, 73 km from Britstown along the Britstown-Prieska national road (30 deg.S and 23 deg.E). The altitude is approximately 1100 metres above sea level.

The location of these demonstration project sites are shown in FIGURE 4.1.

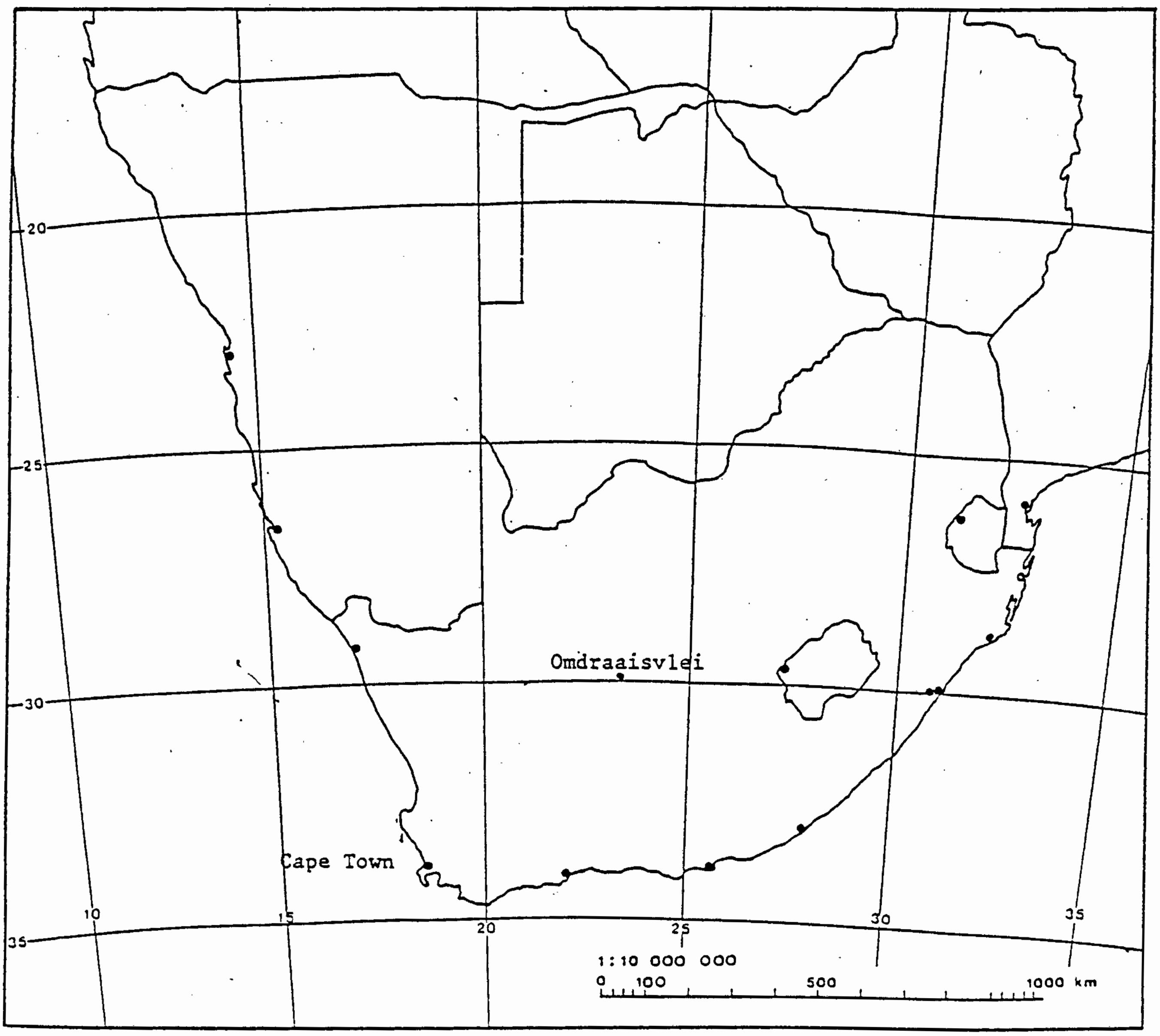



FIGURE 4.1: Location of the PV project sites

## 4.2. TECHNICAL DESIGN

This section describes the two houses which were used as demonstration project sites, the estimated load energy required by each household, the climatic characteristics of each site and the specifications of the proposed PV-powered systems. The sizing methodology used for the design of these two demonstration systems, was that described in section 3.5.

### 4.2.1. Uitsig

#### 4.2.1.1. House specifications

None of the Uitsig houses are electrified and Divco has stated that there is no possibility that they will be in the near future.

In the section of Uitsig where this demonstration project was installed, only the most basic of housing shelter is provided. The houses, which have a total floor area of 36 sq.m, are four-roomed, single-storey dwellings with an outside toilet and tap. The four interleading rooms (two bedrooms, a kitchen and a living room) are equally sized, measuring approximately 3.0 m X 3.0 m. (The Department of Community Development's standard low-cost house has a total floor area of 57 sq.m.)

The house which was selected for this demonstration project is orientated north-south and the roof is A-framed, constructed of corrugated asbestos sheets at a pitch of 17 degrees. No ceiling is provided.

#### 4.2.1.2. The projected load requirement

Initially the family, consisting of seven adults and two children, used paraffin lamps and candles for lighting at night, and a 12 V automotive battery to power a radio-music system. A gas stove is used for cooking and boiling water.

The battery had to be charged regularly at the local garage service station and power was not always available.

A small photovoltaic system was designed to provide the minimal electrical power for lights (11 W fluorescent) in each room, as well as for a portable black-and-white television set (15 W) or a music centre in the living room. Each fluorescent light provides an equivalent illumination to a 60 W incandescent lamp.

Based on previous experiences, it was estimated that each light would be used on average 2 hours per day in summer, 4 hours per day in winter, and the television for 4 hours per day, giving an average daily power requirement of 148 Wh and 236 Wh for summer and winter respectively.

#### 4.2.1.3. Climatic data

Uitsig is situated in the south-western Cape and has a Mediterranean climate with hot, dry summers and cool, rainy winters. The annual rainfall is between 500 and 750 mm with most of it falling between May and August. The average number of days per year with precipitation is estimated at 97.4 days.

The average ambient summer temperature is approximately 23 deg.C, while the average winter temperature is approximately 14 deg.C. The average maximum temperatures for January and June, are 26.1 and 18.0 deg.C respectively.

Horizontal global and diffuse solar radiation data was obtained for Cape Town, based on measurements at DF Malan Airport (Tegen, 1987).

#### 4.2.1.4. Sizing calculations

The first step in the sizing calculations, was to determine the average daily solar radiation on tilted surfaces for each month of the year. This was done using the methodology outlined in chapter three.

The design of the system is based on the "worst" month of the year, which is determined for the month with the worst ratio of solar radiation to load power requirement.

This ratio represents the smallest amount of available sunshine for the greatest load power requirement of the system. Solar radiation data for different tilt angles is analyzed to determine whether this "worst month" ratio can be improved without reducing too substantially the total solar radiation available over the full year.

The optimum tilt angle, that is, the tilt angle corresponding to the smallest system size, and thus the lowest life-cycle cost of the system, was found to be 54 degrees. TABLE 4.1 indicates the variation in solar radiation at different tilt angles, with June being the worst month.

TABLE 4.1: The total daily solar radiation on a surface tilted at DF Malan Airport, Cape Town.

Existing site : optimum angle for max. annual radiation

Site : CAPE TOWN

Ground reflectivity : .13

GLOBAL RADIATION FOR TILTED SURFACE : I(gt)

| Angle : | 40.00 | 45.00 | 50.00 | 55.00 | 60.00 |
|---|---|---|---|---|---|
| JAN | 23.23 | 21.95 | 20.53 | 19.00 | 17.36 |
| FEB | 23.67 | 22.77 | 21.73 | 20.56 | 19.27 |
| MAR | 22.90 | 22.48 | 21.93 | 21.23 | 20.41 |
| APR | 19.23 | 19.24 | 19.12 | 18.88 | 18.53 |
| MAY | 15.18 | 15.37 | 15.46 | 15.45 | 15.35 |
| JUN | 13.51 | 13.77 | 13.95 | 14.03 | 14.03 |
| JUL | 14.10 | 14.33 | 14.47 | 14.52 | 14.47 |
| AUG | 16.21 | 16.29 | 16.27 | 16.15 | 15.93 |
| SEP | 19.22 | 18.99 | 18.65 | 18.20 | 17.64 |
| OCT | 21.48 | 20.83 | 20.06 | 19.18 | 18.19 |
| NOV | 23.38 | 22.24 | 20.97 | 19.59 | 18.10 |
| DEC | 22.81 | 21.47 | 20.00 | 18.42 | 16.74 |
| TOTAL : | 234.92 | 229.72 | 223.14 | 215.21 | 206.01 |

Using these solar radiation data for June, and assuming a battery efficiency of 85 percent, a maximum allowable depth of discharge of 50 percent, and a current regulator efficiency of 95 percent, the PV module power output was calculated as 94 Wp and the battery energy storage as 114 Ah.

4.2.1.5. The system specifications

Based on these calculations the following system components were selected.

4.2.1.5.1. The photovoltaic array

| | | |
|---|---|---|
| PV model | : | ARCO M75 |
| Array configuration | : | 2 panels in parallel |
| Cell material | : | single crystal silicon |
| Cell size | : | 102.9 sq.mm |
| Number of cells | : | 33 cells per panel in series |
| Module area | : | 0.4023 sq.m |

The following electro-optical characteristics were specified by the supplier at 1000 W/sq.m, 25 deg.C, and spectrum of 1.5 air mass:

| | | |
|---|---|---|
| Operating current at load | : | 3.00 Amps at 47 deg.C |
| | : | 2.94 Amps typically |
| Voltage at load | : | 16.0 VDC typically |
| Open-circuit voltage | : | 22 VDC at 0.0 deg.C |
| | : | 19.9 VDC typically |
| Short-circuit amperage | : | 3.27 Amps typically |
| Factory-installed bypass diodes | : | yes |
| Power output ( ypically +/- 10%) | : | 47 Wp |
| Module efficiency | : | 11.7 percent |

The specification IV curve and voltage/temperature curves are shown in FIGURE 4.2.

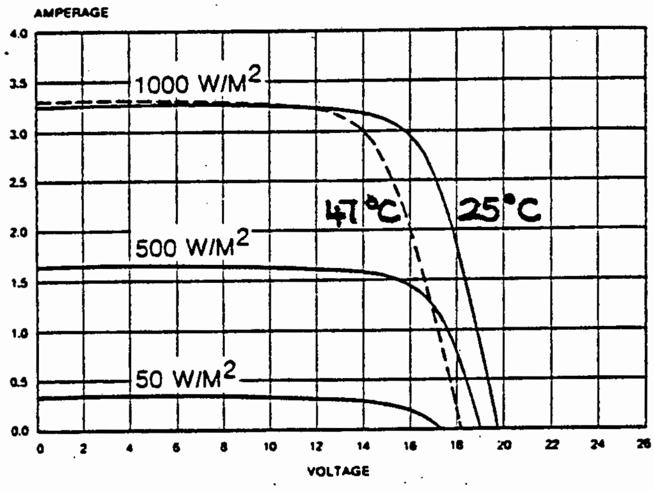



FIGURE 4.2: Supplier's IV and voltage/temperature curves for the PV module

4.2.1.5.2. Voltage regulator

A SOLAR SCIENCES voltage regulator was installed in this project.

The specifications for this unit are as follows:

| | | |
|---|---|---|
| Nominal system voltage | : | 12 VDC |
| Maximum load current | : | 10 Amps |

The regulator provides a number of functions:

1. It is a charge controller with boost/float modes.
2. It is a load management device and operates as an undervoltage protection unit. When the battery voltage level drops below 11.5 +/- 0.2 volts, the load is disconnected from the system by a heavy duty "load shedding" relay, and the "load shed" LED comes on. The relay will stay in this position and the "load shed" LED will stay on until the battery reaches the voltage trip point, ie., 12.1 +/- 0.2 volts. Then the load is reconnected to the battery, the "load shed" LED is switched off, and the unit returns to the "boost"-charge mode of operation.

3. It provides information about the system's daily charge cycle.

Duing charging operation the "boost" LED comes on. This light will stay on as the battery is being charged until the battery reaches the maximum voltage cut-off which was set at approximately 14.5 +/- Ø.2 volts.

Some electrolyte bubbling was observed at approximately 14.3 volts, but this was for a short time period. Some bubbling is helpful in providing a stirring action, thus preventing electrolyte stratification.

At the maximum voltage cut-off point, the boost-charge mode of operation is interrupted. The voltage falls slightly to approximately 13.8 +/- Ø.2 volts, whilst the photovoltaic array is forced to operate at a voltage level of approximately 15.6 +/- Ø.2 volts. At this voltage level, the current is much less, varying from Ø.3Ø to 1.ØØ amps. This is called the "float" mode of operation, and the battery voltage is maintained at a steady 13.8 volts. The "boost" LED is switched off and the "float" LED comes on.

4.2.1.5.3. Battery

Various types of battery were considered, including deep discharge tubular cell and sealed, maintenance-free types. The most cost effective system for this application was found to be an SLI type battery, protected against deep discharge and excessive overcharge.

Tabulated below are the types of batteries considered and their respective prices.

| MODEL | STORAGE CAPACITY | PRICE |
|---|---|---|
| DELCO 115Ø Maintenance-free | 1Ø5 Ah at 2Ø h | R258 |
| RAYLITE Tubular Cell 3RMT1Ø8 | 1Ø8 Ah at 1Ø h | R72Ø |
| RAYLITE Leisure Pak | 9Ø Ah at 2Ø h | R1ØØ |

A 9Ø Ah Raylite Leisure Pack battery was chosen and installed with this project. The following specifications were given with this battery:

| | | |
|---|---|---|
| Type | : | lead-acid |
| Amp-hour capacity | : | 90 Ah |
| Nominal system voltage | : | 12 V DC |

The plates of this battery are thicker than normal to allow for a greater depth of discharge. No further information was available from the manufacturer.

4.2.1.5.4. Lights

Various types of 12 V DC lights were considered, and these are tabulated below with their prices.

| LENGTH | WATTAGE | COST (Rand) | BULB REPLACEMENT COST (Rand) | SUPPLIER |
|---|---|---|---|---|
| 4 ft | 40 | 36.90 | 5.90 | Lascon |
| 3 ft | 30 | 36.90 | 5.90 | Lascon |
| 2 ft | 20 | 36.90 | 5.90 | SCS |
| 18 in | 15 | 40.70 | 9.90 | Eagle |
| 12 in | 11 | 32.60 | 9.90 | Eagle/Comlite |

This house was fitted with four 12 V DC, 11-watt Comlite lights (standard caravan electric lights).

4.2.1.5.5. The television set

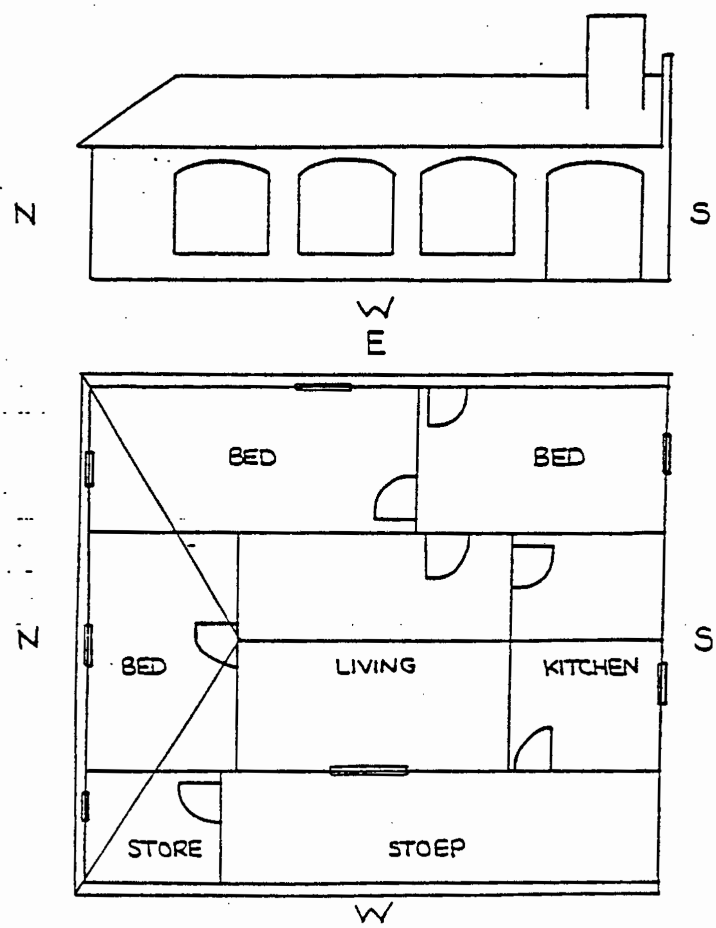
The television set is a portable, PHILIPS 30 cm black and white set. It may be operated either off mains or from a 12 V battery. The set uses about 1.3 amps at 12 volts DC.

4.2.2. Omdraaisvlei

4.2.2.1. House specification

The plan of the farm labourer's house is shown in FIGURE 4.3. The house consists of three bedrooms, a living room, a kitchen, a store-room, and an open veranda. The roof is constructed of corrugated iron sheets with the north-facing surface at an angle of 32 degrees.

The family, comprising two adults and four children, initially used candles at night, whilst running a portable television set off a 12 V motor-car battery. The battery had to be charged regularly by putting it into the farm bakkie. This was an undesirable arrangement because it resulted in the battery being discharged below its final voltage, hence reducing its operating life. It also meant that power was not always available.




Angle of hip = +/- 32 deg.
Latitude = +/- 30 deg.S

FIGURE 4.3: The staff house at Omdraaisvlei farm.

#### 4.2.2.2. The projected load requirement

A small photovoltaic system was designed to power lights in each of the rooms, as well as the portable television set (15 W)in the sitting room. A slightly higher standard of lighting was designed. Four 20-Watt lights and two 11-Watt lights were used. Two of the 20-Watt lights were installed in the sitting room, one in the main bedroom, and one in the kitchen, while the 11-Watt lights were installed as bed side lights in the remaining two bedrooms. An electrical wall-socket was installed in the sitting room for the portable black-and-white television set.

Based on energy usage patterns before the PV-powered system was installed, it was estimated that each light would be in use on average 3 hours per day and the television for 4 hours per day, giving a total daily power consumption of approximately 366 Wh.

#### 4.2.2.3. Climatic data

Omdraaisvlei experiences mild, dry winters and hot summers with very little rain. The annual summer rainfall is between 62 and 125 mm, with most of it falling between November and April. The reliability of this annual rainfall is estimated at between 65 and 70 percent. The average number of days with precipitation per year (number of days with precipitation greater than 0.1 mm) has been estimated to be 42.6 for Prieska and 30 for Upington. The average cloud cover statistics are as follows:

Fog: 5 mornings/year
Completely overcast: 08h00 - 1.9 days/year
14h00 - 2.3 days/year
20h00 - 1.7 days/year

The average summer temperature is approximately 28 deg.C, while the average winter temperature is about 10 deg.C. The average maximum temperatures for January and June are 34.9 and 19.3 deg.C respectively.

Surface solar radiation data was obtained for the two closest meteorological stations, namely, Bloemfontein and Upington, and this data is tabulated in TABLE 4.2.

#### 4.2.2.4. Sizing calculations

Direct and diffuse solar radiation data for a horizontal surface in Bloemfontein were used as a first approximation to determine the average daily solar radiation for each month of the year, for various tilt angles of the photovoltaic array.

The reason for using Bloemfontein radiation data as opposed to that for Upington, which is the closer meteorological station, was to base the design on a conservative estimatation and thereby guarantee power availability in the household.

TABLE 4.2: Mean daily total (1), diffuse (2), and standard deviation (S) of solar radiation on a horizontal surface in MJ/sq.m for stations in Southern Africa

| | | Alexander Bay | S | Bloemfontein | S | Cape Town (Wingfield and D.F. Malan Airports) | S | Durban (Louis Botha Airport) | S | Keetmanshoop | S | Kimberley | S | Maun | S | Pietersburg | S | Port Elizabeth | S | Pretoria | S | Upington | S | Windhoek | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan. | 1 | 31,397 | 1,101 | 26,884 | 1,737 | 30,375 | 0,666 | 21,237 | 2,600 | 30,195 | 0,904 | 26,721 | 1,381 | 23,104 | 2,901 | 26,599 | 2,235 | 24,778 | – | 24,037 | 2,675 | 27,629 | 2,189 | 26,101 | 2,022 |
| | 2 | 6,899 | 0.042 | 7,305 | 0,804 | 6,225 | 0,435 | 8,619 | 0,603 | 5,438 | 0,615 | | | 8,904 | 0,787 | | | 9,356 | – | 8,561 | 1,335 | | | 8,008 | 0,720 |
| Feb. | 1 | 28,140 | 1,540 | 24,489 | 2,796 | 25,955 | 1,264 | 19,826 | 1,344 | 27,428 | 1,344 | 24,946 | 1,980 | 21,216 | 1,997 | 24,008 | 1,005 | 25,398 | – | 21,773 | 1,700 | 25,184 | 2,227 | 23,828 | 1,775 |
| | 2 | 6,242 | – | 6,807 | 0,816 | 6,095 | 0,833 | 7,962 | 0,628 | 5,626 | 0,130 | | | 8,984 | – | | | 6,786 | – | 7,895 | 0,699 | | | 7,498 | 0,812 |
| Mar. | 1 | 23,589 | 1,047 | 20,676 | 2,194 | 21,856 | 0,720 | 17,946 | 0,896 | 23,380 | 1,072 | 20,789 | 1,775 | 20,056 | 2,633 | 22,091 | 0,829 | 19,278 | 0,310 | 20,186 | 1,118 | 21,233 | 2,152 | 21,500 | 1,846 |
| | 2 | 4,563 | – | 5,903 | 0,477 | 5,103 | 0,364 | 6,196 | 0,477 | 4,517 | 0,448 | | | 5,990 | 0,155 | | | 5,706 | 0,151 | 6,807 | 0,783 | | | 6,459 | 0,791 |
| April | 1 | 19,516 | 1,356 | 18,164 | 0,879 | 15,271 | 0,203 | 15,029 | 0,833 | 21,061 | 0,548 | 17,741 | 0,942 | 18,704 | 2,528 | 19,541 | 1,143 | 14,041 | 0,339 | 17,469 | 1,377 | 18,168 | 1,490 | 20,504 | 0,825 |
| | 2 | 4,546 | 0,063 | 4,057 | 0,427 | 4,714 | 0,435 | 4,626 | 0,306 | 3,102 | 0,373 | | | 4,165 | 0,682 | | | 4,496 | 0,264 | 4,768 | 0,682 | | | 4,224 | 0,469 |
| May | 1 | 15,380 | 1,917 | 14,384 | 0,712 | 10,905 | 1,942 | 12,132 | 0,540 | 17,164 | 0,465 | 14,208 | 0,548 | 17,306 | 2,474 | 17,264 | 1,067 | 11,294 | 0,414 | 15,033 | 0,829 | 15,196 | 1,758 | 18,620 | 0,758 |
| | 2 | 4,182 | 0,360 | 3,454 | 0,385 | 4,015 | 0,435 | 3,487 | 0,460 | 2,847 | 0,193 | | | 2,608 | 0,180 | | | 3,098 | 0,205 | 3,315 | 0,331 | | | 2,951 | 0,448 |
| June | 1 | 13,287 | 1,239 | 13,040 | 1,063 | 9,373 | 0,557 | 11,303 | 0,506 | 15,506 | 0,573 | 12,781 | 0,716 | 16,004 | 2,361 | 15,707 | 1,093 | 9,779 | 0,661 | 14,124 | 0,561 | 14,212 | 1,540 | 16,996 | 0,833 |
| | 2 | 2,914 | 0,113 | 2,838 | 0,490 | 3,299 | 0,297 | 2,884 | 0,511 | 2,323 | 0,297 | | | 2,759 | 0,218 | | | 2,780 | 0,264 | 2,868 | 0,331 | | | 2,562 | 0,301 |
| July | 1 | 13,283 | 1,926 | 14,020 | 0,720 | 9,946 | 0,917 | 11,755 | 0,816 | 16,389 | 0,356 | 13,831 | 1,310 | 16,975 | 0,523 | 16,577 | 2,918 | 10,671 | 0,243 | 14,727 | 0,917 | 14,170 | 1,423 | 18,302 | 0,523 |
| | 2 | 3,173 | 0,205 | 2,968 | 0,393 | 3,646 | 0,490 | 3,131 | 0,402 | 2,478 | 0,100 | | | 3,391 | 0,561 | | | 2,935 | 0,188 | 3,119 | 0,410 | | | 2,595 | 0,234 |
| August | 1 | 16,695 | 2,118 | 17,750 | 1,172 | 12,772 | 0,833 | 13,714 | 0,896 | 19,512 | 0,410 | 18,089 | 1,390 | 20,019 | 2,055 | 18,859 | 3,219 | 13,517 | 0,699 | 18,198 | 0,502 | 17,331 | 1,298 | 21,052 | 0,594 |
| | 2 | 4,266 | 0,025 | 3,449 | 0,410 | 4,576 | 0,490 | 4,228 | 0,481 | 3,001 | 0,084 | | | 3,487 | 0,511 | | | 3,906 | 0,427 | 3,634 | 0,293 | | | 3,315 | 0,381 |
| Sept. | 1 | 21,814 | 1,394 | 21,735 | 1,273 | 18,047 | 0,896 | 16,142 | 1,461 | 23,761 | 0,791 | 22,191 | 2,361 | 22,614 | 1,402 | 21,258 | 3,575 | 17,277 | 0,917 | 20,400 | 1,679 | 20,814 | 0,728 | 23,933 | 1,197 |
| | 2 | 5,270 | 0,389 | 4,676 | 0,527 | 6,057 | 0,356 | 5,957 | 0,531 | 4,149 | 0,163 | | | 5,187 | 0,615 | | | 6,221 | 0,682 | 4,848 | 0,444 | | | 4,902 | 0,691 |
| Oct. | 1 | 27,022 | 2,499 | 24,418 | 1,582 | 22,999 | 0,980 | 17,147 | 1,402 | 27,391 | 1,197 | 26,294 | 2,491 | 23,012 | 2,357 | 24,456 | 2,068 | 20,948 | 1,000 | 22,246 | 1,256 | 24,247 | 1,415 | 25,959 | 1,474 |
| | 2 | 6,384 | 0,460 | 6,212 | 0,707 | 7,029 | 0,678 | 7,405 | 0,682 | 5,078 | 0,599 | | | 7,225 | 0,603 | | | 7,338 | 0,427 | 6,773 | 0,335 | | | 6,388 | 0,712 |
| Nov. | 1 | 30,338 | 1,808 | 27,353 | 2,160 | 27,391 | 1,612 | 19,236 | 1,955 | 30,693 | 0,724 | 28,965 | 2,855 | 23,652 | 2,491 | 26,587 | 2,076 | 25,854 | 1,846 | 23,841 | 1,469 | 27,210 | 1,474 | 27,575 | 1,679 |
| | 2 | 6,367 | 0,686 | 6,857 | 0,791 | 7,460 | 0,975 | 8,753 | 0,762 | 4,735 | 0,402 | | | 7,598 | 1,013 | | | 8,829 | 0,607 | 7,523 | 0,800 | | | 6,455 | 0,653 |
| Dec. | 1 | 30,932 | 3,600 | 27,801 | 1,432 | 29,969 | 1,076 | 20,885 | 0,774 | 31,229 | 0,933 | 29,157 | 3,290 | 22,639 | 1,758 | 26,101 | 3,604 | 25,770 | 0,875 | 23,267 | 1,566 | 27,638 | 1,105 | 28,056 | 2,323 |
| | 2 | 6,970 | 0,326 | 7,431 | 0,628 | 7,104 | 0,770 | 9,624 | 0,858 | 5,128 | 0,636 | | | 9,021 | 1,281 | | | 9,213 | 0,737 | 8,498 | 0,703 | | | 6,937 | 0,858 |
| Total for year | 1 | 8 243,837 | | 7 618,371 | | 7 138,762 | | 5 965,706 | | 8 621,699 | | 7 770,566 | | 7 459,712 | | 7 840,354 | | 6 633,625 | | 7 153,154 | | 7 688,067 | | 8 284,774 | |
| | 2 | 1 877,633 | | 1 881,799 | | 1 985,169 | | 2 212,989 | | 1 469,902 | | | | 2 102,259 | | | | 2 147,893 | | 2 083,165 | | | | 1 890,523 | |
| 2/1 % | | 22,8 | | 24,7 | | 27,8 | | 37,0 | | 17,0 | | | | 28,1 | | | | 32,3 | | 29,1 | | | | 22,8 | |
| Approx. latitude | | 29°S | | 29°S | | 34°S | | 30°S | | 27°S | | 29°S | | 20°S | | 24°S | | 34°S | | 26°S | | 28°S | | 23°S | |

Source: Chinnery (1971)

The optimum tilt angle was found to be 35 degrees. Since the roof is pitched at 32 degrees, it was decided to use this angle to minimize the installation costs.

Based on this tilt angle, the average total daily solar radiation was computed for a year, and the results are tabulated in TABLE 4.3.

The "worst" design month was found to be May.

Using these solar radiation data, and assuming a battery efficiency of 85 percent, a maximum allowable depth of discharge of 40 percent, and a current regulator efficiency of 95 percent, the PV array power output was calculated as 91 Wp and the battery energy storage as 95 Ah.

TABLE 4.3: The total daily solar radiation on a tilted surface (32 degrees) at Bloemfontein.

DIFFUSE AND DIRECT SOLAR RADIATION
(average daily values)

| MONTH | DAY NUMBER | DIFFUSE RADIATION (MJ/m2) | DIRECT RAD(hori) (MJ/m2) | DIRECT RAD(incl) (MJ/m2) | INCLINED RAD(total) (MJ/m2) |
|---|---|---|---|---|---|
| JAN | 15. | 7.3 | 19.6 | 16.0 | 23.5 |
| FEB | 45. | 6.8 | 17.7 | 16.3 | 23.4 |
| MAR | 74. | 5.9 | 14.8 | 16.3 | 22.3 |
| APR | 105. | 4.1 | 14.1 | 19.3 | 23.6 |
| MAY | 135. | 3.5 | 10.9 | 18.1 | 21.7 |
| JUN | 166. | 2.8 | 10.2 | 20.0 | 23.1 |
| JUL | 196. | 3.0 | 11.1 | 19.4 | 22.5 |
| AUG | 227. | 3.4 | 14.3 | 21.3 | 25.1 |
| SEP | 258. | 4.7 | 17.1 | 20.5 | 25.4 |
| OCT | 288. | 6.2 | 18.2 | 17.9 | 24.4 |
| NOV | 319. | 6.9 | 20.5 | 17.3 | 24.5 |
| DEC | 349. | 7.4 | 20.4 | 16.1 | 23.8 |

#### 4.2.2.5. The system specifications

The following system components were selected.

### 4.2.2.5.1. The photovoltaic array

Two M.Setek MSP-103 41 Wp Solar Cell Modules were installed on the roof of the labourer's cottage.

The specifications for these panels are as follows:

| | | |
|---|---|---|
| Cell material | : | pure crystalline silicon |
| Cell size | : | 100 mm diameter |
| Number of cells per panel | : | 32 |
| Module configuration | : | 2 panels in parallel |
| Module area | : | 0.3405 sq.m |

At 100 mW/sq.cm and 25 deg.C, the following electo-optical characteristics were specified:

| | | |
|---|---|---|
| Open-circuit voltage | : | 19.0 V |
| Optimum operating voltage | : | 15.3 V |
| Short-circuit current | : | 2.89 A |
| Optimum operating current | : | 2.68 A |
| Maximum power output | : | 41 Wp per panel |
| Cell efficiency | : | 16.4 percent |
| Module efficiency | : | 12.0 percent |

The specification IV and voltage/temperature curves are shown in the following diagram.

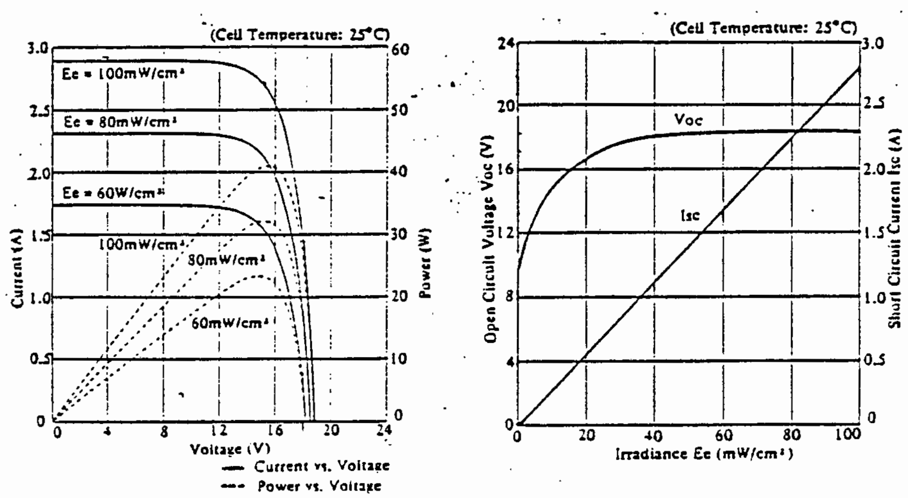



FIGURE 4.4: M. Setek MSP-103 IV and voltage/temperature curves

4.2.2.5.2. The battery protection unit

The ARCO Solar Battery Protector (BP) was used and is shown in FIGURES 4.5 and 4.6.

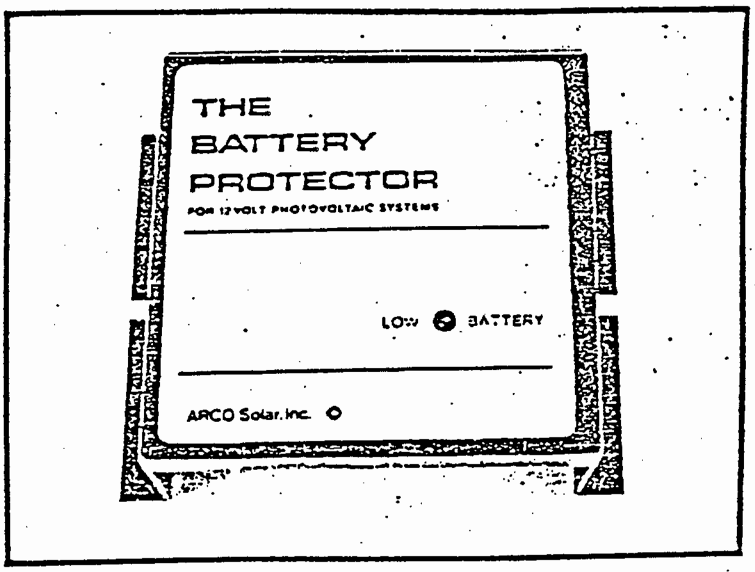



FIGURE 4.5: The ARCO Solar Battery Protector.

Non-essential loads are connected via the BPU to the battery, and essential loads are connected directly to the battery. In this system, the lights were connected as non-essential loads, and the television as an essential load. The BPU has two modes of operation, namely:

1. The direct-charge mode. This occurs from sunrise when the potential difference across the PV panels rises above 10 Volts. All the non-essential loads are switched off and the battery is boost-charged until 14 Volts.

2. The trickle-charged mode. When the voltage across the battery has reached 14 Volts, the BPU switches its mode of operation from the direct- to trickle-charge mode. The battery terminal voltage falls slightly and is slowly recharged to 14 Volts. The non-essential loads come back into operation during this mode.

The specifications for the BPU were quoted as follows:

| | | |
|---|---|---|
| Nominal system voltage | : | 12 VDC |
| Maximum charge current | : | 20 Amps |
| Maximum load current | : | 20 Amps |
| High voltage cutoff | : | 13.9 +/- 0.3 VDC |
| Float charge voltage | : | 14.2 +/- 0.4 VDC |

The battery protector provides four main functions:

1. It is a charge controller. It has a two-step control circuit which allows maximum charging to the point of gassing, and then switches to a float charge mode. This prevents battery electrolyte loss due to overcharging and causes the battery to become fully charged at a safe, low rate.

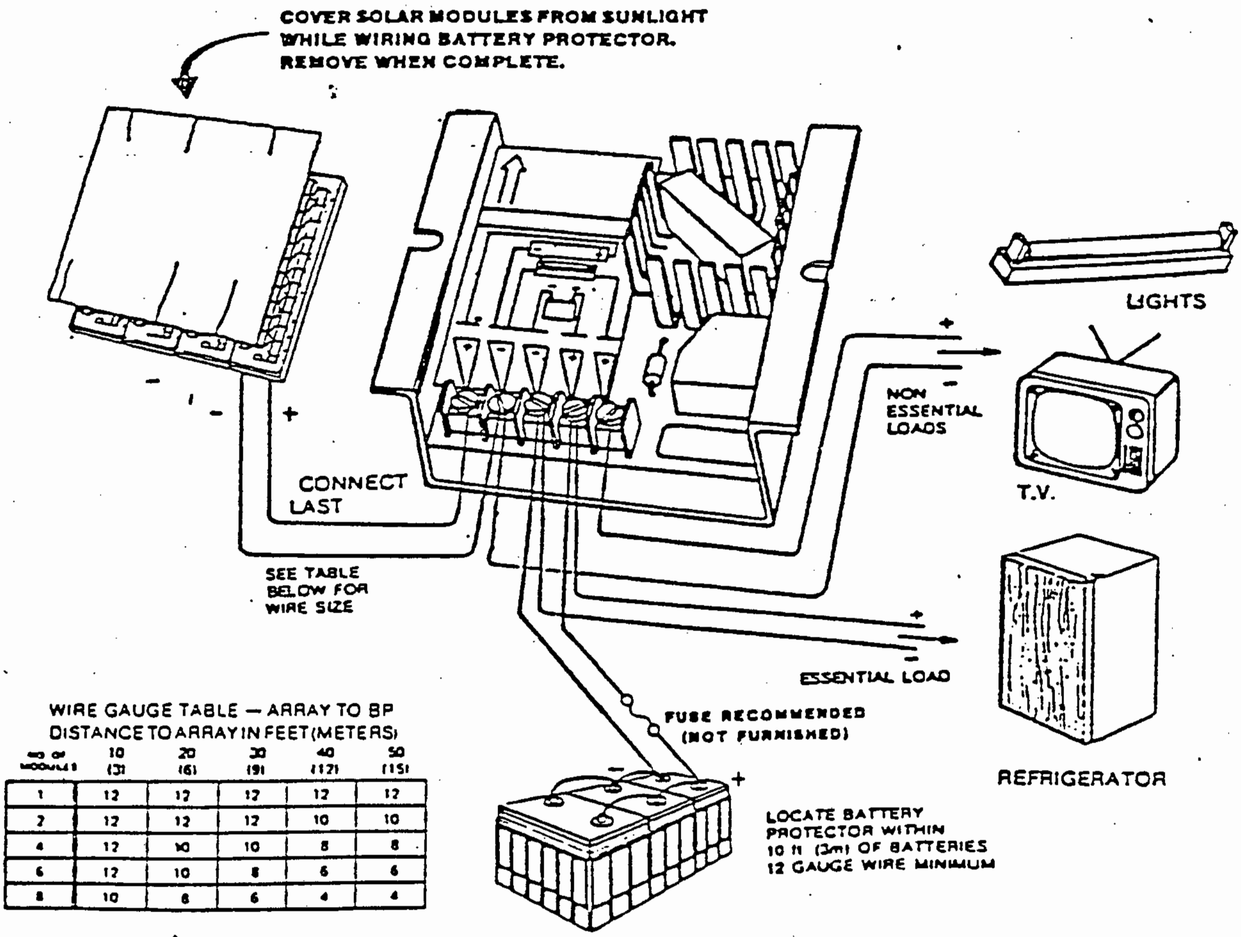
2. It is a load management device which protects against deep discharge by disconnecting non-essential loads during direct-charge mode. This prevents plate sulfation, hence lengthening the working lifetime of the battery. The unit does not, however, have a full battery undervoltage load disconnect facility.

3. The battery protector terminal block provides a central location to interconnect the wiring between the solar panels, the battery and the load appliances.

4. It provides information about the system's daily charge cycle.

In the direct charge mode, the efficiency of the BP is quoted at 99.9 percent, with a voltage drop of 50 mV across the silver-tipped contacts. Some electrolyte bubbling may occur at 14.2 V, but this is for a short time only.

When the battery reaches 14.2 volts, the BP relay opens to interrupt the direct charge mode. Arcing is prevented by a diode and a 10 amp transistor, which are connected across the contacts. The diode and resistor insert a variable resistance, equivalent to 2.4 volts minimum, between the solar array and the battery. Hence, a battery voltage of 13.9 +/- Ø.3 volts forces the array to operate at 16.4 +/- Ø.3 volts, where its current output is much less.




| NO OF MODULES | 10 (3) | 20 (6) | 30 (9) | 40 (12) | 50 (15) |
|---|---|---|---|---|---|
| 1 | 12 | 12 | 12 | 12 | 12 |
| 2 | 12 | 12 | 12 | 10 | 10 |
| 4 | 12 | 10 | 10 | 8 | 8 |
| 6 | 12 | 10 | 8 | 6 | 6 |
| 8 | 10 | 8 | 6 | 4 | 4 |

FIGURE 4.6: Connection diagram for the BPU.

### 4.2.2.5.3. The battery

In this instance it was decided to use the cheapest battery option, a heavy duty automotive type, in order to determine maximum lifetime and the overall economic viability of this choice versus other more appropriate deep-cycle batteries.

A 98 Ah SABAT battery (SABMA code 674) was used at Omdraaisvlei. The following specifications were given for this battery:

| | | |
|---|---|---|
| Type | : | lead-acid |
| Amp-hour capacity | : | 98 Ah, rated for 20 hours |
| Nominal system voltage | : | 12 V DC |

4.2.2.5.4. The lights

Six lights were installed in the house, four were from Semi-Conductor Services (SCS), and two from Comlite. The following specifications were given with the SCS lights:

| | | |
|---|---|---|
| Product code | : | SCS 12-20 |
| Type | : | fluorescent |
| Power consumption | : | 20 watts |
| Maximum current drain | : | 1.5 amps |
| Light output | : | 1500 lumens |

According to the suppliers, these lights were specifically designed for use with solar power. They are fitted with an efficient inverter ballast, which works reliably over a wide range of voltages. The ballast also has built-in diode protection, to prevent damage from accidental reverse connections.

These lights use standard fluorescent light tubes, which are readily available. They are enclosed in a solid metallic casing which may be easily adapted to either recessed mounting or use with diffusers. The Comlites were standard 11-watt, caravan-type lights.

4.2.2.5.5. The television set

The family owned a portable black and white television set which was connected to the PV system. Its maximum power drain is approximately 15 watts.

## 4.3. TECHNICAL EVALUATION

A key feature of the demonstration projects was the automatic and detailed monitoring of system variables in order to evaluate technical performance. Sophisticated sensors, signal conditioning and data capture systems were designed and installed which enabled data to be sent to Cape Town in computer compatible format ready for computer based analysis.

### 4.3.1. Key system parameters

The performance of small stand-alone PV systems may be described in broad terms by the power output from the PV modules and the extent of power consumed by the users. The current output of the PV panels is determined primarily by solar radiation intensity. The voltage across the panels is determined by the load as seen by the panel, and to a lesser extent by the PV cell temperature, which is related to the ambient temperature. In order to determine the efficiency and performance of subsystem components, current and voltage either side of the charge controller and battery were also measured. A schematic diagram of the system is shown in FIGURE 4.7.

The following parameters were thus monitored:

1. Solar radiation
2. Ambient temperature
3. PV cell temperature
4. PV voltage
5. PV current
6. Battery voltage
7. Load current

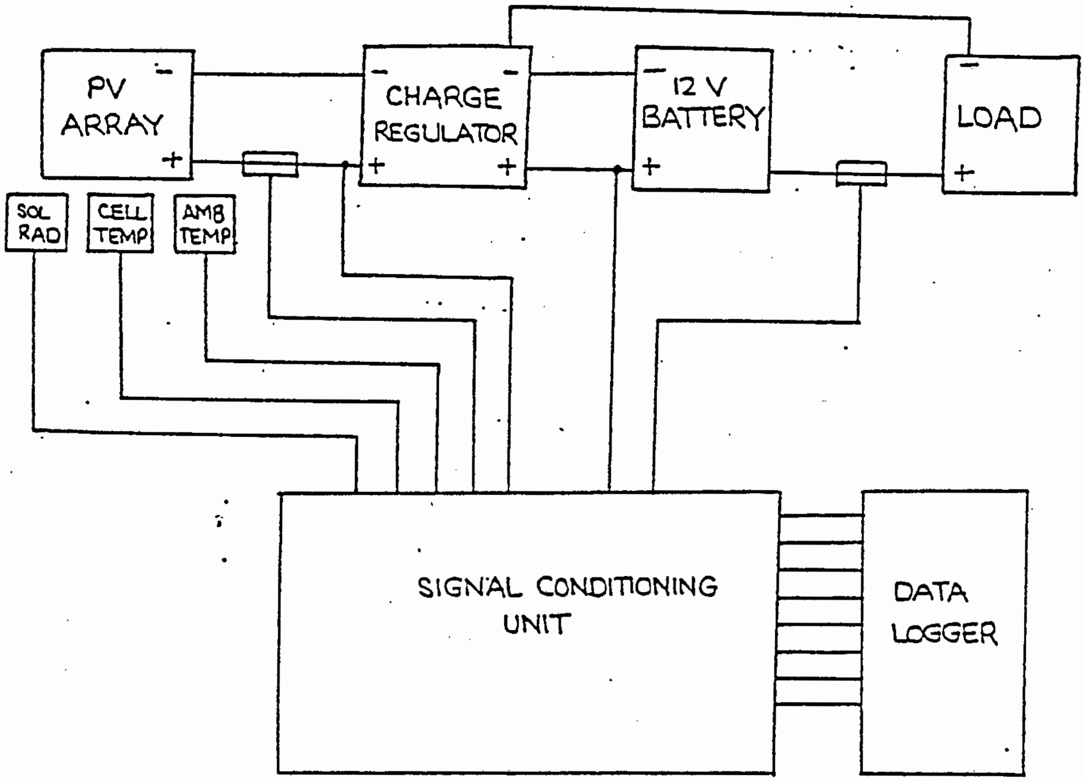



FIGURE 4.7: A schematic diagram of the data monitoring system.

### 4.3.2. Data measurement

The measurement, conditioning and storage of data from these systems presented particular problems - no mains power supply is available; the sites are remote from research laboratories (Omdraaisvlei is 750 km from Cape Town) and are in hostile environments. Battery powered data logging and signal conditioning was necessary, and a robust, but convenient method had to be selected for storing and transmitting data.

#### 4.3.2.1. Temperature sensors

Four main types of electronic temperature sensors were available:

(i) thermistors;
(ii) resistance temperature detectors (RTD's);
(iii) integrated circuits (IC's);
(iv) thermocouples

A thermistor is a composition resistor in which the resistance decreases as temperature increases. They are characterized by their speed, relatively high output and availability.

RTD platinum devices display increasing resistance with increasing temperature. Platinum is chosen because of its exceptional long-term stability at high temperatures (it does not oxidize). RTD's, particularly platinum RTD's, possess the best accuracy, linearity, stability and industrial stabilization of all sensors; however, they are very costly.

Integrated circuits (IC's) are a recent introduction to the temperature measurement scene. Most IC's are designed to a voltage or current which increases with sensor temperature. The signal produced by the IC has a low sensitivity to the power supply and the lead length. An accuracy of +/- 1.Ø deg.C is typical for IC sensors. The maximum allowable operating temperature for an IC sensor is 15Ø deg.C, while temperatures as high as 2ØØ deg.C are permissable for short periods.

Thermocouples are available in many physical forms. These sensors measure the changes in voltage produced by the heating of a junction of dissimilar metals or alloys. This voltage increases with temperature in a non-linear fashion. Special electronic instrumentation and stable references are required to obtain a usable temperature indication from this type of sensor. Induced voltages from other electrical equipment may lead to incorrect readings.

In this project, IC's were used to measure temperature since they were the cheapest and simplest devices available for the required range of accuracy.

#### 4.3.2.2. Solar radiation

An LI-COR LI-2ØØS pyranometer sensor was used to measure solar radiation. This is a cosine corrected sensor and is capable of accurately measuring radiation impinging upon its surface from all angles of a hemisphere. The advantage of a cosine correction response is that it allows for accurate measurement of diffuse radiation conditions as well as at low solar elevations. This sensor was chosen because it is convenient to use, it is easy to install, it has a high degree of accuracy, and is relatively inexpensive.

#### 4.3.2.3. Current shunts

Two different value current shunts were used for measuring current flow. A 6 amp/50 mV shunt was used to measure the current flow between the PV array and the battery, while a 10 amp/50 mV shunt was used to measure the current drawn by the load.

#### 4.3.2.4. Voltage measurement

Voltage signals were taken directly from the voltage sources, namely, the PV array and the battery, to the interface where the signal was passed through a variable resistor which was calibrated such that the outgoing signal was within an acceptable range for input into the data logger.

### 4.3.3. Signal conditioning

The analog input range of the data logger is user selectable and can accomodate single ended DC voltage signals from -5 mV to +2000 mV. A signal conditioning unit was thus designed at the ERI to convert analog input signals from the various measurement devices to standard 0 to 2000 mV signals acceptable to the data logger.

The form of the input and output signals for each sensor is tabulated below.

| SENSOR | ACTUAL INPUT RANGE | MILLIVOLT INPUT RANGE | OUTPUT RANGE |
|---|---|---|---|
| Temperature | 0 - 100 deg.C | 2732 - 3732 | 0 - 2000 mV |
| Pyronometer | 0 - 1400 W/sq.m | 0 - 7.08 | 0 - 250 mV |
| Load current | 0 - 10 amps | 0 - 50 | 0 - 2000 mV |
| PV current | 0 - 6 amps | 0 - 50 | 0 - 2000 mV |
| Battery volts | 0 - 16 V | 0 - 16 000 | 0 - 2000 mV |
| PV volts | 0 - 20 V | 0 - 20 000 | 0 - 2000 mV |

### 4.3.4. Data logger

MCS 120 data loggers, manufactured locally in Cape Town, were selected. They are compact, twelve-channel (eight analog and four digital), low power, microprocessor-controlled devices (FIGURE 4.8).

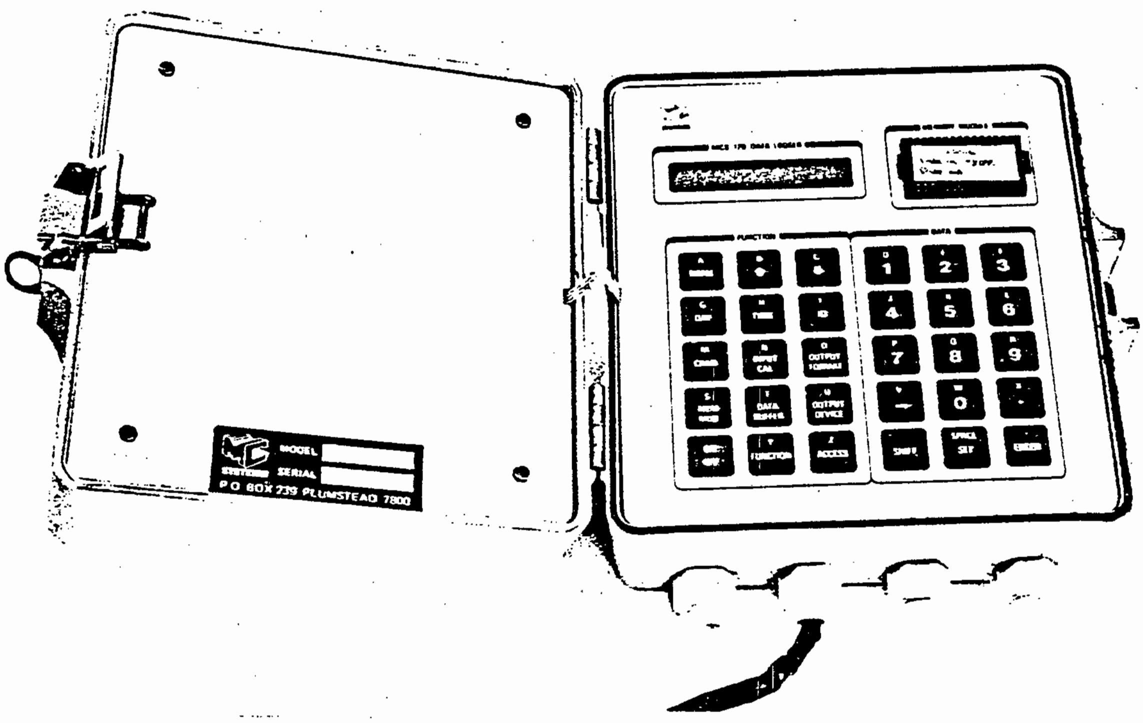


FIGURE 4.8: The MCS 120 data logger

The data logger is ideally suited for remote data capture. It is battery powered and has a robust, lockable housing for protection in harsh environments. It allows for flexible programming for different logging options and stores data on an interchangeable E-PROM micro-chip which is posted back to the ERI for reading and analysis.

The data logger scans the different input channels every five seconds, but can store the data at two different logging periods which may be programmed into the system. Data can be stored at intervals from 1 minute to 99 hours and 59 minutes. The data logger may be programmed to capture and log the data as instantaneous, totalized, average, maxima, or minima from any of the input channels.

The data logger is menu driven from the 35 key membrane keyboard and includes a 16 digit alpha-numeric liquid crystal display. It has a real time clock, Julian day register, alpha-numeric station identification register, and a built-in solid-state memory module recording device, with 8 K or 16 K options.

The data logger is completely self-contained, and is powered by four 1.5 V dry cell batteries which give an operational life of approximately three months. A low battery condition is automatically detected during the one minute scan cycle, or it is stored as a message on the EPROM chip.

### 4.3.5. The data point reader

The MCS 42Ø Data Point Reader (DPR) model is used to transfer data recorded on the MCS memory module (E-PROM) via an RS 232 serial port to a micro-computer.

The DPR has a de-compacting algorithm which converts the compacted data points recorded on the MCS data logger into ASCII strings of Julian days, real time, and data points.

### 4.3.6. Data analysis

The data retrieved from the EPROM micro-chip, was stored on a floppy disc, rearranged in a spreadsheet, and was analyzed using the LOTUS 123 package.

## 4.4. ECONOMIC EVALUATION

The aim of the economic evaluation was to compare small PV-powered systems with alternatives, such as petrol or diesel-powered generators, paraffin lamps, gas and candles, for domestic power and lighting, in order to establish the least-cost option for small systems under all financial scenarios.

The first aspect considered in the economic evaluation was to determine the initial capital cost outlay for the PV-powered systems and then to determine their cost effectiveness by comparing their life-cycle cost (discounted to present values) with that of alternatives. This was done using a levelized annual financial analysis. The methodology is described in chapter three.

The next step of the financial evaluation was to undertake a sensitivity analysis on the important cost parameters over an appropriate range of values. The different variables which were considered are:

(i) the capital cost and efficiency of the PV panels;
(ii) the capital cost, depth of discharge and lifetimes of different types of batteries;
(iii) the discount and interest rates; and
(iv) the cost of alternative fuels.

This sensitivity analysis is a useful exercise since small variations in cost drivers, such as an escalation in the prices of fossil fuels over the system lifetime, can significantly alter the relative preference for competing power systems. The result of this analysis yields an understanding of the effect of uncertainty in parameter values on photovoltaic cost effectiveness.

Interviews were carried out with the recipient households to determine their weekly energy consumption pattern and average expenditure prior to the installation of the PV system. The results of these interviews were then combined with previous surveys carried out by the ERI in order to obtain a more generalised comparison between households using PV systems and those relying on paraffin, gas, candles and batteries.

A direct financial and economic comparison between electric lights and candles or paraffin lamps is of course slightly artificial and the quality of light produced by the latter is so much more inferior. Social costs and benefits are thus also important criteria in the evaluation of these systems.

## 4.5. SOCIAL EVALUATION OF THE SYSTEM

This project covers only the initial stages of a social assessment of these systems. The family life-style before and after the PV-powered system was installed, was compared in terms of:

(i) the proportion of the monthly family income being spent on energy consumption for lighting and television requirements.
(ii) the convenience/inconvenience of either system.
(iii) its effect on family life-style, the standard of living, the aspirations of the family.
(iv) its acceptability in the community.
(v) the possibility of securing amortizing loans to cover the high capital costs of the PV system.

To gather this information, informal interviews were conducted with the family members at the demonstration project sites. Data from previous surveys carried out by the ERI and the South African Labour and Development Research Unit (SALDRU) at UCT, were also used.

### 4.5.1. Proportion of family income spent per month

Although it is difficult to measure precisely, the monthly amount spent on fuel consumption for lighting, television and radio usage was quantified before and after the PV system were installed.

### 4.5.2. The convenience/inconvenience of either system

Social costs, such as the labour, time and effort involved in going to the shops to purchase paraffin, petrol, candles and gas and how regularly they had to have batteries recharged, were recorded. The problems associated with smoke and smell from candles and paraffin, the danger of fires and related health problems (eg. chest and eyes), were also examined.

### 4.5.3. Life-style and standard of living

The families involved in the demonstration projects were interviewed about their life styles before and after the PV system were installed, in order to establish qualitatively the influence of the PV systems. The issues focussed around improved lighting and it's effect on children's school homework, staying up later at night, being able to read with less strain, preparing meals later at night and being able to entertain in more comfortable surroundings.

### 4.5.4. Acceptability in the community

Where this was possible, the neighbours were asked about their reaction to the systems.

### 4.5.5. Special financial arrangements for families installing PV systems

Building societies were consulted to determine if there are any special loan schemes available to families installing PV systems in low-cost housing projects as a means of coping with the high initial capital costs of PV systems and then paying monthly installments perhaps lower than their previous energy bills.

# CHAPTER 5

# RESULTS AND ANALYSIS

The results of the two demonstration projects are presented and analysed under three headings, namely, the technical evaluation, the economic analysis and the social assessment.

## 5.1. TECHNICAL EVALUATION

The technical evaluation involves a description of the observed system performance by analysing the monitored data on typical daily, weekly and monthly bases.

The data was analysed to determine the relationships between system variables and the key factors affecting the system efficiency were examined.

Finally, the number of days where power was unavailable were determined. This relates to acceptable loss of power probabilities and hence has a bearing on appropriate design techniques.

### 5.1.1. Observed system performance

The overall system performance over the monitoring period is described using averaged weekly and monthly data for solar radiation, PV array power output and electrical load energy demand for the respective project sites. From the mass of stored data, three typical days and one "bad" day, when the total daily solar radiation was significantly lower than the daily average, were chosen to describe the performance of the systems in more detail.

These latest results describe the observed changes in solar radiation, ambient and PV cell temperature, PV array current and voltage output, and the electrical loads' current and voltage demand characteristics over the course of a day.

### 5.1.1.1. Uitsig

The Uitsig photovoltaic project was monitored over the winter months. The overall system performance is described using a graphical plot which shows the average daily total solar radiation, the weekly PV power output and the electrical load energy demand (see FIGURE 5.1 at the end of the chapter). These results are tabulated below in TABLE 5.1.

TABLE 5.1: Uitsig overall system performance results

| | Average daily total Solar radiation ($54^{o}$ tilt) Design ($MJ/m^2$) | Average daily total Solar radiation ($54^{o}$ tilt) Measured ($MJ/m^2$) | Average Monthly total PV output (kWh) | Average Monthly total Load demand (kWh) |
|---|---|---|---|---|
| April | 19.28 | 17.7 | 10.2 | 9.2 |
| May | 15.45 | 13.1 | 7.7 | 6.6 |
| June | 14.03 | 14.8 | 9.2 | 8.2 |
| July | 14.50 | 13.3 | 9.3 | 7.3 |
| August | 16.18 | 14.5 | 10.1 | 8.0 |

These results are also tabulated on a weekly basis in the following table, TABLE 5.2.

The solar radiation data in the initial design was calculated from average daily historical data recorded at DF Malan Airport, which is less than 10 km from the project site (Tegen, 1987). The average daily total solar radiation on the $54^{o}$ tilted array surface for April, May, June, July and August was calculated as 19.28, 15.45, 14.03, 14.50, and 16.18 $MJ/m^2$.

TABLE 5.2: Uitsig overall performance data on a weekly basis

| Week Number | Average daily total Solar radiation Measured (54° tilt) ($MJ/m^2$) | Average Weekly total PV output (kWh) | Average Weekly total Load demand (kWh) |
|---|---|---|---|
| 1 | 21.0 | 2.51 | 1.22 |
| 2 | 19.6 | 2.62 | 2.38 |
| 3 | 17.0 | 2.50 | 2.30 |
| 4 | 16.0 | 2.62 | 2.55 |
| 5 | 15.0 | 3.20 | 2.40 |
| 6 | 12.6 | 1.91 | 1.90 |
| 7 | 9.2 | 1.10 | 1.10 |
| 8 | 12.4 | 1.75 | 1.32 |
| 9 | 17.6 | 2.41 | 2.12 |
| 10 | 17.4 | 2.39 | 2.15 |
| 11 | 16.2 | 2.32 | 2.18 |
| 12 | 16.0 | 2.20 | 2.22 |
| 13 | 10.8 | 1.68 | 1.62 |
| 14 | 20.0 | 2.98 | 2.20 |
| 15 | 14.4 | 2.60 | 2.14 |
| 16 | 15.4 | 2.50 | 2.42 |
| 17 | 2.0 | 1.00 | 1.00 |
| 18 | 14.0 | 2.90 | 1.71 |
| 19 | - | 2.42 | 1.82 |
| 20 | - | 2.39 | 1.91 |
| 21 | 14.0 | 2.75 | 2.02 |
| 22 | 13.6 | 2.60 | 2.25 |

Comparing the design month June (14.03 $MJ/m^2$), with the measured value for the same month (14.8 $MJ/m^2$), it is evident that the system was reasonably sized for the actual insolation level for June. However, for rest of the winter months, the measured data is considerably lower than the design data. In order to check the accuracy of measured data, computer print outs were obtained from the Weather Bureau, Pretoria, on solar radiation measured at DF Malan Airport during the same period. The results are tabulated in TABLE 5.3 below.

TABLE 5.3: Measured solar radiation in Cape Town (MJ/m2)

| 1987 | DF Malan | | | Uitsig |
|---|---|---|---|---|
| | Horizontal | | Calculated 54° | 54° tilt |
| | Global | Diffuse | Global | Global |
| April | 15.52 | 6.68 | 17.91 | 17.7 |
| May | 9.75 | 3.07 | 14.83 | 13.1 |
| June | 9.23 | 5.97 | 11.74 | 14.8 |
| July | 9.21 | 5.99 | 11.32 | 13.3 |
| August | 12.25 | 8.26 | 13.23 | 14.5 |

The data does still not match very well but it is at least clear that the winter of 1987, Cape Town had much lower solar radiation levels than usual and that the design figures were too optimistic.

Based on the household's energy utilization pattern, the average daily energy requirement was estimated as 236 Wh during winter. However, from the above table the average daily load energy demand was calculated as 286 Wh, an increase of 21 percent over the design value. Nevertheless, the average monthly PV energy output is always greater than the average load energy demand, with the smallest percentage difference occuring in May and June. On a weekly basis, the same trend was observed for the majority of the monitoring period, except for three weeks where the average weekly PV energy output equalled the average load energy demand for the same period. Both insolation levels and energy consumption were well below the average values. The major reason for this is the lower than average insolation levels resulted in load disconnections for brief periods and power was used only when available.

The three typical days analyzed were the 26 March, 27 May and 27 August 1987, and this data is shown graphically in FIGURES 5.2 to 5.7. Data for 3 June 1987 illustrates an example of a day with low solar radiation, and the results are shown in FIGURES 5.8 and 5.9.

On the three typical days the average daily total solar radiation was 25.4, 19.5 and 19.1 $MJ/m^2$, compared with the "bad" day where the total was 4.3 $MJ/m^2$.

On the typical days the total PV energy output was 503.9, 411.1 and 520 Wh; and the total load energy demand was 237, 351 and 432 Wh, respectively. On the "bad" day the total PV power output was 108.4 Wh, and the load energy demand was 284.7 Wh. FIGURES 5.2 to 5.4 and 5.5 to 5.7 show the daily variations in solar radiation, PV and load current, and PV and battery voltage for the typical days respectively, while FIGURES 5.8 and 5.9 show the daily variations in solar radiation, PV- and load current, and PV and battery voltage for the "bad" day respectively.

On the three typical days the maximum PV cell temperatures were 46.8, 35.2, and 35.0 deg.C, whereas on the "bad" day the maximum temperature was 22.0 deg.C.

The average PV cell temperatures, calculated from sunrise to sunset, were 34.2, 24.6, and 24.9 deg.C respectively, whereas on the "bad" day it was 12.8 deg.C. FIGURES 5.10 shows how the PV cell temperature, compared with the ambient temperature, varied over a day.

All of the previous sample days show the system in boost charge mode where the battery never reaches a full state of charge. On those days where usage patterns and insolation levels result in the battery being fully charged, the charge regulator switches to trickle charge.

The operation of the PV system in the boost- and trickle-charge mode is shown for 28 March 1987, and the variations in solar radiation, PV- and load current, and PV- and load voltage are plotted in FIGURES 5.11 and 5.12 respectively.

On this day, the total solar radiation was 23.8 $MJ/m^2$. The PV system operated in the boost-charge mode from sunrise to approximately 13h00 until the battery voltage was 14.7 V, and thereafter in the trickle-charge mode until sunset (between 18h30 and 19h00), where the PV voltage increased to above 16 V with the current reduced to near zero.

During the boost-mode period, the PV power output was 239 Wh, and the average PV cell and ambient temperatures were 30.6 and 23.1 deg.C respectively (the maximum cell temperature was 41.0 deg.C), whilst during trickle-charge operation the values were 65 Wh, 31.6 deg.C and 23.5 deg.C respectively. The total load energy demand was 121.6 Wh, 90 percent being consumed after sunset (approximately half the winter design load capacity of 236 Wh).

#### 5.1.1.2. Omdraaisvlei

As a contrast to the performance of the Uitsig system in the winter months of the winter rainfall area of the Western Cape, the Omdraaisvlei photovoltaic project in the sunny northern Karoo was monitored during the summer months.

The overall PV-energy system performance is shown graphically in FIGURE 5.13. These results are tabulated in TABLE 5.4.

TABLE 5.4: Omdraaisvlei overall system performance

| | Average daily total Solar radiation ($32^\circ$) | | Average Weekly total | Average Weekly total |
|---|---|---|---|---|
| | Design ($MJ/m^2$) | Measured ($MJ/m^2$) | PV output (Wh) | Load demand (Wh) |
| November | 24.5 | 23.6 | 720 | 680 |
| December | 23.8 | 26.8 | 1210 | 875 |
| January | 23.5 | 25.5 | 1310 | 1000 |
| February | 23.4 | 21.8 | 1280 | 660 |

The solar radiation data in the initial design was based on estimations at Bloemfontein. The average daily total solar radiation on a $32^\circ$ tilted surface used in the design, for November, December, January and February was 23.8 $MJ/m^2$. From the above table, the average measured daily solar radiation was 24.4 $MJ/m^2$, which is 2.5 percent greater than the design value. It was expected that the solar radiation for Omdraaisvlei would be slightly higher than Bloemfontein, since Omdraaisvlei is situated in a drier, hotter region than Bloemfontein. It is interesting to note, however, that in two of the months the measured radiation figures were below design data.

In the design, the average daily power requirement was estimated as 366 Wh. However, from the above table the average daily load energy demand was calculated as 115 Wh, more than three times less than the design value. It is apparent that the family have continued to use energy conservatively. The low consumption can also be ascribed to the much smaller household size (compared to Uitsig) with the consequence that the family would not use all the lights through the evening.

The three typical days examined were 17 November 1986, 2 January 1987 and 21 February 1987, and this data is shown graphically in FIGURES 5.14 to 5.19. Data for 10 February was chosen as an example of a day with low solar radiation, and the results are plotted in FIGURES 5.20 and 5.21.

On these days the total daily solar radiation was 24.4, 26.9 and 26.6 $MJ/m^2$ (see FIGURES 5.14 to 5.16), compared with the "bad" day where the total was 9.4 $MJ/m^2$ (see FIGURE 5.20).

The total PV energy output on the typical days was 206.6, 182.2 and 217 Wh, respectively. It was found that on average, the battery was fully charged every morning between 10h00 and 11h00, and between 45 and 50 percent of the PV power output occurred in the boost-charge mode of operation. FIGURES 5.14 to 5.16 show the variation in solar radiation, PV- and load current, and FIGURES 5.16 to 5.19 show the variation in PV- and load voltage.

On the "bad" day the total PV output was 225.3 Wh, while the system was in the boost-charge mode of operation for the whole day. During this mode of operation, the battery is directly connected to the PV array via the charge regulator and the battery voltage equalled the PV array voltage as shown in FIGURE 5.21.

The average PV cell temperature during the boost-charge mode for the three days were 29.1, 26.5 and 32.7 deg.C respectively, and in the trickle-charge mode they were 40.8, 54.5 and 46.9 deg.C. The maximum PV cell temperatures on those days were 48.0, 65.0, and 57.4 deg.C respectively.

On the "bad" day, the maximum temperature was 40.1 deg.C and the average temperature from sunrise to sunset was 27.5 deg.C.

On the three typical days the daily load energy demand was 93.8, 182.2 and 72.0 Wh respectively. In the first two cases the loads were used exclusively after sunset, whereas in the third case the load was used partially during trickle-charge mode (approximately 26 percent) and was powered directly from the PV array, while the battery was maintained in its fully-charged state.

On the "bad" day the load energy demand was 76.8 Wh, which is 34 percent less than the calculated average of 115 Wh per day. Since the system was in the boost-charge mode for the whole day, the non-essential loads were not able to be used, hence, resulting in a low load energy demand. FIGURE 5.20 shows the variation in solar radiation, PV- and load current.

### 5.1.2. Effect of temperature

The relationship between the difference in cell and ambient temperature and solar intensity is shown in FIGURE 5.22. This relationship proved to be relatively constant from day to day.

The temperature correlation constant was determined graphically from the slope of the line in FIGURE 5.22 and was calculated as 0.0155 deg.C/($W/m^2$), which is equivalent to 0.72 deg.C/($MJ/m^2$).

In section 3.1.2., equations 3.2 and 3.3. show the relationship between PV voltage and cell temperature. For these equations, the PV cell temperature coefficient has been found to vary between -0.004 and -0.006 /deg.C.

Based on the monitored data, the PV cell temperature coefficient was determined graphically from the slope of FIGURE 5.23. Using a reference temperature and reference voltage of 25 deg.C and 16 V from the suppliers' specifications respectively, the slope of the graph was calculated as -0.003 /deg.C. It should be pointed out that the data do not fit this linear relationship very well.

### 5.1.3. System efficiencies

The overall PV system efficiency was calculated as the product of the efficiencies of the various power system components for the PV system operating at different PV cell temperatures and battery voltage levels.

#### 5.1.3.1. PV array and charge regulator efficiencies

The efficiencies of the photovoltaic array and the charge regulator were firstly determined for the Uitsig project site and then for the Omdraaisvlei site. Efficiencies were calculated as the ratio of energy out to energy in.

##### 5.1.3.1.1. Uitsig

Although there was variation in the observed daily weather pattern over the monitoring period, the calculated efficiencies showed negligible variation from day to day. The 26 March 1987 is illustrative of the efficiency of the various system components (see FIGURE 5.24).

In the boost-mode of operation, the efficiency of the charge regulator shows variation from 97.5 percent soon after sunrise to 92.9 percent at 13h30, thereafter increasing again. The average efficiency was 95 percent. (In the trickle-charge mode efficiencies are on average lower at 87 percent.)

A similar trend is observed for the PV module efficiency. In this case, the efficiency varies from 9.6 percent in the early morning to 8.4 percent at 13h00 with an average of 9 percent. These results (for boost-mode operation only) are summarized in TABLE 5.5.

TABLE 5.5: Uitsig PV module and BPU efficiencies

| Time | PV array Current (amps) | PV array Voltage (volts) | PV cell Temperature (deg.C) | Battery Voltage (volts) | PV array Efficiency (percent) | BPU Efficiency (percent) |
|---|---|---|---|---|---|---|
| 9.00 | 1.60 | 12.9 | 24.9 | 12.4 | 9.5 | 96.3 |
| 9.30 | 2.33 | 13.1 | 30.0 | 12.5 | 9.6 | 95.4 |
| 10.00 | 3.00 | 13.3 | 33.5 | 12.6 | 9.6 | 94.6 |
| 10.30 | 3.57 | 13.4 | 37.2 | 12.6 | 9.4 | 94.2 |
| 11.00 | 3.99 | 13.6 | 40.4 | 12.7 | 9.1 | 93.8 |
| 11.30 | 4.27 | 13.7 | 44.8 | 12.8 | 8.8 | 93.6 |
| 12.00 | 4.59 | 13.8 | 44.4 | 12.9 | 8.8 | 93.3 |
| 12.30 | 4.74 | 13.9 | 45.4 | 12.9 | 8.6 | 93.1 |
| 13.00 | 4.81 | 14.0 | 46.7 | 13.0 | 8.4 | 93.1 |
| 13.30 | 4.81 | 14.0 | 43.2 | 13.0 | 8.7 | 92.9 |
| 16.00 | 4.01 | 14.1 | 38.3 | 13.2 | 9.0 | 94.7 |
| 18.30 | 0.70 | 13.4 | 23.8 | 13.0 | 8.9 | 97.5 |

The higher efficiencies in charge regulator operation are probably related to periods of lower current flow from the PV panels in the early morning and late afternoon.

Variations in the efficiency of the PV panels can best be understood by considering the point of operation on the I/V curve which is primarily determined by the state of charge of the battery or its voltage. The I/V curve in turn varies with insolation and temperature. FIGURE 5.25 shows the load line superimposed over a set of I/V curves. Highest efficiencies are obtained when the point of operation approximates the maximum power point (located on the knee of the curve).

Average operating efficiencies are close to those quoted by the PV module supplier (11.7 percent at 25 deg.C and 10.4 at 47 deg.C) but are lower because system voltages cause the PV operating voltage to be lower than the maximum power point would require.

5.1.3.1.2. Omdraaisvlei

Monitored data for a typical day (2 January 1987) was used to calculate the efficiencies of the PV array and the charge regulator in order to determine the overall system efficiency. These results are summarized in TABLE 5.6.

TABLE 5.6: Omdraaisvlei PV module and BPU efficiencies

| Time | PV array Current (amps) | Battery Voltage (volts) | PV array Voltage (volts) | PV cell Temperature (deg.C) | BPU Efficiency (percent) | PV array Efficiency (percent) |
|---|---|---|---|---|---|---|
| 7.15 | 0.41 | 12.7 | 12.8 | 19.1 | 99.8 | 7.7 |
| 8.15 | 1.71 | 13.0 | 13.1 | 25.8 | 99.5 | 9.7 |
| 9.15 | 3.05 | 13.3 | 13.4 | 35.0 | 99.4 | 10.4 |
| 10.15 | 3.30 | 13.7 | 14.5 | 45.8 | 94.7 | 9.1 |
| 12.00 | 0.87 | 13.7 | 16.5 | 59.4 | 83.1 | 2.1 |

In boost-charge mode the regulator efficiency is relatively constant at 99.5 percent (but as expected drops to an average of about 83 percent in trickle-charge mode).

Photovoltaic module efficiencies are highest in early morning when cell temperatures are still moderate. Efficiencies are still lower than the 12 percent (at 25 deg.C) or 10.3 percent (at 50 deg.C) which the PV module manufacturers quote.In trickle-charge mode the PV panels operate far from the maximum power point and efficiencies are thus very low. Load curves are superimposed over I/V curves in FIGURE 5.26. It is clear from these curves that the PV modules do not optimally match battery charging requirements in that the voltage corresponding to the maximum power output ranges from roughly 14 to 16.5 V (depending on temperature) while battery charging voltages vary from 11.5 to 14.5 V.

FIGURE 5.27 graphically illustrates the variation in efficiencies for the charge regulator and PV array over a whole day, and during the boost- and trickle-charge modes of operation.

#### 5.1.3.2. Battery efficiency

Since it was not possible to determine the battery state of charge (SOC) at a given instant, the battery efficiency was estimated as the ratio of the average rate of discharging to the average rate of recharging the battery to a fully-charged state.

Analysis of the daily monitored data at Omdraaisvlei showed that the average daily discharge rate was 7.94 Ah, at an average battery voltage of 12.4 V. This gave an average power output of 98.4 Wh. On the other hand, the average rate of charging was 8.86 Ah at a battery voltage level of 13.1 V. This gave an average energy input of 116.0 Wh. Therefore, using the above definition of battery efficiency, the average amp-hour efficieny was 89.6 percent and the watt-hour efficiency was 84.8 percent.

This approach could not be used for the battery at Uitsig because the battery was fully charged only on one particular day, and on the following day during the recharging process, loads were in use. Furthermore, results for one day only would be quite inadequate for determining battery efficiency.

It is recognized that this approach provides only a crude overall picture of battery efficiency, but in the absence of detailed charge and discharge curves for the battery a more comprehensive model of battery charge and discharge efficiencies under different conditions, could not be constructed.

#### 5.1.3.3. Overall system efficiencies

For the Omdraaisvlei system during the boost-charge mode, the average PV array, charge regulator and battery efficiencies are 10.3, 99.5 and 84.8 percent respectively, yielding an overall system efficiency of 8.7 percent. During the trickle-charge mode of operation, the average regulator and array efficiencies were 83.7 and 2.1 percent respectively, yielding an overall system efficiency of 1.5 percent. The latter mode of operation is of-course designed to be inefficient as energy is dumped so as not to overcharge the batteries.

For the Uitsig system during the boost-charge mode of operation, the average PV array and charge regulator efficiencies were 9.6 and 95.0 percent respectively, and assuming a battery efficiency of 85 percent, an overall system efficiency of 7.9 percent is calculated.

#### 5.1.4. Factors affecting system efficiency

Which factors affect system efficiency the most? It is clear from the above that efficiencies vary relatively little in the boost-charge mode. Battery and regulator efficiencies remain relatively constant while photovoltaic efficiencies vary slightly according to the point of operation on the module's I/V curve which is determined by operating insolation and temperature levels and the state of charge of the battery. These factors are important in ensuring that reasonable efficiencies are achieved and that load lines approximate maximum power points.

Both insolation and temperature vary with meteorological conditions in a far from predictable fashion from day to day, although long term trends can be statistically predicted from historical weather data.

The state of charge of the battery is affected both by the immediate history of charging (which is a function of insolation) and also by usage patterns which also vary in an unpredictable fashion.

The relationships determining the point of operation of photovoltaic modules, and hence their efficiency, are thus complex and difficult to predict. The approach adopted here is to map out the broad area of operation of the photovoltaic modules. It is apparent that most areas of operation are reasonably close to the maximum power point and efficiencies are thus usually within 20 percent of their maximum. But there is room for better matching of PV modules with the requirements of battery charging and maximum power point tracking may be economically justified.

A more exact approach than the above analysis is to develop an accurate simulation model of the PV system both so that PV system performance can be adequately analysed under a range of operating conditions, and also so that, combined with historical data, system performance and efficiencies might be predicted according to appropriate probabilistic functions.

However, of much more significance for overall system efficiency, is the matching of photovoltaic and battery sizes with the load. For example, if the load usage is smaller than predicted, the battery will be fully charged early in the day and the regulator will switch to trickle-charge mode with the photovoltaic modules putting out only a fraction of the energy of which they are capable. The average daily system efficiencies can thus be very low with the photovoltaic panels operating far from their maximum power point.

This phenomenon was particularly evident at Omdraaisvlei where the system operated in boost-charge mode regularly only to 10h00 or 11h00 and thereafter trickle charged the nearly fully charged battery. Thus nearly two-thirds of the available energy of the system was "inefficiently" wasted, and the real cost of power was extremely high.

In terms of design, thus, one of the most important areas of maximizing system efficiencies in small stand-alone systems is in the matching of solar photovoltaic output and load usage.

### 5.1.5. System reliability

The systems at Uitsig and Omdraaisvlei have both been in operation for over a year with no problems observed in the operation of the photovoltaic modules.

At the Omdraaisvlei site, due to the operation of the charge regulator, the non-essential loads are disconnected every morning with the system in the boost-charge mode, and are reconnected once the battery voltage has reached 14 V. Essential loads may still be used during this period. On average it has been observed that the battery voltage reached 14 V between 10h00 and 11h00 every day. During the monitoring period, no power system failure was reported in the evening when the load energy demand is at its greatest.

At Uitsig power was unavailable for three periods when the battery voltage dropped below 12 V and the charge regulator disconnected the loads. The first period occurred at the beginning of June, the second at the end of July and the third at the end of August (see FIGURE 5.1).

These periods coincide with protracted days of low insolation and were exacerbated by slightly higher than design levels of energy consumption.

The system was designed for a specified loss of energy probability (LOEP) of 0.1 for the "worst" or design month. Thus it was anticipated that power would not be available for 10 percent of the days in June (ie. 3 days). An LOEP of 0.1 for the "worst" month is equivalent statiscally to an average monthly LOEP of between 0.02 to 0.04, which corresponds to an average monthly loss of power of between 0.6 and 1.2 days.

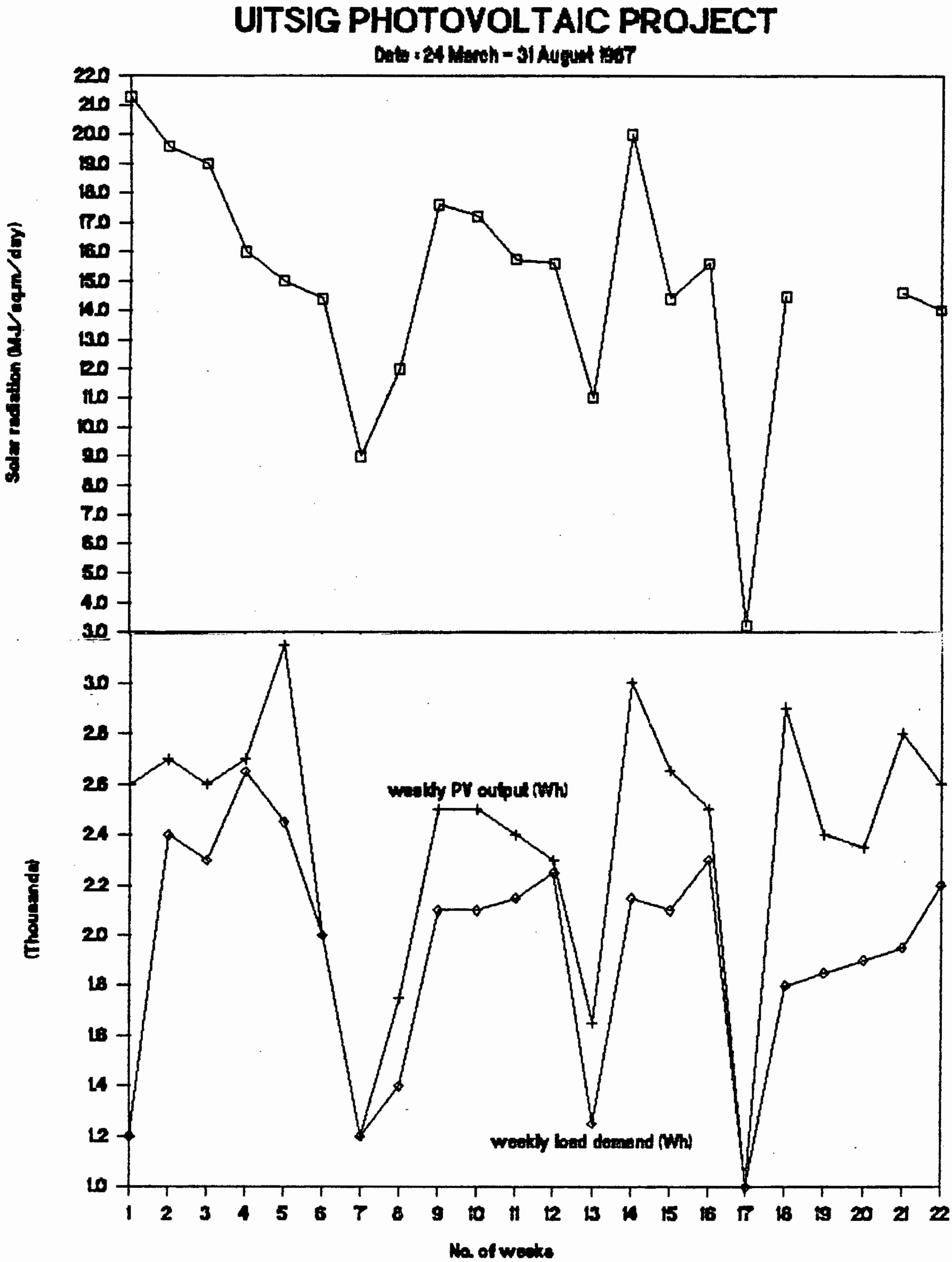



FIGURE 5.1 : Uitsig - overall system performance

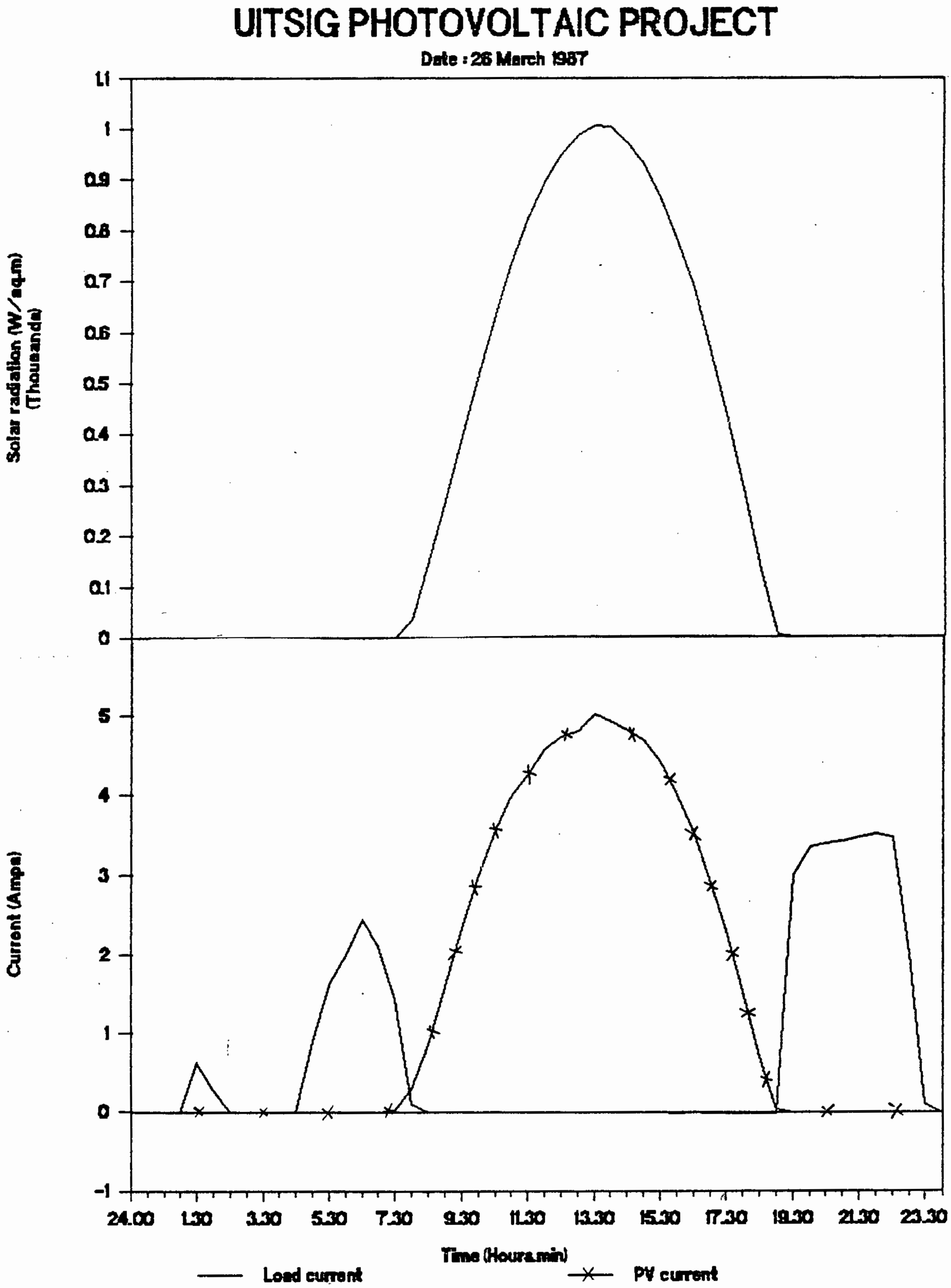



FIGURE 5.2 : Typical day - solar radiation, PV- and load current

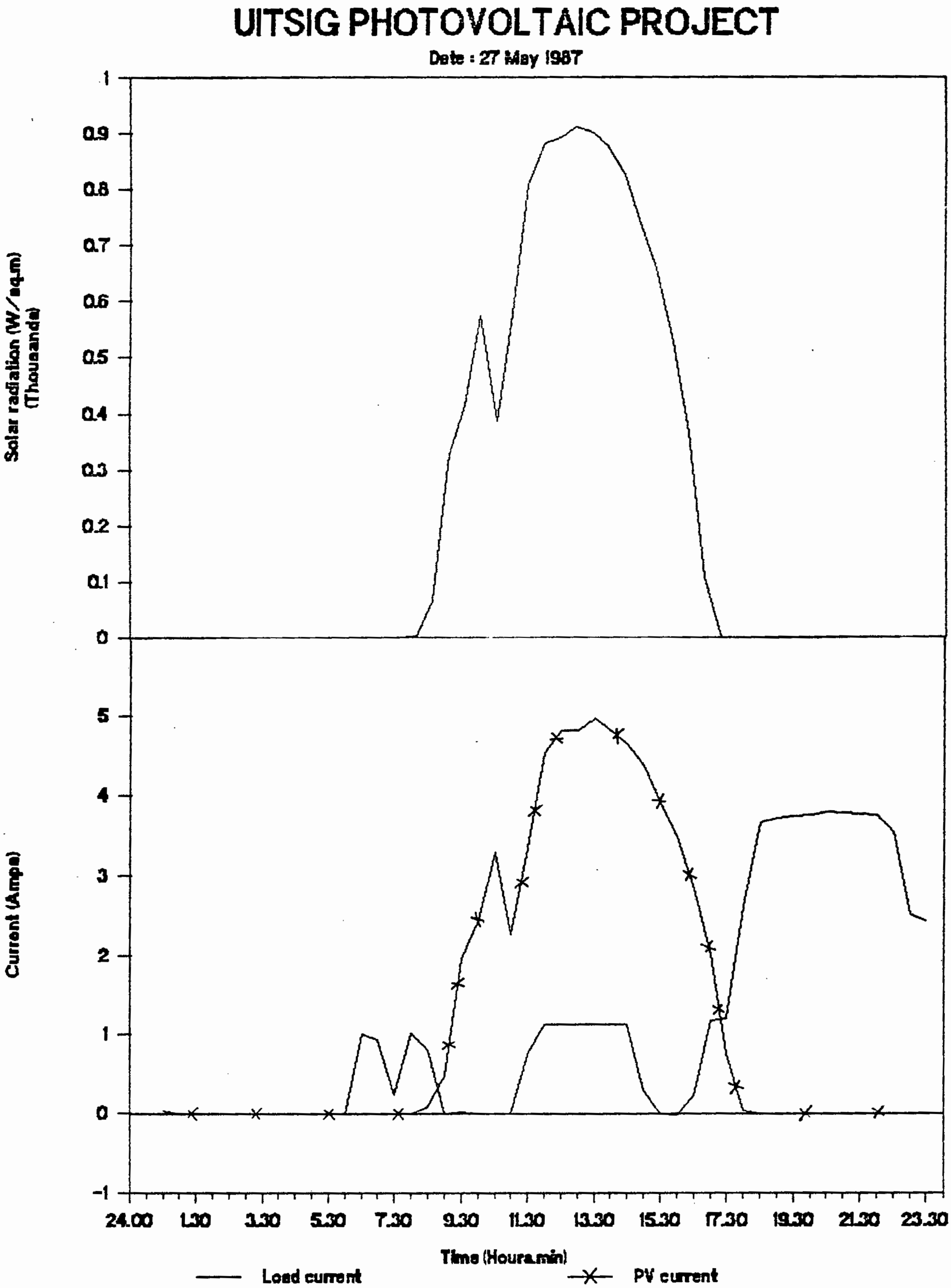



FIGURE 5.3 : Typical day - solar radiation, PV- and load current

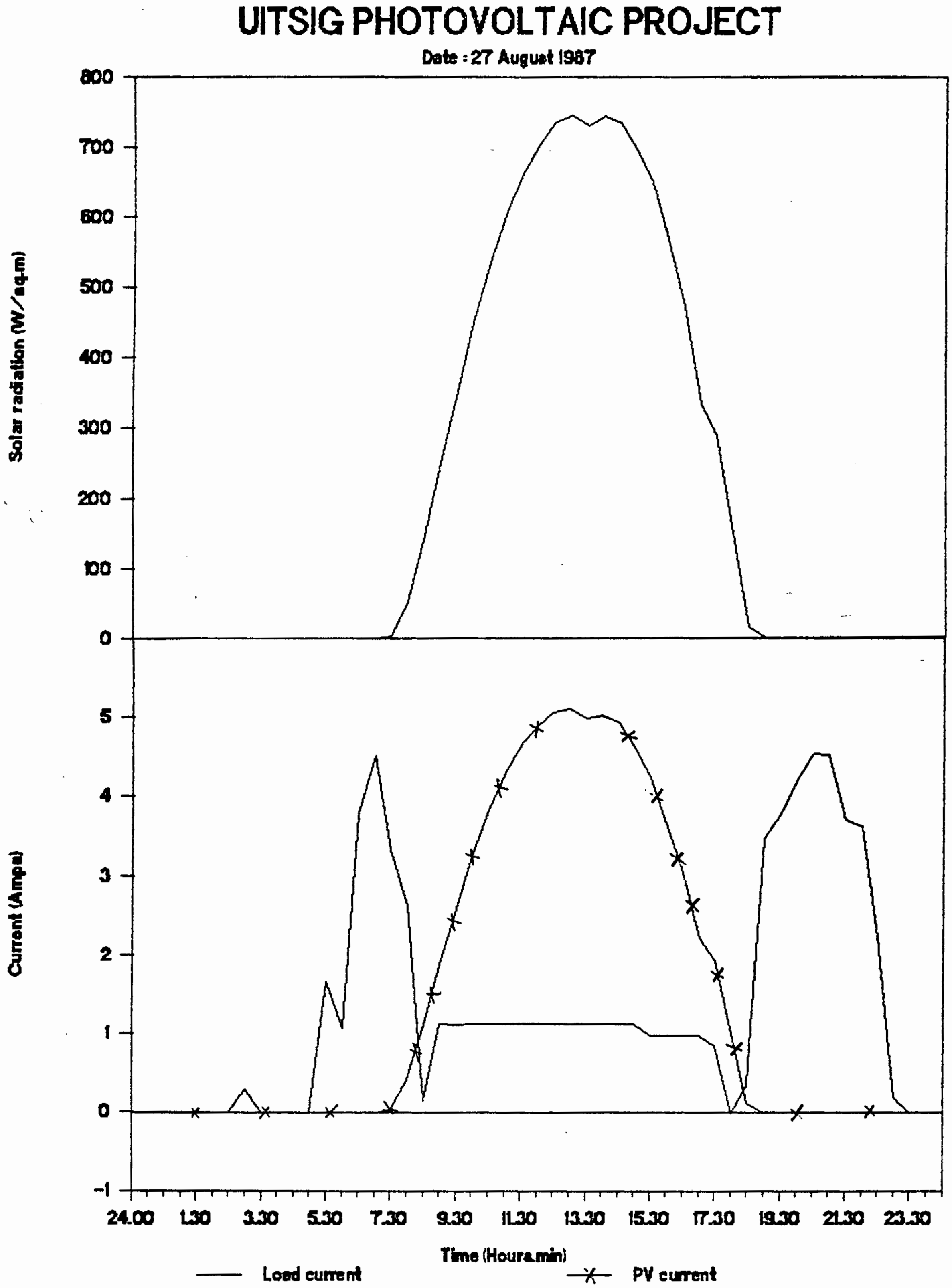



FIGURE 5.4 : Typical day - solar radiation, PV- and load current

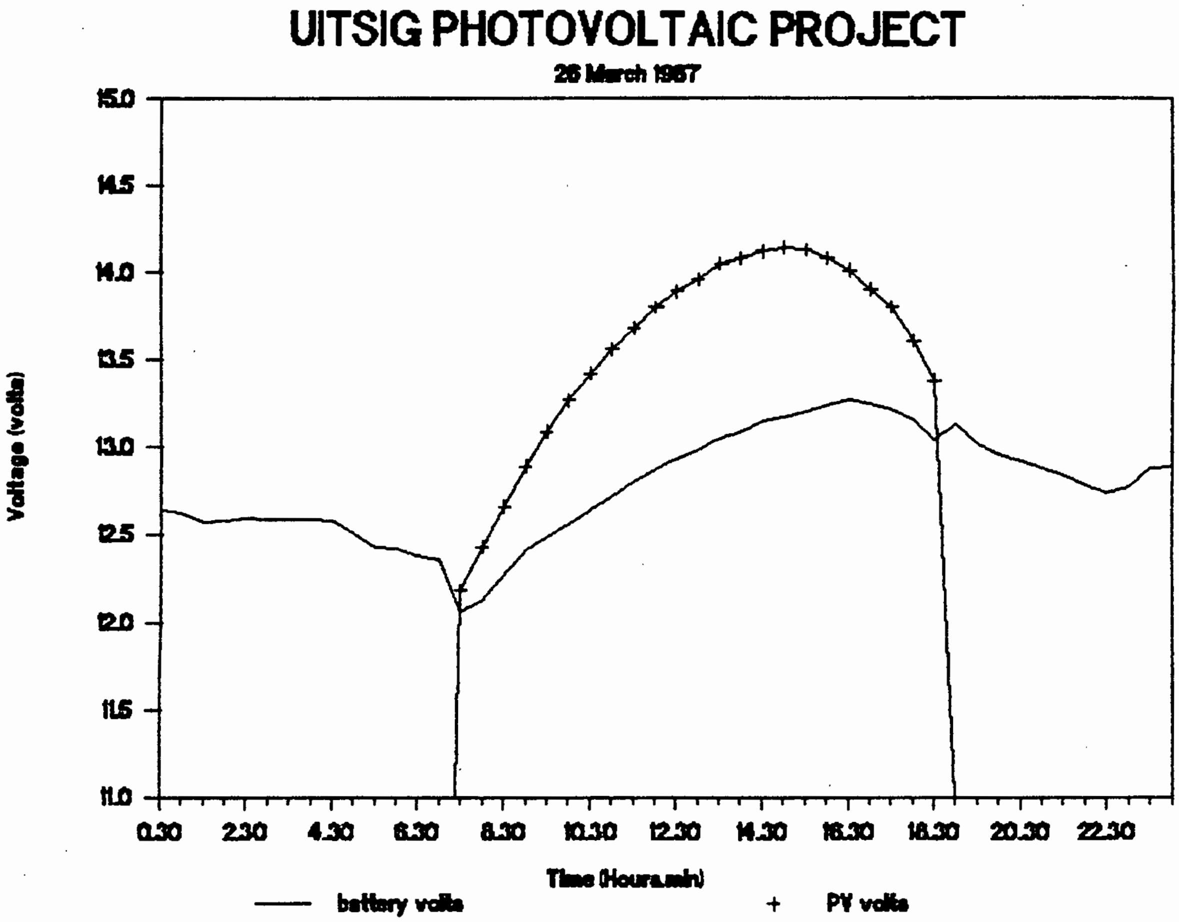



FIGURE 5.5 : Typical day - PV- and battery voltage

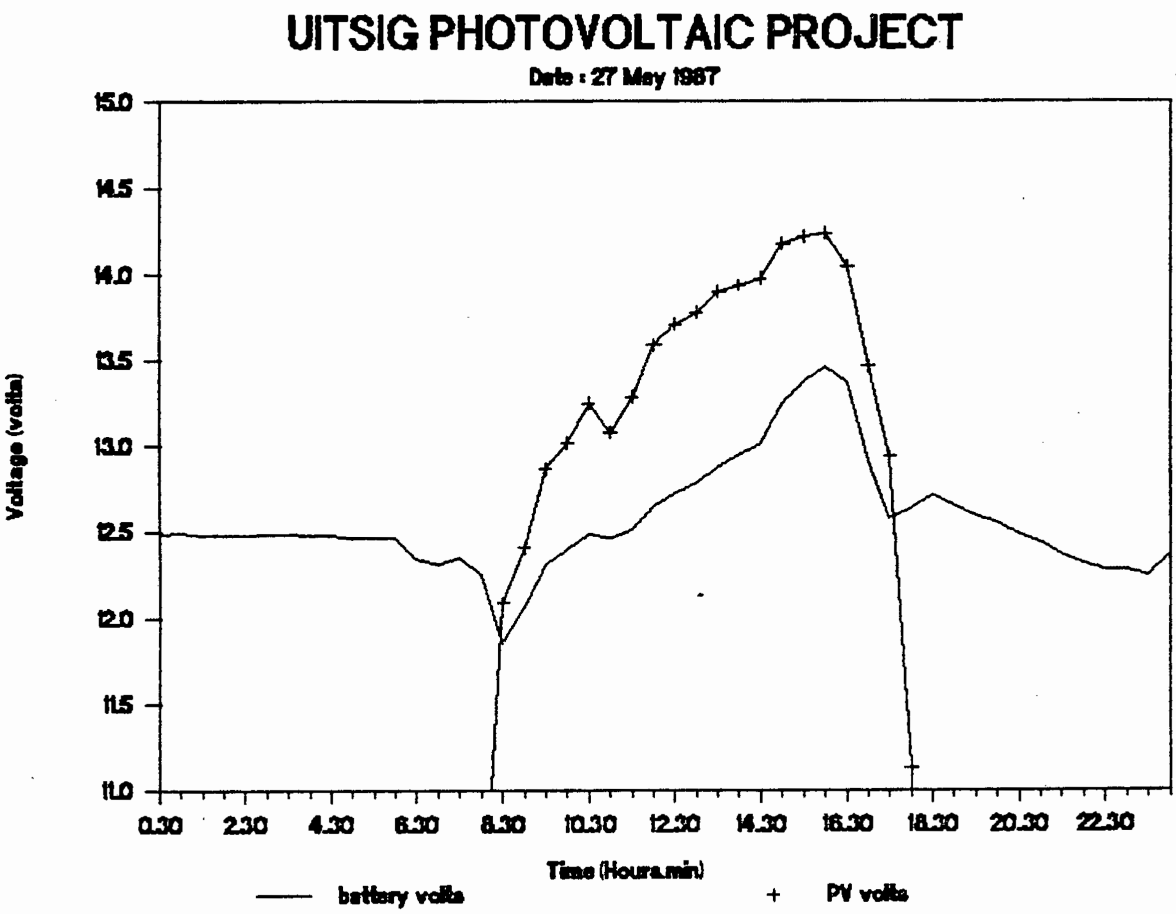



FIGURE 5.6 : Typical day - PV- and battery voltage

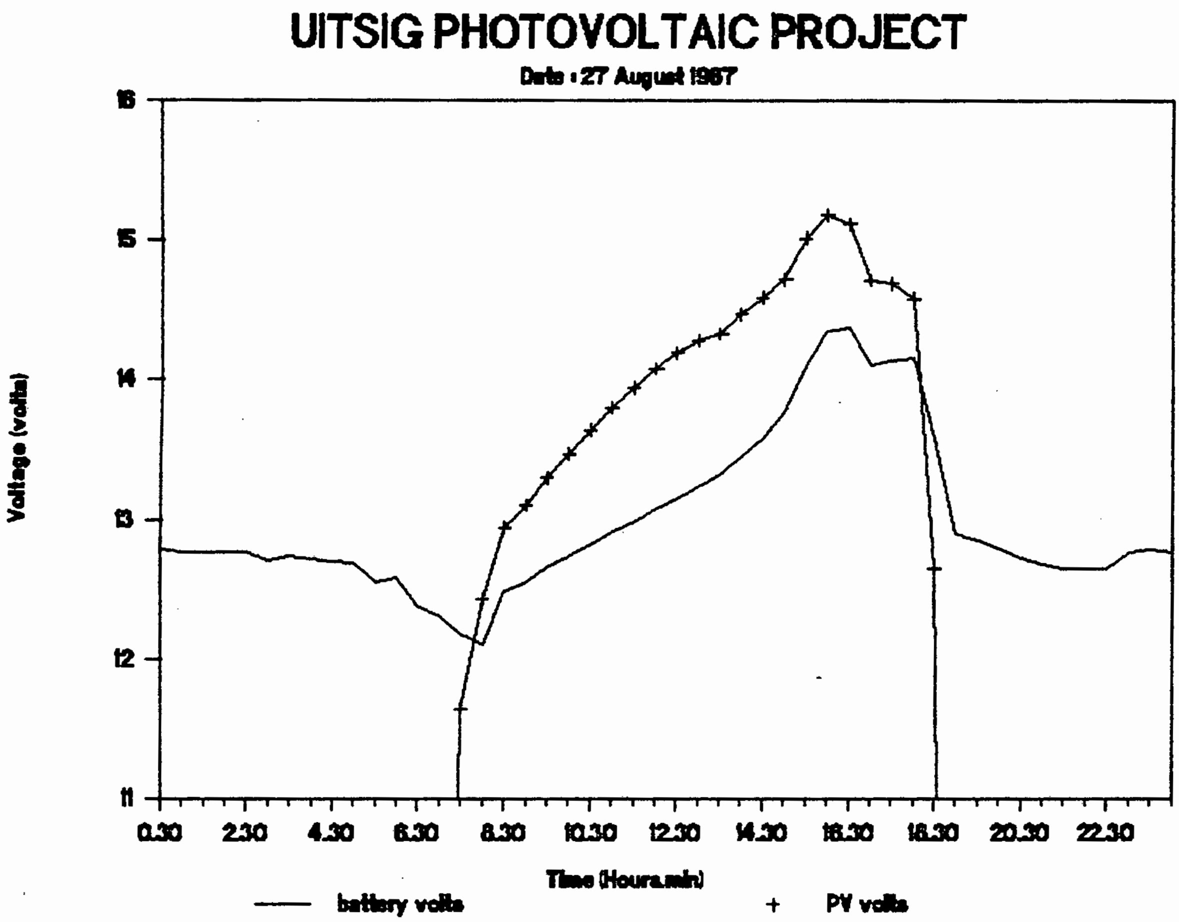



FIGURE 5.7 : Typical day - PV- and battery voltage

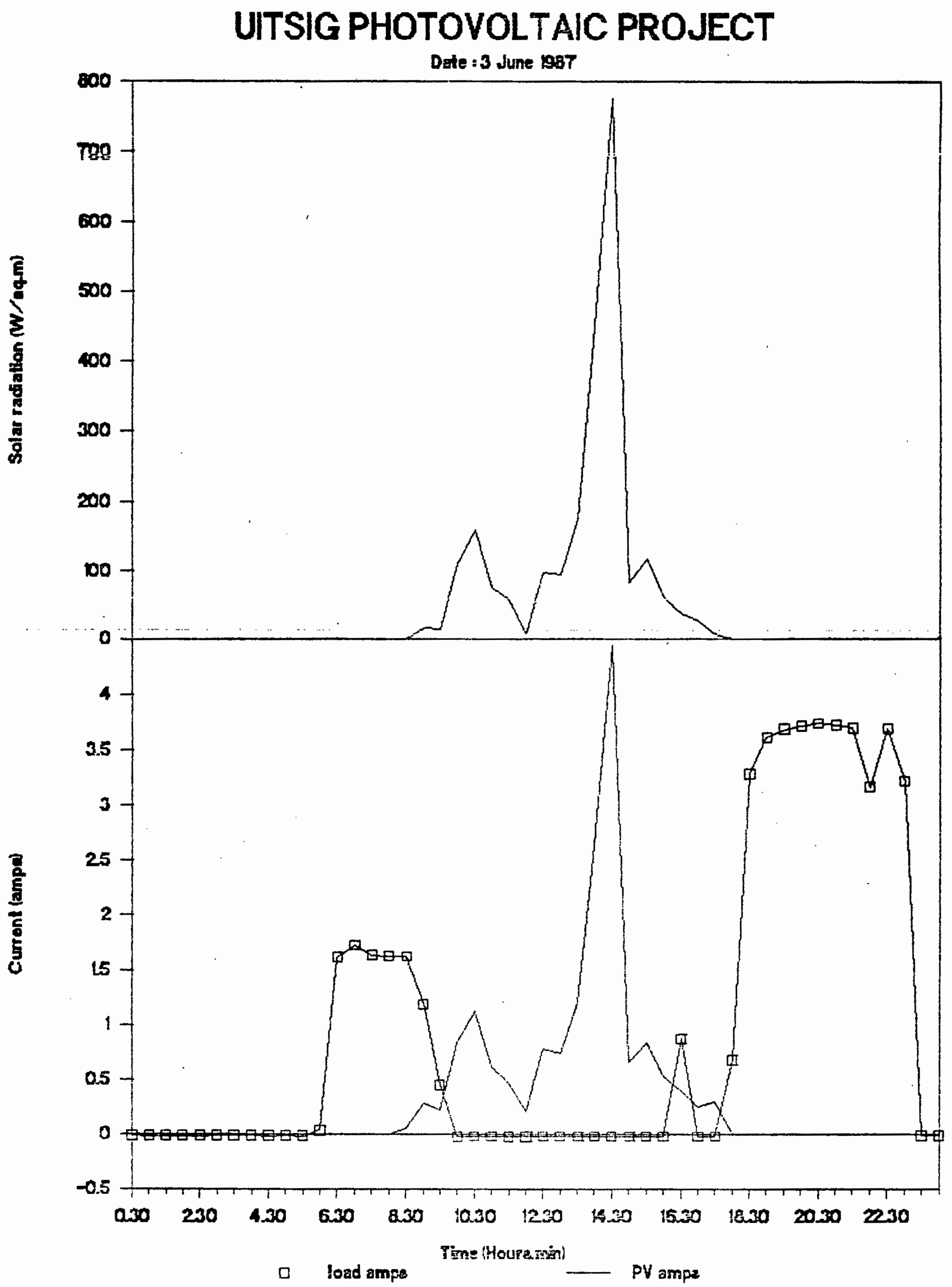



FIGURE 5.8 : Bad day - solar radiation, PV- and load current

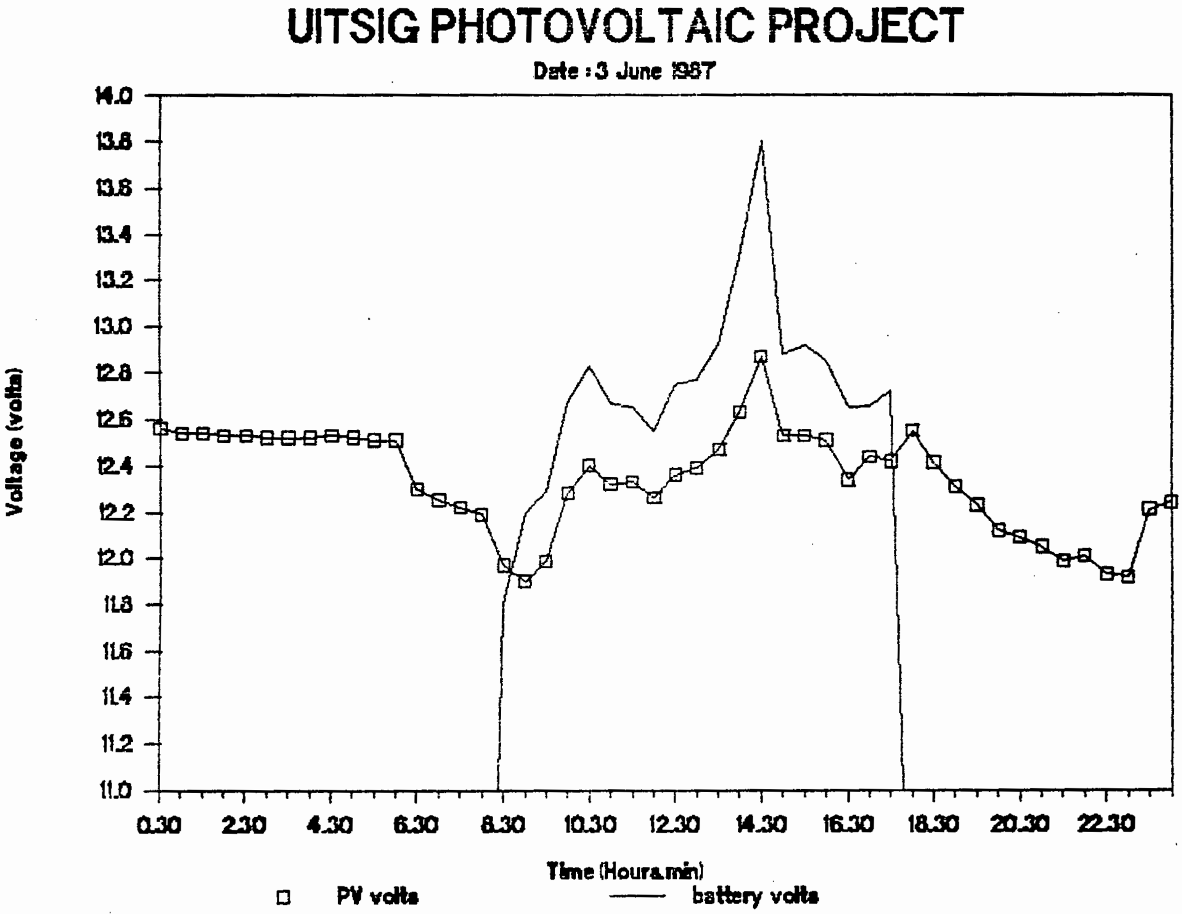



FIGURE 5.9 : Bad day - PV- and battery voltages

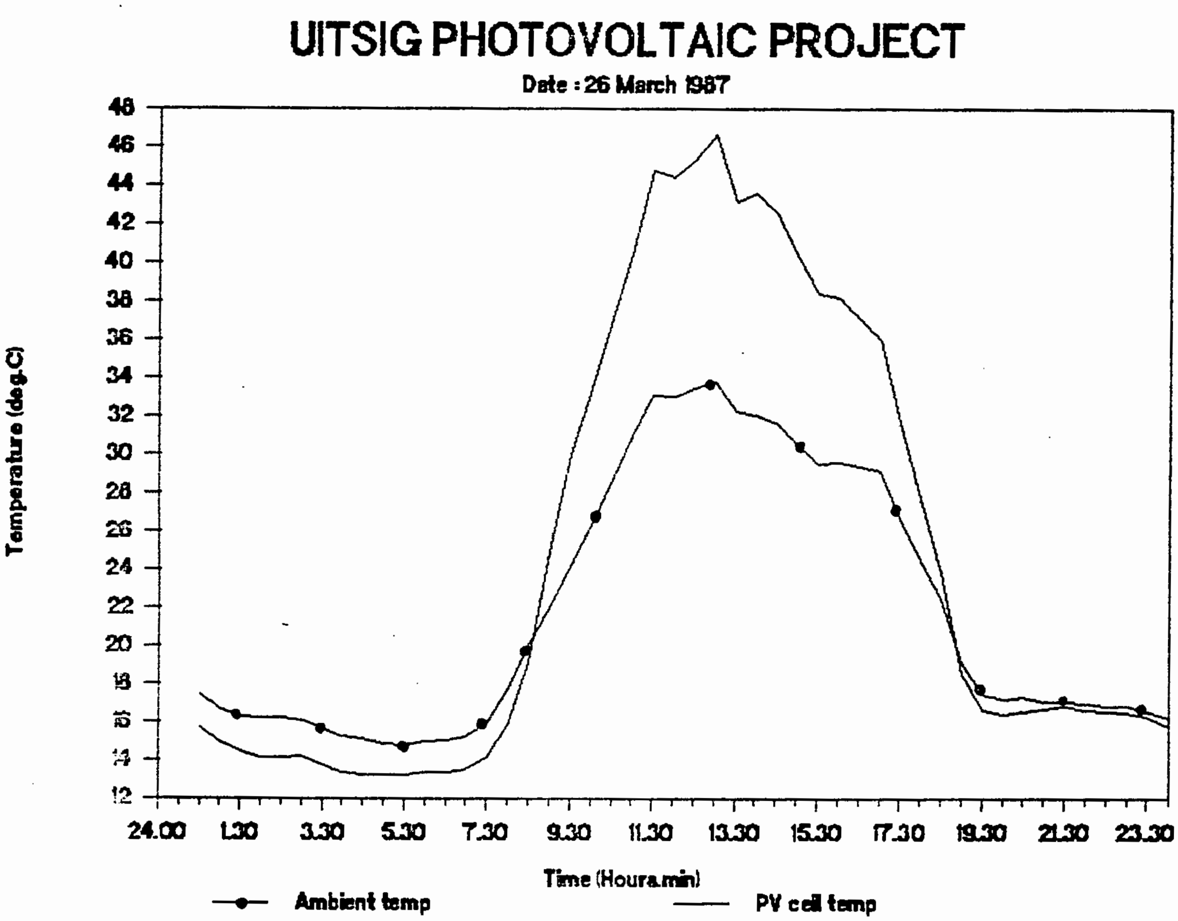



FIGURE 5.10 : Typical day - ambient and PV cell temperature

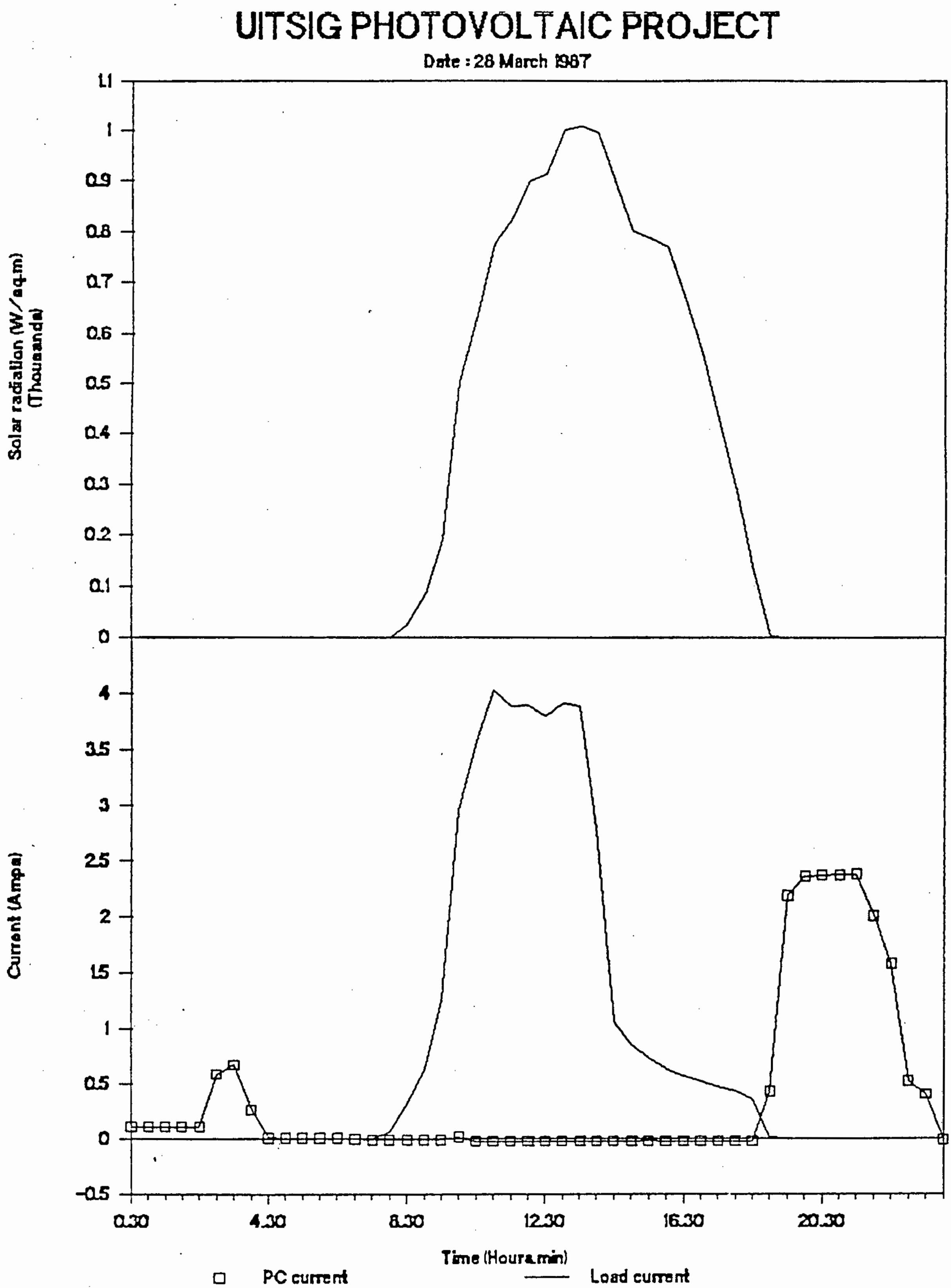



FIGURE 5.11 : Boost- and trickle-charge operation - solar radiation, PV- and load current

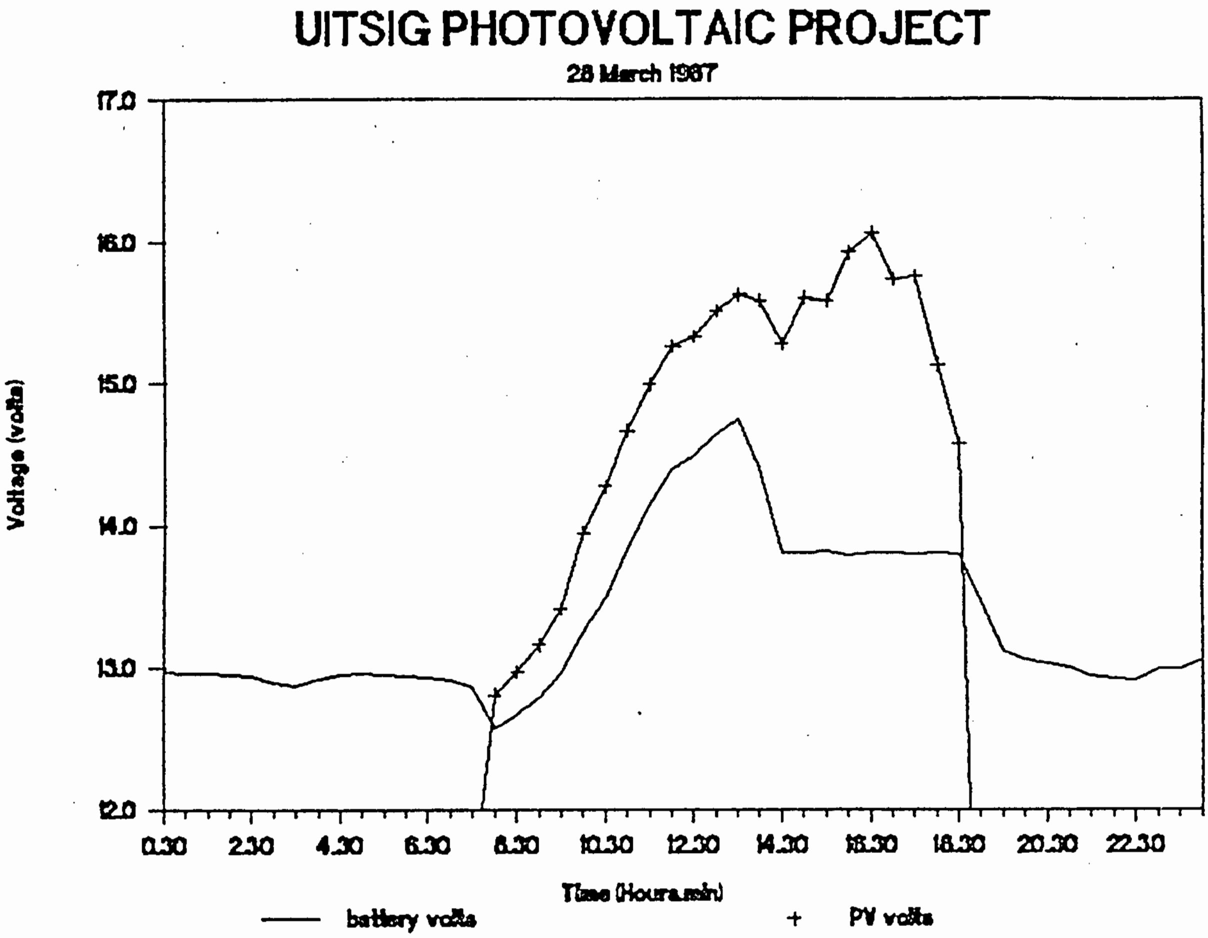



FIGURE 5.12 : Boost- and trickle-charge operation - PV- and battery voltage

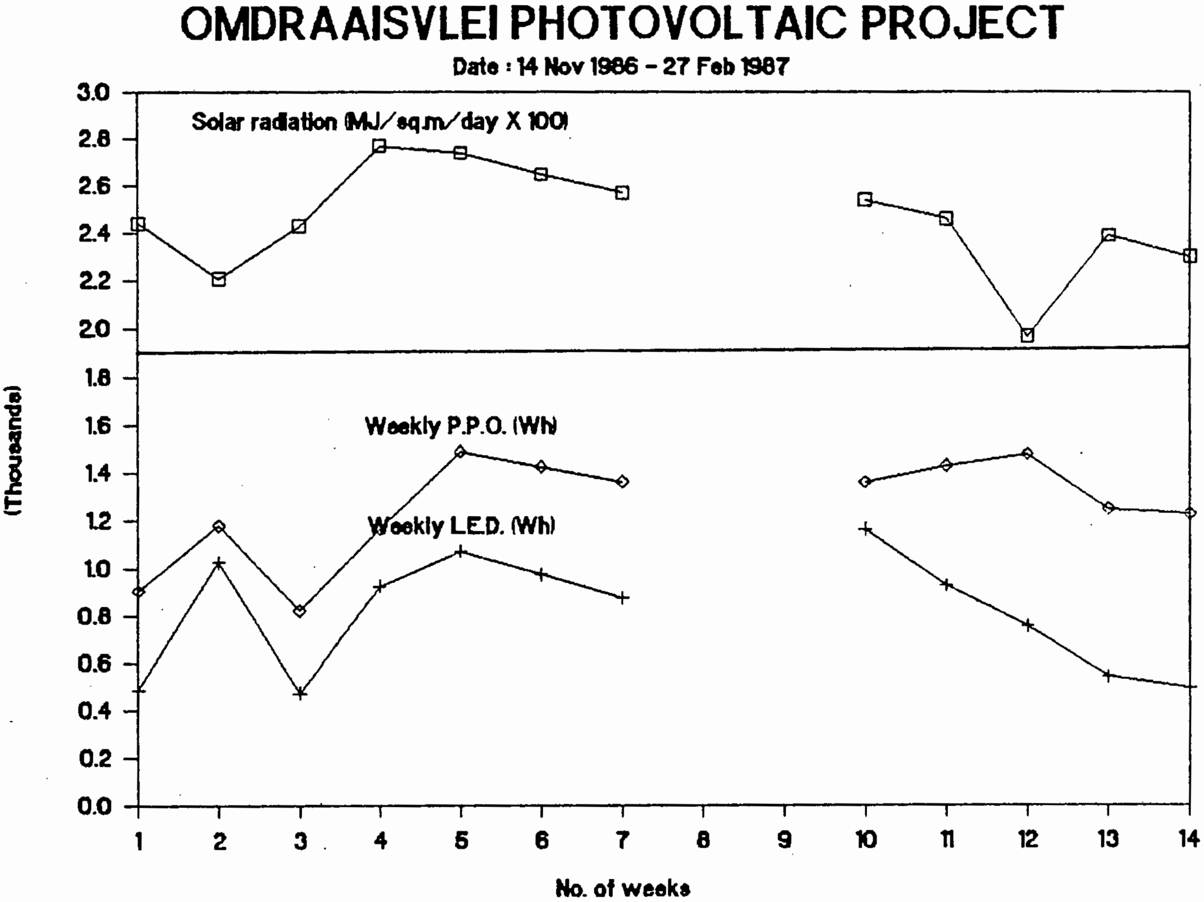



FIGURE 5.13 : Omdraaisvlei - overall system performance

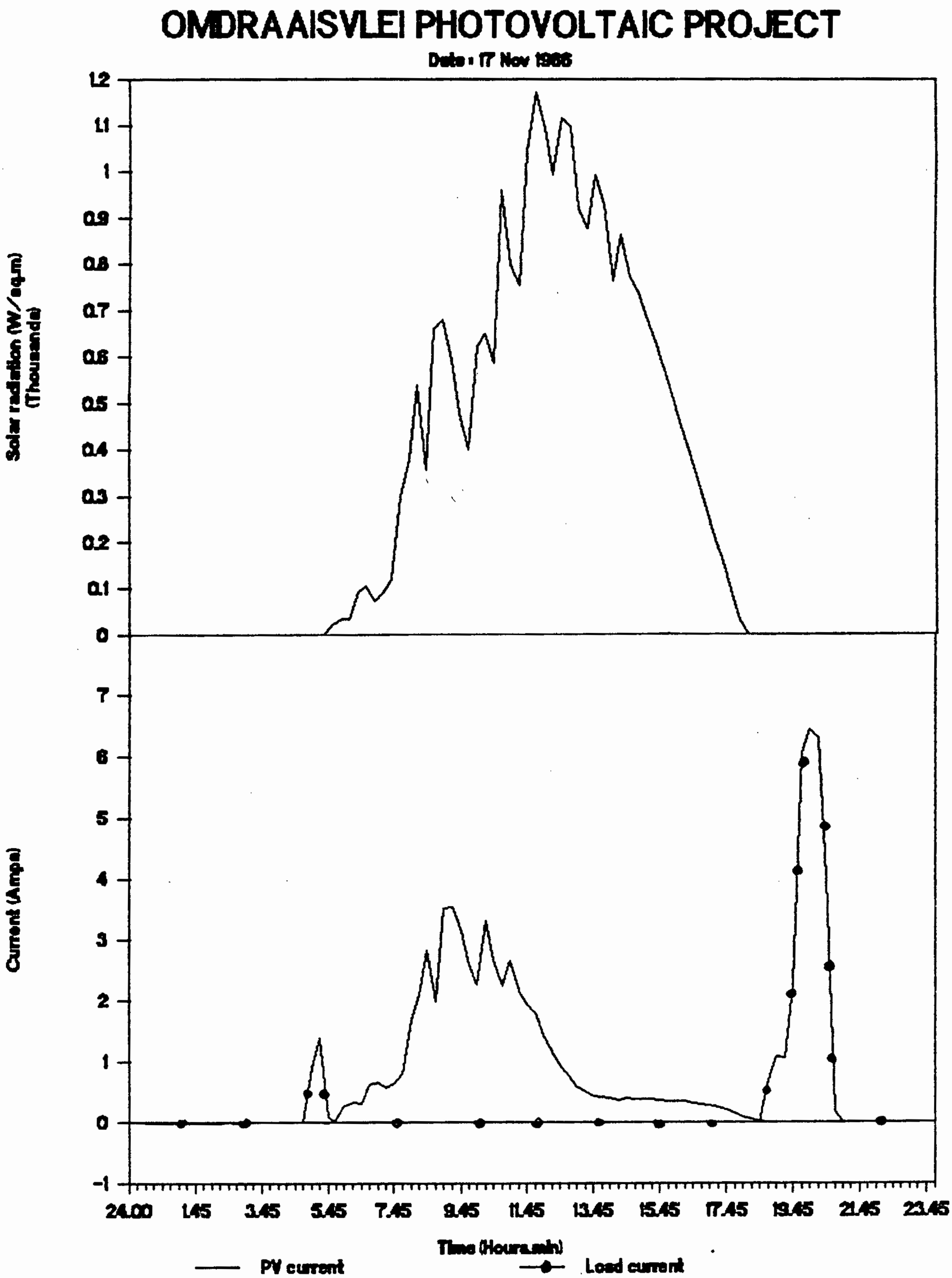



FIGURE 5.14 : Typical days - solar radiation, PV- and load current

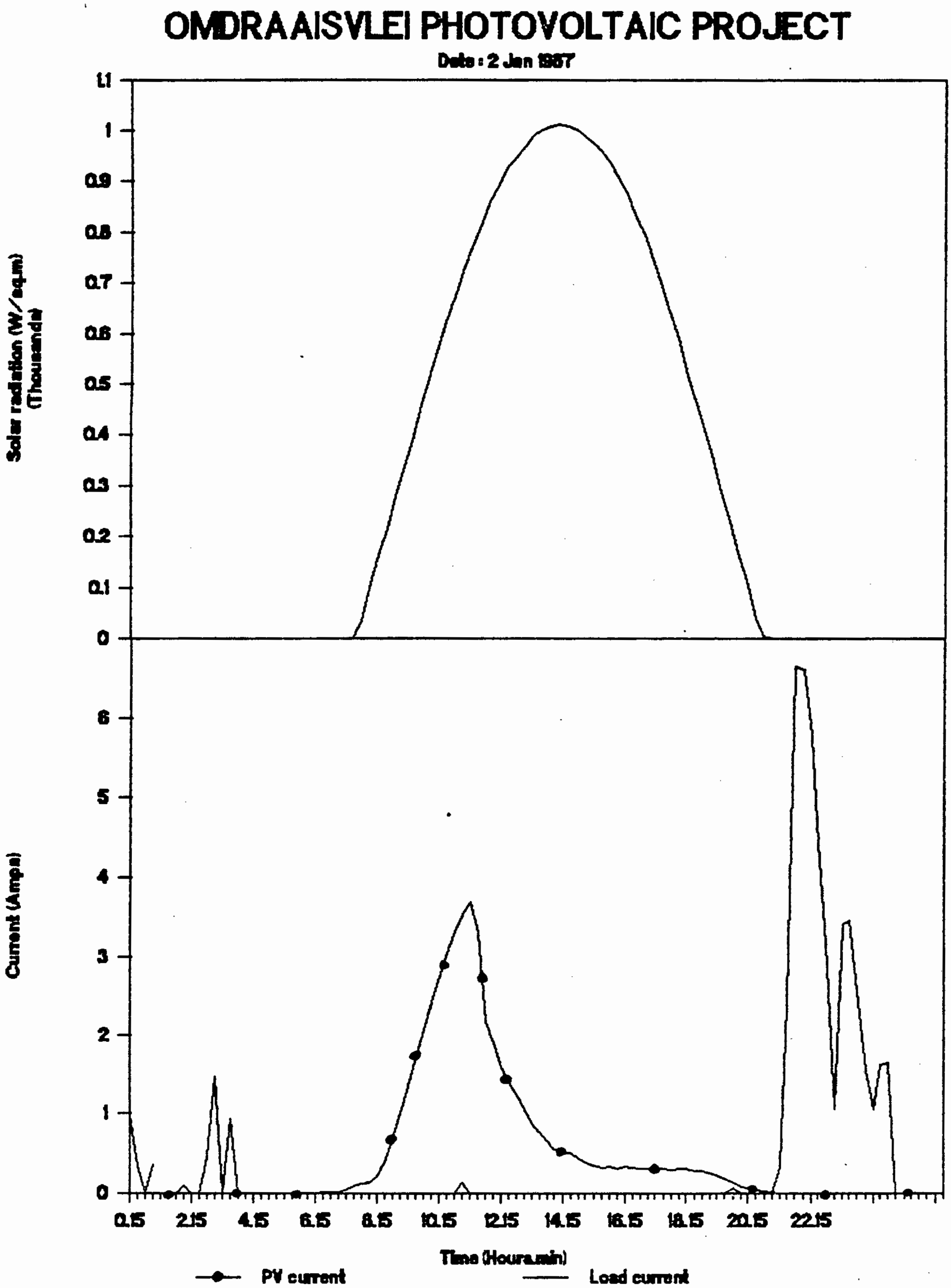



FIGURE 5.15 : Typical days - solar radiation, PV- and load current

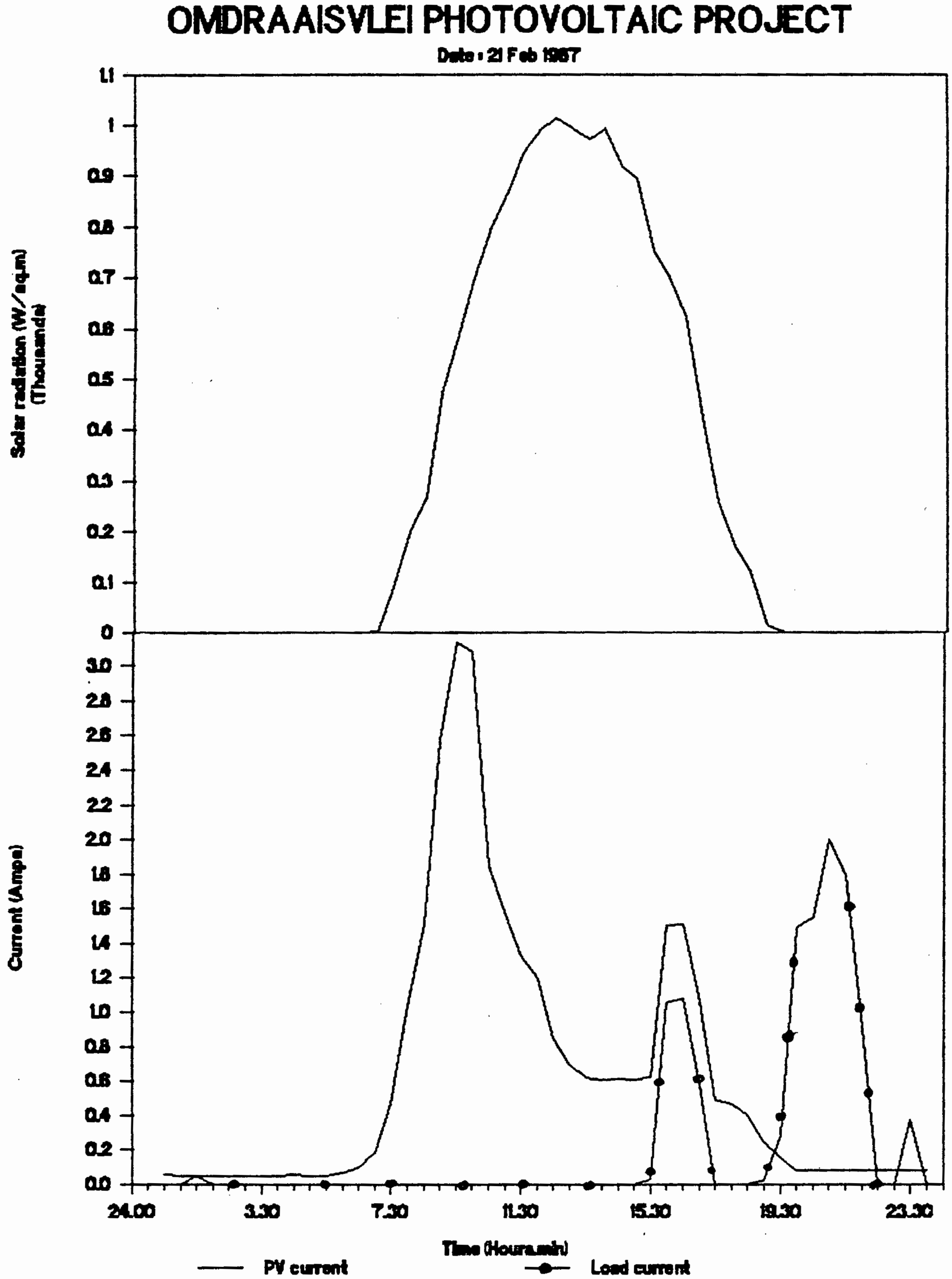



FIGURE 5.16 : Typical days - solar radiation, PV- and load current

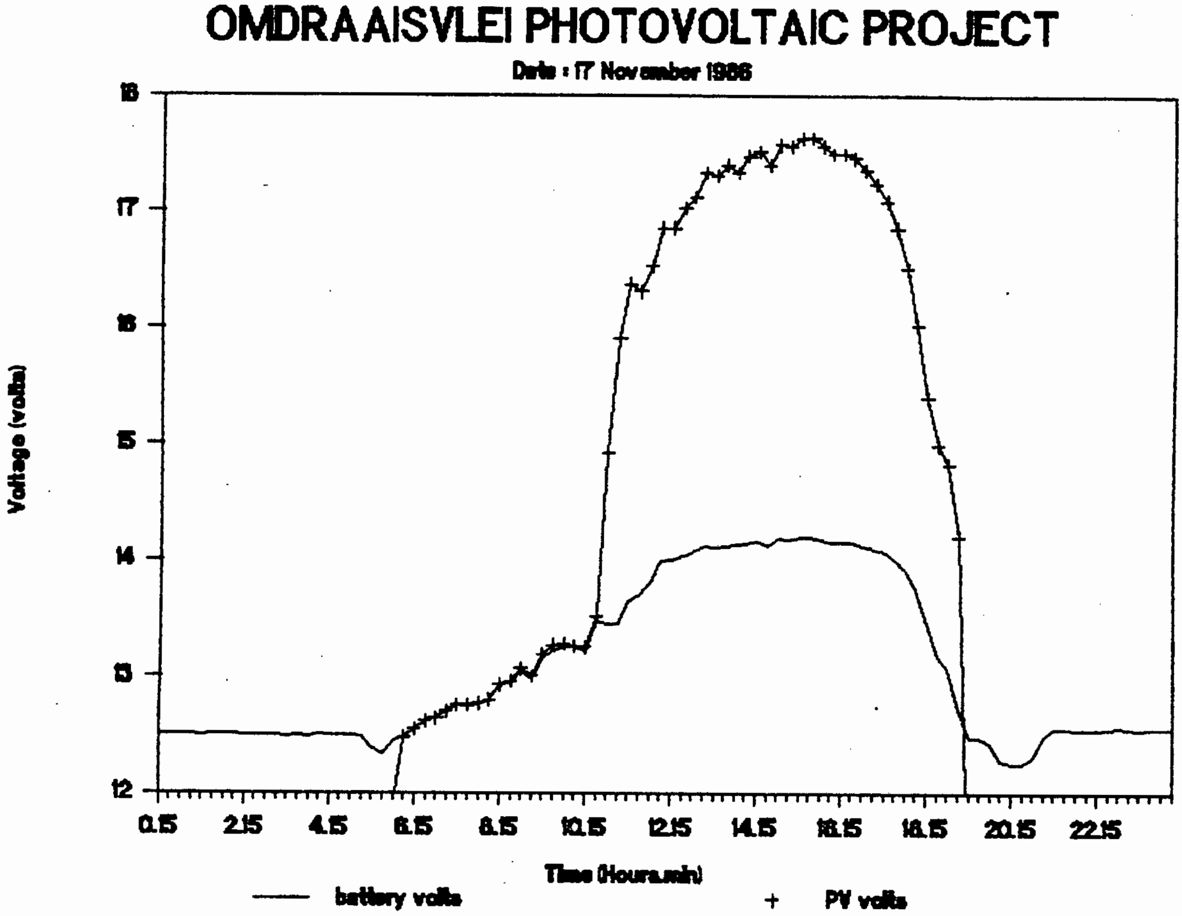



FIGURE 5.17 : Typical days - PV- and battery volts

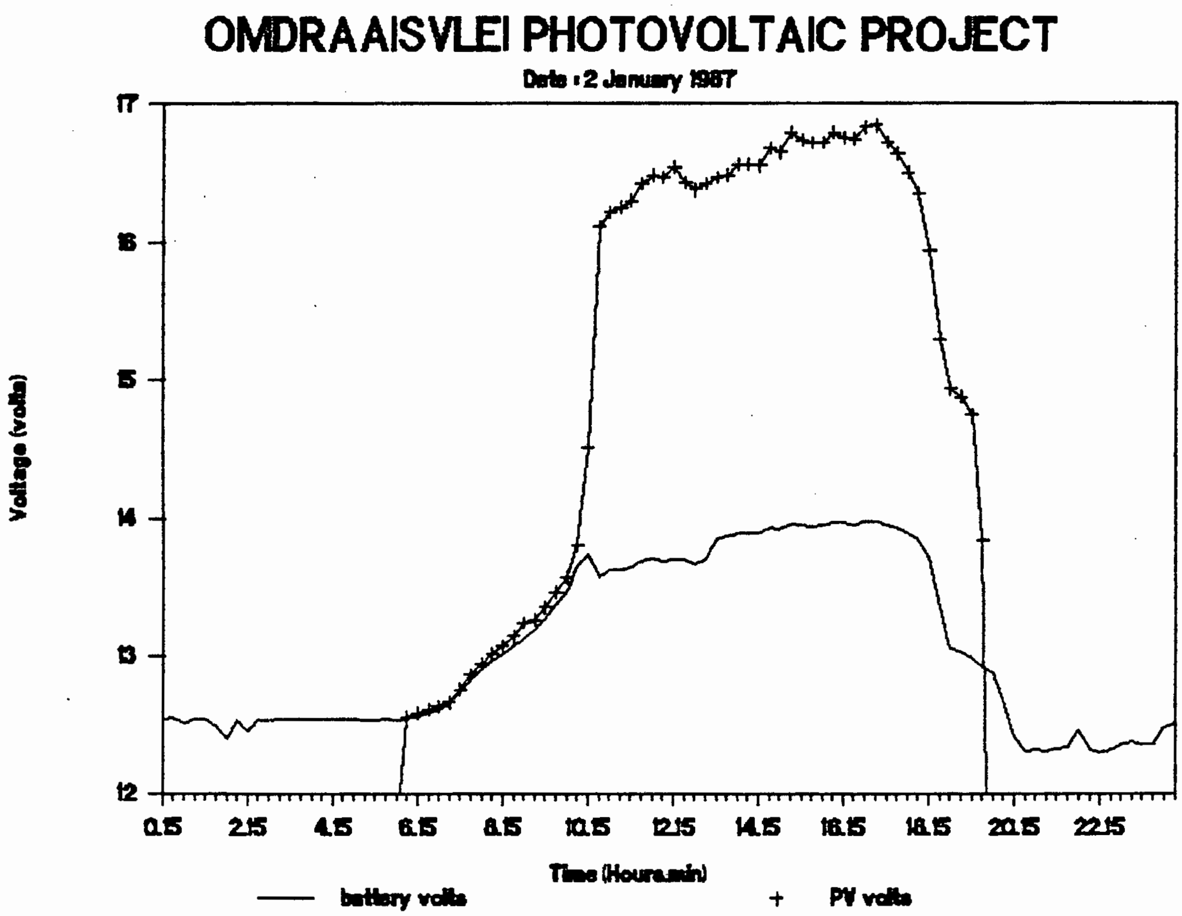



FIGURE 5.18 : Typical days - PV- and battery volts

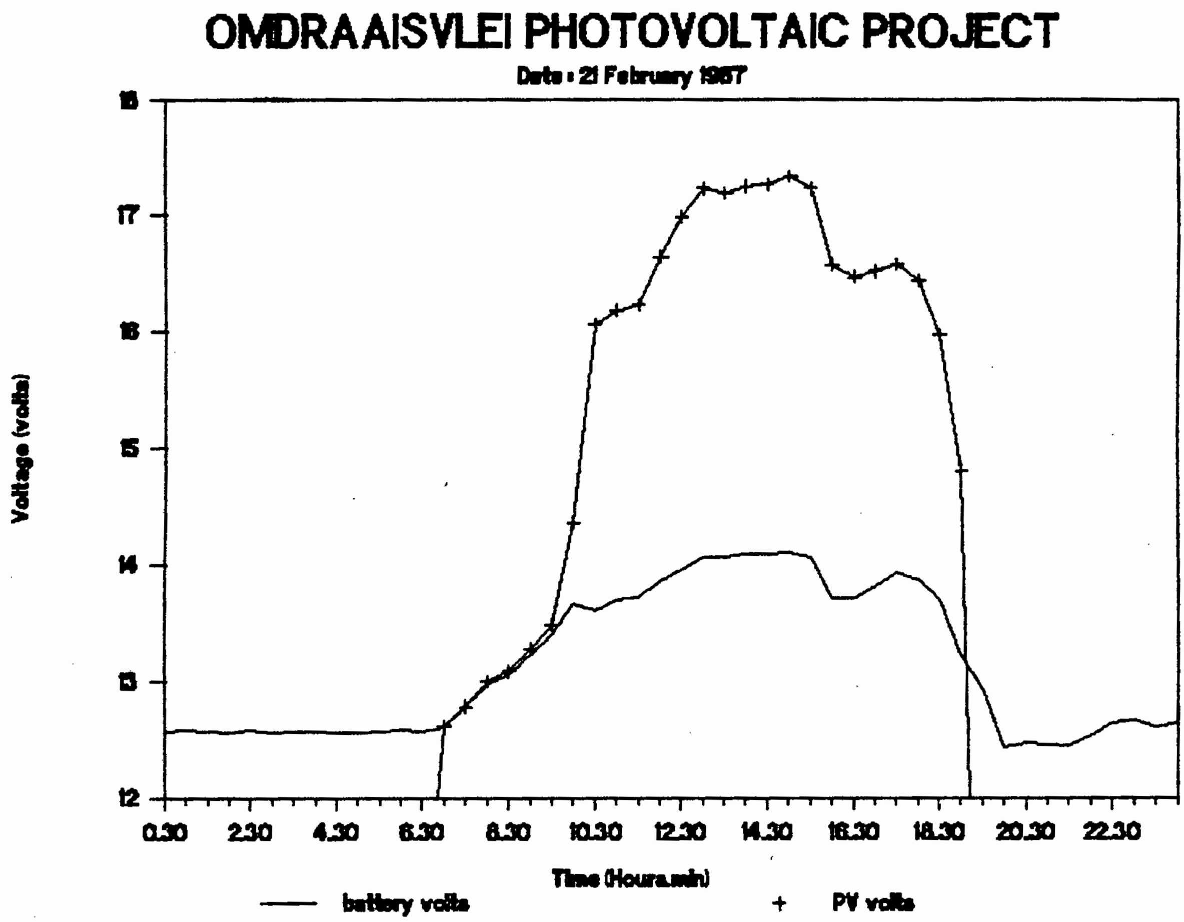



FIGURE 5.19 : Typical days - PV- and battery volts

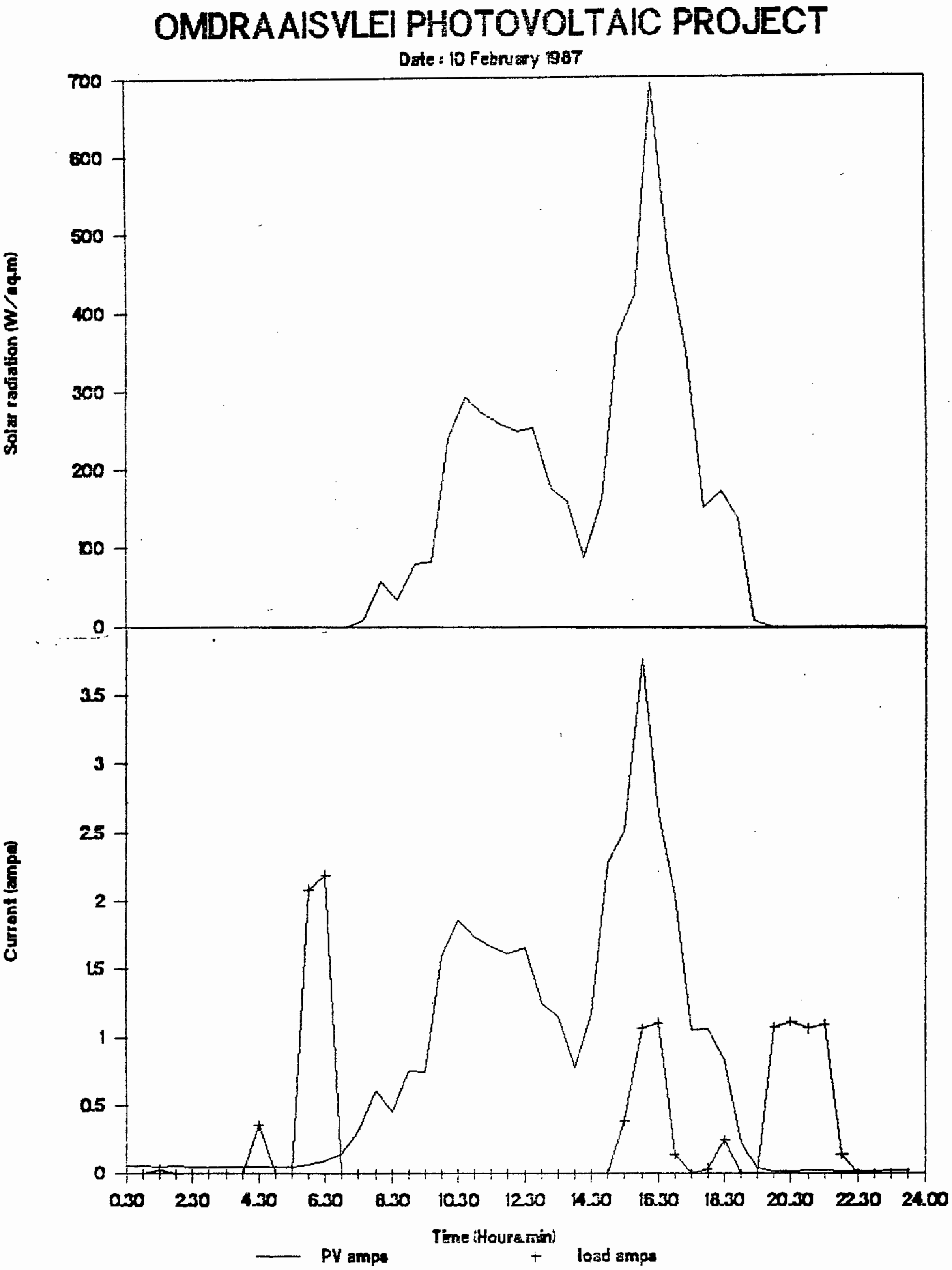



FIGURE 5.2Ø : Bad day - solar radiation, PV- and load current

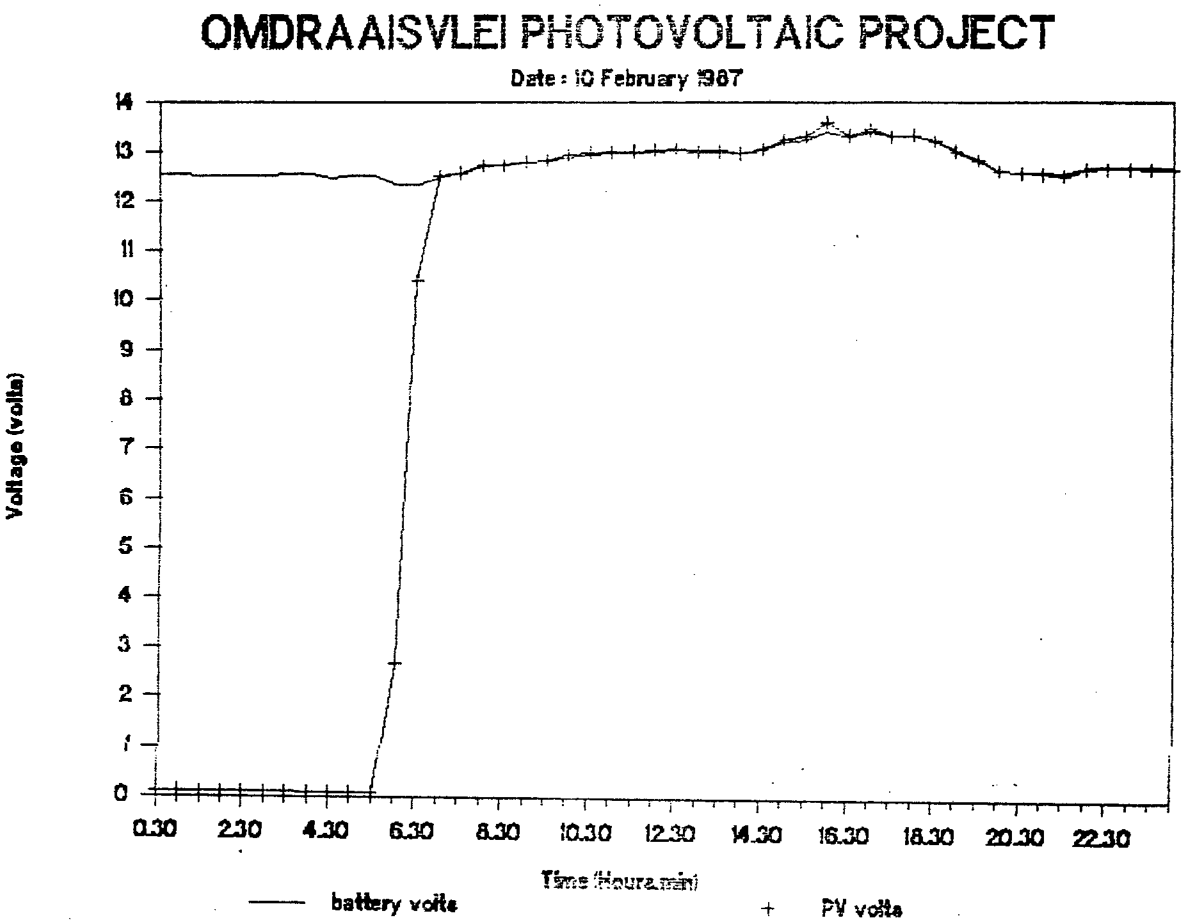



FIGURE 5.21 : Bad day - PV- and load voltages

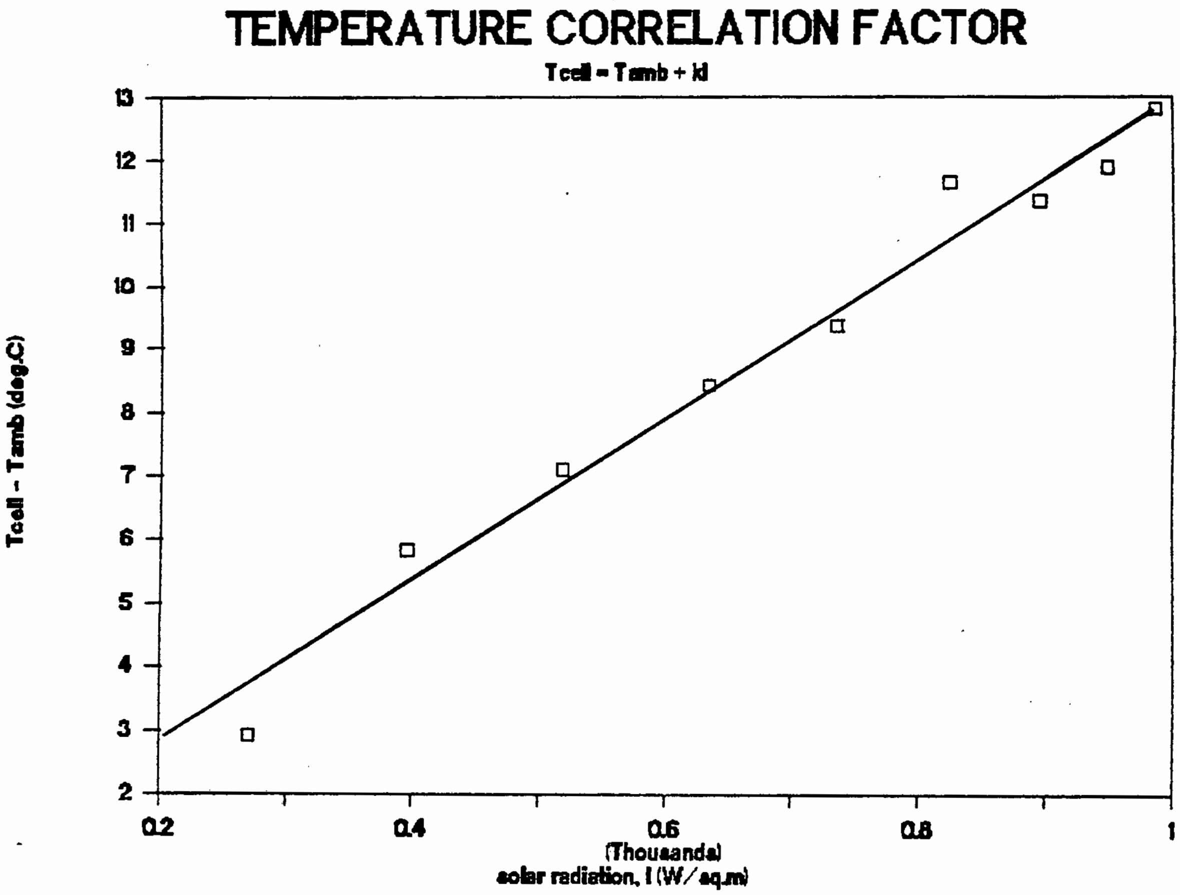



FIGURE 5.22 : Temperature Correlation Constant Determination

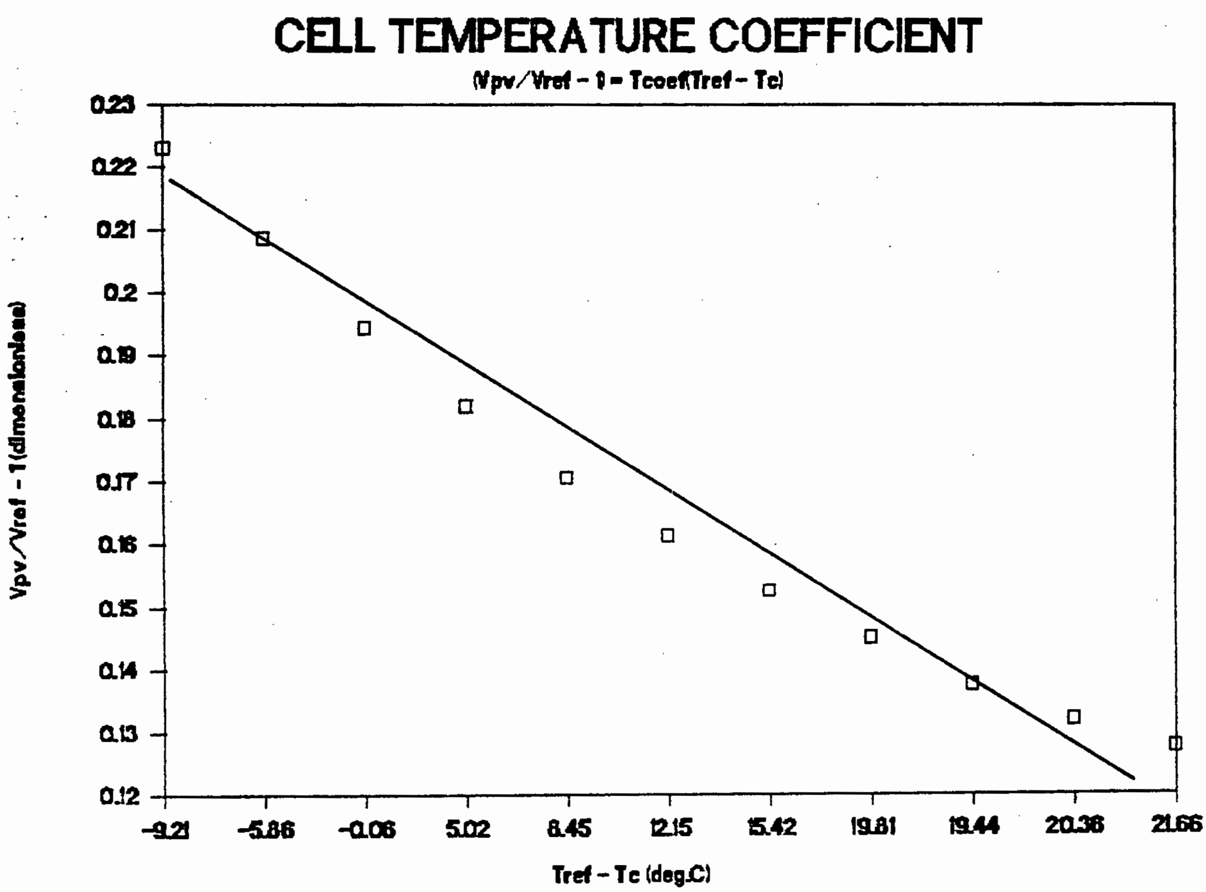



FIGURE 5.23 : PV cell temperature coefficient determination

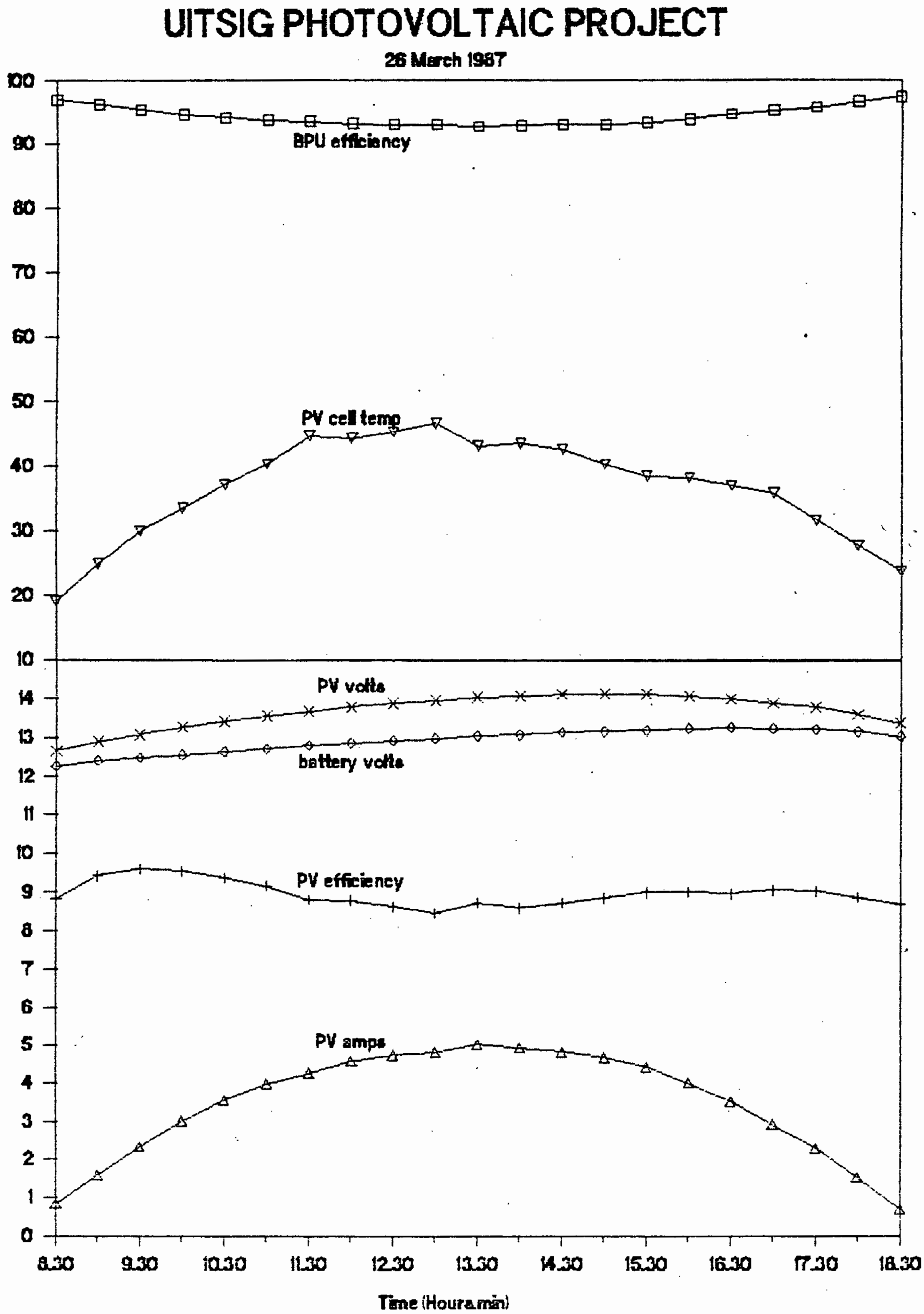



FIGURE 5.24 : Boost-charge operation - PV array and charge regulation efficiencies

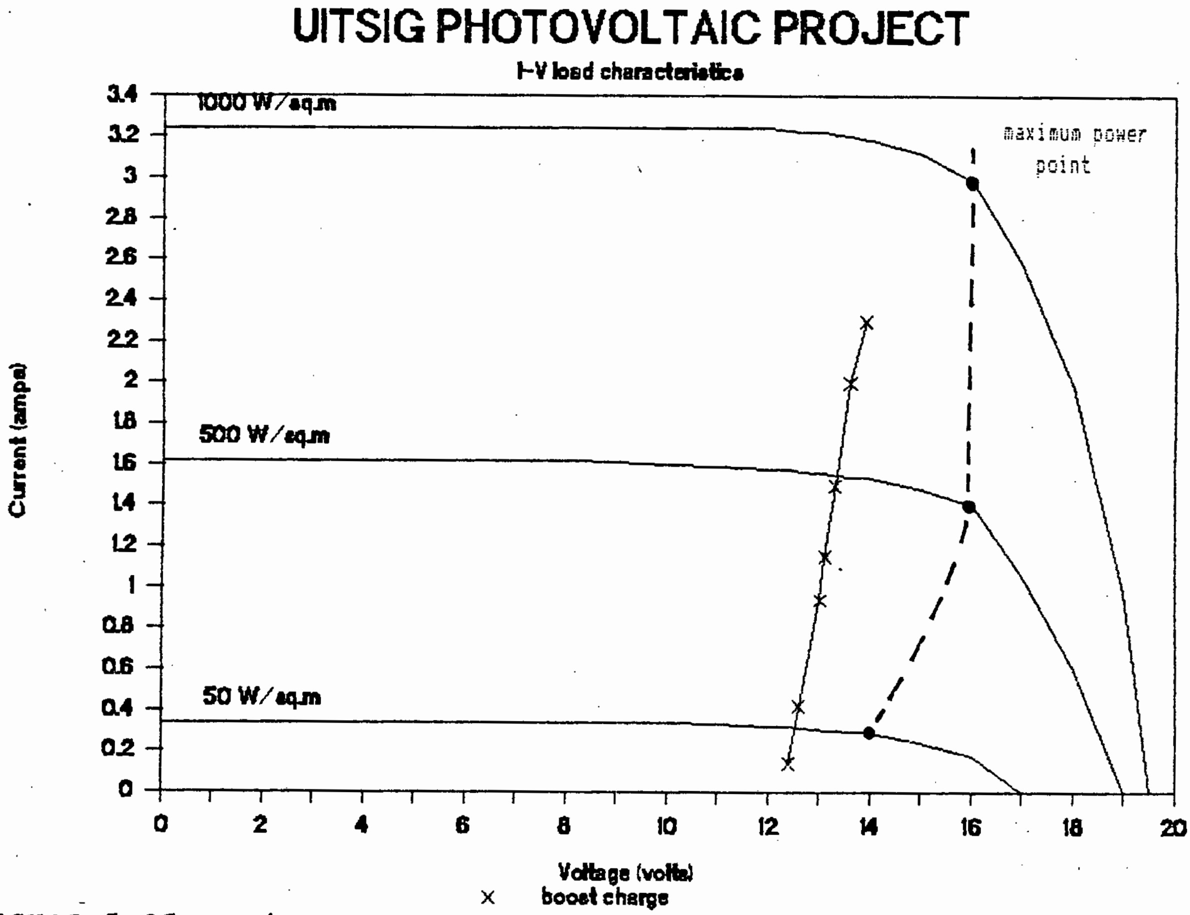



FIGURE 5.25 : I/V Load curve for Uitsig

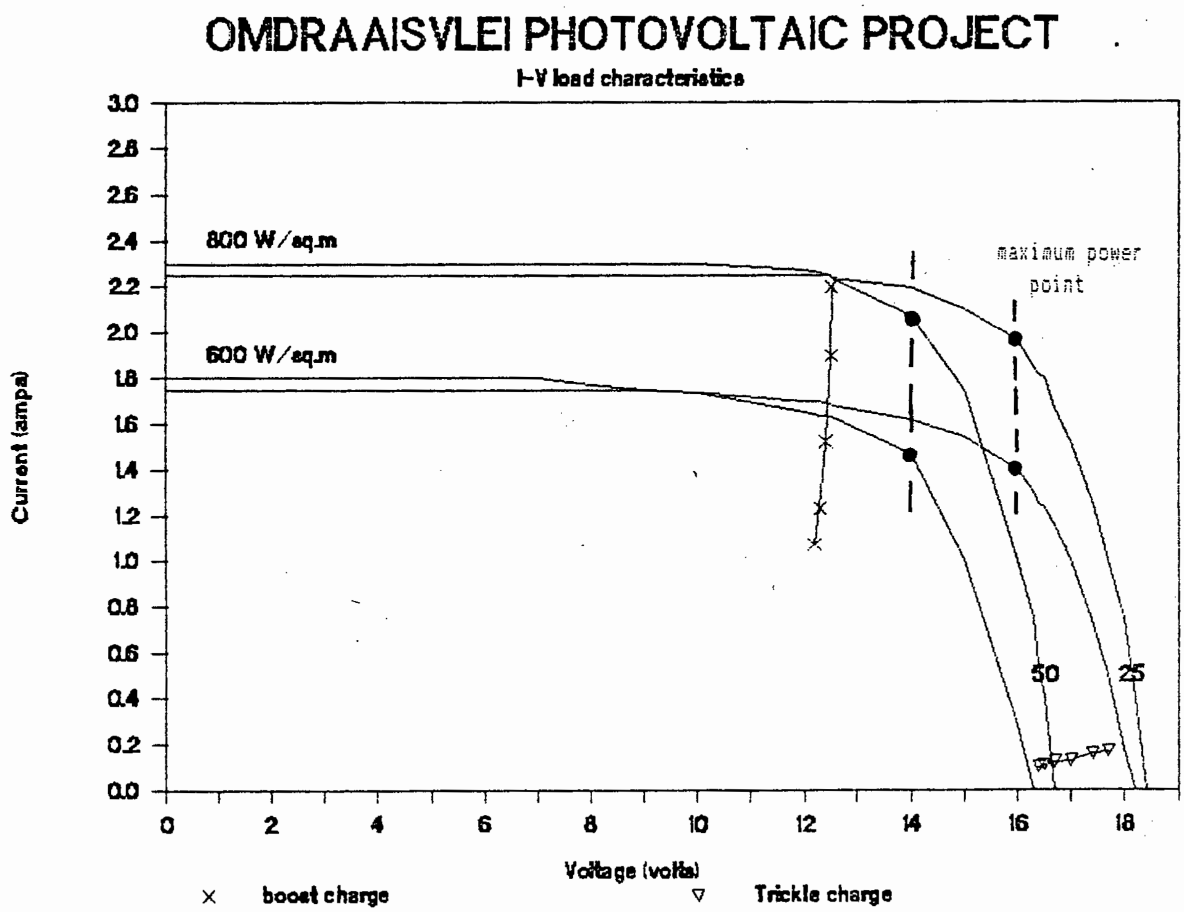



FIGURE 5.26 : I/V Load curve for Omdraaisvlei

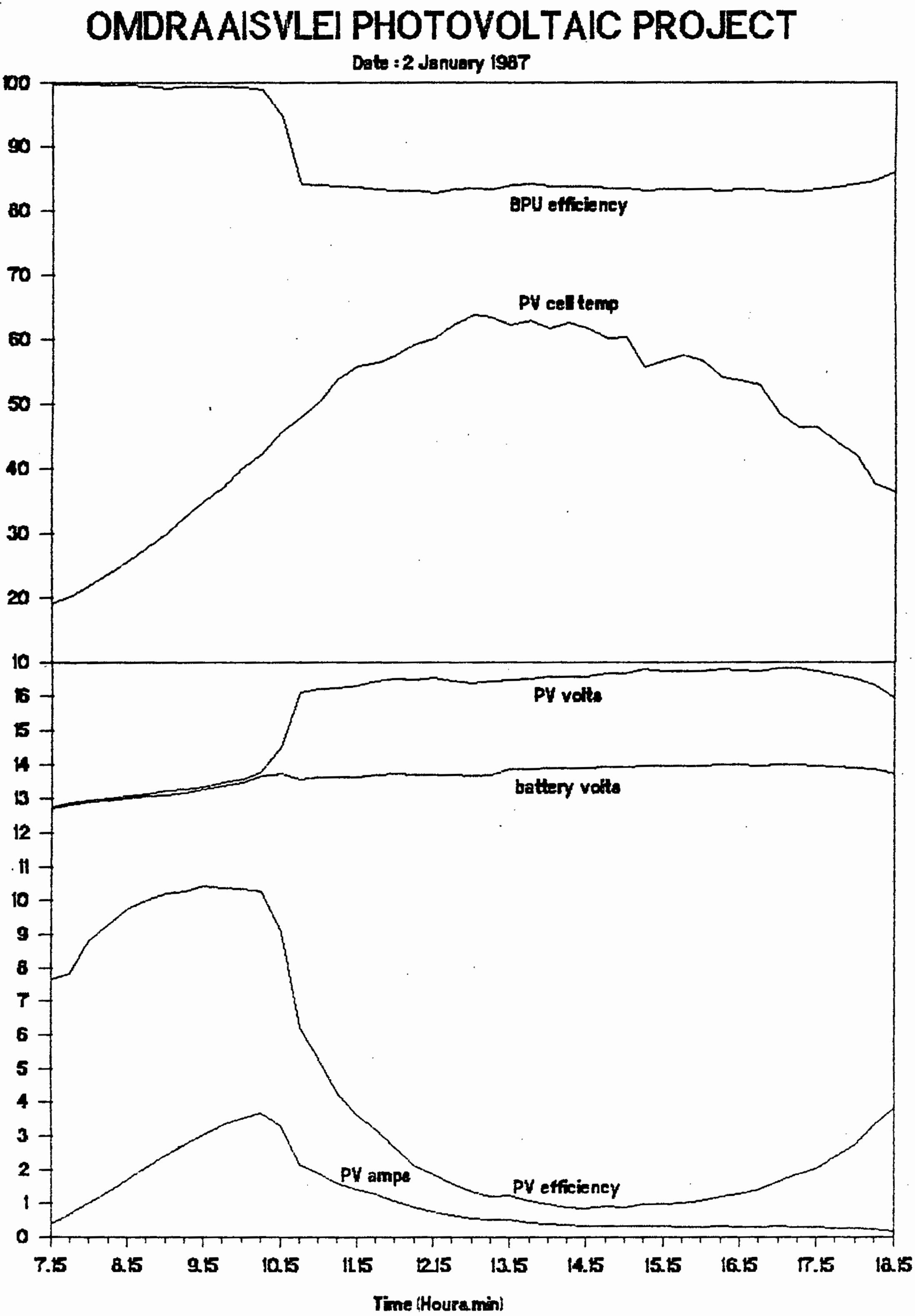



FIGURE 5.27 : Boost-charge operation - PV array and charge regulator efficiencies

## 5.2. ECONOMIC ANALYSIS

As indicated in chapter four, the aim of the economic evaluation is to compare small PV powered systems and alternative power systems, such as petrol or diesel generators or paraffin, candles, and batteries, for domestic power to determine the least-cost option for small power systems under all financial scenarios.

The analysis is based on the total life-cycle costs of competing systems which are discounted to present values and then annualized to arrive at a levelized annual power cost.

### 5.2.1. Capital costs

#### 5.2.1.1. Uitsig photovoltaic system

The Uitsig photovoltaic system components were purchased individually from different suppliers, namely:

| | COMPONENT | | SUPPLIER |
|---|---|---|---|
| (i) | Photovoltaic panels | : | ARCO Solar |
| (ii) | Battery | : | Marathon Battery Centre |
| (iii) | Battery protector | : | Solar Sciences |
| (iv) | Lights | : | Comlite |

The costs of the components are tabulated as follows:

| QUANTITY | COMPONENT | PRICE | TOTAL |
|---|---|---|---|
| 2 | 47 Wp ARCO M75 Modules | R832.20 | 1 664.40 |
| 1 | 10 A Battery Protector | 208.50 | 208.50 |
| 1 | 90 Ah Raylite Battery | 100.00 | 100.00 |
| | | Sub-total | 1 972.90 |
| | | 12 % G.S.T. | 236.74 |
| | | Grand total | 2 209.64 |

Other components which were also purchased are tabulated below. These were not included in the initial capital cost of the PV system as the cost of power supply, storage and regulation only is considered.

| | | | |
|---|---|---|---|
| 4 | 12 VDC, 11 W Lights | 27.00 | 108.00 |
| 4 | Pull switches | 8.00 | 32.00 |
| 1 | Black-and-white TV set | 339.00 | 339.00 |

5.2.1.2. Omdraaisvlei photovoltaic system

For the Omdraaisvlei demonstration project the PV panels and battery were purchased from Semi Conductor Services, and the regulator from an ARCO distributor.

| QUANTITY | COMPONENT | PRICE | TOTAL |
|---|---|---|---|
| 2 | 41 Wp M.SETEK MSP103 Modules | R760.75 | 1 521.50 |
| 1 | 20 A Battery Protector | 172.66 | 172.66 |
| 1 | 98 Ah SABAT Battery | 100.00 | 100.00 |
| | | Sub-total | 1 794.16 |
| | | 12 % G.S.T. | 215.30 |
| | | Grand total | 2 009.46 |

Once again, only the power generating equipment costs are included in the initial capital cost outlay. The load appliances, together with their costs are tabulated below.

| | | | |
|---|---|---|---|
| 2 | 12 VDC, 11 W Lights | 27.00 | 54.00 |
| 4 | 12 VDC, 20 W Lights | 58.00 | 232.00 |
| 4 | Pull switches | 8.00 | 32.00 |

Realizing the potential for small PV-powered systems for home power applications in South Africa, various suppliers have started marketing standardized photovoltaic packages to provide power for minimal electrical requirements. A description of these systems as well as their costs are shown in APPENDIX C.

5.2.1.3. Alternative generating system

The most efficient and economic operation for petrol-driven generators supplying small and varying DC loads is not to couple the generator directly with the loads, but rather to charge a battery which supplies loads on demand. This results in shorter running periods at maximum operating efficiency. Furthermore, it was found that for even better efficiencies of operation, an AC/DC petrol-powered generator could be used by operating DC loads on the rectified AC component of the output while charging a battery on the DC component. When the battery is fully charged, the generator is switched off and the load is met through the battery until a battery protection unit disconnects the load, indicating the need for a new charge cycle.

Although the peak power required by the load at Uitsig is only 60 W, the smallest available petrol generator is typically rated at 200 W. The unit which was selected was the Honda EG500 Portable Generator, capable of charging a 12 V DC battery. The system configuration and specifications are shown below.

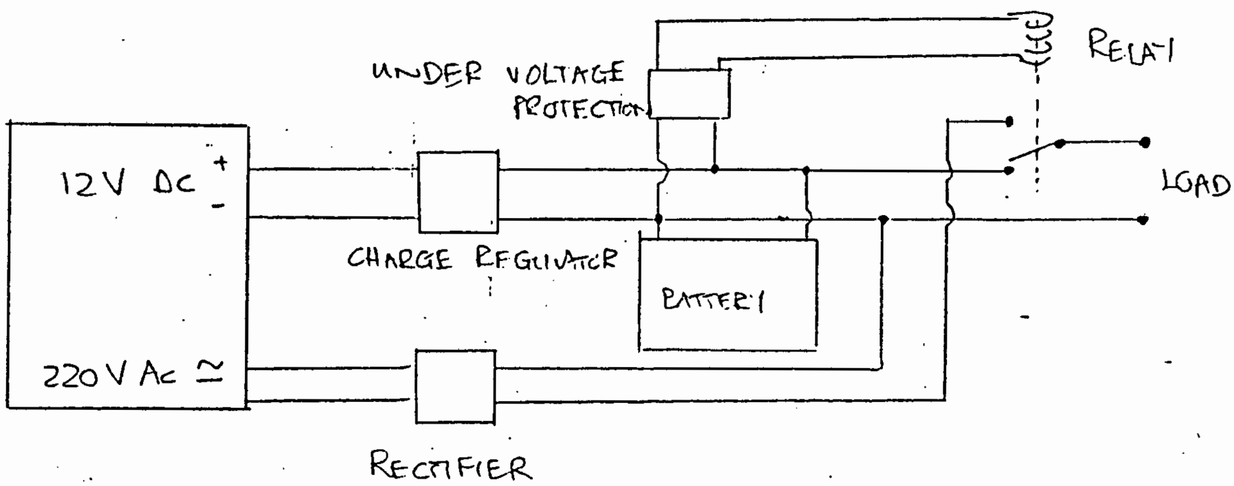



FIGURE 5. 28 : Genset-battery configuration

| | |
|---|---|
| Generator | : Honda EG550 |
| Type | : 4-stroke, air cooled |
| Fuel consumption | : 1.3 litres/2.6 hrs (450 W output) |

| | |
|---|---|
| Maximum AC output (VA) | : 550 |
| Rated AC output (VA) | : 450 (300 W with DC charging) |
| DC output | : 12 V - 100 W |
| Battery | : 90 Ah |
| Charge regulator | : Solar Sciences |
| Maintenance (after 200 hours operation) | : Lubrication, filters, injector adjustments |
| Life time | : 3000 hours |
| Generator cost | : R 800 excl. GST |
| Battery (98 Ah) cost | : R 100 excl. GST |
| Regulator cost (10 A) | : R 200 excl. GST |

### 5.2.2. Assumptions for base case analysis

The following assumptions were made as a basis for comparison between the PV-powered system and the alternative power systems:

(i) Initial costs: The initial cost of the domestic power system was based on the delivered equipment cost only. Indirect costs, such as engineering, management and contingency fees were considered to be negligible. The costs for equipment installation, site preparation and testing were neglected;

(ii) Recurrent costs: For the PV-powered system, the only recurrent cost considered in the estimation of the life-cycle cost, was for battery replacement. A battery lifetime of three years was assumed in this calculation. The fractional salvage value of the battery was taken as 12 percent, and the labour cost for the battery replacement was considered to be negligible. The real annual escalation rate for storage batteries was taken as 0.0 percent, and the discount rate as 4.0 percent.

No recurrent costs were considered for the petrol-powered generator unit.

(iii) Operating and maintenance costs: For the PV-powered system, the annual operation and maintenance expenditures were assumed to be a fixed percentage, namely 1.0 percent, of the initial costs of the equipment.

The present value of the cost of operation and maintenance procedures was based on a system lifetime of 20 years. The real annual escalation rate was taken as 0.0 percent, and the discount rate as 4.0 percent.

For the petrol-powered generator, the annual expenditures for operation and maintenance are based on:

(a) maintenance: lubrication, filter changes, injector adjustments and labour, which was quoted at +/-R65.00 per 300 hours of generator operation by a supplier.

(b) operation: assuming an average battery efficiency of 85 percent, and given the average daily energy load requirement, the hours of daily generator usage were determined, and based on a fuel consumption rate of 0.65 litres/hour and a fuel price of R0.75 per litre, the average daily fuel consumption and expenditure were calculated. The lifetime of the generator is quoted as 3000 hours of operation.

(iv) Levelized annual costs: The net present value levelized annual cost is based on a real interest rate of 4 percent.

### 5.2.3. Levelized annual cost analysis

The results of the financial analysis are summarized below:

#### 5.2.3.1. Uitsig photovoltaic system

| | | |
|---|---|---|
| Initial cost of the Uitsig PV-system | : | R 2 210 |
| Present value of recurrent costs (battery replacement) | : | 455 |
| Present value of operating and maintenance costs | : | 269 |
| Present value life-cycle cost (20 year lifetime) | : | R 2 935 |

| | |
|---|---|
| Levelized annual cost | : R 216 |
| Levelized electricity generating cost | : 251 c/kWh |

5.2.3.2. Omdraaisvlei photovoltaic system

| | |
|---|---|
| Initial cost of the Omdraaisvlei PV-system | : R 2 009 |
| Present value of recurrent costs (battery replacement) | : 453 |
| Present value of operating and maintenance costs | : 247 |
| Life-cycle cost (20 year lifetime) | : R 2 708 |
| Levelized annual cost | : R 199 |
| Levelized electricity generating cost | : 149 c/kWh |

5.2.3.3. Alternative petrol-powered generator system

The initial capital cost of this system, consisting of a petrol-powered generator plus automotive battery, includes the cost of the generator, a battery and a charge regulator. The average daily load energy demand was 0.366 kWh. The efficiency of the generator was assumed to be 90 percent and the battery efficiency 85 percent. Fuel consumption was estimated at 0.65 litres per hour, and maintenance costs as R65.00 per 300 hours of operation.

The calculated present value costs are summarized as follows:

| | |
|---|---|
| Initial cost of generator-plus system | : R 1 232 |
| Present value of fuel costs, and maintenance costs | : 2 006 |
| Life-cycle cost (1.63 year lifetime) | : R 3 238 |
| Levelized annual cost | : R 2 089 |
| Levelized electricity generation cost | : R 15.64 per kWh |

5.2.3.4. Conventional domestic power system

Another important financial comparison to be made, is between the demonstration PV-powered system and the previous energy supply used by the Omdraaisvlei and Uitsig households.

Both families used paraffin and candles for lighting purposes, and batteries for powering radios and television sets. It was not possible to undertake measurements of energy usage and expenditure in the Omdraaisvlei household before the installation of the PV system; however, the Uitsig household energy consumption pattern was as follows:

| | | |
|---|---|---|
| (i) | automotive battery | : recharged 3 times in 2 weeks |
| | cost | : R3.00 per recharge cycle |
| (ii) | paraffin | : 2 litres per week |
| | cost | : R0.80 per litre |
| (iii) | candles | : 9 candles per week |
| | cost | : R1.00 per packet of six |

Based on these figures, the weekly energy consumption expenditure was R7.60, giving an annual average expenditure of R395. It should be noted that this figure excludes the transport costs to purchase these commodities, as well as the cost of replacing wicks or broken paraffin lamps during the year.

This figure (R395) may be compared to the NPV levelized annual costs for the PV system at Uitsig (R216) and Omdraaisvlei (R149). The improved lighting quality should also be taken into consideration, and should have a significant influence on the purchasing decision. For example, it may be assumed that a 15 W fluorescent light provides approximately 100 lux, while a paraffin lamp provides approximately 10 lux on the same surface. This qualitative benefit is extremely important, although it is not easily quantifiable in terms of financial costs.

Results from surveys undertaken in four non-electrified areas in the Cape Peninsula in 1984 compare favourably with the above estimates. Eberhard (1984) found that the mean annual domestic fuel expenditure for these fuels was R300 for paraffin, R78 for candles and R100 for batteries. Assuming 50 percent of the paraffin is used for lighting purposes, the equavilent expenditure was R328. Assuming a 15 percent increase in fuel costs per year, this value is equivalent to R499 in 1987 figures.

### 5.2.4. Sensitivity analysis

The above financial analysis is based on a number of assumptions and it is interesting to examine the implications of variations in key parameters. For example, the large difference in cost between Uitsig and Omdraaisvlei is largely due to the differences in insolation levels with resultant differences in photovoltaic module area. Thus insolation is an important variable to examine. Other variables which should be considered are the cost of photovoltaics, the use of other types of batteries, variations in the discount rate, and for the petrol generator, variations in the price of petrol.

#### 5.2.4.1. Base case

The following base case (which closely approximates Omdraaisvlei) was selected as the basis for comparison with other cases where key variables were varied.

| | | |
|---|---|---|
| (i) | load demand | : 366 Wh/day |
| (ii) | insolation | : 6 $kWh/m^2$/day |
| (iii) | array cost | : R 20/Wp |
| (iv) | system lifetime | : 20 years |
| (v) | batteries | : tractive, 7 year life |
| | | : R 283.30/kWh |
| | | : Depth of discharge 50 percent |
| (vi) | system efficiencies | : module - 12 percent |
| | | : battery - 85 percent |
| | | : regulator - 95 percent |
| (vii) | LOEP | : 0.1 - array sizing factor 5.05 |
| | | : - battery sizing factor 1.16 |
| (viii) | O + M | : 1.0 percent of initial costs |
| (ix) | real discount rate | : 4 percent |
| (x) | zero real escalation rate in equipment replacement costs | |

#### 5.2.4.2. Parameter variation

(i) The following insolation levels were considered: 3, 4, 5 and 6 $kWh/m^2$/day.

(ii) Capital cost of the PV module:
The costs of PV modules has fallen from $130/Wp in 1970 to $9/Wp in 1980 to $5/Wp at present. Although exchange fluctuations between the Rand and Dollar reversed this cost trend in 1985 and 1986 in South Africa - the momentum for falling local costs is now continuing. The expectation is that increased production and new technical innovations, such as thin film amorphorous silicon and high efficiency crystalline cells will result in further cost reductions. Module costs of 3, 5, 10, 15 and 20 R/Wp were considered in the sensitivity analysis.

(iii) For the two demonstration projects, automotive (SLI) type batteries were used. These are far from ideal, as they are not designed for deep discharge cycles, but they are cheap. Latest costs are R 132/kWh. A lifetime of three years has been assumed although there is much uncertainty as to how long they will in fact last.

It is worthwhile to look at more appropriately designed batteries which last much longer but are more expensive.

Tractive type batteries cost R 283.30/kWh and are likely to last 7 years at 50 percent discharge cycle depths.

Specially designed photovoltaic batteries cost R 430.50/kWh, may last 10 years and can be discharged to more than 40 percent of capacity.

(iv) There is always much debate as to which discount rate should be selected. The following real discount rates were considered: 2, 4, 10 and 15 percent.

(v) For the petrol generator, the variable most likely to change is the price of petrol.

### 5.2.4.3. Sensitivity analysis results

| Parameter Variation | Life Cycle Costs Rands | Annualized Unit Cost Cents/kWh |
|---|---|---|
| Photovoltaic system | | |
| Module cost | | |
| 3 Rand/Wp | 1094.92 | 60.31 |
| 5 | 1298.95 | 71.55 |
| 10 | 1809.00 | 99.64 |
| 15 | 2319.06 | 127.73 |
| 20 | 2829.11 | 155.83 |
| Battery type | | |
| Automotive | 2961.61 | 163.13 |
| Tractive | 2829.11 | 155.83 |
| Photovoltaic | 2785.91 | 153.45 |
| Insolation | | |
| 3 $kWh/m^2/day$ | 7357.95 | 405.28 |
| 4 | 5124.55 | 282.26 |
| 5 | 3709.21 | 204.30 |
| 6 | 2829.11 | 155.83 |
| Discount rate | | |
| 2 percent | 2955.43 | 135.30 |
| 4 | 2829.11 | 155.83 |
| 10 | 2590.65 | 227.78 |
| 15 | 2482.32 | 296.86 |

Comparison to a petrol generator

| | | |
|---|---|---|
| Petrol escalation rate | | |
| -5 percent | 3108.34 | 1501 |
| 0 percent | 3238.44 | 1564 |
| +5 percent | 3371.29 | 1628 |
| Petrol discount rate | | |
| 2 percent | 3290.21 | 1549 |
| 4 percent | 3238.44 | 1564 |
| 10 percent | 3096.65 | 1609 |
| 15 percent | 2991.97 | 1647 |

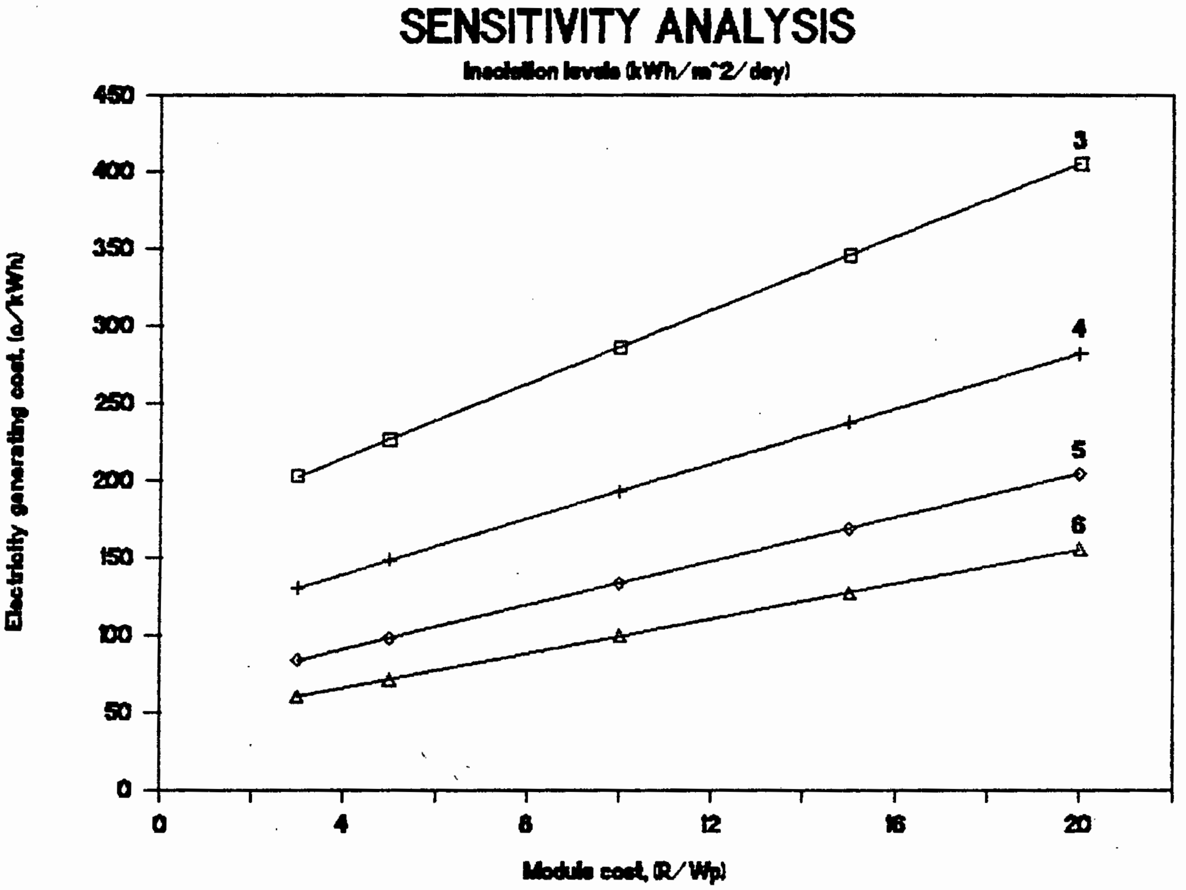



FIGURE 5.29 : PV system generating costs at different

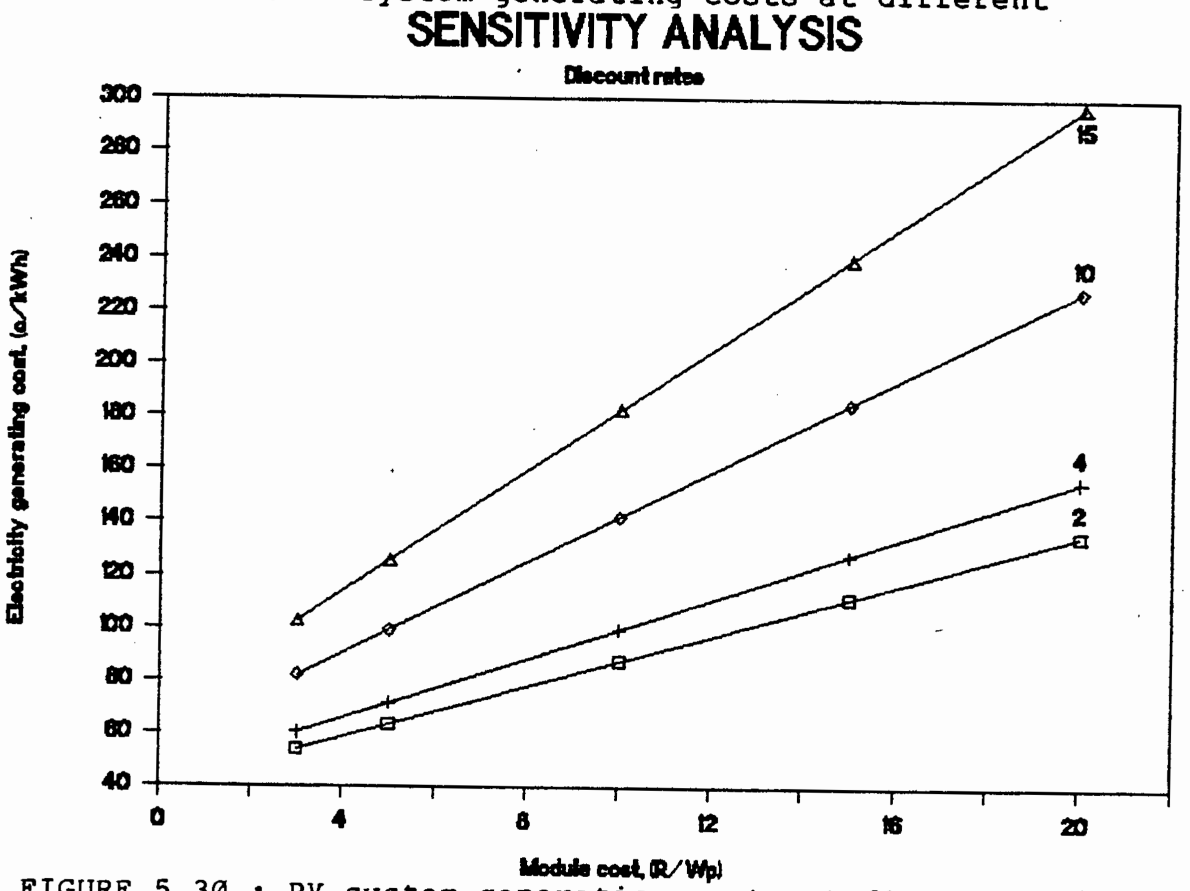



FIGURE 5.30 : PV system generating costs at different discount rates and module costs

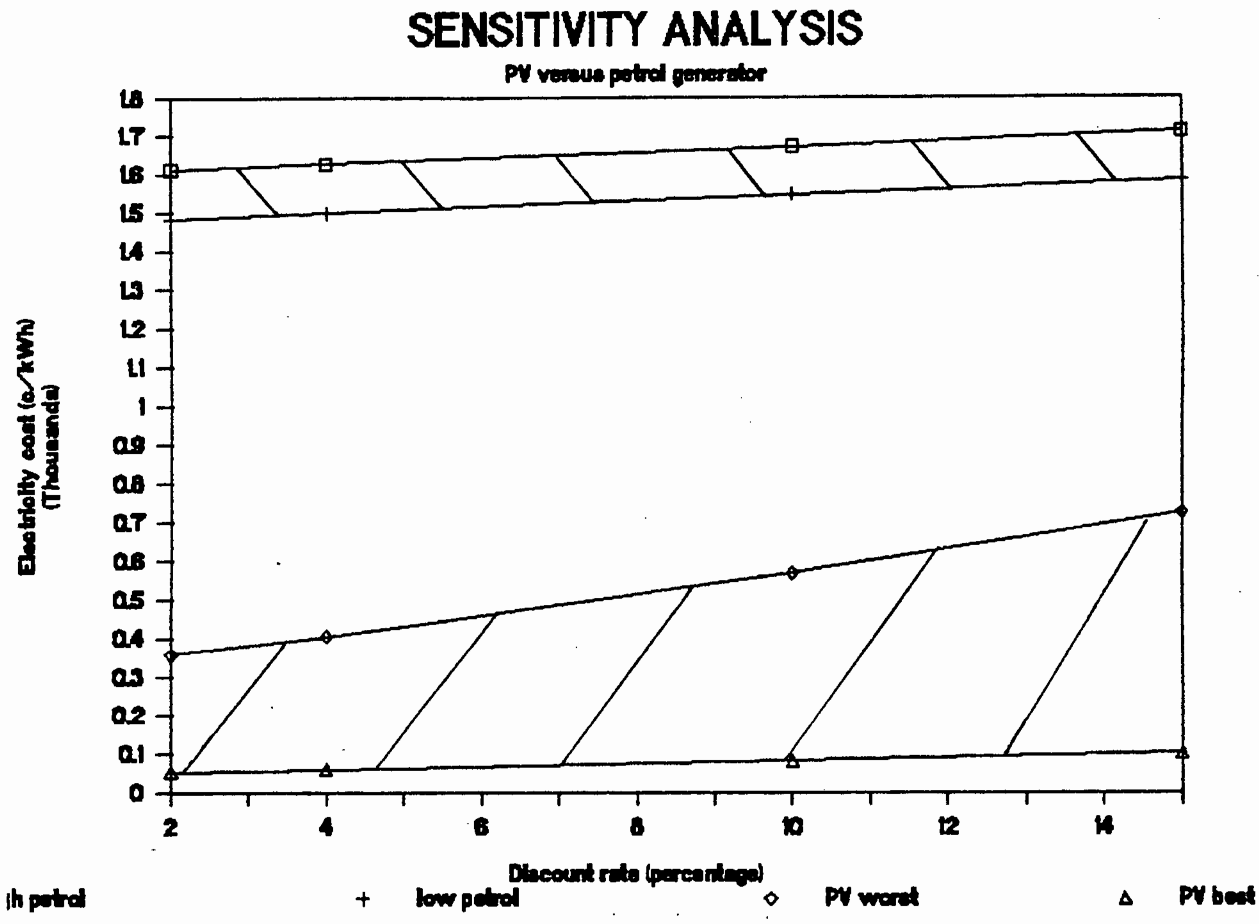



FIGURE 5.31 : Electricity generation costs for PV and petrol generating systems

5.2.4.4. Discussion

It is interesting to note that the use of different types of batteries has relatively little effect on the cost of PV electricity.

The selected discount rate has the predicted effect with capital intensive systems such as photovoltaics being favoured at lower discount rates compared to petrol generators where higher running costs result in the opposite trend.

Insolation levels are a critical parameter in PV generating costs, but the most sensitive factor is the cost of the PV modules themselves.

It is sobering to note that even with a module cost of R3/Wp the generating cost is still relatively high at 60 c/kWh. This would seem to imply that small stand-alone photovoltaic systems are not likely to ever be competitive with grid-supplied electricity, and that viable applications will continue to be restricted to the off-grid market.

It should also be remembered that this cost is for small stand-alone installations and that a completely different figure is likely for larger concentrating systems.

In all cases, examined above, photovoltaics are more cost effective (and convenient) than petrol-driven generators.

## 5.3. SOCIAL EVALUATION

The following issues were examined:

(i) the proportion of the monthly household income spent on energy consumption before the PV system was installed;

(ii) the convenience/inconvenience of either system;

(iii) the effect of the PV system on the household's life-style, their standard of living and the aspirations of the family;

(iv) the neighbours' response to the PV system; and,

(v) the possibility of securing amortizing loans to cover the high capital costs of the PV system.

This information was gathered from informal interviews with the households at the demonstration project sites.

### 5.3.1. Proportion of household income spent per month

In the Uitsig household the total income per month was R384. This figure was calculated from the weekly salaries, a pension and a disability grant received by family members. The average monthly fuel cost for paraffin, candles and batteries was R30. This figure excludes the cost of gas, since gas was used only for cooking purposes. If, however, the gas expenditure is included, the average monthly fuel cost would be R80. This implies that approximately 20 percent of this household's monthly income was spent on energy consumption before the PV system was installed.

It was not possible to determine household income for the Omdraaisvlei household because the family income was supplemented with farm produce, which differed with the season. An added problem was that families in the area also used dry wood and twigs for wood stoves which they collected around the farm. It was not possible to quantify this amount since its use varied considerably from month to month. Gas was also supplied by the farmer.

### 5.3.2. Problems associated with fuel usage

There were many complaints surrounding the use of traditional fuels. The major problem was the cost of these fuels. People interviewed felt that fuels were very expensive, and sometimes they were not able to afford them towards the end of the month. In Uitsig they felt that taking the battery to the garage to be recharged was inconvenient because it was difficult to carry, and the garage was a considerable distance away.

People also complained of the potential fire hazard associated with the use of traditional fuels. They were acutely aware that every year there were many people, particularly children, who suffered severe burns from candles or paraffin or gas appliances.

Another problem, was the paraffin smell and the candle smoke. This strong odour permeates clothing, making the person wearing the garment feel dirty and uncomfortable. People also felt that the smell and the smoke caused bronchial problems which meant expensive medical bills.

In Uitsig, where living conditions are crowded, people found that the bad light caused them to bump into each other and into objects, which often resulted in arguments and unpleasantness.

### 5.3.3. Convenience of using photovoltaic energy

Both household found that the photovoltaic-powered lights provided good lighting. They felt that this was particularly important since there were school children in both households. This meant that the children were now able to do home work at night, as well as prepare for tests and examinations.

In Uitsig, a television was installed with the PV system. This household found the introduction of TV into their home to be a great convenience. It provides an entertaining form of recreation for the elderly members of this household, who previously had nothing else to do (sic).

People also felt relieved that the potential fire hazard had been removed and that they no longer had to endure the strong paraffin odour and the candle smoke. They also felt easier about inviting friends and neighbours over for social get-togethers. They found that the lights made the room appear much bigger than it previously seemed by candle light.

One problem, explained by the Omdraaisvlei household, was that the bright lights attracted many insects. This did not occur previously; however, the problem was to be rectified by placing wire gauze shields over the doors and windows.

### 5.3.4. Life-style and standard of living

Both households reacted very positively towards the PV systems. At Omdraaisvlei, the family initially was mystified by the PV system and afraid to use it extensively because they were concerned that the lights would not work if they used it too much. This fact highlights the problem this household experienced using traditional fuels - they were forced to use their energy very sparingly to ensure that it would last the month. This was not always possible and there were times when they ran short. They employed this same notion for the PV system initially; however, they have since learnt that they have far more energy available with the PV system than they had initially.

Both households found that the lights were very convenient for cooking at night or early morning, especially in winter. They found that they stayed up later, especially over weekends. The lights permitted them to do many activities that were not previously possible. For example, they could read, write or knit at night without strain. It was also possible to entertain in more comfortable surroundings. At Omdraaisvlei, it was pointed out that there was also the possibility of working on small home industries at night.

Both households also pointed to the benefit the lights would have on the education of their children. They felt it was now possible for the children to put in extra work on their studies at night, thus enabling them to do better at school.

In summary, both households found that the PV system had changed their life-style by introducing them to a variety of new experiences which were not previously possible, and at the same time had improved their standard of living considerably.

### 5.3.5. The neighbours' response

At Omdraaisvlei, the neighbouring farm labourers were very impressed with the PV-powered system. Since the installation of the first system, a further system has been installed in another household, providing power for two lights. Local farmers in the area have also shown an interest in these systems, and have also examined the possibility of home improvements for their labourers.

At Uitsig, the neighbours were also impressed by the system. They were particularly impressed by the quality of lighting and the many new activities which were now possible. Many have enquired how the system was procurred, and were interested to know more about the cost and installation of the system.

In summary, it appears that these PV systems generated public interest in the areas where they have been installed. Everyone responded positively to the system. They were especially impressed by the quality of the lights and the instantaneous availability of power at any given time.

### 5.3.6. Special financial arrangements

Although the levelized annual costs of small photovoltaic systems for off-grid households are attractive compared to the alternative of petrol generators, the major costs are incurred with the initial purchase of the photovoltaic panels and many households cannot afford these without special financial arrangements which spread the initial payments over an acceptable period.

Some PV suppliers are offering financial schemes to purchase small PV systems. An example of one such scheme is the package which consists of one photovoltaic module, an automotive battery, charge regulator and two 20 W lamps, and costs R550. This amount can be paid off over a maximum period of two years through a hire-purchase agreement concluded with the supplier. The idea is that the home owner starts with this system and extends it, as his/her financial situation improves, to a large system: for example, one consisting of four solar modules, six 20 W lamps, an automotive battery, charge regulator, and two 12 V wall socket power outlets for a radio, television or refrigerator. This system costs R4000 and can be paid off at R280 per month over a period of two years.

These hire purchase schemes usually incorporate very high interest rates. A more appropriate channel would be building society or bank loans for home-improvements. Some employees receive employer subsidies for home loan repayments.

However, a major problem is that most black families do not own their own homes and would thus not be eligible for home loans. The challenge of widespread use of photovoltaics for low-income off-grid households and informal settlements is thus closely linked to the national housing problem and the access of poor households to adequate security of tenure and finance.

# CHAPTER 6

# CONCLUSIONS AND RECOMMENDATIONS

## 6.1. TECHNICAL ISSUES

One of the first conclusions from an analysis of the performance of the two demonstration projects, was that, in spite of careful design procedures, the Uitsig installation was undersized and the Omdraaisvlei project, grossly oversized - the former because of unusually low winter insolation levels in Cape Town over 1987 and higher than expected energy consumption, and the latter because of conservative energy usage. This experience highlights two important factors which are important in the design of small PV systems.

### 6.1.1. Solar insolation data

Firstly, it is important to obtain accurate solar insolation data. It is no use striving to ever higher cell efficiencies (where maximum improvements of an additional 6 percent efficiency are expected over the next few years) when solar radiation data may be overestimated by up to 20 percent. It seems apparent that solar radiation data for Cape Town which has hitherto been published is too high. A recent project at the ERI which has carefully screened solar radiation data from existing meteorological stations has calculated much lower average data.

It is also disturbing that measured data from the Uisig site and at DF Malan Airport, less than 10 kilometres away, differ by so much. This may be partly due to poorly calibrated instrumentation, but may also be the result of the calculation method used to convert horizontal radiation data to tilted surface values. (The Uitsig data was measured at 54$^{o}$ and the

DF Malan data at the horizontal). This is an area where very little empirical and theoretical work has been done in South Africa.

The presentation of solar radiation data should also incorporate some statistical measure of likely variability.

### 6.1.2. Estimation of loads

Actual energy usage in both demonstration projects differed substantially from projected design load levels which were basd on installed loads and estimated usage. There was no actual consultation with the households concerning their estimates of usage before the designs were undertaken and equipment ordered.

This highlights an important issue as the efficiency and cost effectiveness of small PV systems is greatly affected by the degree of matching between installed PV capacity and usage levels.

Actual load usage is intrinsically difficult to estimate and is likely to change over time with changing life-styles. Nevertheless an important lesson from these demonstration projects is that close consultation with prospective clients is necessary for better estimations of design loads.

### 6.1.3. System reliability

The design methodolgy was based on the loss of energy probability data presented by the Jet Propulsion Laboratory in the USA. It was difficult to assess, over the short monitoring period of the demonstration project, whether this data is relevant to South African conditions.

Certainly it is important to size systems on an acceptable loss of energy probability rather than on an arbitrary design margin or level of autonomy. The latter design techniques would lead to oversized and thus unduly expensive systems, although guaranteeing almost 100 percent reliability, while systems designed according to specified loss of energy probabilities would be smaller and cheaper.

Low income household who have previously relied on poor quality fuels would probably find a loss of power of a few days a year acceptable if the systems were more affordable. There is thus a need for a proper assessment of the applicability of a loss of energy probability methodology for sizing small stand-alone PV systems in Southern Africa and for determining what loss of energy levels are socially acceptable.

After evaluating the LOEP technique used in this report it would appear to have certain limitations. The LOEP curve used is a statistical condensation of theoretical meteorological data and the least cost curve for array and battery combinations is derived from American data.

A better approach would seem to be the use of typical meteorological year data combined with a micro-computer based PV system simulation model to determine loss of energy probabilities for various system configurations. Ideally such an analysis should be combined with a menu driven system sizing methodology. Some programmes are available (for example, PVFORM from Sandia Labs) but simplifying assumptions have been incorporated such as maximum power tracking or lumped battery efficiencies. Further work in this area has been proposed by the ERI for 1988/9.

### 6.1.4. Batteries

The analysis of subsystem efficiencies of the two demonstration projects was hamstrung by the lack of performance data on the batteries. This highlights an area where knowledge is lacking. No charge or discharge curves could be obtained from the battery manufacturers and it was impossible to accurately link state of charge to charge and discharge voltages.

Batteries have been treated like black boxes in PV system designs with the consequence that simplifying and often inaccurate assumptions are made. There is a definite need to empirically determine key performance data which would enable accurate simulation models for PV systems. The ERI has proposed that work be undertaken in this area in 1988/9.

Most companies marketing small home power PV systems for low-income households are offering standard automotive or SLI type batteries. The economic analysis has shown that more appropriately designed batteries such as those for tractive power are just as cost effective over the lifetime of the systems. Given that automotive batteries are unlikely to last beyond 3 years and probably much less if used without battery protection units, it would make sense to examine more closely the technical and economic aspects of specialized batteries for PV applications and to involve local manufacturers in this process.

### 6.1.5. Regulators

The experience of designing, procuring and installing the two demonstration system has exposed another area where further development work is necessary:- the need for low-cost, efficient controllers which would provide over-voltage battery protection with two stage charging, under-voltage battery protection with load shedding and perhaps also maximum power point tracking if this is economically justified.

Voltage regulators are available off the shelf, but these are mostly expensive, often more expensive than the battery itself. It is suspected that most development work has been done with larger systems in mind. For small (typically two panel) systems for home power for low-income households, new low-cost, simple devices are necessary.

The high cost of regulators has led most companies who market home power PV systems to omit regulators (see APPENDIX C).

As most of these systems are also sold with automotive type batteries, it is unlikely that the batteries will last beyond the 2 year hire purchase repayment period. It is thus vital that appropriately designed and costed controllers are made available for this market.

The question has also been raised as to whether maximum power tracking is justified for small stand-alone systems. The analysis of results from this project has demonstrated that module operating points may be up to 20 percent lower than maximum possible efficiencies at the maximum power point. It is recommended that the modelling exercise be undertaken to determine whether the extra power which may be derived from maximum power tracking will be sufficient to pay for the additional cost of this control device.

## 6.2. ECONOMIC ISSUES

The results of this project have demonstrated that in all situations small stand-alone PV systems are cheaper than petrol generators and are, in most cases, also more cost effective than currently used fuels such as paraffin, gas, candles and batteries.

The cost of PV systems is dependent mainly on insolation levels and module cost although even at very low PV module costs, the balance of system costs (mainly batteries) are still high. Small stand-alone PV systems are thus only economically viable in applications remote from the national electricity grid.

## 6.3. SOCIAL ISSUES

The major complaint with currently used fuels is the cost. Approximately 20 percent of households' monthly income is spent on energy.

There sre also a number of social costs attached to the uise fuels such as candles, paraffin and gas:- fire and burn hazards, unpleasant and penetrating smells and possible health problems.

Both demonstation project households were very pleased with the quality of the PV-powered lights, and of new opportunities offered in terms of recreation, enertainment and education.

Thus in economic and social terms, photovoltaic systems offer many advantages and appear to to be an appropriate technology to meet minimal electrical requirements for off-grid households.

However, a major stumbling block in acquiring these systems is the high initial capital costs. Added to this, most black families do not own their own homes and are thus not eligible for home improvement loans. It is thus clear that the wide spread application of photovoltaics for low-income off-grid households is closely linked to problems of adequate finance and security by poor households.

## 6.4. RECOMMENDATIONS

Based on the results of the two demonstration sites the following recommendations are made:

(i) Better insolation data is required to improve system sizing. This project is already underway at the ERI.

(ii) More attention should be given to consultation with users in order to size PV systems appropriately.

(iii) A local LOEP sizing methodology needs to be developed which is micro-computer based and consists of a simulation/design model with typical meteorological year data. The ERI has proposed such a research project for 1988/89.

(iv) More information on battery design and operation is required to develop and manufacture appropriate batteries for local conditions. The ERI has proposed a project in this field for 1988/9.

(v) Further research and development is required in the design of low-cost, reliable and efficient charge regulators.

(vi) Attention should be given by funding agencies (such as the Development Bank) and other financial institutions to the provision of loan schemes which would make small PV systems more affordable.

(vii) Finally, the dissemination of appropriate information to local suppliers is extremely important to ensure more appropriately sized PV systems.

# CHAPTER 7

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# APPENDIX A:

## SAMPLE DATA USED TO DESIGN AND SIZE TWO SMALL STAND-ALONE PV SYSTEMS

THE INPUT DATA REQUIRED BY THE PROGRAM

THE LATITUDE OF LOCATION = 34.0 deg. SOUTH
THE ANGLE OF TILT OF THE COLLECTOR = 54.0 deg.
THE SURFACE REFLECTIVITY = .4

DIFFUSE AND DIRECT SOLAR RADIATION

(average daily values)

| MONTH | DAY NUMBER | DIFFUSE RADIATION (MJ/m2) | DIRECT RAD(hori) (MJ/m2) | DIRECT RAD(incl) (MJ/m2) | INCLINED RAD(total) (MJ/m2) |
|---|---|---|---|---|---|
| JAN | 15. | 6.2 | 24.2 | 14.3 | 21.7 |
| FEB | 45. | 6.1 | 19.9 | 15.1 | 22.1 |
| MAR | 74. | 5.1 | 16.8 | 17.5 | 23.4 |
| APR | 105. | 4.7 | 10.6 | 15.9 | 20.9 |
| MAY | 135. | 4.0 | 6.9 | 13.8 | 17.8 |
| JUN | 166. | 3.3 | 6.1 | 16.1 | 19.5 |
| JUL | 196. | 3.6 | 6.3 | 15.3 | 19.0 |
| AUG | 227. | 4.6 | 8.2 | 14.1 | 18.8 |
| SEP | 258. | 6.1 | 12.0 | 14.5 | 20.8 |
| OCT | 288. | 7.0 | 16.0 | 13.7 | 21.2 |
| NOV | 319. | 7.5 | 20.1 | 12.8 | 21.0 |
| DEC | 349. | 7.1 | 22.9 | 12.6 | 20.7 |

THE AVERAGE DAILY SOLAR RADIATION = 20.6 MJ/m2
THE YEARLY TOTAL SOLAR RADIATION = 7491. MJ/m2

| ELEMENT | WATTS | HOURS IN SERVICE PER DAY JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BEDROOM1 | 12. | 2.5 | 2.5 | 2.5 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 2.5 | 2.5 |
| BEDROOM2 | 12. | 2.5 | 2.5 | 2.5 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 2.5 | 2.5 |
| KITCHEN | 12. | 2.0 | 2.0 | 2.0 | 2.5 | 3.0 | 3.0 | 3.0 | 3.0 | 2.5 | 2.0 | 2.0 | 2.0 |
| LOUNGE | 12. | 3.0 | 3.0 | 3.0 | 3.5 | 4.0 | 4.0 | 4.0 | 4.0 | 3.5 | 3.0 | 3.0 | 3.0 |
| TELEVISION | 15. | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |

| MONTH | LOAD (KWatt-H) | INSOLATION (KW/m**2) | INSOL/LOAD (ratio) |
|---|---|---|---|
| JAN | .180 | 6.034 | 33.52 |
| FEB | .180 | 6.131 | 34.06 |
| MAR | .180 | 6.500 | 36.11 |
| APR | .204 | 5.800 | 28.43 |
| MAY | .216 | 4.956 | 22.95 |
| JUN | .216 | 5.412 | 25.06 |
| JUL | .216 | 5.265 | 24.37 |
| AUG | .216 | 5.216 | 24.15 |
| SEP | .204 | 5.790 | 28.38 |
| OCT | .192 | 5.876 | 30.60 |
| NOV | .180 | 5.832 | 32.40 |
| DEC | .180 | 5.744 | 31.91 |

THE WORST-MONTH RATIO = 22.95
THE WORST MONTH = MAY
THE ENERGY LOAD REQUIRED = .216 KWatts-H
THE SOLAR RADIATION = 4.956 KWhours/m**2/day
THE ARRAY POWER = .071 KWatts
THE ARRAY AREA = .476 m**2
THE RATED BATTERY ENERGY STORAGE = 1.728 KWatt-hours

THESE ARE THE RESULTS OF A COST ANALYSIS FOR THIS PHOTOVOLTAIC SYSTEM

| UNIT | COST (in rands) |
| --- | --- |
| MODULE COSTS (R/Wpeak) | 20.00 |
| BALANCE-OF-SYSTEM COSTS (R/m**2) | 150.00 |
| CONVERTER COSTS (total) | 0.00 |
| BATTERY COSTS (R/BKWatt-hour) | 105.00 |
| INITIAL COSTS (total) | 1831.35 |
| BATTERY REPL. COSTS (pres. value) | 400.63 |
| OPERATING etc. COSTS (pres. value) | 124.44 |
| TOTAL LIFE-CYCLE COSTS | 2356.43 |

THE INPUT DATA REQUIRED BY THE PROGRAM

THE LATITUDE OF LOCATION = 30.0 deg. SOUTH
THE ANGLE OF TILT OF THE COLLECTOR = 32.0 deg.
THE SURFACE REFLECTIVITY = .4

DIFFUSE AND DIRECT SOLAR RADIATION

(average daily values)

| MONTH | DAY NUMBER | DIFFUSE RADIATION (MJ/m2) | DIRECT RAD(hori) (MJ/m2) | DIRECT RAD(incl) (MJ/m2) | INCLINED RAD(total) (MJ/m2) |
|---|---|---|---|---|---|
| JAN | 15. | 7.3 | 19.6 | 16.0 | 23.5 |
| FEB | 45. | 6.8 | 17.7 | 16.3 | 23.4 |
| MAR | 74. | 5.9 | 14.8 | 16.3 | 22.3 |
| APR | 105. | 4.1 | 14.1 | 19.3 | 23.6 |
| MAY | 135. | 3.5 | 10.9 | 18.1 | 21.7 |
| JUN | 166. | 2.8 | 10.2 | 20.0 | 23.1 |
| JUL | 196. | 3.0 | 11.1 | 19.4 | 22.5 |
| AUG | 227. | 3.4 | 14.3 | 21.3 | 25.1 |
| SEP | 258. | 4.7 | 17.1 | 20.5 | 25.4 |
| OCT | 288. | 6.2 | 18.2 | 17.9 | 24.4 |
| NOV | 319. | 6.9 | 20.5 | 17.3 | 24.5 |
| DEC | 349. | 7.4 | 20.4 | 16.1 | 23.8 |

THE AVERAGE DAILY SOLAR RADIATION = 23.6 MJ/m2
THE YEARLY TOTAL SOLAR RADIATION = 8601. MJ/m2

| ELEMENT | WATTS | HOURS IN SERVICE PER DAY JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BEDROOM1 | 20. | 2.0 | 2.0 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.0 | 2.0 | 2.0 |
| BEDROOM2 | 12. | 3.0 | 3.0 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.0 | 3.0 | 3.0 |
| BEDROOM3 | 12. | 1.0 | 1.0 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.0 | 1.0 | 1.0 |
| KITCHEN | 20. | 1.0 | 1.5 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 1.5 | 1.5 | 1.0 |
| LOUNGE 1 | 20. | 1.5 | 1.5 | 1.5 | 1.5 | 2.5 | 2.5 | 2.5 | 2.5 | 1.5 | 1.5 | 1.5 | 1.5 |
| LOUNGE 2 | 20. | 1.5 | 1.5 | 1.5 | 1.5 | 2.5 | 2.5 | 2.5 | 2.5 | 1.5 | 1.5 | 1.5 | 1.5 |
| TELEVISION | 15. | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |

| MONTH | LOAD (KWatt-H) | INSOLATION (KW/m**2) | INSOL/LOAD (ratio) |
|---|---|---|---|
| JAN | .228 | 6.541 | 28.69 |
| FEB | .238 | 6.489 | 27.26 |
| MAR | .270 | 6.205 | 22.98 |
| APR | .270 | 6.555 | 24.28 |
| MAY | .310 | 6.040 | 19.48 |
| JUN | .310 | 6.407 | 20.67 |
| JUL | .310 | 6.261 | 20.20 |
| AUG | .310 | 6.961 | 22.45 |
| SEP | .270 | 7.066 | 26.17 |
| OCT | .238 | 6.781 | 28.49 |
| NOV | .238 | 6.801 | 28.58 |
| DEC | .228 | 6.606 | 28.97 |

THE WORST-MONTH RATIO = 19.48
THE WORST MONTH = MAY
THE ENERGY LOAD REQUIRED = .310 KWatts-H
THE SOLAR RADIATION = 6.040 KWhours/m**2/day
THE ARRAY POWER = .081 KWatts
THE ARRAY AREA = .686 m**2
THE RATED BATTERY ENERGY STORAGE = 1.860 KWatt-hours

# APPENDIX B:

## FORTRAN PROGRAMME FOR PV SYSTEM SIZING

```
***************************************************************************
*                                                                         *
*              PHOTOVOLTAIC SYSTEM DESIGN                                 *
*              --------------------------                                 *
*                                                                         *
*    THIS PROGRAM CALCULATES THE TOTAL DAILY SOLAR RADIATION ON AN        *
*    INCLINED SURFACE , FOR A SPECIFIC DAY OF EACH MONTH OF THE YEAR ,    *
*    READING THE FOLLOWING PARAMETERS FOR EACH MONTH :                    *
*                                                                         *
*     1. DAYNO : THE DAY NUMBER                                           *
*     2. RFLAT : MEAN DAILY DIRECT RADIATION ON A HORIZONTAL SURFACE      *
*     3. RDIFF : MEAN DAILY DIFFUSE RADIATION                             *
*                                                                         *
*    THIS INFORMATION IS STORED IN A DATA FILE , WHICH IS ACCESSED BY     *
*    THE COMMAND : OPEN (UNIT=9,FILE='B:SUN') , IN THE PROGRAM .          *
*    IT ALSO READS THE FOLLOWING INFORMATION :                            *
*                                                                         *
*     4. PHI   : LATITUDE OF LOCATION ; -VE IN THE S. HEMISPHERE          *
*     5. THETA : ANGLE OF TILT OF THE COLLECTOR                           *
*     6. RHO   : SURFACE REFLECTIVITY                                     *
*                                                                         *
*    THIS PROGRAM STARTS BY COMPUTING THE SUNRISE HOUR ANGLE , AND THEN   *
*    IT CALCULATES THE HOUR ANGLE FOR THE MORNING SUNSHINE . IT THEN      *
*    COMPUTES THE RATIO OF THE SOLAR RADIATION ON A TILTED SURFACE        *
*    VERSES THAT ON A HORIZONTAL SURFACE , INCLUDING A CORRECTION         *
*    FACTOR , R , TO ACCOUNT FOR THE DIFFERENCE IN THE THICKNESS OF THE   *
*    ATMOSPHERE AT THE DIFFERENT POSITIONS OF THE SUN DURING THE DAY .    *
*    IT THEN CALCULATES THE DIFFUSE SOLAR RADIATION ON A TILTED SURFACE,  *
*    AND , THEN , IT CALCULATES THE TOTAL DAILY SOLAR RADIATION ON        *
*    THE TILTED SURFACE . THESE CALCULATIONS ARE CARRIED OUT FOR EACH     *
*    MONTH OF THE YEAR . AN AVERAGE DAILY SOLAR RADIATION IS THEN         *
*    COMPUTED , AND THEN A YEARLY TOTAL SOLAR RADIATION IS CALCULATED     *
*    FOR ONE SPECIFIC TILT ANGLE .                                        *
*                                                                         *
*    THE PROGAM THEN CALCULATES THE TOTAL ENERGY LOAD , USING THE POWER   *
*    DRAWN BY EACH ELEMENT FOR A CERTAIN LENGTH OF TIME PER DAY . IT      *
*    THEN FINDS THE 'WORST' MONTH , ie. THE MONTH WITH THE SMALLEST       *
*    RATIO OF INSOLATION TO LOAD REQUIREMENT . THE NEXT SECTION OF THE    *
*    PROGRAM DETERMINES THE SIZE OF THE POWER ARRAY AND THE ARRAY AREA .  *
*    IT THEN SIZES THE BATTERY , AND COMPUTES A COST ANALYSIS FOR THE     *
*    PROPOSED PHOTOVOLTAIC SYSTEM .                                       *
*                                                                         *
*        THIS PROGRAM WAS WRITTEN AND COMPILED BY DONOVAN MULLER          *
```

```
*          DATE : 21 MAY 1986 .                                            *
*                                                                          *
****************************************************************************


*****************************************************************************
*
*          DECLARATION OF VARIABLES IN ALPHABETICAL ORDER
*          ----------------------------------------------
*
*  ABOS   : AREA RELATED BALANCE-OF-SYSTEM COSTS (R/m**2)
*  ALPHA  : ANGLE BETWEEN THE NORMAL AND THE POSITION OF THE SUN
*  ARRAY  : ARRAY AREA (m**2)
*  AVERGE : THE AVERAGE DAILY SOLAR RADIATION ON A TILTED SURFACE
*
*  BAT    : BATTERY COSTS (R/BWh)
*  BATENG : RATED BATTERY ENERGY STORAGE (Battery KWatt-hours)
*  BATRAY : BATTERY STORAGE SIZING FACTOR
*  BATREP : BATTERY REPLACEMENT COSTS
*  BLIFE  : BATTERY LIFE-TIME (years)
*  BRPV   : BATTERY REPLACEMENT COSTS - PRESENT VALUE
*
*  CONV   : CONVERTER COSTS (R/Wp)
*  CORNUM : THE CORRECTED VALUE OF COSNUM
*  CORDEN : THE CORRECTED VALUE OF COSDEN
*  COSNUM : FRACTION OF THE SOLAR RADIATION FALLING ON THE INCLINED SURFACE
*  COSDEN : FRACTION OF THE SOLAR RADIATION FALLING ON THE HORIZONTAL SURFACE
*
*  DAYNO  : DAY NUMBER
*  DEPTH  : MAX. ALLOWABLE DEPTH OF DISCHARGE, 0.10
*  DSRATE : DISCOUNT RATE (cost of money to system owner)
*  DTILT  : THE DIFFUSE RADIATION ON AN INCLINED SURFACE
*
*  EFFBAT : EFFICIENCY OF THE BATTERY, 0.85
*  EFFMOD : EFFICIENCY OF THE MODULE, 0.15
*  EFFINV : EFFICIENCY OF THE INVERTER/CONVERTER, 0.90
*  EFFVOL : EFFICIENCY OF THE VOLTAGE REGULATOR, 0.90
*  ESCB   : REAL ANNUAL ESCALATION RATE FOR STORAGE BATTERIES
*  ESCOM  : REAL ANNUAL ESCALATION RATE OF OPERATING AND MAINTENANCE COSTS
*
*  F      : ARRAY DEGRADATION FACTOR , 0.90
*  FRACA  : FRACTION OF THE POWER SUPPLIED BY THE ARRAY , 0.0
*  FRACB  : FRACTION OF THE POWER SUPPLIED BY THE BATTERY , 1.0
*
*  GLOBAL : THE TOTAL AVERAGE RADIATION ON A HORIZONTAL SURFACE
*
*  HOURS  : HOURS/DAY EACH ELEMENT IS IN SERVICE
*
*  ICOUNT : COUNTER
*  INCOST : INITIAL COSTS
*  IND    : FRACTION INDIRECT COSTS (engineering,management,contingency)
*  INST   : FRACTION INSTALLATION COSTS (site preparation,commission)
*  INV    : INVERTER COSTS
*
*  LABREP : LABOUR REPLACEMENT COSTS
*  LCC    : LIFE-CYCLE COSTS
*  LIFE   : LIFE-TIME OF THE SYSTEM
*  LOAD   : AVERAGE DAILY ENERGY LOAD FOR EACH MONTH
*
*  MOD    : COST OF THE MODULE (R/Wp)
*  MONTH  : THE WORST MONTH
*
*  OM     : ANNUAL OPERATING AND MAINTENANCE COSTS
*  OMPV   : PRESENT VALUE OF THE ANNUAL OPERATING AND MAINTENANCE COSTS
*
*  PHI    : LATITUDE OF LOCATION ; -VE FOR THE S. HEMISPHERE
*  PI     : CONSTANT USED TO CONVERT DEGREES TO RADIANS
*  POWER  : POWER DRAWN BY EACH LOAD ELEMENT
*  POWRAY : ARRAY POWER (KWatts)
*
```

```
*   RDIFF   : THE AVERAGE DIFFUSE RADIATION ON A HORIZONTAL SURFACE
*   REG     : VOLTAGE REGULATOR COSTS (R/max watts putting through the regulator)
*   RESULT  : THE WORST MONTH RATIO
*   RFLAT   : THE AVERAGE DIRECT RADIATION ON A HORIZONTAL SURFACE
*   RHO     : THE SURFACE REFLECTIVITY
*   RTILT   : DIRECT RADIATION FALLING ON THE TILTED SURFACE
*
*   S       : SUNRISE HOUR ANGLE ; IN RADIANS
*   SIZRAY  : ARRAY SIZING FACTOR (KWh/m**2/day)
*   SOLAR   : THE WORST MONTH SOLAR RADIATION (KWatt-hours)
*   SUMCST  : TOTAL PRESENT VALUE OF ALL BATTERY REPLACEMENT COSTS
*   SUMDEN  : SUM OF THE FRACTIONS OF SOLAR RADIATION ON THE HORIZONTAL SURFACE
*   SUMNUM  : SUM OF THE FRACTIONS OF SOLAR RADIATION ON THE INCLINED SURFACE
*   SV      : FRACTION OF THE SALVAGE VALUE OF THE BATTERIES, 0.83
*
*   TCONV   : TOTAL COST OF THE CONVERTER (rand)
*   TEMPCO  : MODULE TEMPERATURE COEFFICIENT , 0.005/deg.C for Si
*   TEMPOP  : MODULE OPERATING TEMPERATURE (deg.C)
*   THETA   : ANGLE OF TILT OF THE COLLECTOR
*   THETA1  : ANGLE OF DECLINATION
*   THETA2  : HOUR ANGLE ; IN RADIANS
*   TOTAL   : THE TOTAL RADIATION ON AN INCLINED SURFACE
*
*   WAC     : RATED POWER OF THE INVERTER
*   WMAX    : MAXIMUM WATTS PUTTING THROUGH THE REGULATOR
*   WORST   : CONVERTING MJ TO KWh
*   WPEAK   : RATED POWER OF THE CONVERTER
*
*   YEARLY  : THE TOTAL YEARLY SOLAR RADIATION ON A TILTED SURFACE
*
*****************************************************************************

      program MAIN

     real        INCOST
     real           IND
     real          INST
     real           MOD
     real           INV
     real        LABREP
     real          LIFE
     real           LCC
     real             S(20)
     real             R(20,20)
     real         ALPHA(20,20)
     real        THETA2(20,20)
     real         RDIFF(20)
     real         RFLAT(20)
     real        COSNUM(20,20)
     real        COSDEN(20,20)
     real        CORNUM(20,20)
     real        CORDEN(20,20)
     real         POWER(20)
     real         HOURS(20,20)
     real         DAYNO(20)
     real        THETA1(20)
     real         TOTAL(20)
     real        SUMDEN(20)
     real        SUMNUM(20)
     real         RATIO(20)
     real         RTILT(20)
     real        GLOBAL(20)
     real         DTILT(20)
     real          LOAD(20)
     real         SOLAR(20)
     real         WORST(20)
     real          BRPV(20)

     character* 10 NAME(15)
     character* 10 SUPPLY(10)
```

```
*    *****  READING THE INPUT DATA  *****
*           *********************

        open (unit=1,file='PRINTER')
        open (unit=9,file='B:CAPE')
        open (unit=8,file='B:HOUSE')


       print 2
2      format (10X,'  *****  ENTER ALL ANGLES IN DEGREES  ***** '/
&              10X,'         **************************   -     '//
&       5X,'THE LATITUDE OF THE LOCATION , -VE FOR THE S. HEMISPHERE ?')
      read *,PHI

      print  3
3     format (5X,'THE ANGLE OF TILT OF THE  COLLECTOR , -VE FOR THE S. HEMIS ?')
      read *,THETA

        print 4
4       format (5X,'THE SURFACE REFLECTIVITY ?')
      read *,RHO

        print 5
5       format (5X,'THE NUMBER OF SEPARATE LOAD ELEMENTS ?')
      read *,N

        read (8,*) (SUPPLY(I),POWER(I),(HOURS(I,J),J=1,12),I=1,N)

        read (9,*) (NAME(I),RFLAT(I),RDIFF(I),DAYNO(I),I=1,12)

*   *****  CALCULATING THE SUNRISE HOUR ANGLE  *****
*          *********************************

           PI=3.141592654
         THETA=THETA*PI/180
           PHI=PHI*PI/180

       do 20 I=1,12
        THETA1(I)=23.45*(SIN(360*(284+DAYNO(I))*PI/180/365))
           THETA1(I)=THETA1(I)*PI/180
             S(I)=-(TAN(THETA1(I))*TAN(PHI))
           S(I)=ACOS(S(I))
20    continue

*   *****  CALCULATING THE HOUR ANGLES  *****
*          *************************

       do 30 J=1,12
          THETA2(1,J)=S(J)
             THETA2(2,J)=75
                do 40 I=3,6
                  THETA2(I,J)=THETA2(I-1,J)-15
40               continue
             THETA2(7,J)=0.0
30     continue

*   *****  CONVERTING THE HOUR ANGLES FROM DEGREES TO RADIANS  *****
*          ************************************************

          do 50 J=1,12
            do 60 I=2,6
              THETA2(I,J)=THETA2(I,J)*PI/180
60         continue
50        continue

*   *****  CALCULATING THE NUMERATOR AND THE DENOMINATOR  *****
*          ******************************************

     do 70 J=1,12
         do 80 I=1,7
```

```
          COSDEN(I,J)=SIN(THETA1(J))*SIN(PHI)
&             +COS(THETA1(J))*COS(PHI)*COS(THETA2(I,J))
          print*,' COSNUM = ',COSNUM(I,J),'   COSDEN = ',COSDEN(I,J)
80      continue
70    continue

*  *****  INCLUDING A RADIATION-LOSS CORRECTION FACTOR , R  *****
*         ******************************************

      do 90 J=1,12
        do 100 I=1,7
           ALPHA(I,J)=ACOS(COSDEN(I,J))
              ALPHA(I,J)=ALPHA(I,J)*180/PI
                 if ((90-ALPHA(I,J)).gt.1.00) then
                     R(I,J)=(ALOG(90-ALPHA(I,J)))/4.5
                   else
                     R(I,J)=1.00
                 end if
         print*,'   R = ',R(I,J),'   ALPHA = ',ALPHA(I,J)
100     continue
90    continue

*  *****  CALCULATING THE CORRECTED FUNCTIONS  *****
*         ********************************

      do 110 J=1,12
        do 120 I=1,7
           CORNUM(I,J)=R(I,J)*COSNUM(I,J)
           CORDEN(I,J)=R(I,J)*COSDEN(I,J)
120     continue
110   continue

*  *****  SUMMING THE NUMERATOR AND THE DENOMINATOR  *****
*         *************************************

      do 130 J=1,12
        SUMNUM(J)=0.0
        SUMDEN(J)=0.0
        do 140 I=1,7
           SUMNUM(J)=SUMNUM(J)+CORNUM(I,J)
           SUMDEN(J)=SUMDEN(J)+CORDEN(I,J)
140     continue
       print*,'SUMNUM = ',SUMNUM(J),'   SUMDEN = ',SUMDEN(J)
130   continue

*  *****  CALCULATING THE RATIO  *****
*         ******************

       do 150 J=1,12
           RATIO(J)=SUMNUM(J)/SUMDEN(J)
           RTILT(J)=RATIO(J)*RFLAT(J)
150    continue

*  *****  CALCULATING THE DIFFUSE RADIATION ON A TILTED SURFACE  *****
*         **********************************************

       do 160 J=1,12
         GLOBAL(J)=RDIFF(J)+RFLAT(J)
         DTILT(J)=0.5*(1+COS(THETA))*RDIFF(J)+0.5*(1-COS(THETA))*RHO*GLOBAL(J)
160     continue

*  *****  CALCULATING THE TOTAL DAILY RADIATION ON A TILTED SURFACE  *****
*         ************************************************

       do 170 J=1,12
           TOTAL(J)=DTILT(J)+RTILT(J)
           print*,'  TOTAL RADIATION = ',TOTAL(J)
170    continue

*  *****  CALCULATING THE DAILY AVERAGE  *****
```

```
        DAILY=0.0
        do 180 I=1,12
            DAILY=DAILY+TOTAL(I)
180     continue

        AVERGE=DAILY/12

*    *****  CALCULATING THE YEARLY TOTAL SOLAR RADIATION ON A TILTED SURFACE  ****
*           *****************************************************************

         YEARLY=AVERGE*364.25

*    *****  CALCULATING THE DAILY ENERGY LOAD   *****
*           *********************************

      do 190 J=1,12
        LOAD(J)=0.0
          do 200 I=1,N
            LOAD(J)=LOAD(J)+POWER(I)*HOURS(I,J)/1000
200       continue
190   continue

*    *****  CONVERTING MJ/m**2 TO KWhours   *****
*           ***************************

      do 210 J=1,12
          SOLAR(J)=TOTAL(J)*1000/3600
210   continue

*    *****  DETERMINING THE WORST-MONTH INSOLATION AND LOAD RATIO   *****
*           ******************************************************

      do 220 J=1,12
        WORST(J)=SOLAR(J)/LOAD(J)
220   continue

*    *****  FINDING THE 'WORST' MONTH   *****
*           *************************

      do 230 J=1,12
        if (J .eq. 1) then
           RESULT = WORST(J)
           MONTH=NAME(J)
           ICOUNT=J
        else if (RESULT.gt.WORST(J)) then
           RESULT=WORST(J)
           MONTH=NAME(J)
           ICOUNT=J
        end if
230   continue

       print *,'THE WORST-MONTH RATIO IS ',RESULT
       print *,'THE WORST MONTH IS ',MONTH
       print *,'THE SOLAR RADIATION IS ',SOLAR(ICOUNT),' KWatt-hours'


************************************************************************
*
*   THIS SECTION OF THE PROGRAM DETERMINES THE SIZE OF THE POWER ARRAY
*
*   AND THE ARRAY AREA . IT THEN SIZES THE BATTERY , AND THEN COMPUTES
*
*   A COST ANALYSIS FOR THE SYSTEM .
*
************************************************************************


*    *****  DETERMINING THE SIZE OF THE POWER ARRAY   *****
*           ***************************************
```

```
      FRACB=1.00
      FRACA=0.00
     EFFVOL=1.00
     EFFBAT=0.85
     EFFMOD=0.15
      DEPTH=0.40
     TEMPCO=0.005
     TEMPOP=25

     print*,'THE SIZE OF THE ARRAY SIZING FACTOR (KWhours/m**2/day) ?'
     read*,SIZRAY

     print*,'THE BATTERY STORAGE SIZING FACTOR (days) ?'
     read*,BATRAY

    POWRAY=LOAD(ICOUNT)/(SIZRAY*F*EFFINV*(FRACB*(EFFVOL*EFFBAT)+FRACA))

    ARRAY=POWRAY*1000/(EFFMOD*(1+TEMPCO*(TEMPOP-28))*1000)

    BATENG=(LOAD(ICOUNT)*BATRAY)/(DEPTH*EFFINV)

************************************************************************
*
*  THIS SECTION OF THE PROGRAM PERFORMS A COST ANALYSIS FOR THE PROPOSED
*
*  PHOTOVOLTAIC SYSTEM . IT THEN PERFORMS A COST ANALYSIS FOR AN ALTERNATIVE
*
*  FUEL , AND FINALLY CALCULATES THE NETT PRESENT VALUE FOR THE TWO SYSTEMS .
*
*************************************************************************

        IND=0.0
       INST=0.10
        MOD=20
       ABOS=150
       CONV=0.0
      WPEAK=0.0
        INV=0.0
        WAC=0.0
        REG=0.0
       WMAX=0.0
        BAT=105
         SV=0.12
     LABREP=0.0
       ESCB=0.0
     DSRATE=0.04
      BLIFE=5.0
       LIFE=20.0
      ESCOM=0.0

     TCONV=CONV*WPEAK

*   ***** THE INITIAL COST OF THE SYSTEM *****
*         ******************************

     INCOST=(1+IND+INST)*((MOD*POWRAY*1000)+(ABOS*ARRAY)+(CONV*WPEAK)+(INV*WAC)
&         +(REG+WMAX)+(BAT*BATENG))

*   ***** THE CURRENT COSTS : BATTERY REPLACEMENT *****
*         ************************************

     BATREP=(BAT*BATENG)*(1-SV)+LABREP

*   ***** THE PRESENT VALUE OF ALL BATTERY REPLACEMENT *****
*         ****************************************

      do 240 I=1,4
       BRPV(I)=BATREP*(((1+ESCB)/(1+DSRATE))**(I*BLIFE))
240   continue
```

```
      SUMCST=0.0

     do 250 I=1,4
         SUMCST=SUMCST+BRPV(I)
250 continue

*   ***** CALCULATING THE OPERATING AND MAINTENANCE COSTS *****
*          ********************************************

      OM=0.005*INCOST
    OMPV=OM*((1+ESCOM)/(DSRATE-ESCOM))*(1-(((1+ESCOM)/(1+DSRATE))**LIFE))

*   ***** CALCULATING THE LIFE CYCLE COSTS *****
*          ******************************

      LCC=INCOST+SUMCST+OMPV

*   *****  PRINTING THE INPUT DATA  *****
*          **********************

     if (PHI.lt.0.0.and.THETA.lt.0.0) then
        THETA=ABS(THETA)
          PHI=ABS(PHI)
           PHI=PHI*180/PI
             THETA=THETA*180/PI
             write (1,15) PHI,THETA,RHO
15   format (' ',10X,'THE INPUT DATA REQUIRED BY THE PROGRAM',/11X,38('-')/
&    5X,'THE LATITUDE OF LOCATION               =  ',F5.1,' deg. SOUTH',/
&    5X,'THE ANGLE OF TILT OF THE COLLECTOR =  ',F5.1,' deg. ',/
&    5X,'THE SURFACE REFLECTIVITY               =  ',F4.1)
     else
           PHI=PHI*180/PI
             THETA=THETA*180/PI
             write (1,25) PHI,THETA,RHO
25   format (' ',10X,'THE INPUT DATA REQUIRED BY THE PROGRAM',/11X,38('-')//
&    5X,'THE LATITUDE OF LOCATION               =  ',F5.1,' deg. NORTH',/
&    5X,'THE ANGLE OF TILT OF THE COLLECTOR =  ',F5.1,' deg. ',/
&    5X,'THE SURFACE REFLECTIVITY               =  ',F4.1)
     end if

*   *****  FORMATTING THE OUTPUT DISPLAY  *****
*          ****************************

      write (1,35)
35    format (//,6X,'DIFFUSE AND DIRECT SOLAR RADIATION'/6X,34('=')/
&      12X,'(average daily values)'//
&       2X,'           DAY     DIFFUSE       DIRECT       DIRECT     INCLINED '/
&       2X,'MONTH   NUMBER   RADIATION    RAD(hori)    RAD(incl)   RAD(total)'/
2)'/
&       1X,64('-'))

     write (1,45) (NAME(I),DAYNO(I),RDIFF(I),RFLAT(I),RTILT(I),TOTAL(I),I=1,12)
45    format (T3,A,T12,F4.0,6X,F4.1,9X,F4.1,7X,F4.1,8X,F4.1)

     write (1,55)  AVERGE,YEARLY
2'/
2')

     write (1,65)
65   format (/,T2,'ELEMENT',4X,'WATTS',8X,'HOURS IN SERVICE PER DAY'/
&     T20,'JAN',2X,'FEB',2X,'MAR',2X,'APR',
&     2X,'MAY',2X,'JUN',2X,'JUL',2X,'AUG',2X,'SEP',2X,'OCT',2X,'NOV',2X,'DEC'/
&     77('-'))

     write (1,75) (SUPPLY(I),POWER(I),(HOURS(I,J),J=1,12),I=1,N)
75   format (T2,A,T15,F3.0,2X,F3.1,2X,F3.1,2X,F3.1,2X,F3.1,2X,F3.1,2X,F3.1,
&          2X,F3.1,2X,F3.1,2X,F3.1,2X,F3.1,2X,F3.1,2X,F3.1)

      write (1,85)
85    format (/T2,'MONTH',7X,'LOAD',5X,'INSOLATION',5X,'INSOL/LOAD'/
&         11X,'(KWatt-H)',3X,'(KW/m**2)',7X,'(ratio)'/55('-'))
```

```
      write (1,95) (NAME(J),LOAD(J),SOLAR(J),WORST(J),J=1,12)
95    format (T2,A,T13,F5.3,6X,F5.3,10X,F5.2)

      write (1,105) RESULT,MONTH,LOAD(ICOUNT),SOLAR(ICOUNT)
105   format (//T10,'THE WORST-MONTH RATIO     = ',F5.2/
&             T10,'THE WORST MONTH           = ',A/
&             T10,'THE ENERGY LOAD REQUIRED = ',F5.3,' KWatts-H'/
&             T10,'THE SOLAR RADIATION       = ',F5.3,' KWhours/m**2/day')

      write (1,115) POWRAY,ARRAY,BATENG
115   format (T10,'THE ARRAY POWER             = ',F6.3,' KWatts'/
&             T10,'THE ARRAY AREA              = ',F6.3,' m**2'/
&             T2,'THE RATED BATTERY ENERGY STORAGE = ',F6.3,' KWatt-hours')

      write (1,125)
125   format (//,2X,
&     'THESE ARE THE RESULTS OF A COST ANALYSIS FOR THIS PHOTOVOLTAIC SYSTEM'/
&     2X,70('='))

     write (1,135) MOD,ABOS,TCONV,BAT,INCOST,SUMCST,OMPV,LCC
135  format (//,2X,'UNIT',25X,'COST (in rands)'/2X,46('-')/
&                 2X,'MODULE COSTS (R/Wpeak)',T38,F7.2/
&                 2X,'BALANCE-OF-SYSTEM COSTS (R/m**2)',T38,F7.2/
&                 2X,'CONVERTER COSTS (total)',T38,F7.2/
&                 2X,'BATTERY COSTS (R/BKWatt-hour)',T38,F7.2//
&                 2X,'INITIAL COSTS (total)',T38,F7.2/
&                 2X,'BATTERY REPL. COSTS (pres. value)',T38,F7.2/
&                 2X,'OPERATING etc. COSTS (pres. value)',T38,F7.2/T37,9('-')/
&                 2X,'TOTAL LIFE-CYCLE COSTS',T37,F8.2/T37,9('='))

    stop
    end

*         *****  THIS IS THE END OF THE MAIN PROGRAM  *****
*                ***********************************
```

# APPENDIX C:

## LOCALLY AVAILABLE COMPLETE PV SYSTEMS

# SEMI CONDUCTOR SERVICES



Prop.: (Pty.) Ltd.
Eien.: SEMCOTRONICS (Edms.) Bpk.
REG. No. 81/04659/07

P.O. Box/Posbus 133
Mondeor 2110
FACTORY/FABRIEK:
Cnr./Hv. Evans & v.d. Bijl Streets
Alrode South/-Suid Ext./Uitbr. 2

Telex/Teleks: 4-23416 SA
Tel.: (011) 868-1154/1155/3112

16th July, 1987

Energy Research Institute,
University of Cape Town,
Private Bag Rondebosch,
7700

Att: Dr. A.A. Eberhard

Dear Dr. Eberhard,

Semi Conductor Services is involved in the marketing of the photovoltaic home power kits, for low income households.

We have various systems available which power from 2 lamps to 6 lamps. In addition to powering lamps as the systems increase in size the facilities you can power also increase.

Solar packages are as follows:-

1.

The Philidelphia

this includes:-

1 X 25 Watt SCS 1/25 Solar Panel
4 X 20 Watt SCS T.W. Lamps
1 X 12V Battery
1 x Plug
Wiring

Price: R1202,00

This system will power 2 lamps for 3 hours each evening.

2.

The Las Vegas

This includes:-

2 X 25 Watt SCS 1/25 Solar Panels
6 X 20 Watt SCS T.Q. Lamps
1 X 12V Battery
1 X Plug
Wiring

Price: R2388,00

This system will power 2 lamps for 3 hours each and 1 X 51cm colour T.V. for 2 hours.

3.

The New Yorker

This includes

3 X 25 Watt SCS 1/25 Solar Panels
6 X 20 Watt SCS T.Q. Lamps
1 X 12V Battery
1 X Plug
Wiring

Price: R2719,00

This system will power 4 lamps for 3 hours each and 1 x 51cm colour T.V. for 2 hours.

4.

The Americano

---

This includes

4 X 25 Watt SCS 1/25 Solar Panels
6 X 20 Watt SCS T.Q. Lamps
1 X 12V Battery
1 X Plug
Wiring

Price: R2812,00

This system will power 4 lamps for 4 hours each and 1 x 51cm colour T.v. for 3 hours.

Please find enclosed solar systems specifications and a plot of the panel yield.

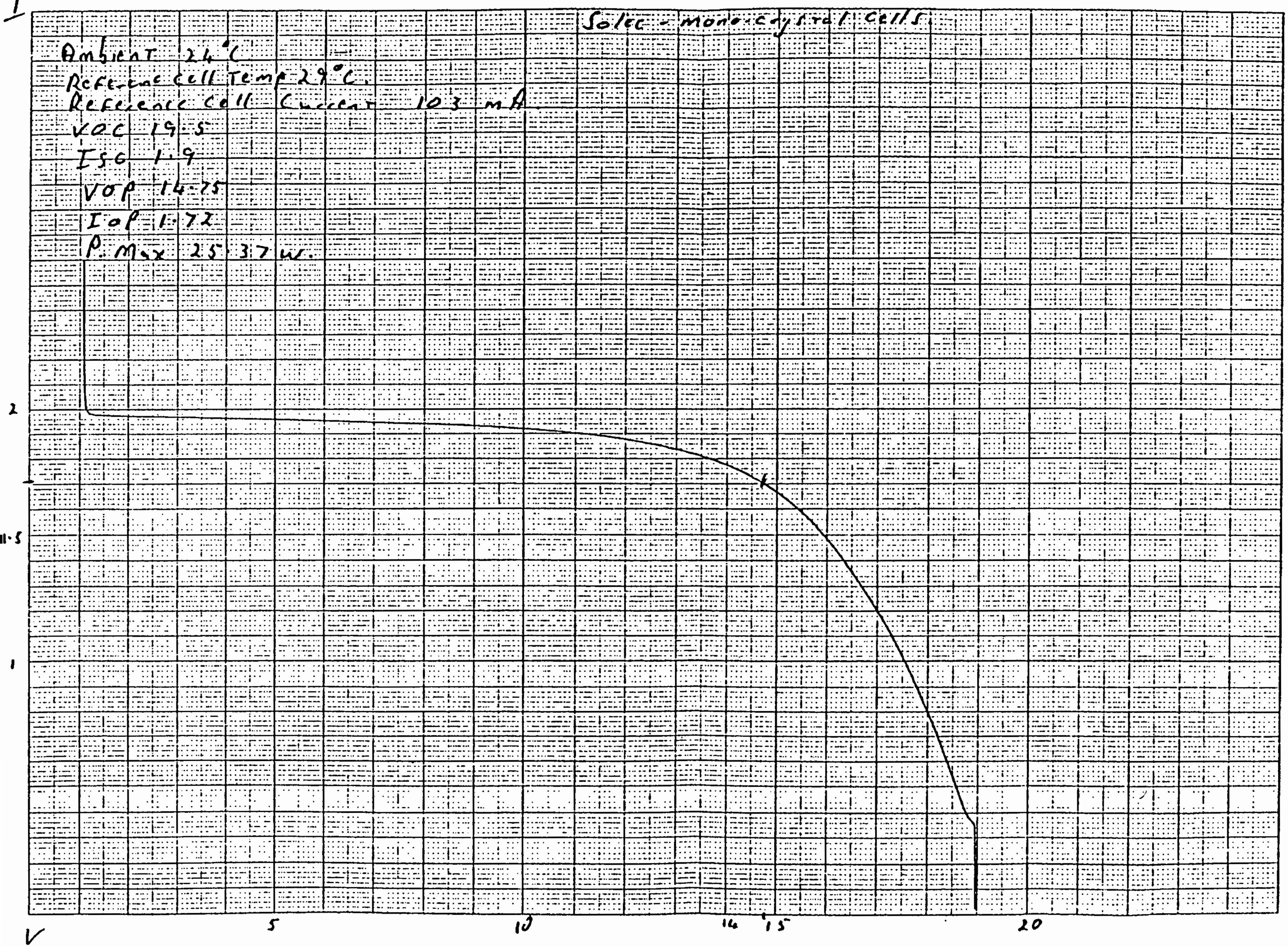
These modules are locally manufactured and guaranteed for 5 years.

Should you require further information please do not hesitate to contact me.

Yours faithfully,
SEMI CONDUCTOR SERVICES

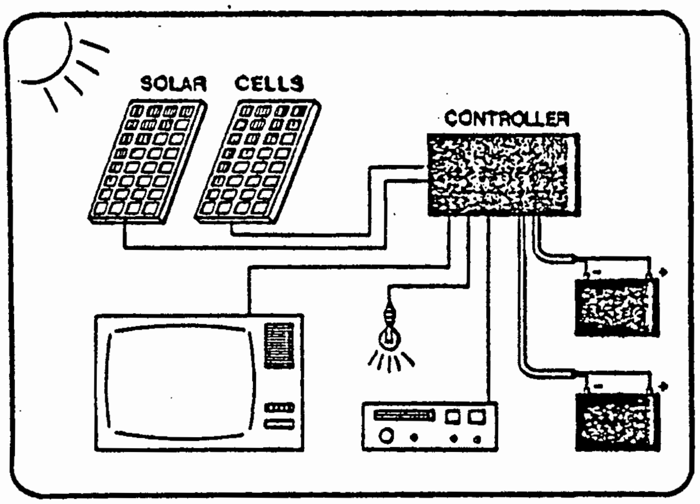
..............
I. VERVLIET

90059015



Solec - mono-crystal cells
Ambient 24°C
Reference cell Temp 29°C
Reference cell Current 103 mA
VOC 19.5
ISC 1.9
VOP 14.75
IOP 1.72
P. Max 25.37 w.
I
V
2
1.5
1
5
10
14
15
20

# Solar Energy




ELECTRICITY produced from Solar Cells to run home appliances

ELECTRICITY TO POWER

* LIGHTS
* TELEVISION
* RADIO
* FANS
* FRIDGES
* FREEZERS

## SOLAR SYSTEMS SPECIFICATIONS

1 x 25 Watt Panel
Will power 2 lamps for 3 hours each evening

2 x 25 Watt Panels
Will power 2 lamps for 3 hours each and
1 x 51cm colour TV for 2 hours

3 x 25 Watt Panels
Will power 4 lamps for 3 hours each and
1 x 51cm colour TV for 2 hours.

4 x 25 Watt Panels
Will power 4 lamps for 4 hours each and
1 x 51cm colour TV for 3 hours.

5 x 25 Watt panels
Will power 4 lamps for 4 hours each and
1 x 51cm colour TV for 3 hours and
Radio and Hifi for 3 hours.

6 x 25 Watt panels
Will power 6 lamps for 4 hours each and
1 x 51cm colour TV for 4 hours and
Radio and Hifi for 4 hours.

## ADDITIONAL INFORMATION

SOLAR PHOTOVOLTAIC PANELS

Available from 7 watts to 45 watts.

FLUORESCENT LIGHTS
- 12 volts 15 / 20 watts.

T.Q. LAMPS
- 12 volts 20 watts.

T.V.
- 12 volts B/W and Colour.

FRIDGE
- 12 volts 120 Litres.

FREEZER
- 12 volts 60 Litres.

MESSINA ELECTRONICS (PTY) LTD

REG. NO. 76/03326/07

THORA CRESCENT
WYNBERG, SANDTON
PO BOX 93
BERGVLEI, 2012
REPUBLIC OF SOUTH AFRICA
TELEX: 4-29464 SA
TEL: (011) 885-1523

OUR REF: 612/87/HDK/dg

20TH JULY 1987

Energy Research Institute
University of Cape Town
Private Bag
RONDEBOSCH
7700

<u>**ATTENTION: DR A A EBERHARD**</u>

Dear Dr Eberhard,

Thank you for your letter dated 10 July regarding our "Home Power Kit".

To cut the cost of this kit to the absolute mininum we are now offering the V12/28 low cost solar module with a power output of 28 Watt or 1,75A.

The typical daily power output of this module will be 10AH. This is sufficient to operate 2 fluorescent light fittings as supplied with the kit for +/- 5 hours every night.

We have deleted the regulator since the general tendency is to try to use more power than what is generated in any case. Only once a user starts expanding the kit with more modules will a solar regulator be recommended.

To eliminate the possibility of overcharging the battery, we recommend the use of a battery with a capacity of 90AH.

Prices are now as follows:

| | |
|---|---|
| V12/28 Solar Module | R465,00 |
| Fluorescent light (15 Watt / 0,9A) | R 30,00 each |
| Battery (90AH) | R120,00 |
| Mounting bracket | R 50,00 |
| Cable | R 20,00 |
| Regulator (Optional) | R135,00 |

MESSINA ELECTRONICS

The installation can be done by the purchaser or alternatively by a local electrician.

I will be visiting Cape Town in the near future, and would be grateful if we could discuss the above on a more personal basis during this visit.

Yours sincerely

HARRY DE KOK

**BP Southern Africa (Pty) Ltd — BP Suidelike Afrika (Edms.) Bpk.**
(Reg. No. 04/02602/07)



BP House, 10 Junction Avenue, Parktown 2193 — BP-Huis, Junctionlaan 10, Parktown 2193

Tel. 643-6633 P.O. Box : Posbus 1554 Johannesburg 2000 Telex : Teleks 4-30320 SA Tel. address : adres "Beepee"

Energy Research Institute
University of Cape Town
Private Bag
RONDEBOSCH
7700

Our reference : Ons verwysing

Your reference : U verwysing

ATT: DR A A EBERHARD

Date : Datum

17 July 1987

Dear Dr Eberhard,

Thank you for your interest in our domestic lighting products. We are currently in the process of launching our "Telelite" range. I have included a preliminary brochure as well as the instruction manual for the 33L3 system (the first of the range to be launched).

Prices are as follows:

| Description | Approved Dealer 10+ | Approved Dealer 1 - 9 | Recommended Retail |
|---|---|---|---|
| 10L1 | 631,00 | 665,00 | 1 019,00 |
| 10L3 | 752,50 | 791,50 | 1 215,50 |
| 20L1 | 760,50 | 800,50 | 1 229,00 |
| 20L3 | 881,50 | 928,00 | 1 424,00 |
| 20L5 | 1008,00 | 1061,00 | 1 629,00 |
| 33L1 | 973,00 | 1024,00 | 1 571,00 |
| 33L3 | 1097,50 | 1155,00 | 1 771,50 |
| 33L5 | 1231,50 | 1262,00 | 1 990,00 |

The first two digits in the nomenclature indicate module peak-power, the final digit indicates the number of lights supplied.

Key features of the systems are:

-- self regulating module
-- tidy wiring and safe battery by means of the battery box with integral distribution board
-- easy-to-fit lights with integral pull switches
-- all necessary cable, screws, bolts, clips etc supplied
-- comprehensive instructions
-- versatile module-mounting frame

2/....

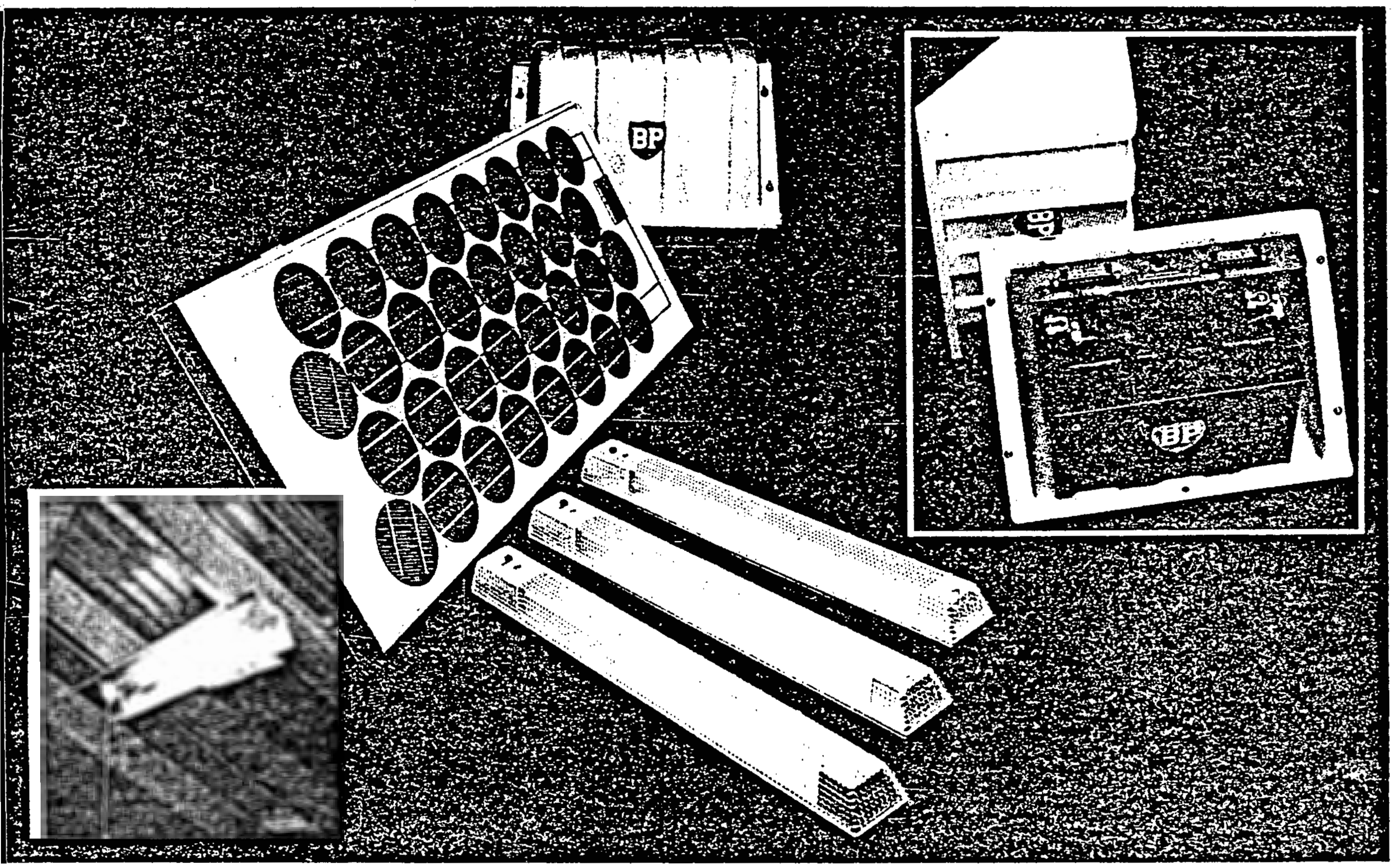
As you are involved in demonstration projects and are keen for feedback on our systems we are willing to support you in your research.

Yours faithfully,

M. P. Gasson

M P GASSON
SYSTEMS ENGINEER

| SYSTEM | LIGHT SIZE | NUMBER OF LIGHTS | HOURS USAGE FOR ONE LIGHT | RECOMMENDED BATTERY TYPE |
|---|---|---|---|---|
| 10L1 | 8w | 1 | 6 | 638 |
| 10L3 | 8w | 3 | 6 | 638 |
| 20L1 | 8w | 1 | 10 | 638 |
| 20L3 | 8w | 3 | 10 | 638 |
| 20L5 | 8w | 5 | 10 | 638 |
| 33L1 | 15w | 1 | 11 | 674 |
| 33L3 | 15w | 3 | 11 | 674 |
| 33L5 | 15w | 5 | 11 | 674 |



The elements of this lighting/hi-fi/television 'do-it- yourself' package are a solar module, a galvanised steel structure to support the module, cables, battery box and lights.

The module bolts to the steel structure, which is firmly fixed onto the roof or wall. A cable from the module leads down through the ceiling into the room where a battery will be used to power lights or television.

A unique part of BP Solar's package is the battery box. The box is robust, can be locked with a padlock to prevent tampering or theft, is ventilated to prevent any dangerous hydrogen build-up and also makes a good sturdy seat.

From the battery box, two-core cables lead to the lights. One solar module will run one light for 10 hours or a black-and-white television set for $3^1/_2$ hours.

The package will suit any house and will provide safe reliable electricity for years.


10 Junction Avenue
Parktown
2193

Telephone 643-6633

**BP SOLAR ELECTRICITY**

Telefax 642-2614

P.O. Box 1554
Johannesburg
2000

Telex 430320

# WIDER BP SHARE-HOLDINGS WELCOMED

**British Petroleum p.l.c. is preparing for an influx of new shareholders because of the British Government's intended sale of its 31,6 per cent holding in the company.**

The sale - to be completed during the Treasury's current fiscal year which ends on March 31, 1988 - will mean new owners for shares together worth about £5 billion at today's prices.

News of the sale was welcomed by BP Chairman Sir Peter Walters. 'It will clear up a number of uncertainties which have affected both the financial markets' attitudes to BP and our own financial planning,' he said.

'The expectation that the company's major shareholder might be considering selling more than 30 per cent of our equity inevitably has had an unsettling influence on the share price and has added to the complexities of our longer-term financial planning.'

BP would like to see many of the shares bought overseas to reflect the international structure of its operations.

It believes continuation and widening of the trend in international ownerships of its shares would benefit all shareholders.

BP shares are now quoted in London, New York, Paris, Switzerland, Germany, Amsterdam and Canada. Application will shortly be made for a listing on the Tokyo stock exchange.

The Government, throughout 70 years as the company's largest shareholder, has traditionally and consistently stood back from the management and commercial operations of the BP Group.

Its holding dates back to 1914 when it took a majority interest in the then Anglo Persian Oil Company. The main purpose was to ensure supplies of fuel oils for the Royal Navy.

The first sale of Government-held shares was in 1977 when the interest was reduced to 51 per cent from 68,3 per cent.

Another sale in 1979 reduced the holding to 46 per cent.

Because the Government did not take up its entitlement under BP's 1981 rights issue, its holding fell by a further 7,15 per cent to 38,85 per cent.

The last sale, in 1983, reduced the Government holding to below 32 per cent.

## Mr Ian Sims joins board of Standard Bank

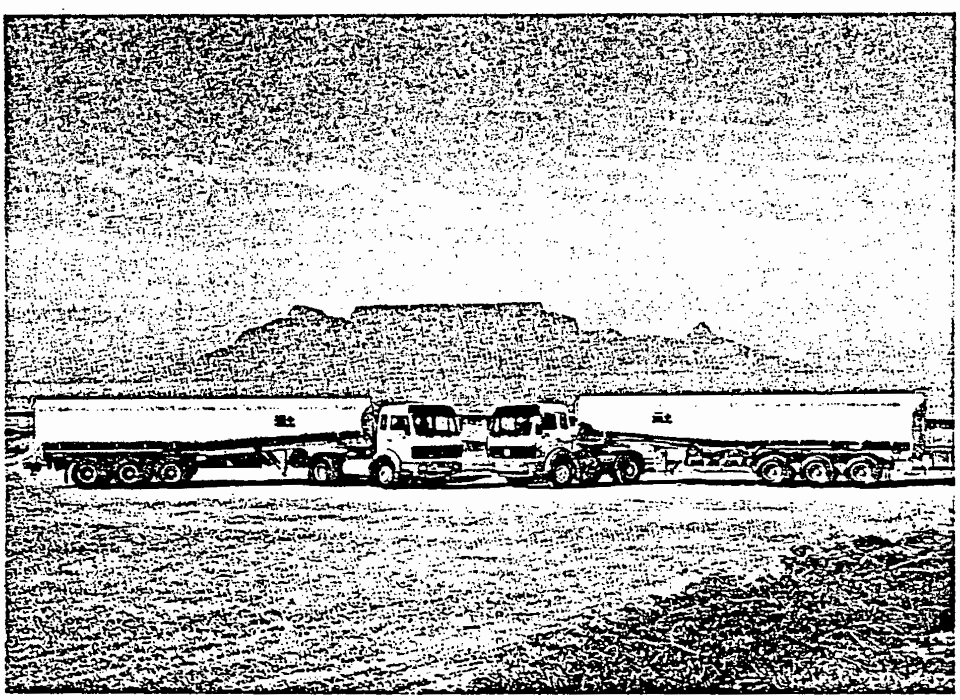
BPSA Chairman Mr Ian Sims has been appointed to the Regional Board of Standard Bank of South Africa Limited.

# BP'S GIANTS IMPROVE CUSTOMER SERVICE

**BP's biggest depot, Killarney in Cape Town, recently took delivery of two giant tri-axle semi-trailers, the first of their kind to be used at this terminal and certain to improve customer service and time spent on deliveries.**

The tri-axle semi-trailer has a capacity of 34 000 litres in comparison to the maximum 27 000 litre load of the largest bulk vehicles at the terminal. It also has a metering system which enables two products to be dropped simultaneously, greatly reducing the length of time a customer is interrupted while his tanks are being filled. The vehicles will improve the terminal's delivery pattern, as sites that formerly needed to be visited several times a week, are now able to be serviced with one delivery a week only.

The only problem is that these jumbo acquisitions are not able to turn on the proverbial tickey and are unsuitable for smaller sites. However careful preplanning ensures that they have room to manoevre with ease at all their destinations.



*Above: Killarney's jumbo acquisitions with Lion's Head and Table Mountain in the background.*

# BP SOLAR TURNS ON THE LIGHTS

**For many electricity is a commodity taken for granted and forgotten, until the odd, rare power-cut disrupts life for an hour or two. However for thousands of South Africans, the prospect of ever having electricity is remote, and lights and television luxuries only dreamt of. Now, only a year since its inception, BPSA's pilot project, BP Solar, has come up with its very own 'first' - a solar lighting/television power package. What's more, BP Solar International (BPSI) will be using BPSA's technology to produce similar lighting packages which by July it hopes to have available in every solar operation sales area throughout the world.**

When BP Solar set up shop last year, they divided their marketing efforts into two distinct areas - the consumer market and the institutional market. Bearing in mind their goal of identifying solar power applications to improve the quality of life of people living in developing areas, BP Solar was keen to tackle the black township consumer market first.

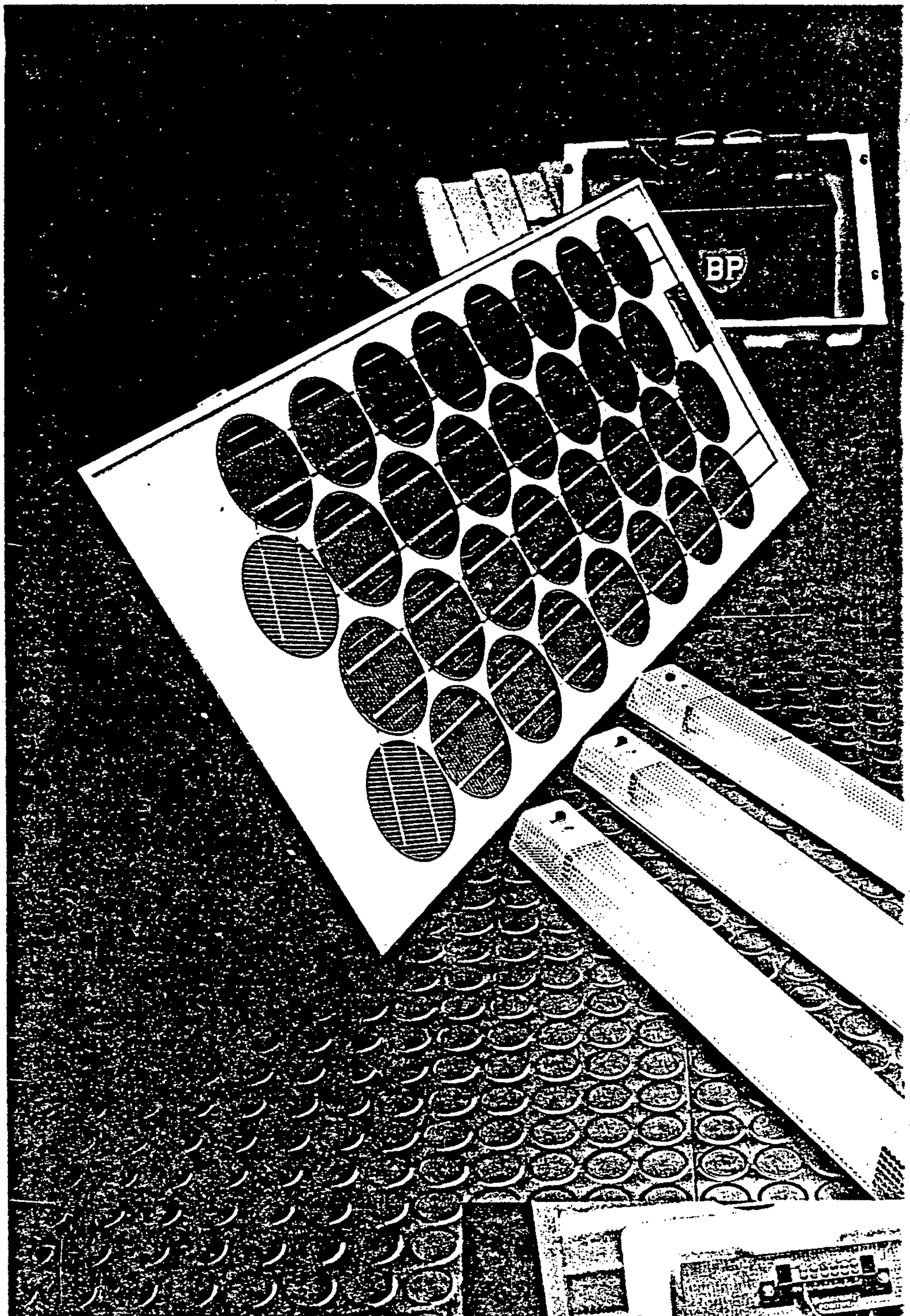
Lights and television were identified as a primary need. Instead of trying to provide individual systems for different situations, it was then decided to produce a package that could be adapted to a variety of needs.

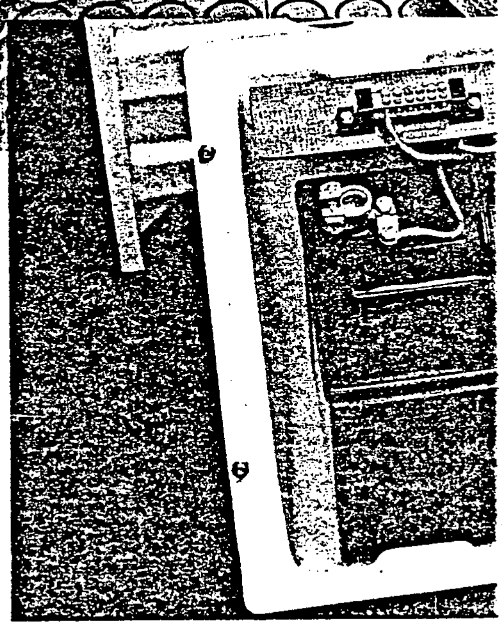
The basic elements of this 'do-it-yourself' kit are a solar module, a steel structure to support the module, cables, a battery, battery box, and a light.

The module will be attached to the steel structure, which will in turn be screwed firmly onto the roof. A cable from the module will lead down through the ceiling into the room where the battery will be used to power either television or lights.

While this sounds fairly simple, a great deal of research and experimentation went into the choice and manufacture of each component.

The only imported component is the self-regulating, glass laminated solar module. Most modules include a regulator which switches the panel off when it has become fully charged. However the team decided on a self-regulating module which is easier to maintain and less expensive. With self-regulation, as the battery voltage increases with its state of

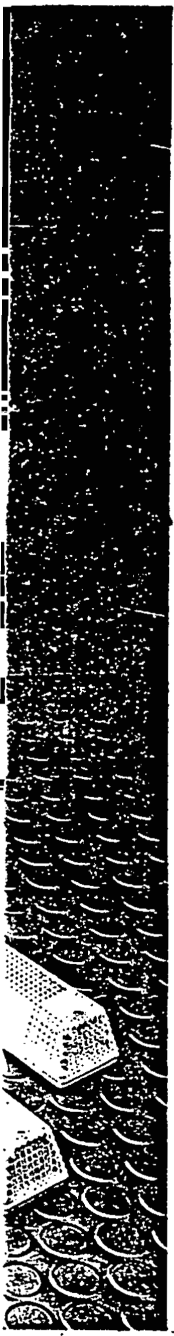




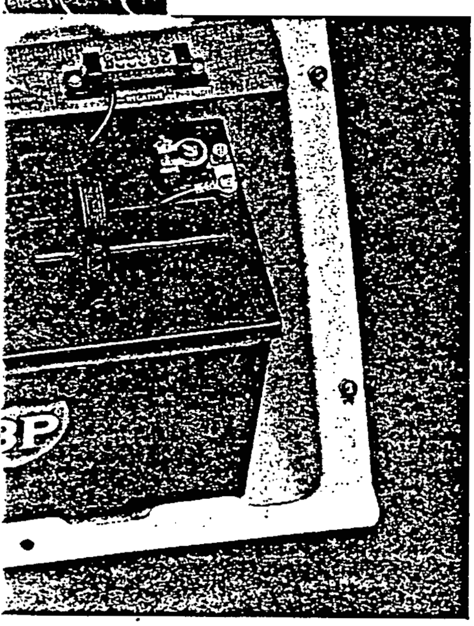
*Above: A BP first - the solar lighting/ television power package.*

*Right: The battery is designed to stand on a floor, probably under a kitchen table. It is enclosed in a sturdy plastic box to protect children from the battery or to prevent tampering.*

*Far right: One solar module will run one 15 watt light for ten hours.*

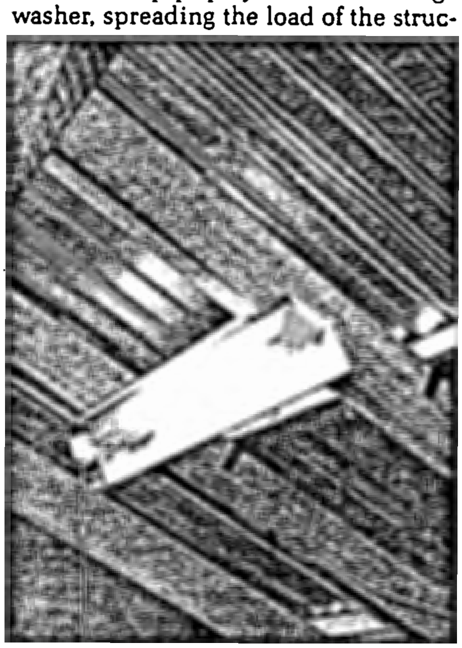



*Above: From l-r: The BPSA team responsible- Win Kurzyca (Sales Engineer), John Samuel (Market Development Manager) and Mark Gasson (Systems Engineer).*



charge, the solar module's output decreases. A self-regulating panel consists of 32 photovoltaic cells rather than the usual 36, so its top-end voltage is smaller. Therefore when the battery is fully charged the panel is forced to operate at a lower voltage.

BP Solar assumed that most modules would be mounted on a corrugated iron roof, making it necessary for the user to drill through the crest of the corrugation. The structure's kit includes an adjustable steel plate and pipe to be placed along the corrugation under the roof's surface. The pipe plays the role of a large washer, spreading the load of the structure on the roof sheeting and is so versatile that it will fit onto a wall or roof of any profile and can even be fitted to thatch with simple fencing wire.



The junction cable will then be fed through the ceiling and down into the room where it will join the battery. A unique part of BP Solar's package is the battery box. The BP Solar Team invisaged that the battery would probably stand under a kitchen table. To protect children crawling on the floor from the battery, it was necessary to design a box to ensure the product was 100 per cent safe.

The box is robust, locks with a padlock to prevent tampering or theft, is ventilated to prevent any dangerous hydrogen build-up and also makes a good sturdy seat. The mould for the box is one item that may possibly be imported by BP Solar International for the Group's other lighting packs, as well as the 15 watt lights, designed and manufactured in Johannesburg.

From the battery box, a two-core cable leads to the lights or television. One solar module will run one light for 10 hours or a black-and-white television set for three to four hours.

By cutting costs BP Solar has arrived at a reasonably-priced package at the same time managing not to sacrifice quality or strength. It is geared at any community without electricity and could be used anywhere from Soweto to a remote Transkei village. It would also be suitable for game lodges, forest stations or caravans.

bulletin BP

# ALL ABOUT 'MF' BATTERIES

**BPSA's Superstart Mod 4 Maintenance Free Battery manufactured by Raylite Batteries, is the most sophisticated of its kind on the market and is the only make of maintenance free (MF) battery that can boast the South African Bureau of Standards' stamp. However, many people are still unaware of the qualities of MF batteries and regard them as something of a gimmick. BP Bulletin spoke to Len Penman, Automotive Operations Manager of Raylite Batteries, about the benefits of MF batteries.**

Maintenance free batteries were first introduced in 1984 and since then in conjunction with their American associate, Globe Union (which is the largest manufacturer of starter batteries in the States), Raylite have made a number of improvements.

What exactly does 'maintenance free' mean? Is it gain or gimmick?

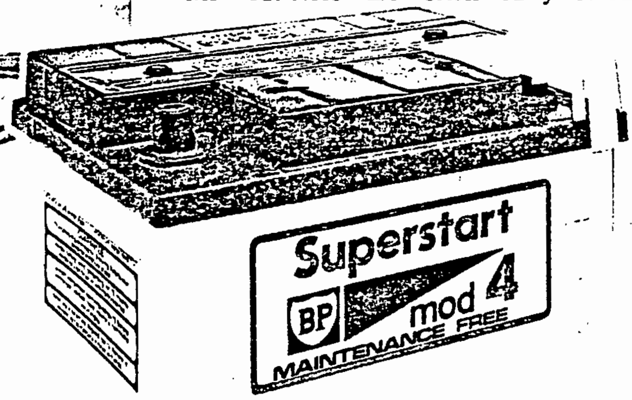
■ The MF battery has low antimony which means that less antimony (a property of lead) is used to strengthen the battery's plates. 'Through our American associate, Globe Union, we have a special grid-casting machine which allows us to cast a grid using less antimony,' explains Len. 'Most manufacturers use five per cent antimony in their plates while Raylite uses below two per cent. Low antimony means less corrosion, longer shelf-life and less topping up.'

■ The MF battery is made of translucent polypropylene enabling the user to see when topping-up is necessary. 'Polypropylene was introduced to South Africa by Raylite and is seven times stronger than rubber. It is also lighter and thinner which means that there is more space in the battery to put extra plates,' says Len. 'Raylite puts more plates per cell into heavy-duty batteries than anyone else, so there is additional cranking power when you need to get going on a cold morning.'

■ Unlike a conventional battery, the terminals are cast into the lid of the battery so they cannot work loose or leak.

■ The BP Superstart has removable vents for topping up in the unlikely event of the water level dropping. Other MF batteries are often fully-sealed which makes topping up, should it become necessary, almost impossible.


*Above: Len Penman, Automotive Operations Manager of Raylite Batteries, who manufacture BPSA's MF battery, the Superstart Mod 4.*




Len Penman cautions that the term 'maintenance-free' is not synonomous with long life as the battery has the usual service life of three to four years. 'Motorists tend to think that MF batteries are a fit-and-forget kind, and in theory they are. It doesn't mean they last forever though,' says Len.

'Under normal operating conditions the BP Superstart is maintenance free, but if your car is charging over the rate of 13,8 to 14,2, which are the recognised normal operating voltages, the battery will use water,' he explains. 'In this case the motorist will have to have an auto electrician reset or replace the unit.'

Len recommends that when buying a battery a motorist should have his car's charging system checked to see that it is within the recognised normal operating voltages. Instructions should also be carefully read.

'Using a fully-charged MF battery, motorists should be able to leave their cars standing for a full year without any problems and there is no other battery that can do that,' says Len. 'So its long shelf life is also a great attribute.'

## SENIOR BP APPOINTMENTS

Mr Ian Sims, Chairman of BP Southern Africa (Pty) Limited, has announced two new appointments.

Roger Griffiths has been appointed Manager: Public Affairs, based at BPSA's Head Office in Cape Town.

Phil Peakin has been appointed Regional Consumer Manager.

PHIL PEAKIN

ROGER GRIFFITHS

 27 JUN 1988