

PHOTOVOLTAICS FOR EDUCATIONAL TELEVISION IN RURAL SCHOOLS

William Douglas Cowan, M.A.(Oxon)

Submitted to the University of Cape Town in partial fulfilment of the requirements for the degree of Master of Philosophy in Engineering.

Cape Town

September 1989

The University of Cape Town has been given the right to reproduce this thesis in whole or in part. Copyright is held by the author.

The copyright of this thesis vests in the author. No quotation from it or information derived from it is to be published without full acknowledgement of the source. The thesis is to be used for private study or non-commercial research purposes only.

Published by the University of Cape Town (UCT) in terms of the non-exclusive license granted to UCT by the author.

DECLARATION

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

W D Cowan

...29th... day of *September*... 1989

ABSTRACT

One application for photovoltaic (PV) technology is in providing electricity for educational aids, in developing areas remote from grid supply. Technical, social and economic aspects of this option are investigated, in local context, by examining the use of small PV systems to power educational television and video in secondary schools in Bophuthatswana. Technical performance was assessed through monitoring PV system behaviour and climatic variables over an extended period, using remote data-capture techniques at a demonstration site. Modelling provided for further prediction of performance in non-observed conditions. Social and educational aspects of the schools television project were investigated through interviews with educationists, planners, project administrators and a limited sample of teachers and pupils in Bophuthatswana. Overall conclusions are that PV systems can provide a reliable and technically appropriate solution to the problem of powering light electrical loads in off-grid schools. Levelised unit energy costs can be acceptable if PV systems are critically sized, and if there is close match between designed capacity and actual load energy demand. If this is not the case - as in Bophuthatswana school systems - unit energy costs may be very high. Organisational features of project implementation and inadequate central resources, particularly for delivering appropriate educational software to schools, have impaired the potential of the project, and the equipment in schools is under-utilised.

Proceeding from an inductive performance analysis of the monitored system, a PV system performance model was developed, in order to assess the optimum sizing of components in small stand-alone photovoltaic systems in such applications, and to judge the sizing of the systems installed. The model is based upon critical runs of adverse weather, leading towards system loss of power to load. It predicts the minimum insolation required to avoid system loss of power to load over runs of days, and compares this with percentiles for plane-of-array insolation over runs of days, derived from long term hourly weather station records. The approach allows development of a loss of power probability (LOPP) sizing methodology which preserves the run-length characteristics of local climatic data. Sizing predictions from this method are compared with other sizing methodologies, and are used to indicate design savings possible for the monitored systems. The proposed critical-run LOPP sizing method has potential for incorporation in a microcomputer-based sizing tool, suitable for more accurate design of photovoltaic systems with battery storage in local applications.

ACKNOWLEDGEMENTS

I would like to offer warm thanks to my colleagues in the Energy Research Institute and in the Department of Sociology for their support throughout this study.

Many of my colleagues in the social sciences have migrated there from other disciplines, including engineering. It is less common to move in the opposite direction. I wish to thank the University of Cape Town for granting study and research leave which in part made this possible. The masters programme in Alternative Energy for Developing Areas at the Energy Research Institute, convened by Dr Anton Eberhard, provided a welcoming and rapid induction into a field where cross-disciplinary research is valuable. The National Energy Programme of the CSIR not only provided research funding for the present project, but also lent encouragement by calling for social scientists to enter the field of energy research for developing areas.

Representatives of the company which supplied photovoltaic systems for educational television in Bophuthatswanan schools played a vital role in allowing their equipment to be monitored for research purposes. I would like to thank them for their assistance, advice and friendly hospitality.

Many individuals in Bophuthatswana shared their time and knowledge. While their views have not been personally identified, respecting confidentiality, I hope they will recognise their opinions, and their own contribution to this study.

Chris Wosniak, of the Energy Research Institute, provided great assistance with instrumentation, and characteristic human support.

Dr Anton Eberhard, for his vision, encouragement and empathy, stands out as a project leader and supervisor, and as the moving spirit behind this and many other energy studies in Southern Africa. I would like to thank him professionally and personally.

Finally, I am also grateful to Eskom for permitting countless hours of computer use, without a single power failure.

TABLE OF CONTENTS

ABSTRACT	(i)
ACKNOWLEDGEMENTS	(ii)
TABLE OF CONTENTS	(iii)
LIST OF TABLES	(viii)
LIST OF ILLUSTRATIONS	(x)
 CHAPTER 1: INTRODUCTION	
1.1 Locating the Research	1.1
1.2 Initial Formulation	1.5
1.3 Background to Solar-Powered Educational Television in Bophuthatswana	1.7
1.4 Structure of Report	1.9
 CHAPTER 2: DESCRIPTION OF SYSTEM	
2.1 Television and Video	2.2
2.2 Battery Storage	2.4
2.3 Power Management System	2.7
2.4 Photovoltaic Generator	2.8
2.5 System Specifications	2.11
 CHAPTER 3: INSTALLATION, MAINTENANCE AND RELIABILITY	
3.1 Installation	3.1
3.2 Maintenance	3.2
3.3 Reliability	3.3
3.3.1 Photovoltaic modules	3.3
3.3.2 Batteries	3.4
3.3.3 Power management circuitry	3.6
3.3.4 Applications equipment	3.7
 CHAPTER 4: MONITORING METHOD	
4.1 Choice of Site, and Location	4.1
4.2 Variables Recorded	4.1
4.3 Instrumentation	4.2
4.4 Procedure	4.7
4.5 Specific Instrumentation Problems	4.10
4.6 Supplementary Tests	4.12

CHAPTER 5: OBSERVED SYSTEM PERFORMANCE

5.1 An Illustration of Daily Performance	5.1
5.2 Statistical Summary of Monitored Variables	5.8
5.2.1 Plane of array insolation	5.8
5.2.2 Ambient temperature	5.10
5.2.3 Load energy and power	5.11
5.2.4 Battery voltage	5.12
5.2.5 Battery currents	5.17
5.2.6 Photovoltaic array voltage and current	5.19
5.2.7 Module cell temperature	5.28

CHAPTER 6: ASSESSMENT AND TREATMENT OF INSOLATION MEASUREMENTS

6.1 Comparing the Insolation Measurements with Weather Station Records	6.1
6.1.1 Sources of data for weather station records	6.2
6.1.2 Methods for calculating insolation on a tilted plane	6.2
6.1.3 Discrepancies between monitored and expected plane of array insolation	6.6
6.2 Analysis of Discrepancies	6.8
6.2.1 Climatic differences	6.8
6.2.2 Air pollution	6.10
6.2.3 Shading	6.10
6.2.4 Factors leading to reduced insolation	6.11
6.2.5 Pyranometer error	6.12
6.2.6 Signal conditioning error	6.17
6.2.7 Errors in statistical analysis of monitoring data	6.18
6.3 Adjustment of Monitoring Site Insolation Measurements	6.19
6.4 Implications	6.22

CHAPTER 7: TESTED OUTPUT CHARACTERISTICS OF THE ARRAY, COMPARED WITH SUPPLIED (MONOCRYSTALLINE) MODULE SPECIFICATIONS

7.1 Reasons for the Tests	7.1
7.2 Method	7.2
7.2.1 Climatic conditions during the tests	7.3
7.2.2 Recommendations for module performance testing in natural sunlight	7.3
7.2.3 Test procedure compared with recommended procedure	7.4

7.3 Assessment of Accuracy	7.6
7.4 Results	7.8
7.5 Comparison Between Test Results and PW-P 800 Specifications	7.11

CHAPTER 8: SYSTEM EFFICIENCIES

8.1 Observed System Efficiencies	8.1
8.1.1 Observed module conversion efficiencies	8.2
8.1.2 Delivered energy efficiencies	8.6
8.1.3 Consumed energy efficiency	8.9
8.2 Factors Affecting System Efficiencies	8.10
8.2.1 Circumstantial factors	8.11
8.2.2 Probabalistic factors	8.14
8.2.3 Design factors	8.17
8.3 Analysis of Efficiencies in the Monitored System	8.27
8.3.1 Observed loadlines	8.27
8.3.2 Array output characteristics	8.32
8.4 Conclusions	8.40

CHAPTER 9: MODELLING THE SYSTEM

9.1 Approach	9.1
9.1.1 Full simulation	9.2
9.1.2 Reductive model for critical conditions	9.6
9.2 Form of the Model	9.6
9.2.1 POA insolation energy demand curves	9.7
9.2.2 Probability curves for POA insolation	9.14
9.2.3 Modelling the POA probability curves	9.19
9.3 Combining the Curves for Loss of Power Probabilities .	9.21
9.3.1 Adjustment to battery capacity	9.22
9.4 LOPP Predictions for the Monitored System	9.25
9.4.1 Maximum predicted daily load	9.26
9.4.2 Could battery capacity be reduced?	9.28
9.4.3 Could array size be reduced?	9.29
9.4.4 Combinations of array power and battery capacity to support the design load	9.31
9.4.5 Uncertainties in the model, and degradation allowances	9.40
9.4.6 Comparative LOPP predictions using modules with greater predicted optimum power losses	9.43

9.5	Comparing Model Predictions With Other Sizing Methods	9.45
9.5.1	Method 1	9.45
9.5.2	Method 2	9.54
9.5.3	Method 3	9.63
9.5.4	Summary of sizing comparisons	9.70

**CHAPTER 10: PHOTOVOLTAIC-POWERED SCHOOLS TELEVISION
IN BOPHUTHATSWANA: SOCIAL, EDUCATIONAL
AND ECONOMIC ASPECTS**

10.1	Motivation for the Edutel Project	10.3
10.1.1	Educational motives	10.4
10.1.2	Political and commercial motives	10.5
10.2	Edutel Delivery to Schools	10.11
10.3	Utilisation	10.15
10.4	Problems and Constraints	10.17
10.4.1	Educational software	10.17
10.4.2	Scale of implementation	10.20
10.4.3	Teacher and pupil attitudes	10.24
10.5	Aspects of "Appropriateness"	10.31
10.5.1	Centralisation versus decentralisation	10.31
10.5.2	Self-sufficiency versus dependency	10.39
10.6	Photovoltaic Supply to Schools:	
	Economic Assessment of Energy Costs	10.51
10.7	Summary	10.62

CHAPTER 11: TECHNICAL CONCLUSIONS AND RECOMMENDATIONS

11.1	Installed Systems for Solar Powered Television and Video	11.1
11.2	Project Implementation and Technical Choice	11.5
11.3	General Points For Local Photovoltaic System Design	11.5
11.4	Specific Proposals for Evaluating and Developing a Locally-Applicable Loss of Power Probability Sizing Method	11.9

APPENDICES:

A REFERENCES AND BIBLIOGRAPHY

B METHODS

- B1 Pyranometer Test Method
- B2 Method for Assessment of Shading of Monitored Array, By Month
- B3 Calculation of Battery Lifetime
- B4 Interface Design Parameters and Treatments
- B5 Circuit Diagrams for Signal Conditioning Interface
- B6 Array and Battery Combinations Predicted to Satisfy LOPP 0.01 and 0.001 in Pretoria Weather, Using PW-P 800 (monocrystalline) Modules
- B7 Sizing Nomogram Used in the Borden et al (1984) Loss of Energy Probability PV System Sizing Method
- B8 Assessing the Long-term Loss of Power Probability of the System Sizing Indicated by the Borden et al (1984) Method, Through Comparison with Critical Run LOPP Model Predictions

C COMPUTER PROGRAMS

- C1 Program for Calculating Insolation on a Tilted Plane, Using an Isotropic Trigonometric Method
- C2 Program for Calculating Tilt Plane Insolation, Using the Perez Anisotropic Approach for the Diffuse Component. Code Adapted from PVFORM (Menicucci and Fernandez, 1985)
- C3 Program for Screening and Reformatting Solar Radiation Data From South African Weather Bureau Tape
- C4 Excerpt from BMDP Runstream for Cumulative Frequencies and Percentiles for Average Daily POA Insolation, Over Runs of Days
- C5 Code for Obtaining Convergence Between POA Insolation Supply and System Energy Demand, for Given LOPP Levels, By Varying Array Size and Battery Capacity

D SUPPLEMENTARY

- D1 Questioning the Assumption that Distribution of Daily Insolation is Independent of Locality or Type of Climate as Employed in Chapman's (1987) Loss of Load Probability Sizing Methodology

LIST OF TABLES

Table 4.1	Summary of Monitoring Data Collected, and Reasons for Failures	4.9
Table 5.1	Observed Daily Plane of Array Insolation (Wh/sq.m/day), By Month	5.9
Table 5.2	Observed Ambient Temperatures By Month	5.10
Table 5.3	Observed Daytime Ambient Temperatures By Month	5.10
Table 5.4	Daily Load Energy Consumption By Month	5.11
Table 5.5	Current to Batteries During Daylight Hours	5.17
Table 5.6	Battery Energy Supply to Load and Battery Energy Efficiency, July to September 1987	5.19
Table 5.7	Observed Array Voltages, Daylight Hours	5.20
Table 5.8	Mean Array Power, Plane of Array Insolation and Daily Load: July, August, September 1987	5.26
Table 5.9	Module Cell Temperatures, By Month, Daylight Hours	5.29
Table 6.1	Mean Daily Insolation, Per Month, Predicted on a Plane Tilted 30 Degrees North from Long-term Insolation Records for Pretoria	6.5
Table 6.2	Monitored Plane of Array Insolation compared with Long-term Pretoria Records, Converted for Tilt	6.6

Table 6.3	Monitored Plane of Array Insolation Compared With Expectations	6.7
Table 6.4	POA Insolation Discrepancies After Cosine-Error Adjustment and Estimation of Factors Leading to Reduced Insolation at the Site	6.20
Table 7.1	Comparative Performance of PW-P 800 and PW-P 801 Photovoltaic Modules	7.12
Table 8.1	Mean Consumed Energy Efficiencies, July to September 1987	8.9
Table 8.2	Comparative Power Output of PW-P 801 and PW-P 800 Modules, Taking Account of Array/Loadline Matching	8.39
Table 9.1	Critical Combinations of Array and Battery Size for LOPP = 0.001 and 0.01	9.36
Table 9.2	Rules of Thumb for Judging PV Sizing in Highveld Conditions (based on Pretoria weather)	9.38
Table 9.3	Comparison of LOPP Sizings for Modules With Differing Output Characteristics	9.44
Table 9.4	Model-Predicted Loss of Power for Method 2 Sizing, Using Pretoria Weather Data	9.60
Table 9.5	Summary of Array and Battery Sizing Indicated By Different Sizing Methods	9.72
Table 10.1	Some Developmental Features of Centralisation and Decentralisation	10.33
Table 10.2	Some Requirements for Increased Self- Sufficiency at Various Levels in the Educational System	10.42

LIST OF ILLUSTRATIONS .

Figure 2.1	Schematic of the Monitored Photovoltaic System	2.1
Figure 3.1	Map of Educational Circuits in Bophuthatswana	3.1
Figure 4.1	Schematic of Current and Voltage Measuring Points in the System Circuitry ...	4.4
Figure 5.1	Interaction of Monitored Variables: Illustration, 17-18 September 1987	5.3
Figure 5.2	Cumulative Frequency Distribution of Recorded Plane of Array Insolation	5.9
Figure 5.3	Battery Voltages in High Demand Conditions	5.14
Figure 5.4	Battery Voltages in Low Demand Conditions	5.15
Figure 5.5	Cumulative Frequency Distribution of Daily Battery Depth of Discharge	5.16
Figure 5.6	Average Monthly Battery Energy Flows	5.18
Figure 5.7	Array Operating Voltages, Compartmentalised By Array Current	5.21
Figure 5.8	Array Voltage Distribution, September 1987	5.22
Figure 5.9	Array Current Distribution	5.23
Figure 5.10	Observed Array Power, With Controlled Load	5.24

Figure 5.11	Observed Array Power, With Negligible Load	5.24
Figure 5.12	Array Energy Generated, Cumulative Frequency Distribution	5.27
Figure 5.13	Array Energy Generated, Daily Sequence With 5-Day Rolling Mean	5.27
Figure 6.1	Comparison of Daily Insolation Profiles, Pretoria and Monitoring Site, for Two Days in June	6.9
Figure 6.2	Tested Discrepancy Between Li-Cor and Kipp and Zonen Pyranometer Measurements, as a Function of Incidence Angle	6.13
Figure 6.3	Relative Spectral Response of Li-Cor Pyranometer	6.15
Figure 6.4	POA Insolation Values Used for System Sizing by Two Manufacturers, Compared with Perez Model Predictions	6.25
Figure 7.1	Relative Spectral Response of (a) Li-Cor and (b) Generic Solar Cell	7.5
Figure 7.2	Recorded Array IV Characteristics at 810 W/sq.m	7.9
Figure 7.3	Recorded Array IV Characteristics at 723 W/sq.m	7.9
Figure 7.4	Array IV Characteristics Derived From Tests (for Two PW-P 801 Modules in Parallel)	7.11
Figure 8.1	Measurement Points for Efficiency Measures	8.2

Figure 8.2	Observed Module Conversion Efficiency, July-Sept 1987	8.3
Figure 8.3	Observed Module Conversion Efficiencies in Months of Negligible Load Demand	8.5
Figure 8.4	Delivered Energy Efficiency, July-Sept 1987	8.7
Figure 8.5	Delivered Energy Efficiency, July 20 1987	8.8
Figure 8.6	Example of PV Module Output Characteristics at Constant Cell Temperature and Varying Insolation.....	8.18
Figure 8.7	Module IV Curves and Sample Loadlines	8.19
Figure 8.8	Matching Array Output Characteristics to Battery Charging Input Characteristics	8.23
Figure 8.9	The Relationship Between Optimum Power and Optimum Voltage Deviations For Two Photovoltaic Modules	8.25
Figure 8.10	Input Load Characteristics in States of Low Energy Demand	8.29
Figure 8.11	Input Load Characteristics With Batteries at High Charge, and Television Load On	8.30
Figure 8.12	Input Loadlines at Lower Battery States of Charge	8.31
Figure 8.13	Matching of Array and Load Characteristics for the Monitored System, at Expected Operating Cell Temperatures	8.34

Figure 8.14	Optimum Power Voltage Deviations for PW-P 801 Modules In Relation To Expected Cell Temperature and Loadline Ranges	8.36
Figure 8.15	Optimum Power Loss as a function of Deviations from Optimum Power Voltages, for PW-P 800 and PW-P 801 Modules	8.37
Figure 8.16	Optimum Power for an Array of Two PW-P 800 and PW-P 801 Modules, per 1000 W/sq.m POA Insolation, as a function of Cell Temperature	8.38
Figure 9.1	Sample POA Insolation Demand Curves For Fixed Load and Varying Battery Capacity	9.13
Figure 9.2	Sample POA Insolation Demand Curves For Fixed Battery Capacity and Varying Load	9.13
Figure 9.3	POA Insolation Probability Curves for Pretoria (from 10 years' records, at 30 degrees tilt)	9.16
Figure 9.4	POA Insolation Probability Curve Compared With Lower Confidence Bound of Day-Run Means Using Z-Coefficient for $P=0.01$	9.17
Figure 9.5	Loss of Power Probability Curves for the Monitored System at Design Load	9.21
Figure 9.6	LOPP Curves for Monitored System Before and After Battery Capacity Adjustment, at Design Load	9.24
Figure 9.7	LOPP Predictions of Maximum Load Demand for the Monitored System	9.26
Figure 9.8	LOPP Predictions of Minimum Battery Capacity for the Monitored System	9.26

Figure 9.9	LOPP Predictions of Minimum Array Size for the Monitored System	9.30
Figure 9.10	Array/Battery Combinations Predicted to Satisfy LOPP = 0.01 for the Design Load in Pretoria Weather	9.34
Figure 9.11	Array/Battery Combinations Predicted to Satisfy LOPP = 0.001 for the Design Load in Pretoria Weather	9.34
Figure 9.12	Summary of Array and Battery Sizing Indicated By Different Sizing Methods	9.71
Figure 10.1	Annual Levelised Unit Cost of Consumed Electrical Energy, Varying Discount Rate and Battery Service Life	10.54
Figure 10.2	Annual Levelised Unit Cost of Consumed Electrical Energy, Varying Project Lifetime and Array Salvage Value	10.56
Figure 10.3	Annual Levelised Unit Cost of Consumed Electrical Energy, as a function of Utilisation Levels	10.57

Chapter 1

INTRODUCTION

The broad aims of this study were to examine the technical, social and economic appropriateness of using small stand-alone photovoltaic systems to supply electrical power for educational purposes in rural areas.

To this end, research has been conducted on the technical performance of photovoltaic systems which are currently used to power educational television in non-electrified schools in Bophuthatswana. To supplement the technical study, social, educational and economic aspects of Bophuthatswana's schools television project have been considered, leading to an assessment of the appropriateness of solar-powered educational television in this particular local context.

1.1 Locating the Research

The present study was initiated by the Energy Research Institute, University of Cape Town, at a time when increasing local applications for photovoltaic technology, in the field of development, were becoming evident. Falling equipment costs, gains in knowledge, and entrepreneurial activity were stimulating rapid expansion in the use of photovoltaics for off-grid electrical power, both in rural and non-electrified peri-urban areas. Little systematic local research, however, had been undertaken to support these developments.

For example, in the technical realm of sizing the components of a stand-alone photovoltaic system economically for a particular application, under local environmental conditions, vendors of photovoltaic systems in Southern Africa have typically been reliant on the expertise and sizing methods of overseas equipment manufacturers. As will be shown, such methods may not be optimal for local applications in developing areas, and may also be based on inadequate local climatic data.

Secondly, a need was perceived for research which would examine, from a broader multidisciplinary perspective, how photovoltaic power could contribute to and mesh with the fabric of life of users, in a variety of developmental applications. This concern reflects the widely accepted view that the benefits of technological innovation in developing areas are strongly dependent on socio-economic factors and social context.

A series of parallel first phase studies was therefore initiated by the Energy Research Institute, to evaluate the technical, social and economic appropriateness of photovoltaic technology for potentially significant local applications such as domestic power for off-grid households (cf. Muller, 1987; Morris, 1988), water pumping (Gosnell, in progress) and power for educational purposes in rural areas. An overview of such local research directions, against an international background, is provided by Sinclair (1989).

The initial studies, including the present investigation, were framed in an inductive, exploratory manner, with the purpose of generating baseline knowledge from selected case studies, in order to identify critical issues for subsequent more focussed research.

Remote data-logging techniques were employed to monitor continuously and over an extended period the system behaviour of selected photovoltaic installations in the course of their use. This approach has enabled a more realistic assessment of system performance through a variety of actual environmental and user-determined conditions. Since such conditions are locally specific, variable, and at best probabilistic in their variation, and since stand-alone photovoltaic systems with energy storage respond in fairly complex, non-linear fashion to variations in weather and utilisation, extended continuous performance monitoring was considered an appropriate means of collecting data for analysis, rather than proceeding from a more theoretical analysis of component performance characteristics, which on the whole and to a certain level of accuracy are reasonably well established (cf. Macomber et al, 1981; Buresch, 1983; Lasnier and Gan Ang, 1988 for useful synopses) but the interactive operation of which has been less fully modelled (cf. Menicucci, 1985; 1986b; Menicucci and Fernandez, 1985 for perhaps the most comprehensive attempt to simulate photovoltaic system performance through a combination of

analytical and empirically derived relationships).

One of the presently fluid areas in international photovoltaic system research, arising from the complexities of interaction between non-linear system behaviour and probabilistic environments, is that of sizing methodology - in particular, the search for reliable ways of predicting the size of components in a photovoltaic system sufficient and economically optimal to satisfy a specified load demand, with a specifiable weather-related probability of loss of power to load. The advantages, in principle, of such a "Loss of Power Probability" approach in the design of terrestrial photovoltaic systems include (i) compatibility with the probabilistic nature of the prime source - solar radiation received on earth - ; (ii) enhanced ability to compare photovoltaic systems, at equivalent levels of power availability, with alternative generating systems; and (iii) improved techniques for assessing the economic tradeoffs between the exceptionally high levels of availability which can be achieved through over-sizing photovoltaic systems, and the cost savings of installing critically sized systems with an acceptable probability of weather-related failure. This last aspect is of particular relevance for the design of photovoltaic systems in a development context, where capital is scarce.

In the course of investigating the performance of photovoltaic systems used to power schools television in Bophuthatswana, the economic sizing of system components emerged as a foreground issue. Owing to this, the study has provided an opportunity to examine critically some existing commercial and theoretical sizing methodologies, and to propose a new Loss of Power Probability sizing method, with allied proposals for the statistical treatment of local solar radiation data. This has become the main analytical thrust of the present phase of research, while attendant difficulties (such as uncertainties in the measurement of solar irradiance and in relating irradiance measurements to photovoltaic module performance specifications) have been highlighted for further enquiry.

It is interesting to note that the inductive analysis of data obtained from the monitoring study (described in Chapters 2 to 8) played little part, directly, in the formulation of the sizing method proposed in Chapter 9. What is suggested, though, is the usefulness of such

exploratory studies as a means of drawing a team of local researchers into a field of enquiry, immersing them in the issues, and guiding their attention to more specific research questions, relevant to local applications of the technology.

Turning to the social aspects of the present enquiry, Chapter 10 discusses the social context of solar-powered educational television in Bophuthatswana, and weighs up the many criticisms which have been levelled at this implementation of schools television.

Although Bophuthatswana's "Edutel" project has followed in the pathways of other developing countries' experience with this educational technology, over two decades, and perhaps presages similar planned initiatives in "mainland" South Africa, the schools television project has developed in a locally specific historical, organisational and political framework. This means that while common themes emerge, which have been reported from other developing countries as well, the scope for generalising from Bophuthatswana's specific experience is limited. Nonetheless, important lessons can be drawn from Bophuthatswana's experience, which should be heeded before any similar projects are attempted in the region. Decision-making structures, forward planning, consultation with users, provision of suitable software and support services, responding and adapting to teachers' needs, the scale of the project, and stretched resources are amongst the problem areas which are discussed in detail in Chapter 10. Under-utilisation of the equipment installed in schools reflects such problems in linking a technological "solution" to educational needs and wants amid structural weaknesses of underdevelopment.

Unfortunately, the depth of enquiry here has been limited by political constraints, in that the Bophuthatswanan cabinet eventually refused permission for more detailed field research to evaluate the course of the schools television project to date, which would have included a representative survey of schools. In such respects, it is sometimes easier to make progress with technical aspects of multidisciplinary research than to assess the important socio-economic and behavioural determinants of technological innovation in developing areas.

1.2 Initial Formulation

The research, as initially conceptualised, included a component of "action research". Original intentions were to develop associations with a rural community, preferably as part of an integrated development initiative, to undertake a sociological assessment of needs and wants in the community, and (assuming that the selected community expressed a desire for electrical power for educational purposes) to design and install a suitable photovoltaic system to power lights and audio-visual equipment; then to monitor the technical performance of the system and to evaluate the the social and economic appropriateness of the technology.

This approach was pursued, for several months, and although the research design was subsequently modified it is useful to record these initial stages and their outcome. What emerged was the difficulty in linking a pre-conceptualised project with the dynamics of community needs and wants and social organisation.

Relationships were developed with residents in Friemersheim, an ex-mission community in the Southern Cape. A need had already been expressed by a spokesman in the village for audio-visual facilities (primarily video) to assist in formal and informal education activity. A community researcher moved to live in the village, and residents were surveyed to develop a detailed community profile. Key figures and other selected residents were canvassed about local needs and aspirations. Partly to encourage participation in these enquiries, and partly to test local interest in using audio-visual equipment, a video film was made, with interviews conducted mainly by a group of enthusiastic and talented local high-school students.

In this process, both positive and negative factors came to light which could affect the course of the project. Enthusiasm was generally expressed for the proposed photovoltaic system and audio-visual equipment; however, after more detailed enquiry, it became apparent that this was perceived as a relatively minor need, compared with more pressing community concerns (such as improved water supply). It also became apparent that intricate local politics could either block development initiatives, or else lead to a monopolisation of facilities to serve only sectional interests. To develop new forms of

local organisation which could control use of the equipment and make its potential available for wider community benefit would evidently take time, and might not succeed. Finally, the appropriateness of installing the photovoltaic system in a formal education setting, such as the local primary school, came into question for several reasons. Some were circumstantial, such as impending moves to relocate the school premises; others were more persistent discouraging factors, such as the difficulties of accessing suitable video material for primary education, especially in the Afrikaans medium, and the likelihood that community access to the school buildings at night would be restricted by the educational authorities.

The depth of these initial enquiries was valuable in disclosing potential problems which might otherwise have surfaced later during the project and rendered it valueless. After further discussions and negotiations with residents, it was agreed not to proceed with the proposed photovoltaic project, in this form, at the present time, and attention was devoted to other development initiatives in the village.

The research on photovoltaic power for rural education was therefore redirected, and a more suitable opportunity for study came up, following Bophuthatswana's decision to adopt this technology on a large scale for rural secondary schools in that region. This provided a substantial case study for exploring the appropriateness of the technology in a non-artificial context. For purposes of technical monitoring, contacts were made with the company which was supplying equipment for Bophuthatswanan schools, who provided generous assistance in allowing monitoring equipment to be linked up to an identical installation installed for demonstration purposes at a farm school in the Transvaal.

1.3 Background to Solar-Powered Educational Television in Bophuthatswana

Since 1985, Bophuthatswana has installed television and video facilities in over 350 secondary schools. Roughly 80% of pupils in Bophuthatswana attend schools in rural areas (following the Department of Education's classification) and approximately the same proportion of secondary schools do not have connections to grid electricity. In these non-electrified schools, the television and video facilities are powered by photovoltaic systems.

The background to the Edutel schools television project is described in greater detail in Chapter 10. This section provides a brief introductory summary.

Following acceptance of "independence" from the the South African government (a status not recognised, however, beyond the borders of South Africa) in 1977, Bophuthatswana identified improved education provision as a developmental priority. Concerted efforts have been made since then to increase both the quantity and quality of educational provision in the region. School enrolments increased rapidly. In secondary schools, for instance, enrolments had risen from approximately 66 000 pupils in 1977 to nearly 150 000 pupils by 1984, the time when the educational television project was initiated (De Clercq, 1984:36-37; Rep. Bophuthatswana, Assembly Debates, 1984:336).

As has happened in many developing countries embarking on educational expansion and reform, resource constraints were experienced, especially with respect to a shortage of suitably qualified teachers in secondary schools.

Educational television was proposed (by a local educational technologist) as a means of alleviating such problems. The intention was that school television could play a supplemental role, not replacing the teachers' functions, but, by bringing standard high quality instructional material into classrooms, could add to pupils' learning resources, compensate in part for the shortage of qualified teachers, and of facilities such as libraries and laboratories, and at the same time help to upgrade the knowledge and teaching methods of existing teachers.

The proposal went ahead, and equipment was installed in schools. (This equipment is described in the next chapter.) Video programmes were duplicated and distributed to schools, from central Edutel offices, since not all schools could receive broadcast signals without further microwave extensions or a satellite link. Originally, the proposal was that three Edutel production teams would produce a steady output of local educational programmes, adapted for Bophuthatswanan school syllabuses. However due to organisational, technical and financial constraints, Edutel remained largely dependent on imported software from overseas sources.

Educational or instructional television has been tried in several developing countries, since the sixties. Within Africa, the most notable ventures have been in Francophone countries, such as Niger, the Ivory Coast, and Senegal. In the Southern African region, Bophuthatswana's Edutel project has been the first systematic attempt to use this technology, on a wide scale, in rural education. It can be noted that the scale of the Edutel project was ambitious from the outset, with its efforts targetted to all secondary schools in the region, and within these schools, all school subjects, and all school standards (standards 5 to 10). Implications of the scale of the project are discussed in Chapter 10.

1.4 Structure of Report

Chapters 2 to 8 are concerned with a technical evaluation of the equipment used for television and video in Bophuthatswanan schools, focussing on the photovoltaic power sub-system. The monitoring method is described, and the data collected in the course of the monitoring study are summarised and analysed. Chapter 9 develops a model for prediction of photovoltaic system performance in critical conditions (ie. adverse climatic conditions leading towards system loss of power to load) from which a sizing method is derived that makes use of statistically condensed historical weather data. Sizing indications from this model are compared with other sizing methods and with the design of the installed systems. Chapter 10 addresses social and educational aspects of the Edutel project, discusses aspects of "appropriateness" of technology in social context, and analyses the economics of photovoltaic energy supply in this particular application. Chapter 11 summarises the technical conclusions reached in the course of this study, and sets out recommendations for further research and development.

Note on referencing style: When references are to published sources, the citation style follows the Harvard system, with full references appearing in the Bibliography appendix. Where references are to verbal communications and are otherwise not explained in the text, the attributions are provided in notes at the end of each chapter, which are numbered in square brackets, eg. [1].

Chapter 2

DESCRIPTION OF SYSTEM

This chapter describes the components used in the systems which were installed in Bophuthatswanan schools to provide solar-powered television and video facilities. Manufacturers' specifications for the principal components are included, where available, as well as the overall system specifications.

Physically, the systems used in the non-electrified schools in the Edutel project comprise two photovoltaic modules, mounted on a rack in the school grounds, and a cabinet, housed inside the school, which contains a colour television receiver/monitor, a video cassette recorder, and storage batteries.

These systems are the same as the monitored installation.

Functionally, the photovoltaic-powered system can be divided into the following sub-systems:

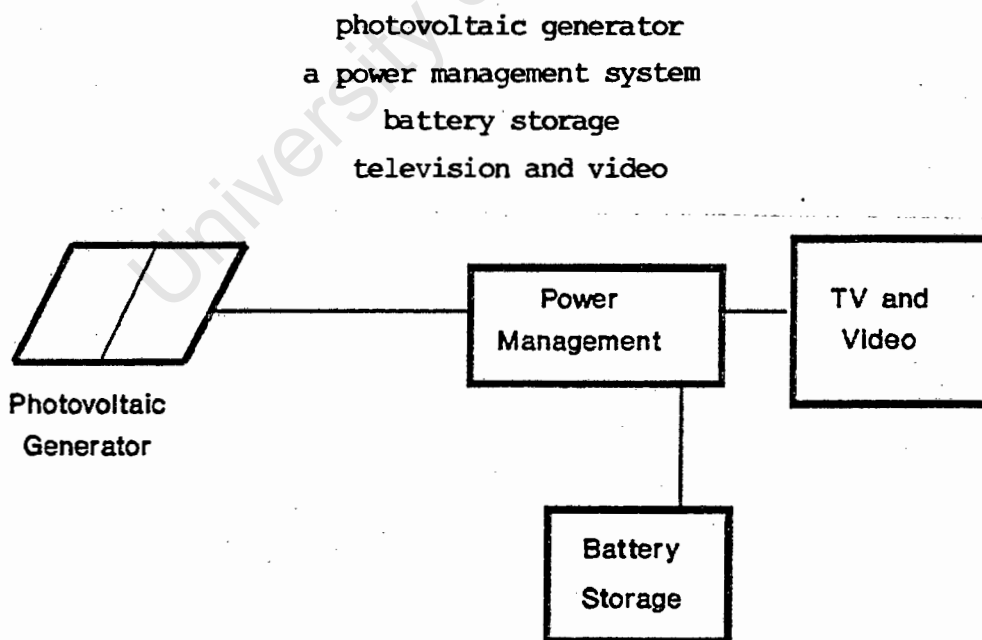


FIGURE 2.1 Schematic of the Monitored Photovoltaic Installation

2.1 Television and Video

The television receiver/monitor (with associated power control) is probably the most innovative aspect of the system. Developed and manufactured by the French company S-International, specifically for remote areas operations, it is designed to run off a low voltage d.c. supply, with low power consumption. It delivers a full-size (56 cm) colour picture, from broadcast or video source, at a specified average power consumption of between 38 and 40 Watts. This compares favourably with locally available domestic television sets in a number of respects relevant to solar-powered applications:

- 1) The low power draw means that the size of the photovoltaic array and battery storage can be reduced, for equivalent performance. (By comparison, according to the supplier company, locally available sets which were tendered for the Edutel contract were a Sony portable television receiver, with a 38 cm screen and a power consumption of 68 Watts, and a Blaupunkt 51 cm receiver, with a rated power consumption of 80 Watts, a.c.)
- 2) Being specifically adapted for d.c. power supply, there is no requirement for an intervening inverter, with associated losses in efficiency and reliability.
- 3) Combining the functions of TV receiver and video monitor means that broadcast signals can be received (and videotaped), while direct video sources can be played back without the picture loss of an r.f. connection.
- 4) The circuitry is modular, making for easy and rapid onsite repair. Modules, contained in drawers beneath the screen, can be replaced in a matter of minutes by relatively inexperienced maintenance personnel, who can then return any faulty module to workshops for repair of electrical components.

Certain additional features are intended to make for easy use, by people who may be unfamiliar with television set controls, or to guard against misuse. The reception channels (three v.h.f. and three u.h.f.), once tuned, can be selected but not altered by the ordinary user. If the broadcast signal is lost, for example through leaving

the set switched on beyond transmission times, there is an automatic power cut-off. Further, a clock-timer can be set to regulate the hours when the television may be used.

The unit, designated as Model 747C, is housed in a heavy lockable cabinet (which includes a fitted burglar alarm, set off by unlicensed opening). The cabinet encloses the television, video and batteries, and has space for locked storage of videotapes. Anticipating daytime use in classrooms, the screen is winged by small side shields, to reduce reflections.

The design of this set has benefitted from French interests in extending solar-powered instructional television, demonstrated in such countries as Niger (the first French educational television venture in Africa, beginning in the 1960's), the Ivory Coast and Senegal. The telling features are the low power consumption and the modularity of components, for which there is at present no local competitor.

Disadvantages are that the unit is relatively expensive, and that the original French company is withdrawing from this area of development (perhaps reflecting a trend by certain petroleum companies to withdraw subsidiaries from diversification in such alternative energy technologies [1]). However, the South African suppliers of this set have obtained the license and established the routes for local manufacture [2]. Entry into local manufacture will depend on local (and possibly export) market potential.

The competitive edge of this presently efficient design could be challenged in the future by lower-power flat-screen TV technology.

The unit provides a 12 V d.c. power take-off, which is used to power the video cassette recorder.

The model employed in the Bophuthatswana installations is a VHS format "portable" Japanese VCR, manufactured by J.V.C., model HR2650.

Designed for battery operation, this model possesses the advantages of low power consumption (around 8 to 9 Watts) and d.c. input. Further, while the HR2650 is less known in South Africa (this model being no longer available) its close "industrial" equivalent, Model BR-6200, has an established reputation for ruggedness and reliability.

2.2 Battery Storage

The batteries used are imported Delco 2000 Solar "maintenance-free" batteries, each with a rated capacity of 105 amp-hours and nominal voltage of 12 V. The capacity here is specified for a 100-hour discharge rate, at 25 degrees C. Four such batteries are employed per installation, two in series, two in parallel, to provide the 24 V (nominal) system with 210 Amp-hours rated storage. The effective installed storage capacity, however, depends on the depth-of-discharge allowed by the charge controller settings, and to some extent on the actual discharge rates, and battery temperatures - factors which are discussed below.

Delco 2000 batteries have lead-calcium plates and are designed for moderate-depth cycling in solar-compatible conditions.

There seems little consensus in the literature, or in usage, about the optimal design of batteries for small-scale stand-alone photovoltaic applications. In general, lead-acid batteries are favoured, for reasons of performance and cost. There are then choices about the composition of the plates, grid construction, and electrolyte density. For solar applications which require regular cycling of the batteries, the plates must be designed to sustain such repeated cycling without great reduction in battery life.

A sealed battery such as the Delco 2000, which has heavy construction lead-calcium plates, has the following advantages over a traction-type battery with heavy duty lead-antimony plates, in the application under consideration.

- 1) The calcium component in the plates reduces gassing, compared with lead-antimony plates. This carries several benefits. One aspect is that of safety, especially when batteries are housed in an enclosed space: there is a much reduced risk of explosion. Another aspect is that of maintenance. Although the batteries are safety-vented, they are effectively sealed and do not need electrolyte maintenance, since water losses are much less. This could be a crucial advantage in remote rural applications.

- 2) A low self-discharge rate. For example, Delco specifications quote a self-discharge rate of < 4% per month, while lead-antimony batteries typically have a higher self-discharge rate of about 12% per month (Lasnier and Gan Ang, 1988:92).
- 3) In principle, a longer battery life is expected from lead-calcium plates, provided the charging regime does not exceed the recommended depths of discharge. However, grid construction and permissible depth of cycling enter as crucial variables. Delco 2000 lifetime ratings are discussed below.
- 4) The Delco 2000 Solar model is somewhat adapted for long term freedom of maintenance, in solar applications, through an enlarged electrolyte volume. In addition, the manufacturers say it has "special electrolyte" suited for photovoltaic operation, but do not specify in what way. (Specific gravity at full charge is stated as 1.27 at 80 degrees Fahrenheit.)

The disadvantages of such a battery would appear to be mainly economic.

- 1) The available storage capacity, under a recommended charge/discharge regime, can be less than that of a lead-antimony traction-type battery of the same rated capacity, since the latter type can sustain deeper discharge cycles.
- 2) Delco batteries are imports to South Africa.

Three factors which affect the **installed capacity** of the batteries in the system are:

- the charge controller settings
- the rate of discharge, in typical operation
- the operating temperature of the batteries

In the Bophuthatswana installations, typical charge controller settings are an upper charging limit of 27.5 volts and a lower load-shedding setting of 23.8 volts. These control limits are set to prevent over-charging and over-discharging of the batteries, in order to prevent damage and prolong battery life.

The set upper limit appears slightly conservative by comparison with manufacturers' recommendations. (Delco recommends voltage regulation at 28.2 volts (temperature 27 degrees C) or 28.8 volts (temperature 16 degrees C). However monitored data show that when a battery has reached the set upper limit of 27.5 volts, under charge, it returns to an open circuit voltage of over 25.5 volts (eg. at night, with no load). According to manufacturers' specifications this indicates the batteries have reached 100% state of charge. This upper limit therefore appears suitable for this mode of pulse width modulated charge regulation, at observed operating temperatures.

Available battery capacity depends partly on rates of discharge. It increases at lower discharge rates. For the present system, the highest discharge current rate (assuming full load and no power from the array) would be slightly less than the 100 hour discharge rate. Empirical data from the manufacturers indicate a full capacity delivery of 120 amp-hours, at this discharge rate and at 25 degrees C. Under these conditions, according to this data, 85 amp-hours would be delivered by the time the lower cut-off voltage of 23.8 volts is reached. Thus the upper and lower set charge/discharge limits should allow a maximum cycle depth of about $85/120 = 70\%$ of the batteries' capacity.

The manufacturers' specifications are more conservative than the additional empirical data supplied, giving a rated capacity of 105 amp-hours. Using this specification rated capacity as the reference, one would expect the four batteries in the system to provide about $70\% * 210$ amp-hours, or 147 amp-hours available storage.

At 24 volts nominal, this is equivalent to 3,53 kWh storage.

2.3 Power Management System

One of the modules in the television system circuitry is termed an "Energy Management Unit" (EMU). This module, which interfaces with the PV array, the batteries, and the load, performs the following functions:

- 1) Electronic control of the battery charging rate.
- 2) Control of admitted array power (voltage and current) for combinations of load-on and battery charge/discharge.
- 3) Load-switchout when battery voltage falls to a set minimum.
- 4) Power disconnection under certain other conditions (eg. when broadcast signals are lost, or in response to a settable timer).

The mode of power control is through pulse width modulation, operating on feedback from load demand and battery voltage. As a commercial proprietary design, the circuitry cannot be reproduced here, but can be broadly described as follows.

The feedback enters a comparator circuit, against reference voltages, some clamped and some settable (eg. for battery charge/discharge limits). Output from this circuit interacts with an oscillator, to produce a square wave signal of variable pulse width. The signal is stepped up through two bipolar transistors to provide the signal and power to drive a power FET (field effect transistor) which chops the PV array input in the shape of a pulse width modulated square wave.

This square wave modulation has the effect of dynamically controlling the average voltage and current admitted from the PV array.

The waveform varies both in frequency and duty-cycle. Information from oscilloscope tests by the supplier company indicated, for example, that with steady d.c. input, the waveform under full load had a frequency of 100 Hz and equal on:off pulse width, while under float charge conditions the frequency was measured at about 29 Hz, with on:off = 0.4.

There is no evidence, from the partial circuit diagrams made available by the supplier company, that this Energy Management Unit fulfils an optimum power tracking function. This would require a form of feedback and control which regulated the apparent input impedance to draw maximum power from the photovoltaic array, and d.c./d.c. conversion to supply this power at the system demand voltage. The mode of power regulation (PWM switching, using a power FET) is well suited for such control, and would appear rather elaborate and non-robust if optimum power tracking were not intended. However the local system suppliers believe that the EMU does not incorporate an optimum power tracking function. As a proprietary product, full information was not available and the module was not readily available for bench tests.

2.4 Photovoltaic Generator

In the monitored system, and in the Bophuthatswana installations, the photovoltaic generator consists of two Photowatt PW-P 801 modules, wired for a 24 volts (nominal) supply.

Each module contains 72 polycrystalline silicon cells in a laminated encapsulation, mounted in an aluminium frame of outer dimensions 70 * 154 cm. The area of each module is 1,078 sq.m. Each silicon cell is 10 * 10 cm, yielding a total cell surface area, per module, of 0.72 sq.m.

Difficulties were experienced in ascertaining the rated power output of these modules.

The supplier company had performance specifications, provided to them by Photowatt SA, which indicated a rated power of 82 Wp (peak watts) per module. The rating in peak watts denotes the rated optimum power of a module at an insolation of 1000 W/sq.m and a cell temperature of 25 degrees C.

This would indicate an array power of 164 Wp, and is in line with the supplier company's specification of 160 Wp for the installed array.

However, these ratings apply to a different model of Photowatt module from those installed, namely the PW-P 800 (which has monocrystalline silicon cells) as opposed to the polycrystalline PW-P 801.

When direct enquiries were made to Photowatt SA headquarters in France for PW-P 801 product information, the specifications supplied were again for the PW-P 800 model. Specifications for PW-P 801 modules appear not to be currently available.

A South African agent for Photowatt products offered the opinion that the PW-P 801 modules may have been a one-off batch, manufactured as a polycrystalline replacement for, and equivalent to, PW-P 800 modules.

Performance specifications for PW-P 800 modules, obtained from Photowatt SA, are reproduced below. All values are stated as given within $\pm 12,5\%$ latitude.

TYPICAL DATA FOR PW-P 800 MODULES (FOR 24 VOLTS CONFIGURATION)

At insolation of 1000 watts/square metre

Air mass: 1.5

Junction temperature (degrees C)	25	45	60
Maximum power (watts)	82	75,4	70.7
Voltage at maximum power (volts)	34	31	28.8
Current at maximum power (amps)	2.41	2.43	2.45
Short circuit current (amps)	2.67	2.70	2.72
Open circuit voltage (volts)	42.4	39.1	36.8

Normal Operating Cell Temperature (NOCT): 45 degrees C

at standard conditions:

Insolation	800 watts/square metre
Ambient temperature	20 degrees C
Wind speed	1 metre/second

[Source: Photowatt product specifications.]

While these performance specifications, supplied by Photowatt SA, formed the basis for the supplier company's array power specifications, the fact that they are for a different model and type of module is not without consequence. It was felt necessary to perform tests on the array output characteristics at the monitoring site, to get an indication of differences in performance from PW-P 800 specifications.

The site tests indicated an array power of 135 Wp, or a module power of 67.5 Wp (with estimated uncertainty $\pm 8.5\%$), and significantly lower open-circuit and optimum-power voltages than those specified for PW-P 800 modules. These tests are reported in Chapter 7.

Additional information was received from local Photowatt agents, sent to them by Photowatt SA in February 1988, which presents a lower power rating for PW-P 800 modules than previously, adding to uncertainties about the manufacturer's product information. These specifications indicate a rated power of 73 Wp $\pm 12.5\%$.

The local agent was not able to explain the change from earlier specifications.

Since an aim of this study, in addition to assessing the observed performance of the system monitored, is to scrutinise the method of sizing the components in a stand-alone photovoltaic system, and since Photowatt's sizing advice to the local suppliers was based on the original PW-P 800 module specifications, the ratings presented above will be of relevance in later sections. They are explored further and compared with tested array output characteristics in Chapter 7.

The **orientation** and **tilt** of a photovoltaic array determine the proportion of available insolation received by the array at different times of day, different times of the year, and in different weather conditions (eg. varying components of diffuse and direct insolation, according to cloudiness). The method of **mounting** the modules has an impact on operating temperatures, and hence conversion efficiencies.

The installations in Bophuthatswana are designed to orient the arrays to true North, and the inclination of the arrays is designed at 23.5 degrees from the horizontal. Modules are mounted side by side in a fixed position. Styles of mounting may vary, but permit air flow back of the modules; roof mounting is avoided, for reasons of module cooling, non-optimal orientations, and questions of structural support.[3]

The mounted array may be fenced off, to avoid accidental or intentional mechanical damage [4], for example from flying stones, and as an electrical safety precaution.

At the monitoring site, the array is mounted on a constructed steel frame situated in the school courtyard. The modules are raised two to three metres from the ground, oriented North, but tilted at a declination of 30 degrees from the horizontal (unlike Bophuthatswana installations). Some occlusion of direct solar radiation occurs in the early morning and late afternoon due to the shadow of the low school buildings surrounding the courtyard.

2.5 System Specifications

Some of the salient component specifications have been presented above. Observed component performance and system performance, analysed from data from the monitoring site, are discussed in Chapter 5 onwards.

As background for discussions of observed system performance, here are the system performance specifications on which the suppliers based their design:

Design Load

The systems are designed to support 10 hours television usage per day. For 5 hours per day, use of the video cassette recorder is added in this design load.[5]

Taking average power consumptions of the television and VCR as 38 watts and 9 watts respectively, this amounts to a daily design load of

425 watt-hours. At higher consumptions (eg. using the television at high volume) the load could rise to about 450 watt-hours per day.

"Autonomy"

As a measure of the reliability of the power system, the battery storage is intended to provide at least 5 days' "autonomy", ie. in the absence of input power from the PV array, starting with fully charged batteries, the design load would be supported for at least 5 days.[6]

This requires battery storage capable of delivering about 2.13 to 2.25 kWh to the load, a requirement more than met by the actual installed battery capacity of approximately 3,53 kWh.

Notes

- [1] Interview with supplier company representative, 29/10/86.
- [2] Interview with supplier company representative, 14/11/86.
- [3] Interview with supplier company representative, 4/86.
- [4] As [1]. The representative estimated at this time that approximately 20 out of some 600 modules had been damaged by "half-bricks" thrown at them, predominantly in areas of Bophuthatswana close to urban areas, such as GaRankuwa. Whether such actions represented student protest specifically against this technology, or was incidental to broader protest in black schools, is so far not established.
- [5] This information is taken from the Photowatt sizing advice telexed to the supplier company, kindly made available for this research.
- [6] This conservative specification for the autonomy of the system is contained in the suppliers' system specifications. The Photowatt sizing advice specified 14 days' autonomy for this system.

Chapter 3

INSTALLATION, MAINTENANCE AND RELIABILITY

3.1 Installation

Installation of systems in schools for the Edutel project in Bophuthatswana began in the portions of Bophuthatswana close to the Rand, and then progressed westwards and southwards, into "more remote educational circuits" [1].

Portions of Bophuthatswana are fragmented and dispersed (see Figure 3.1 for a map of the region, divided into seventeen educational circuits), and the location of many rural schools was unmapped. Despite this, company representatives estimated their installation rate as averaging about two to three schools per day [2,3]. On-site installation time was estimated as up to 4 hours per system.

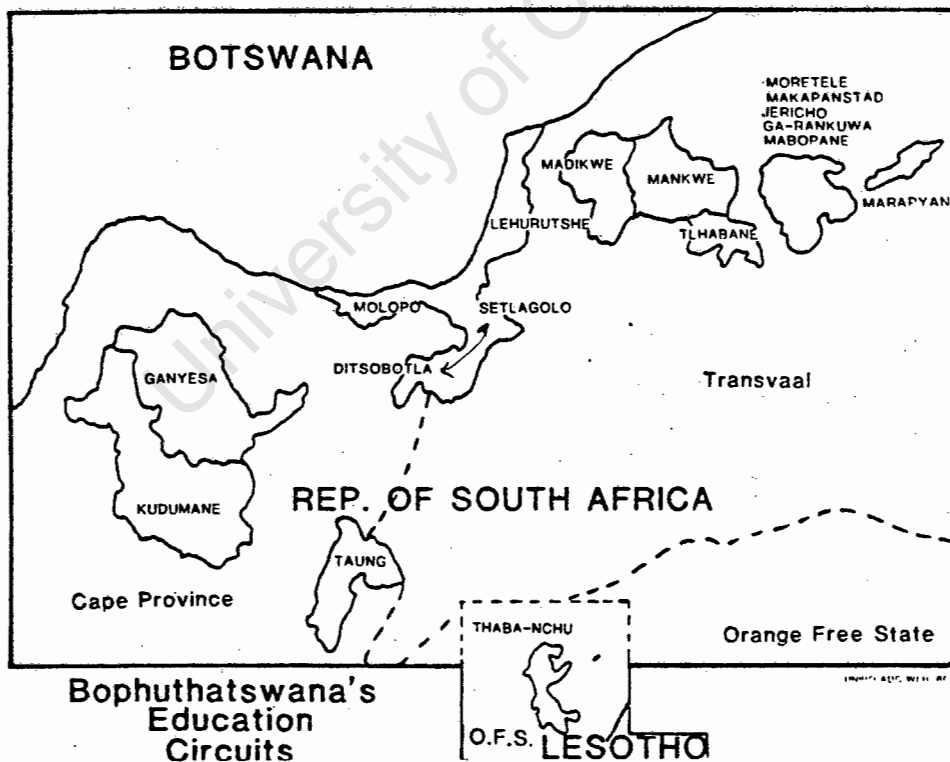


FIGURE 3.1 Map of Educational Circuits in Bophuthatswana
[reproduced from Holderness, 1986:10]

As of July 1987, 354 schools in Bophuthatswana had been supplied. Of these, 284 had systems powered by photovoltaic generators [4]. The remaining 70, having access to grid supply, did not require solar power, but otherwise were supplied with identical systems, adapted for mains supply by means of battery charging. In support of this policy, mention was made of the maintenance advantages of standardisation [5] coupled with the modularity of the offered television set, and the advantages of battery back-up power in the face of periodic failures in the grid supply [4].

3.2 Maintenance

There are no routine maintenance tasks which need to be performed by system users, except that in dry and dusty weather it may be necessary to wipe any collected dust from the surface of the PV array, to maintain optimum generating efficiencies.

Malfunctions of the equipment are identified and repaired by maintenance teams. In 1986, the supplier company supported two maintenance teams, locally based in Bophuthatswana [1]. Equipped with exchangeable modules, relatively unskilled maintenance workers can broadly diagnose electronic failures, replace the affected module, and return the failing module to a central workshop for repair.

In late 1986, the supplier company began to train Bophuthatswanan nominees for maintenance functions, with the aim of reducing Edutel's dependence on the company for maintenance.

Besides responding to reported malfunctions, the company has mounted systematic maintenance "sweeps" of installed equipment, in order to monitor system performance and to make adjustments and repairs where necessary. The first of these, some four to six months after installation, played the important role of identifying faults which could not be detected at installation time, such as battery-charging faults which would not initially be identifiable due to the reserve charge of installed batteries [1].

This first sweep picked up sporadic first-time component faults, such as damage to joints and coils, caused by bumpy transport; otherwise, the only systematic failures reported have been in the area of the Energy Management Unit, surrounding the power FET, with a typical pattern of protecting diodes burning out. It is probable that these failures were due to lightning-induced pulses, as also occurred at the Transvaal monitoring site. From company records, it appears that the incidence of this fault-pattern was less than 2% of installed systems in a year.[4,6]

3.3 Reliability

The reliability of the photovoltaic generator and battery storage in meeting the specified design load, under varying climatic conditions (in the absence of component malfunction), is discussed at length in later chapters. Here, discussion is restricted to the question of the functional reliability and expected lifetime of important components in the system, and is limited by available information. Information derives from manufacturers' specifications and secondary literature. The brief monitoring period does not provide an empirical basis for assessing components' reliability.

3.3.1 Photovoltaic modules

It is widely believed that PV modules, if not subjected to mechanical damage, have a long useful life expectancy. For accounting purposes, the life expectancy is often rated at 20 or 25 years. This is largely a notional figure. As new technology, field experience is not to hand to provide representative estimates of the productive lifetime of photovoltaic modules.

An average rate of module degradation is implied in the assumptions of some systems sizing procedures, which allow for an average lifetime degradation of 10% in module performance in the sizing calculations. Certain module manufacturers also guarantee that their modules will deliver within 90% of their rated power, over a specified lifetime.

Mechanical damage to the modules can of course impair their performance, or necessitate replacement if severe. The most likely cause of such mechanical damage in the Bophuthatswanan schools television context would be damage to the laminate from stones thrown at the array. This could happen accidentally or could be a deliberate act, and to date such damage has determined the replacement rate of modules, rather than any detected inherent failures.

Impact from a flying stone can cause crazing of the laminate, in itself not of serious implication; but if the laminate is sufficiently damaged to allow rain to enter, then cell junctions can deteriorate and there is a possibility of short circuits, leading to cell burn-outs.

3.3.2 Batteries

The batteries, in a stand-alone photovoltaic system with battery storage, are regarded as the major replacement cost during a system's lifetime, since the cycle life of batteries is limited.

Cycle life, for a given model of lead-acid battery, depends on the depth of cycling, and on battery operating temperatures. In a system environment where regular cycling is demanded, cycle life is likely to determine the useful lifetime of the batteries, provided a well regulated charging regime is maintained.

If a breakdown in the charge/discharge regime occurs, then premature damage could result, due to prolonged overcharging or undercharging. In this case, battery reliability would be jeopardised by failures of other components. For example, a failure in the Energy Management Unit of the present system can result in unregulated connection between array and battery. Such a fault was observed at the monitoring site in November 1986, following lightning damage, and battery charge voltages subsequently rose above 30 volts at times. No observable damage was caused, since the period before detection was less than a week. If however such high charging voltages continued for months, one would expect increased corrosion of the positive plates, higher battery operating temperatures, and consequently a decreased useful battery lifetime.

Under normal regulated conditions, the relationship between depth of cycling and expected battery cycle life is illustrated by the following figures, from Delco manufacturers' specifications.

For Delco 2000 Solar batteries.

Operating temperature: not specified.

Cycle depth (% of rated capacity)	Cycle lifetime (number of cycles)
5%	> 4000
10%	2000
15%	1300
20%	850
30%	500
50%	270

Source: Delco manufacturers' specifications.

Note: It is common practice to judge the end of a battery's lifetime as the point where its available capacity has declined to 80% of initial rated capacity. The cycle lifetime figures provided here, however, use a different assumption, namely that battery life has ended when battery capacity has declined to 50% of original capacity.

It is clear that battery lifetime will be extended if the depth of cycles is restricted. This means that, for a given cyclic energy demand, there is a trade-off between rated battery capacity and expected battery lifetime, since a larger storage capacity implies cycles of less depth.

In photovoltaic applications, however, actual depths of discharge are expected to be highly variable, according to climatic conditions, and the estimation of expected lifetime becomes complex. In Section 2.2 above, it was estimated that the charge control settings permit up to 70% depths of discharge of the batteries in the system. However, this depth may be very rarely (if ever) reached, and average depths of discharge may be small enough to indicate a long battery cycle lifetime.

Calculations, based on monitored data, are provided in Chapter 5 and Appendix B3. These indicate that with a steady daily load of about 370 Wh/day, and climatic conditions equivalent to those monitored in July, August and September, 1987, the predicted battery lifetime according to Delco specifications and criteria would be greater than 5.5 years.

However, this should be a very conservative estimation of expected battery lifetime in typical Bophuthatswanan installations. Firstly, the observed climatic conditions in the months referred to above were considerably worse than average yearly expectations in Bophuthatswana, leading to deeper cycling of the batteries than could typically be expected. Secondly, although the monitored load of 370 Wh/day in these months was below the specification design load, in practice it is doubtful if the systems in Bophuthatswana are likely to reach such a level of utilisation in the foreseeable future (the equivalent of more than 8 hours operation every day). The expected average battery lifetime, in the absence of malfunctions, should therefore be considerably greater than 5 years, and possibly closer to 10 years.

3.3.3 Power management circuitry

This is the section of the power-supply subsystem most susceptible to failure, due to the complexity (large number of components) and the precision of design necessary to maximise efficiencies.

There are no grounds for suspecting unreliability of any individual component, under normal operation. (If this were the case, components to higher specifications could be substituted.) But two factors lead to the expectation that failures would be more likely in this part of the system:

- 1) The number of components, and their interdependence, indicates that random failure chances are increased.
- 2) The design precision in many instances implies a lower tolerance to abnormal events. For example, Schottky diodes surround the power FET (for low forward impedance). But they cannot protect against the magnitude of pulse surges caused by nearby lightning strikes.

Opinion has been expressed that simpler and more robust modes of charge regulation are more reliable [7], but at the expense of system efficiency. Further, such regulators are also no proof against extreme events such as lightning.

In critical applications, such as repeater stations (where a single failure could bring down the whole chain) maximum safeguards against such events may be warranted. But in the kind of non-critical application exemplified by solar-powered school television, it is unlikely that the extra costs of maximum lightning protection would be justified, since the incidence of lightning-induced failures is quite low. The facility for rapid response to failure, and rapid repair time, would be more valuable and cost-effective than a system design aimed at protecting the electronics from such exceptional events.

Under normal operation, the reliability of pulse width modulation power regulation is not established by prolonged field experience, but there are no obvious reasons (other than complexity) to suspect a high chance of failure.

3.3.4 Applications equipment

No quantitative information is to hand concerning the reliability or expected lifetime of the television or VCR components.

A general observation drawn from the literature on remote area standalone photovoltaic systems is that, compared with the established high availability of PV power systems (including battery storage), failures in applications equipment are a more frequent problem. For example, a summary of experience with 58 remote photovoltaic installations in 27 countries, under the NASA Lewis research programme (Ratajczak, 1985), reported only one incidence of module failure and battery failure respectively since 1979, while failures in the applications equipment had been routinely reported - exceeded in frequency only by instrumentation failures.

These observations include school televisions and VCRs, but apply to a much wider range of applications equipment, and so make a general point rather than one specific to television/video. Standard

commercially available items were used for applications equipment in the installations monitored. The observations suggest the benefits of employing applications equipment of rugged design and underline the advantages of the modular construction and ease of rapid repair of the present French television set design.

Ratajczak (1985:7) notes that while none of the failures in applications equipment observed in the study was attributable to the photovoltaic power sub-system, users may misinterpret such faults and become mistakenly sceptical about solar generation. High quality, reliable applications equipment is therefore of additional importance in fostering rational dissemination of photovoltaic technology.

Notes

- [1] Interview with supplier company representative, 29/10/86.
- [2] Interview with supplier company representative, 4/86.
- [3] Interview with supplier company representative, 24/11/86.
- [4] Written communication from supplier company, 28/7/87.
- [5] These points were raised by Minister Holele in response to critical questions in the House of Assembly (Republic of Bophuthatswana Assembly Debates, 1985:600).
- [6] The supplier company kindly made available their maintenance records for inspection.
- [7] Verbal communication, Gunter Becker, 29/10/86.

Chapter 4

MONITORING METHOD

4.1 Choice of Site, and Location

As indicated in Chapter 1, the installation selected for performance monitoring was not in Bophuthatswana, but was instead in the Transvaal, not far to the north-east of Johannesburg. The system, the same as those installed in Bophuthatswana, had been installed in 1986 as a demonstration project, with a view to interesting the South African Department of Education and Training in the technology.

This installation was selected for monitoring primarily because of ease of access and frequent supervision by company personnel, who generously assisted with interfacing the monitoring equipment and in regularly exchanging the EPROMS on which monitoring data was logged.

The school, Bluegill Waters Farm School, is situated approximately 8 km from Jan Smuts airport, and 40 km from The South African Weather Bureau "Forum" weather station in Pretoria, the closest landmark being Eskom's Bredell sub-station. Latitude and longitude are approximately 26 degrees South and 28 degrees West.

4.2 Variables Recorded

The following electrical and climatic variables were continuously monitored. Average values per period were recorded every half-hour.

- 1 Voltage of PV array
- 2 Battery voltage
- 3 Current flowing into or out of battery
- 4 Current flowing to load
- 5 Outdoor ambient temperature

6 Cell temperature of PV modules

7 Global insolation received in the plane of the array

From addition of 3 and 4 the PV array current was obtained.

The date (Julian day) and time of each log period were also recorded.

4.3 Instrumentation

Temperature measurements

The temperature sensors used to monitor ambient temperature and array cell temperature were IC sensors, model LM335 (National Semiconductor), operating on the zener breakdown voltage effect, where breakdown voltage is directly proportional to absolute temperature.

The LM335 is designed for an operating temperature range of -10 to $+100$ degrees C., with a typical mid-range accuracy of 0.5 degrees C.

Calibration was conducted at sea level in ice and boiling water, and checked on site against a thermocouple probe.

For measuring ambient temperature, a sensor was suspended in the shade below the PV array. For measuring array cell temperature, thermocouple readings were first taken at different points at the back of the modules to establish temperature distributions (maximum measured differences less than 1.2 degrees C.) and then a point was selected which reflected the area average of these measurements. The protective layer on the back of the panels was removed at this spot and the sensor attached there, with a seal of epoxy.

Insolation measurement

A LI-COR pyranometer sensor, model LI-200SZ-05 (S/N PY7653), was attached to the frame between the two PV modules to measure insolation received in the plane of the array (POA). This sensor had been calibrated by LI-COR, Ltd against an Eppley Precision Spectral

Pyranometer in November 1985 under natural daylight conditions. Maximum absolute error is specified as $\pm 5\%$, with $\pm 3\%$ typical.

Using a silicon photocell, the spectral response of this model of sensor is not ideal (it is classed as a Class 2 pyranometer by the World Meteorological Organisation) but has been rated similar to Class 1 thermopile pyranometers for measuring natural unobstructed daylight conditions (Flowers, 1978). It carries the advantage, in some respects, of having a similar spectral response to that of the photovoltaic modules, and a further advantage of suffering no error due to tilted mounting. (Tilt-mount error is distinguished from tilt-radiance error, the former denoting errors arising from the physical orientation of the sensor, the latter denoting errors attributable to the incidence angle of received radiation). However, problems were experienced in the use of this sensor, which are discussed in Section 4.4 and in Chapter 6.

The silicon cell of the sensor generates a current proportional to insolation, in this case calibrated as 54.2 microamps per 1000 watts/square metre. Linearity errors are stated as less than 1% over seven decades, but temperature error can be more than 0.1 % per degree C. (say up to 2% in on-site operating conditions). Typical tilt-radiance error is specified as less than 5% at an incidence angle of 80 degrees, but this error (also referred to as cosine error) was found to exceed the specifications, as described below.

As with the temperature sensors, the pyranometer was connected to a signal conditioning interface inside the school by means of screened signal cable.

Current measurements

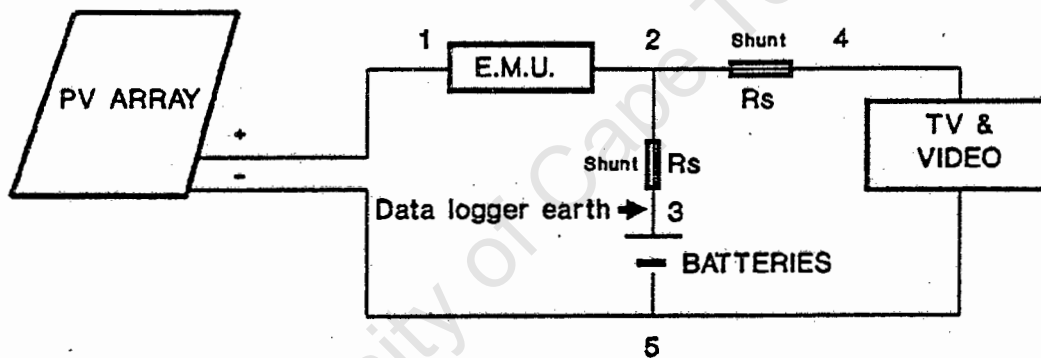
The current flowing into or out of the battery and the current flowing to load were monitored by measuring the voltage drop across current shunts, inserted in the circuitry at points shown in Figure 4.1.

The shunts were rated for a voltage drop of 50 mV at a current of 6 amps.

The power dissipated by one of these shunts is calculated at just over 0.1 % of the power measured, so as to be effectively transparent.

Voltage measurements

Voltages were taken at points in the circuitry shown in Figure 4.1 and communicated directly to the signal conditioning interface.



- A. Battery Voltage: $dV[3 - 5]$
- B. Array Voltage: $dV[3 - 5] + dV[1 - 3]$
- C. Battery Current: $dV[2 - 3] / R_s$
- D. Load Current: $dV[4 - 2] / R_s$
- E. Array Current: $= C + D$

FIGURE 4.1 Schematic of current and voltage measuring points in the system circuitry.

Data logger

Before describing the design of the signal conditioning interface, it is desirable to describe the data logger used in the monitoring process. A model MCS 120 data logger was employed, providing eight analog input channels, sampled instantaneously in sequence once a minute under control of a menu-programmable microprocessor.

Each channel can be programmed as to the treatment of input signals before they are logged: in this exercise, an average of sampled values over the logging period was recorded for all variables. Each channel is assigned to one or two settable logging periods. In this instance, all variables were logged at 30 minute intervals.

Selectable measurement ranges are offered for analog input signals. For all variables except insolation measurement, the highest range (0 - 2500 mV) was used, to provide maximum accuracy, specified as $\pm 0.2\% \pm 1$ count for this measurement range. The amplified signal from the pyranometer was entered at a lower range, 0 - 250 mV, with a corresponding specified accuracy of $\pm 0.2\% \pm 2$ counts.

Logged data was recorded on "memory modules" - exchangeable EPROMS with 128 kilobit capacity (allowing about three weeks' logging per EPROM).

The mode of operation of the data logger proved of some significance. Measurement of the input signal, on each channel, is achieved by charging a capacitor prior to measurement, then discharging it to the point where its voltage is equal to the voltage of the input signal. The time-span of such discharge is then converted to a digitalised voltage reading. This means that there is no integration of input signals, such as would be achieved with dual-slope integration circuitry. For steady or slowly changing signals, eg. from temperature sensors, this does not present a problem; but for any oscillating signal, the point at which the waveform was struck was variable, leading to unstable readings.

Secondly, arising from this design, any negative input voltage failed to be equalled during the capacitor's discharge period, resulting not

only in errors in that particular channel, but a cascade of errors in subsequent channels.

The purposes of the signal conditioning interface therefore included the following:

- Accurate amplification of sensor signals to attain the 0-2500 mV range of the data logger

- Buffered voltage offsets, where necessary, to avoid negative inputs to the data logger

- Integration of oscillating signals (caused by the FET regulator) by means of low-pass filters

Signal conditioning interface

Since it was impractical to measure currents in the negative rail of the system, as a consequence of its modular construction, the signal conditioning interface and data logger were grounded at the positive terminal of the system's batteries. (The data logger and interface had their own dry cell power supplies.) This reduced the common mode component in taking differential voltage measurements across the current shunts.

After information was obtained about the voltage waveform after the FET in the Energy Management Unit, a chopper regulator was constructed at the Energy Research Institute and the system emulated, with connections to a photovoltaic panel, batteries and various loads, to investigate waveforms and power factors with an oscilloscope. This emulation revealed ripple components in the waveforms at salient points in the system, but no observable leads or lags. It was therefore decided to filter a number of the electrical measurements, and to assume unity power factors at points of measurement.

The interface was designed on standard principles of instrumentation amplification, principally by Chris Wosniak, an electronics engineer at the Energy Research Institute. The design inputs to and outputs from the interface, and intervening treatment, are summarised in Appendix B4, while the circuit diagrams appear in Appendix B5.

4.4 Procedure

Data capture, transfer and inspection

At regular intervals, company personnel removed and replaced the EPROM in the data logger, posting the one containing data to Cape Town. This data was then uploaded into a PC, using an MCS memory module reader in conjunction with the emulation software PC-VT.

The ASCII data file was then imported into a Lotus spreadsheet, where macros eliminated redundant information, such as channel numbers, and formatted the data for convenient inspection.

Spreadsheet files were retained for aspects of analysis easily handled by Lotus capabilities. Formatted data was also "exported" into ASCII files for transfer to the mainframe, using Kermit software.

Before analysis, initial inspection of the data received revealed

- a) very low levels of load usage in initial months
- b) a sequence of failures in data capture from January to May, 1987

Controlling the load

Although the intention had been to conduct a "natural" study of a system under normal on-site conditions of usage, this was not a profitable approach in this instance. Partly because the monitored system was a demonstration project, and not integrated into an educational television programme, spontaneous utilisation of the television and video facility at Bluegill Waters school was very low. (Judging by opinions of educationists interviewed in Bophuthatswana, the same problem of under-utilisation would have been likely at a Bophuthatswanan monitoring site, if to a lesser degree.)

This posed a problem for monitoring system performance, since the capacity of the system would never be stretched, and a small range in values for important variables would limit the scope for analysis.

It was therefore decided to manipulate the "usage" of the system, by automatically turning on the television each day for a period during the afternoon (a day-time load) and again in the evening. This was first attempted in June 1987, but interference occurred between the timing circuit and the monitoring circuitry. The cause of the problem was identified and resolved in mid-July. From 19 July onwards, the system was set to run a daily television load of approximately eight-and-a-half hours, spread between daylight hours and darkness, at an average energy consumption of about 370 Wh/day.

Hardware failures

The lag and turnaround time in making recorded data available for scrutiny in Cape Town provided opportunities for hardware failures to persist uncorrected for weeks at a time. Except where faulty operation was already suspected, EPROMS remained in position for three weeks. Postage and uploading took further time, followed by diagnosis delay, and repair time. During the first half of 1987, successive overlapping hardware failures produced a sustained gap in valid data collection. Table 4.1 summarises the extent of valid data collected, and reasons for failures.

Despite the gaps in data retrieval, the monitoring produced more than 21 000 valid datapoints for analysis.

Specific instrumentation problems are discussed in Section 4.5.

Analysing data

Most statistical analysis of the data has been performed with the aid of the BMDP statistical package on a Sperry mainframe.

Analysis was preceded by systematic data screening, detecting error values and outliers. In a small minority of cases, error values could be replaced by interpolation. Otherwise they were recoded as missing values, and treated accordingly in the analyses.

TABLE 4.1 Summary of Monitoring Data Collected, and Reasons for Failures

MONTH	DATA COLLECTED				REASONS FOR FAILURES
	Number of days valid data per month	% valid records (all variables)	% valid records (daylight hours)	Load regime	
Nov 86	23	92 %	92 %	natural	
Dec 86	23	97 %	97 %	natural	
Jan 87	--	--	--		Data logger battery failure
Feb 87	--	--	--		Lightning damage
Mar 87	--	--	--		
Apr 87	--	--	--		Two faulty EPROMS
May 87	--	--	--		Interface opamp failure
Jun 87	21	72 %	75 %	failed	Fatal handshake between load timer and interface
Jul 87	13	82 %	93 %	controlled	
Aug 87	24	83 %	83 %	controlled	
Sep 87	30	93 %	98 %	controlled	

4.5 Specific Instrumentation Problems

Array voltage, current and power

The presence of the pulse-width-modulating Energy Management Unit (EMU) complicated the measurement of array output. Time-integrated measurements of array voltage and current were taken. The multiplication of these measurements does not always yield the power output from the array. When the EMU is fulfilling a power-limiting function (ie. when batteries are approaching full charge) the switching action of the EMU has the following effect on time-integrated measurements:

- (a) Array voltage is pulsed between the battery charging voltage (switch closed) and the array open-circuit voltage (switch open), with the time-integrated voltage measurement representing the average value determined by the duty cycle.
- (b) Array current is pulsed between charging current (switch closed) and zero current (switch open), with the time-integrated current measurement again representing the average value determined by the duty cycle.

Under these conditions, the multiplication of measured volts and measured amps will be greater than the actual array power. This is because for the portion of the cycle where current is zero, no energy is transmitted. The actual power is the array voltage times the array current while the switch is closed, multiplied by the fraction of time the switch is closed, which is not the same as the multiplication of time-integrated voltage and current.

The impact of this feature of the instrumentation is discussed in the context of data interpretation in Section 5.2.6 below. The limitations could have been avoided through conducting a separate power measurement, passing voltage and current signals through a multiplier circuit before integration. However, for present purposes the problem is of minor importance since array performance under charge-limiting conditions is of considerably less significance than behaviour under full demand conditions, where the discrepancy between measured and actual power effectively falls away.

PV module cell temperature measurement

Less confidence is placed in this measurement owing to the placement of the sensor. It was not possible to make non-destructive measurement on the exposed surface of the silicon cells, and the attachment to the rear surface could have led to lower cell temperature measurements, despite the substantial insulation around the sensor.

Insolation measurements

The most serious instrumentation problem arose through the performance of the Li-Cor pyranometer. Discrepancies between recorded insolation, and expected insolation (with expectations based on weather-station insolation records from Pretoria, 40 km away), are analysed in detail in Chapter 6. Since insolation measurements are central in the analysis of system efficiencies, an attempt to identify the source of the discrepancies, and to make corrections for identified errors, has been made.

Uncertainties in insolation measurement also predominate over estimated uncertainties in other measurements, so attention has been given to assessing the remaining uncertainties in insolation measurement, after corrections.

Briefly, the Li-Cor pyranometer was found to exhibit substantial **tilt-radiance or cosine error**, when compared with readings from Kipp and Zonen thermopile solarimeters. It was possible to make calculated corrections for this error component, since it tested as a linear function of incidence angle.

Secondly, added to the tilt-radiance error, it appeared from supplementary tests that the **spectral selectivity** of the Li-Cor instrument contributed to the discrepancies. It was not possible to correct for this factor. In a way, the Li-Cor measurements in this respect may provide a "truer" record of irradiance available to the photovoltaic modules, since measurements reflect the spectral response of silicon cells. However, weather station records are based on thermopile instruments with a broader spectral response, and

photovoltaic sizing procedures are often based on weather station insolation data, so the discrepancies attributable to spectral selectivity are of significance.

These issues are taken up in Chapters 6 and 7.

In a system performance monitoring exercise such as the present study, there is no clearly preferable alternative to using silicon cell pyranometers for insolation measurement. It is desirable to measure irradiance received in the plane of the array, which implies tilted mounting of the instrument, a source of uncertainty in thermopile solarimeters, which are partly dependent on convection within their sealed domes. Thermopile instruments are also less robust.

However it would be advisable in similar studies to establish first the reliability of specifications for the accuracy of a particular sensor, and to assess the likely impact of spectral variations in irradiance.

4.6 Supplementary Tests

Suspected errors in insolation measurement, and inability to obtain reliable specifications for PV module performance, led to supplementary tests, designed to supply information not obtained through continuous monitoring of system performance.

Insolation measurement

Readings from the Li-Cor pyranometer were compared with readings from a Kipp and Zonen thermopile solarimeter, at three locations (including the monitoring site), for varying angles of incidence of the direct beam, and for varying positions of the sun in the sky. The results of these tests are included in Chapter 6, while the method is detailed in Appendix B1.

PV array output characteristics

The current-voltage output characteristics of the array were tested under natural skylight conditions, in July 1988, at the monitoring site. The method employed, and the results of these tests, are discussed in Chapter 7, where the derived array IV characteristics are compared with the performance specifications supplied by the manufacturers.

University of Cape Town

Chapter 5

OBSERVED SYSTEM PERFORMANCE

This chapter illustrates and provides statistical summaries of the data obtained during the monitoring period. The purpose is principally one of description. System performance is described here in terms of single monitored variables, or simple combinations of variables. System efficiencies, and other multivariate aspects of system performance, are taken up in Chapter 8.

5.1 An Illustration of Daily Performance

Firstly, to illustrate the behaviour and interaction of the variables which were used to monitor system performance, data from two days' records are depicted in Figure 5.1.

The two consecutive days selected for this (September 17 and 18, 1987) are not intended to signify representative system states, but rather they have been chosen because they show a range of climatic and system states useful for illustrating features of system performance.

In each graph, the common horizontal axis represents the progression of half-hourly data loggings, between 00h00 17 September and 24h00 18 September.

Inspection of Figure 5.1(a) shows the daily profile of insolation received on the plane of the array. The first day was intermittently cloudy, while the second day shows the typical sinusoidal profile of a clear day. September 17 was in fact the last in a sequence of cloudy days, with the result that the batteries were below full charge: September 18 thus shows "recovery" conditions, where the array power from a cloudless sky is used to bring up the state of charge of the batteries, in addition to powering the load.

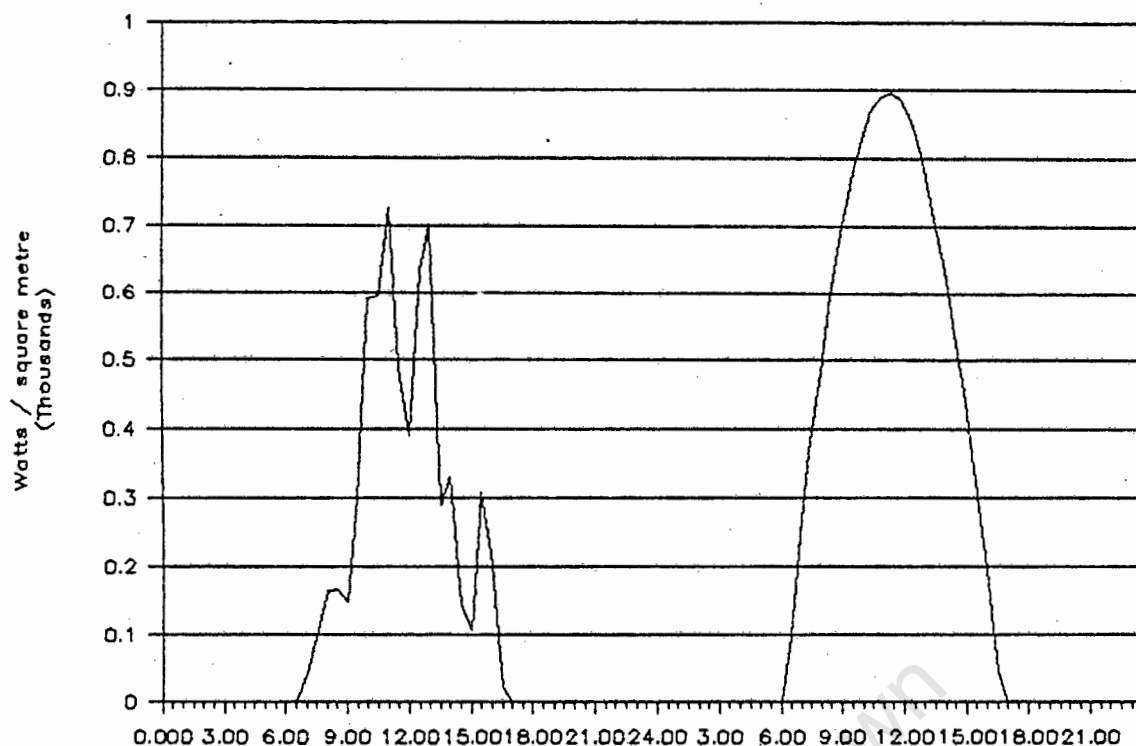
Figure 5.1(b) shows the temperature variations accompanying these climatic conditions. As expected, ambient temperature tends to follow insolation during the day, at a slight lag, and falls during the night

until early morning. The array cell temperature follows the insolation profile even more closely and directly, reaching maxima of 31 to 32 degrees C just after midday. At night, (though this is not of interest to system performance) the cell temperature cools to temperatures below ambient, an effect presumably accentuated by moisture and wind.

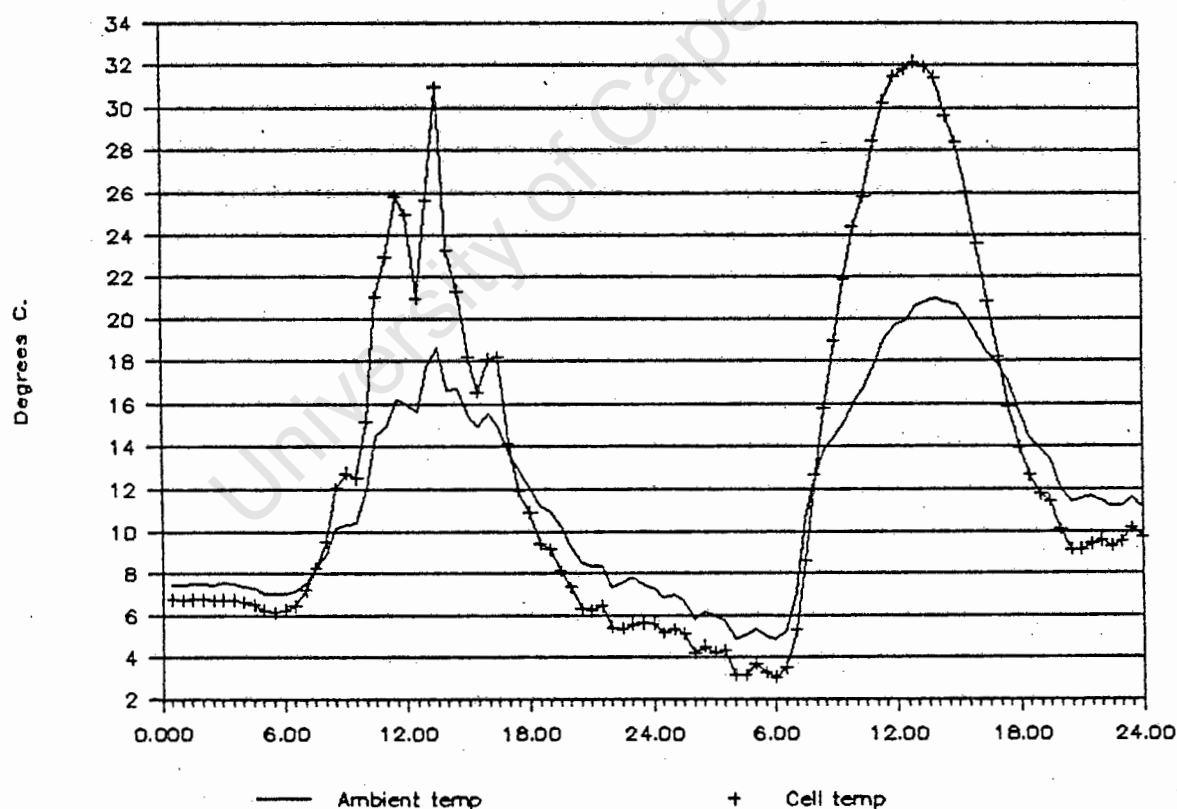
Other factors being equal, cell temperature is a determinant of array voltage - the array short-circuit voltage falling with increases in cell temperature. However, in Figure 5.1(c) this effect is masked by the dominant influence of other factors. Variations in insolation, battery state of charge and load demand account for most of the variation in observed array voltage. At times of relatively low insolation, and high current demand, the operating voltage of the array is brought closer to that of the batteries (point A); while at higher insolation levels (point C), where the batteries are approaching full charge, the system presents a higher input impedance. Array voltage rises and array current falls. The troughs in array voltage between 13h00 and 16h00 each day (Points B and D) correspond with the switching in of the television load: the higher current acceptance then brings down the array voltage slightly.

Array output current is shown in Figure 5.1(d). On 17 September it can be seen that array current closely follows the insolation profile. This is because the batteries are not at full charge, so that available array current (primarily a function of POA insolation) is accepted. On 18 September the picture is different. Between 09h00 and 13h00 (Points A and B) the array current falls sharply and steadily, despite the increasing insolation. This is because the batteries are approaching full charge. The battery resistance is increasing and the charge regulator is limiting transmission to the batteries. When the television load is switched in (Point C), the array current returns to higher levels (above 2 amps).

Array current is the sum of current flowing into the battery and current flowing to the load (plus about 30 to 50 mA, drawn by the electronics of the Energy Management Unit). These components are shown in Figure 5.1(e).



(a) Plane of Array Insolation



(b) Ambient Temperature and Module Cell Temperature

FIGURE 5.1 Interaction of Monitored Variables:
Illustration, 17-18 September 1987

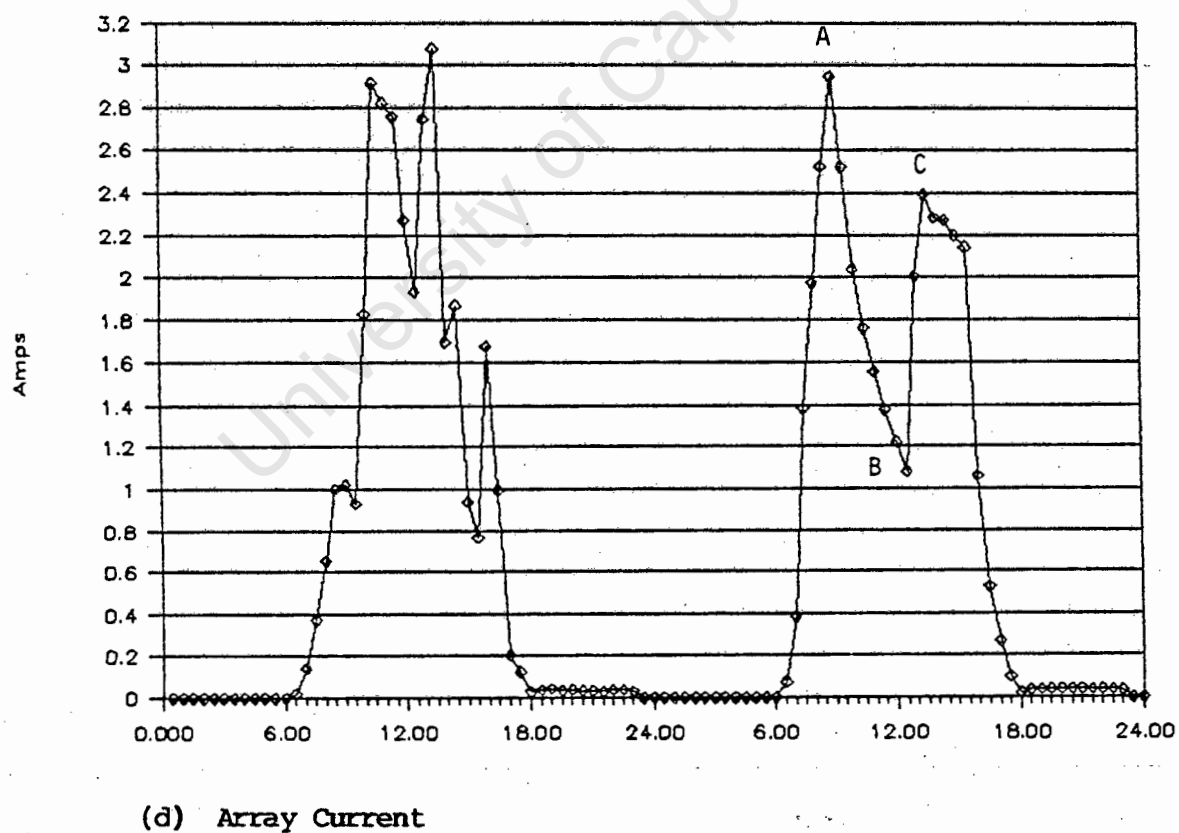
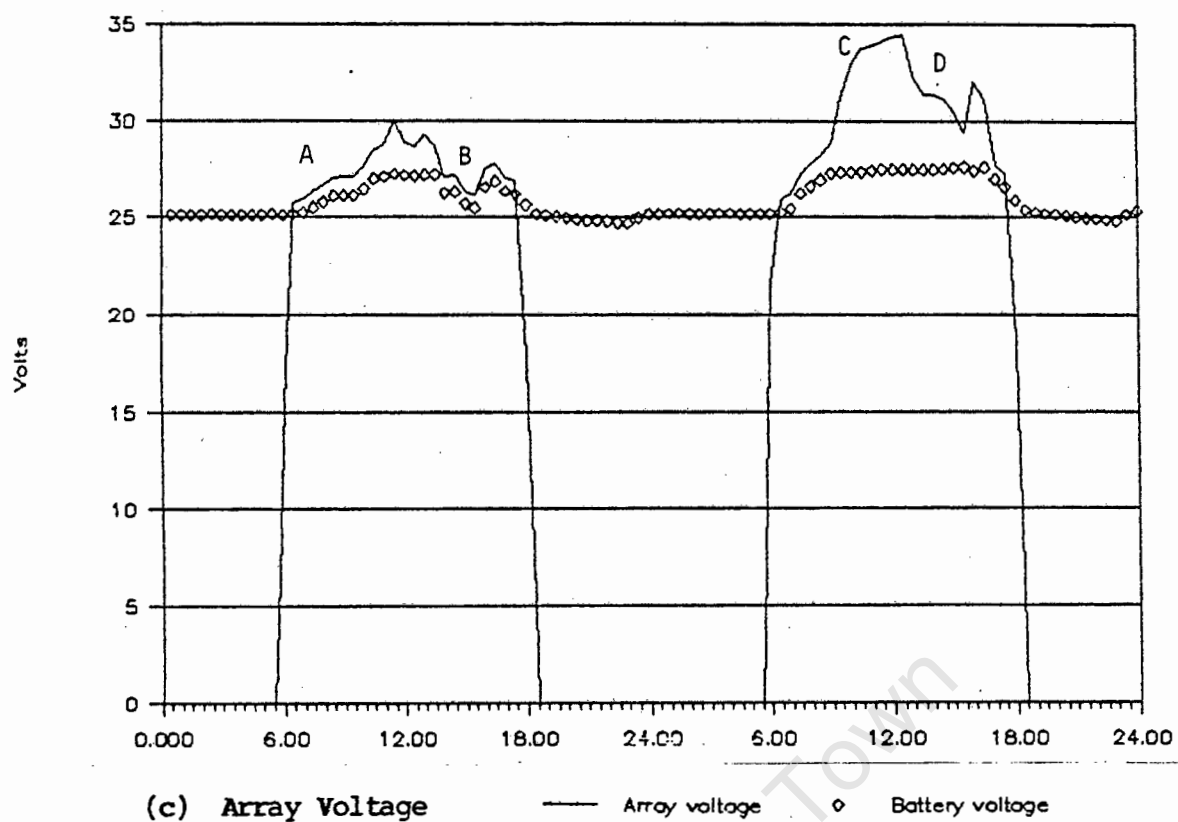


FIGURE 5.1 Interaction of Monitored Variables:
Illustration, 17-18 September 1987

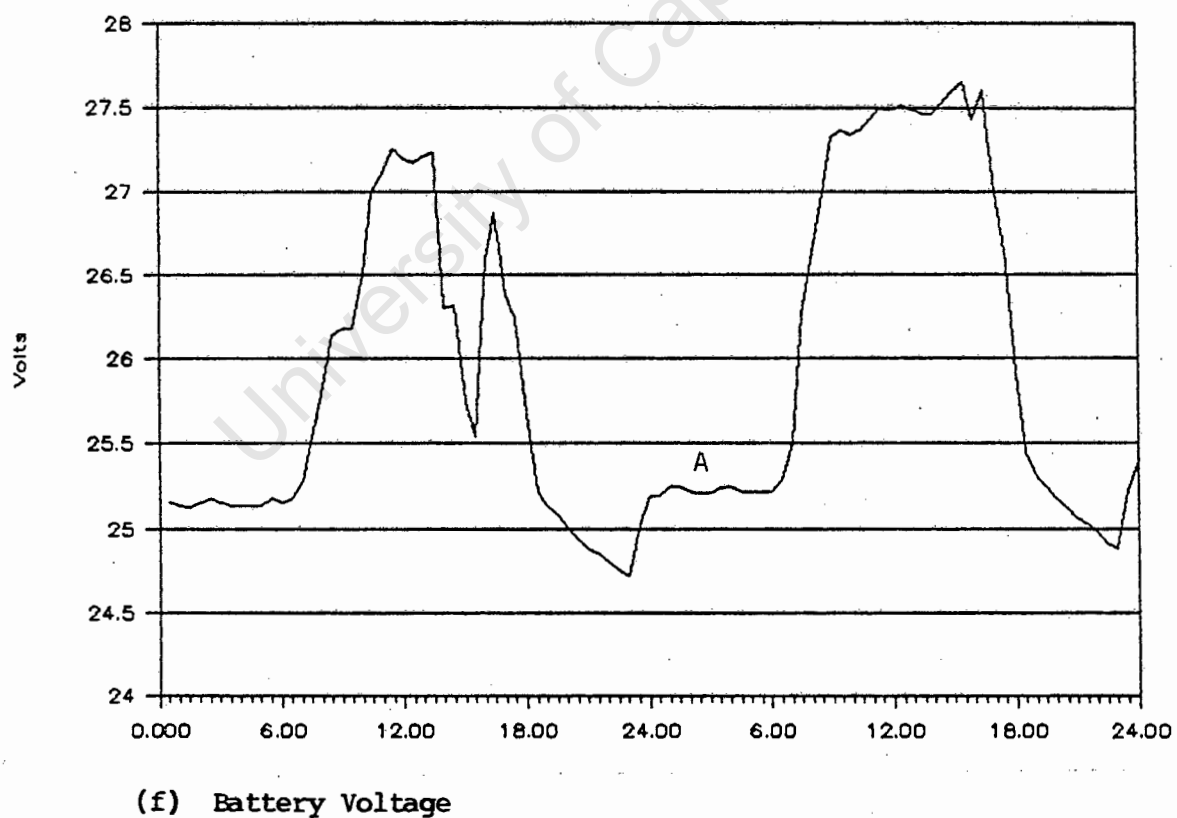
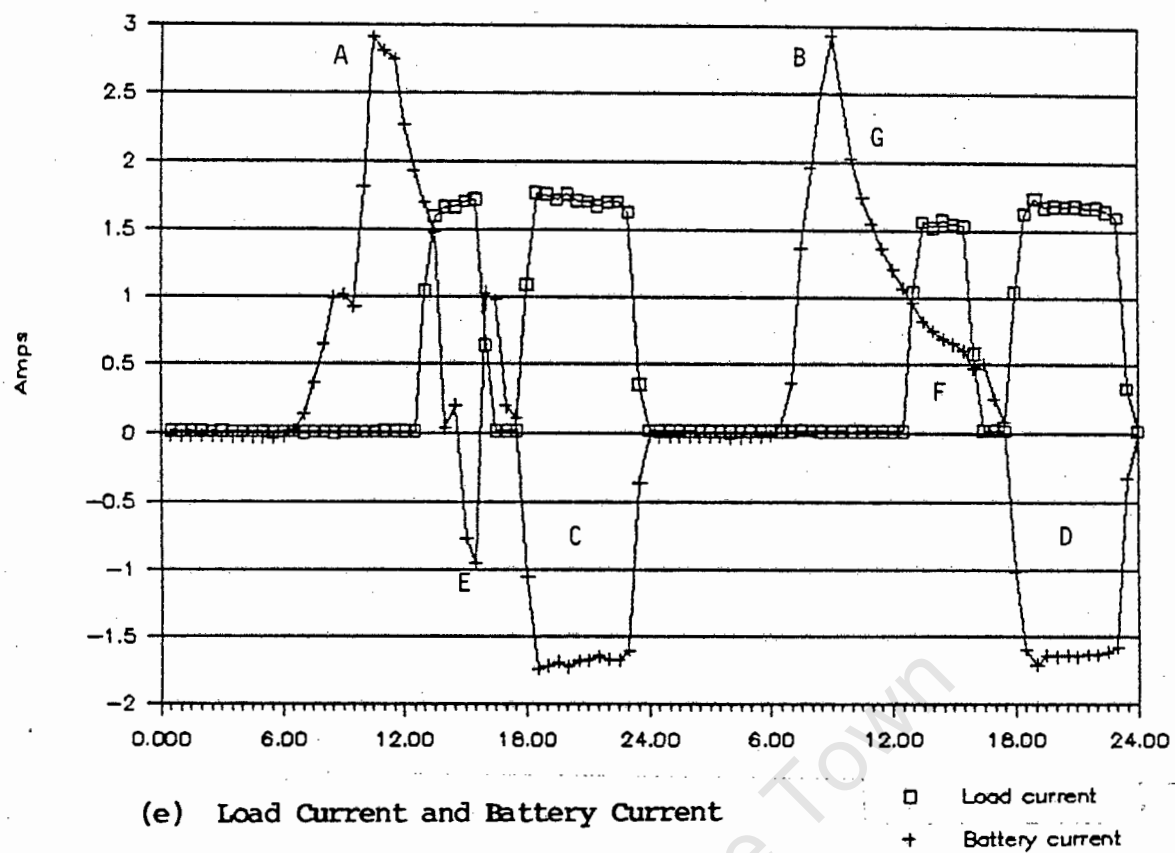


FIGURE 5.1 Interaction of Monitored Variables:
Illustration, 17-18 September 1987

The television is timed to switch on at approximately 13h00 each day, and again at 18h00 in the evening. (The approximation arises because of possible differences between the system's clock and the data logger's clock). From the logged data, it is impossible to judge accurately the times of switching, or the exact duration of the load, since logged values are half-hourly averages. The afternoon load session is about three hours, and the evening load session is about 5.5 hours. These uncertainties are not important, since total load energy consumption is computed from the half-hourly averages, while average load power can be obtained from those readings (for load amps and battery volts) where the load is steadily on throughout the log periods. Combining these calculations, the durations of loads on September 17 and 18 are estimated as

		Daytime load	Night load	Total	
Sept 17	Energy consumed	132.39	232.82	365.11	Wh
	Average power	43.89	42.87		Watts
	Duration of load	3.02	5.43	8.45	hours
Sept 18	Energy consumed	129.21	227.76	356.97	Wh
	Average power	42.73	42.02		Watts
	Duration of load	3.02	5.42	8.44	hours

It will be noted from these figures, and from inspection of the load currents displayed in Figure 5.1(e), that there are differences between daytime and night-time operation, with respect to load currents and average power consumptions. This is because the source voltages are generally different. During the day, if there is more than enough array power to supply the load, the voltage supplied to load is the battery terminal voltage under charge, which is higher than the night-time battery terminal voltage under discharge. The load, in turn, has downline voltage regulation, so more power is consumed/dissipated when the load supply voltage is higher.

More broadly, Figure 5.1(e) shows how, under this load regime, array power goes towards charging the batteries during the morning (Areas A and B), while at night the load current is obtained from an equivalent battery discharge (Areas C and D).

During the period of daytime load, the division of power between battery and load depends on the insolation and state of charge of the batteries. For example, at Point E on September 17 there was insufficient insolation to power the load. The deficit was supplied by battery discharge. But on September 18 in Area F of the graph, battery charging continues steadily during the daytime load period, reflecting the high insolation levels.

Finally, at Point G in Figure 5.1(e) there is a sharp decline in battery charging current. This is because the batteries are approaching full charge, and the Energy Management Unit is progressively limiting the power transmitted to the batteries.

Fluctuations in battery voltage, over these two days, are expanded in Figure 5.1(f). Battery state of charge is the single best indicator of state of system from day to day. A declining state of charge indicates that more energy has been consumed than produced. Unfortunately, battery terminal voltage is not directly convertible into battery state of charge, firstly because of the differences between terminal voltage under charge, under discharge, and in open circuit; and secondly because battery temperature affects the relationship between open-circuit terminal voltage and available capacity. Assuming the second effect is minor, over a limited period, then the best indicator of battery state of charge at the end of each day is the night-time voltage, after midnight, when there is no load on the batteries (except the 30 to 50 mA current draw of the sleepless electronics).

This battery voltage is referred to in following pages as the "midnight open-circuit battery voltage" (in fact, values are taken some time after midnight, when the battery rest voltage has stabilised). Figure 5.1(f) shows that at the start of 17 September, this voltage was about 25.14 volts. Between 17 and 18 September (Area A on graph) it had risen to about 25.22 volts - a net gain in energy for the day - while at the end of 18 September (out of picture) the rest voltage had risen to 25.45 volts.

According to battery specifications, full charge is associated with an open-circuit voltage of 25.5 volts at 27 degrees C. electrolyte temperature.

5.2 Statistical Summary of Monitored Variables

The purpose of monitoring a photovoltaic system over an extended period is to investigate system performance in a range of climatic and operating conditions. Data for the entire monitoring period are now presented, statistically summarised. (The periods of successful data acquisition were detailed earlier, in Table 4.1).

What follows is a summary of single monitored variables, or simple combinations of variables. Relationships between the variables, which are of analytical interest, are discussed in subsequent sections.

The aim of the statistical summaries is to reflect the central tendencies and the variations in the monitored data with economy of detail. Where appropriate, cumulative frequency distributions are chosen as the method of summarising variables with values dispersed over time periods. They minimise data degradation, representing the frequency of all recorded values, and marginalise outlier errors.

CLIMATIC VARIABLES

5.2.1 Plane of array insolation

The recorded plane of array (POA) insolation is summarised in Table 5.1. (Note that this is a summary of raw data values, before any calculated corrections.)

The observed daily means for each month except December 1986 are considerably below what could be expected on the basis of long-term weather-station records. Factors contributing to this include site-specific factors (such as partial shading of the array), exceptionally adverse weather in the month of September, and pyranometer error, as discussed in Chapter 6 below.

The summaries of raw data for recorded POA insolation are included here in preparation for that discussion, but also to show the distribution of irradiance in those months as "seen" by the silicon cell pyranometer, incorporating for instance a spectral response taken to be comparable with that of the PV modules.

TABLE 5.1 Observed Daily POA Insolation (Wh/sq.m/day), by Month

	Jun 87	Jul 87	Aug 87	Sep 87	Nov 86	Dec 86
Mean	3876	5092	5116	4675	4500	5500
Maximum	4233	5761	6204	6587	7221	7016
Minimum	1706	4359	1563	908	161	3104
S.D.	675	385	1065	1971	1903	1156
f (days/month)	20	12	22	25	21	21

Figure 5.2 provides a cumulative frequency distribution for daily POA insolation, as recorded, for all the months above. This enables one to see what percentage of days fell below any selected insolation level, over the monitoring period. For example, on roughly 10% of recorded days, the recorded POA insolation was below 3000 Wh/sq.m/day.

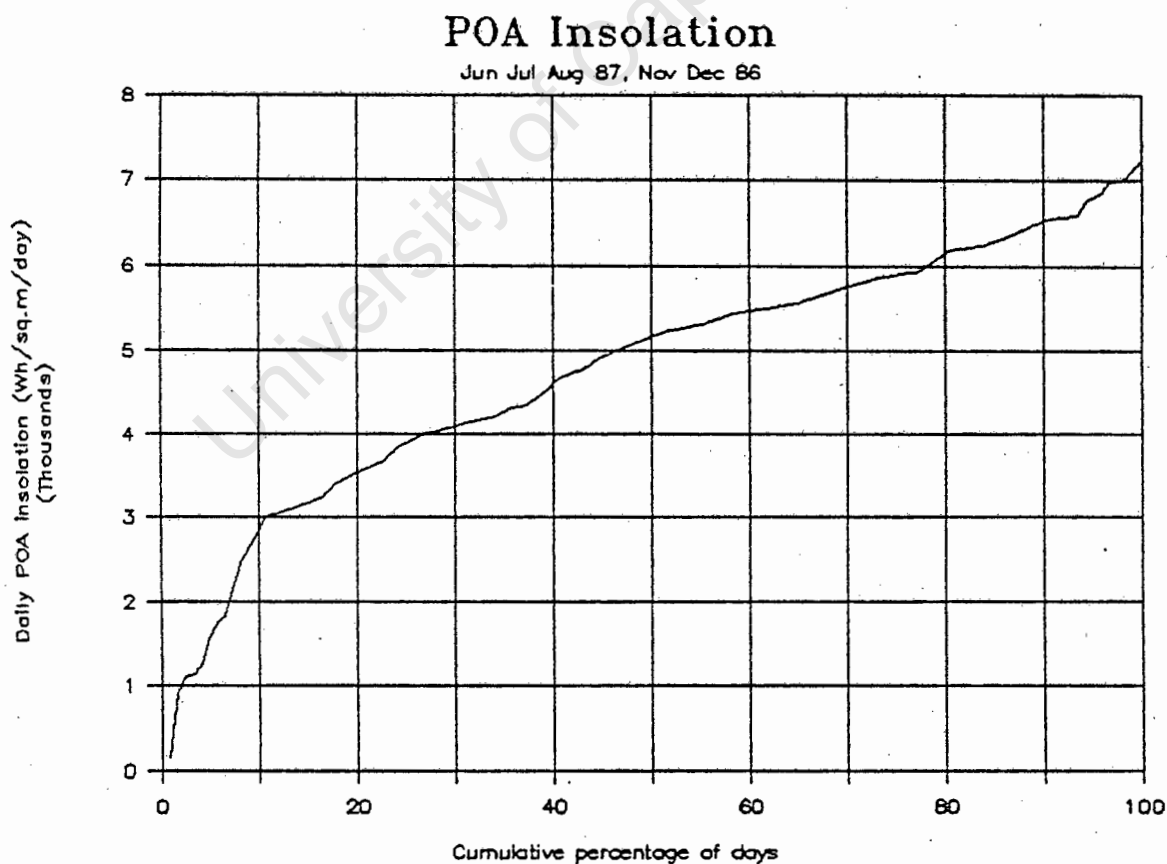


FIGURE 5.2 Cumulative frequency distribution of recorded daily plane of array insolation

5.2.2 Ambient temperature

Recorded ambient temperatures are summarised in Tables 5.2 and 5.3. The second table presents temperatures during daylight hours only, since only these affect module performance.

TABLE 5.2 Observed Ambient Temperatures (degrees C.) by Month

	Jun	Jul	Aug	Sep	Nov	Dec
	87	87	87	87	86	86
Mean	(10.2)	(8.8)	12.1	14.7	18.0	20.7
Maximum	25.2	25.6	29.9	33.4	32.6	36.1
Minimum	(-0.9)	(-8.0)	(0.4)	1.6	5.0	8.1
S.D.	7.3	8.3	7.4	6.6	5.8	6.1
f (logs/month)	776	582	963	1413	1018	1070

Note: Figures in parentheses may be unreliable due to instrumentation errors at very low temperatures.

TABLE 5.3 Observed Daytime Ambient Temperatures (degrees C.) by Month

	Jun	Jul	Aug	Sep	Nov	Dec
	87	87	87	87	86	86
Mean	17.0	12.9	18.8	20.6	22.6	25.3
Maximum	25.2	25.6	29.9	33.4	32.6	36.1
Minimum	2.4	(-8.0)	4.5	7.0	7.7	11.3
S.D.	4.9	9.7	5.0	5.5	5.1	5.1
f (logs/month)	337	278	406	518	426	502

Note: Figures in parentheses may be unreliable due to instrumentation errors at very low temperatures.

SYSTEM VARIABLES

5.2.3 Load energy and power

Load energy, obtained from the time integral of battery voltage multiplied by load current, is summarised in Table 5.4. It is clear that prior to the automatic controlling of the load, from 19 July 1987 onwards, spontaneous usage of the television and VCR was very low.

TABLE 5.4 Daily Load Energy Consumption (Wh/day), by Month

	Jun 87	Jul 87	Aug 87	Sep 87	Nov 86	Dec 86
Mean	16	372	378	362	33	1
Maximum	219	389	423	400	157	12
Minimum	0	267	357	345	0	0
S.D.	52	36	15	14	52	3
f (days/month)	21	11	19	22	20	23

As mentioned earlier, the power consumption of the television set varied somewhat according to fluctuations in battery voltage, the principle differences occurring between daytime and night-time operation. Using data from August and September 1986, the power consumption of the television set (without VCR) was:

Daytime operation

Mean 44.3 W
S.D. 1.64 W

Night-time operation

Mean 43.0 W
S.D. 2.17 W

If batteries were depleted to 24 volts (discharge voltage) or below, then night-time consumption would be expected to fall to a mean of about 41 W, by these measurements.

Usage of the television monitor plus VCR was infrequent, and seldom extended through an entire logging period, so valid measurements for the power consumption of television and VCR combined were sparse. They ranged from 49.5 to 50.6 Watts for VCR and monitor combined. These were all daytime readings. At night, or under low insolation and lower battery terminal voltage, the equivalent power consumption would be slightly less than this range indicates.

5.2.4 Battery voltage

Since battery voltage is the single best indicator of state of system, daily values throughout the monitoring period are depicted in Figures 5.3 and 5.4.

The central variable in these graphs is the "midnight open-circuit voltage" of the batteries, corresponding to a time of day where the current draw on the batteries is so low (milliamps) that the readings closely approximate open-circuit terminal voltage, and hence indicate the batteries' state of charge, after a full day's operation.

The daily maximum battery voltage is the battery terminal voltage under charge conditions, and thus reflects specific combinations of insolation and load demand, superimposed on battery SOC.

The daily minimum battery voltage is also shown, in Figure 5.3. This occurs typically under discharge conditions at night, if there is a night-time load. This minimum value is then reduced below the open-circuit voltage of the battery due to the voltage drop over the batteries' internal resistance during discharge. The daily minimum battery voltage is not shown in Figure 5.4 because in the absence of night-time loads during this period it coincided closely with the midnight open-circuit voltage.

Figure 5.3 illustrates a period when the average daily load energy (from 19 July onwards) was 370 Wh/day. This period includes days where there is a net energy deficit, and battery voltage falls. The lowest open-circuit battery voltage in this period was 25.0 volts.

Figure 5.4 illustrates periods where load energy demand was sporadic and low. Battery state of charge is predictably stable. Of some interest is the period 6 - 12 November 1986. Here the Energy Management Unit had failed, apparently as a result of lightning damage, and subsequent to this the daytime charging voltage of the batteries was unregulated. However, despite the notable increases in maximum battery voltage during the day, midnight open-circuit voltage remains quite steady.

It is worth noting, however, that the charge voltages attained during the time of this regulator failure exceed the recommended float-charge voltage for these batteries (between 28 and 29 volts, in this temperature range) by a small amount. A short term failure should not cause damage, but long term unregulated charging would diminish battery life.

Battery voltages

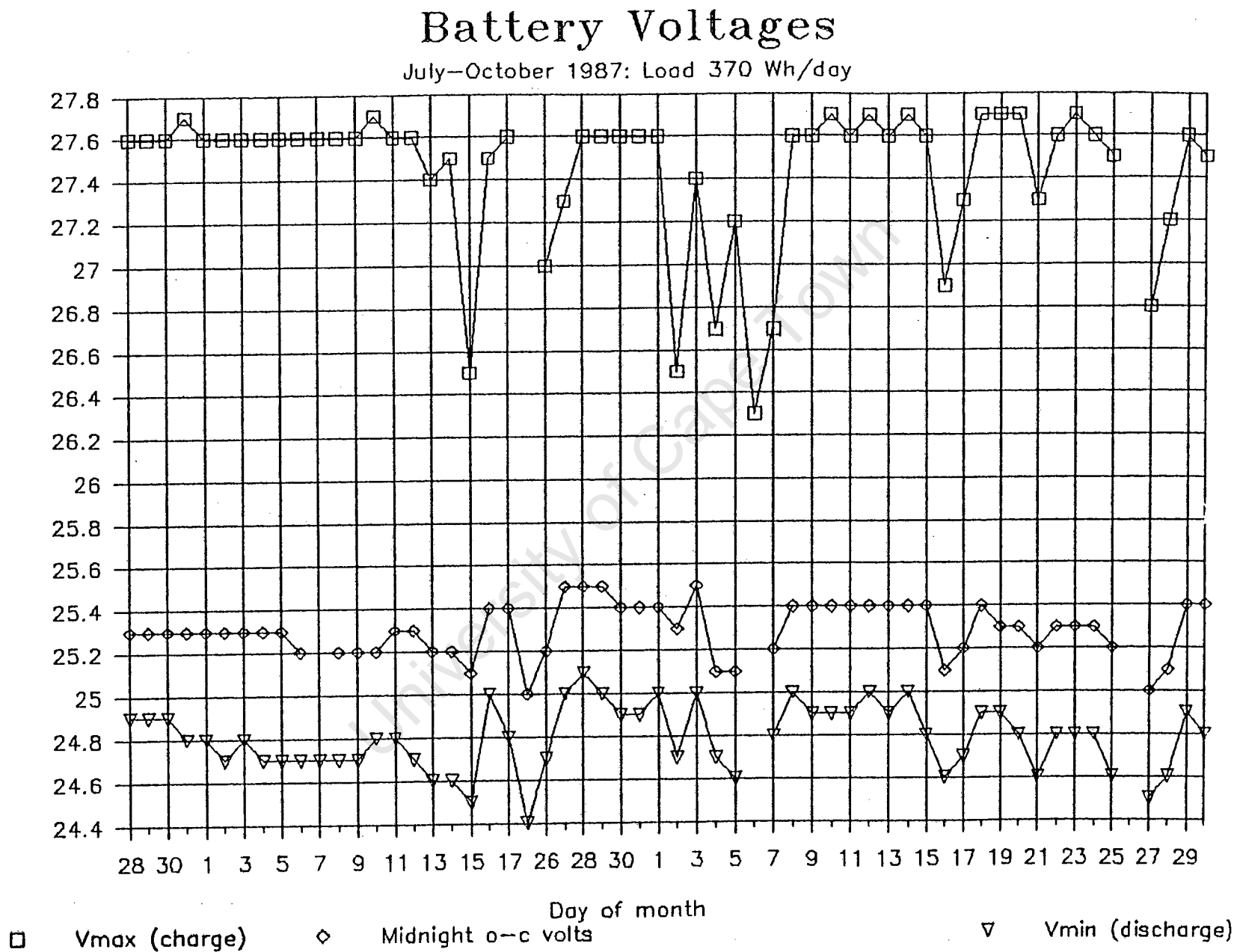


FIGURE 5.3 Battery Voltages in High Demand Conditions
(July–Sept, 1987; Load 370 Wh/day)

Battery Voltages

Nov86, Dec86, Jun87: insignificant load

Battery voltages

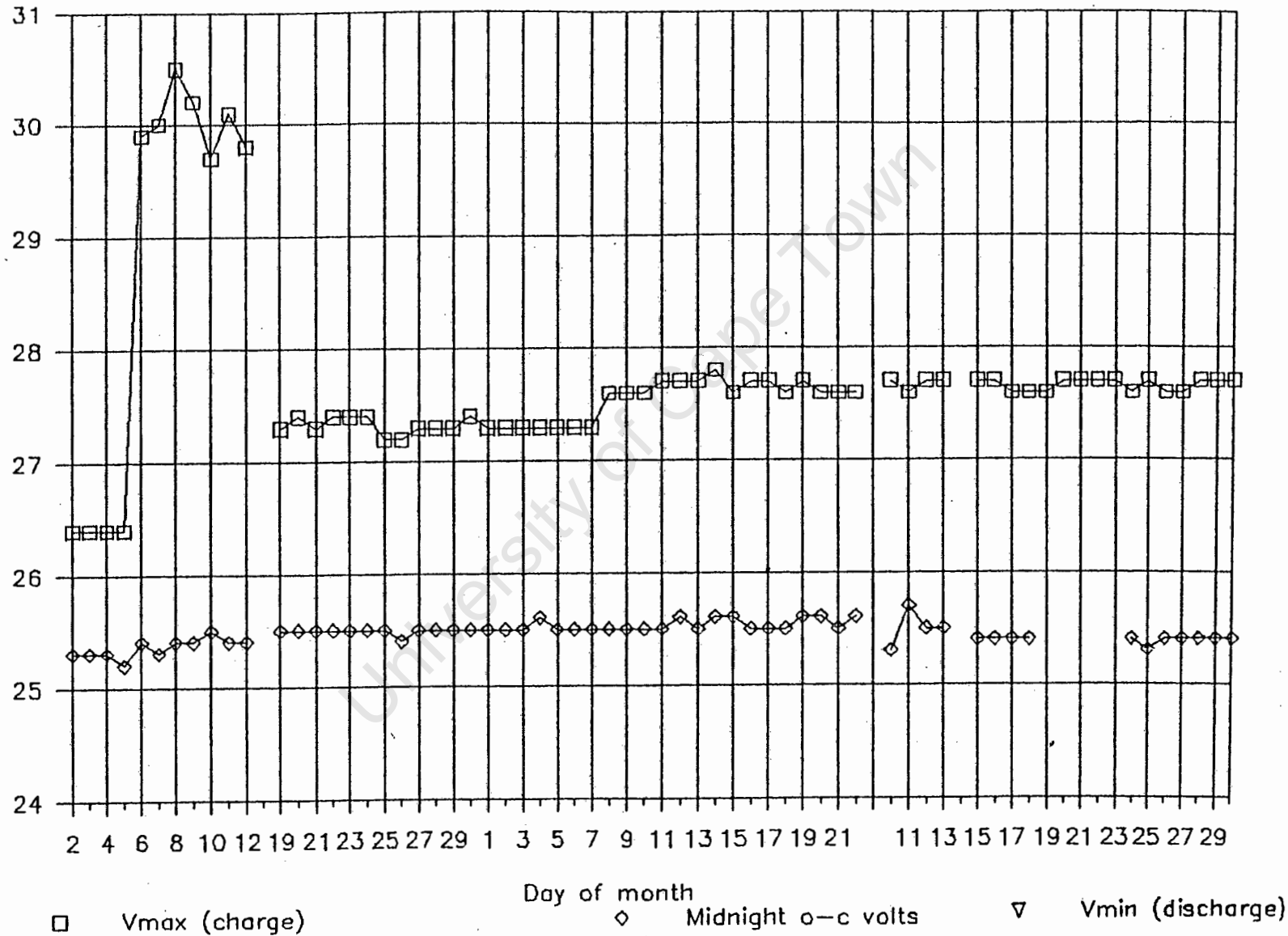


FIGURE 5.4

Battery Voltages in Low Demand Conditions
(Nov, Dec 1986 and June 1987)

Figure 5.5 provides a cumulative frequency distribution of battery voltage for the period in July-September 1987, when there was a steady controlled daily load, through variable weather conditions. In this graph, "midnight open-circuit voltage" has been converted to battery state of charge, using manufacturers' specifications and estimated adjustments for battery temperature. The vertical axis measures the daily maximum depth of discharge of the batteries, as a percentage of their rated capacity, while the horizontal axis sets out the cumulative relative frequency distribution of daily readings. For example, it is seen that for almost 50% of the days in this period the maximum depth of discharge of the batteries was less than 5% of the batteries' rated capacity (range A to B on the graph). Over the worst 10% of days, the maximum DOD was between 17% and 25% of rated battery capacity (range C to D on the graph). The expected battery lifetime corresponding to such a usage profile has been estimated from manufacturer's product information (see Appendix B3 for method). The results were presented earlier in Section 3.3.2, with qualifications attached.

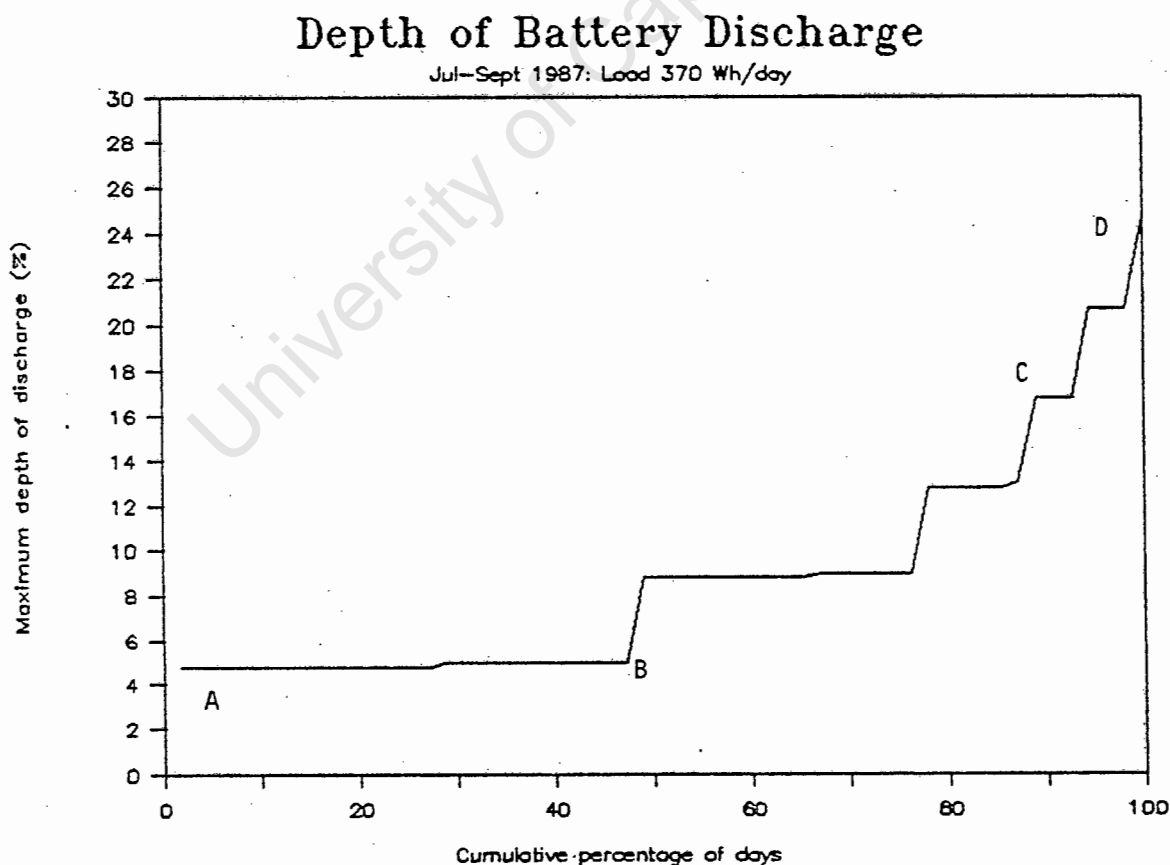


FIGURE 5.5 Cumulative frequency distribution of daily battery depth of discharge

5.2.5 Battery currents

During night-time operation, battery discharge current is the same as the current flowing to load. In daylight hours, the batteries receive a charging current from the array, if sufficient power is available.

At times when the load is on during the day, the battery current may be positive (charging) or negative (discharging), dependent on whether array power is more than enough to supply the load demand.

When charging, the charge current depends on available array power and also the batteries' state of charge, since the charge regulator cuts back power acceptance as the batteries approach full charge. This is why in Table 5.5, which summarises battery currents recorded during daylight hours, the monthly means are low for those months in which there was a very low load energy demand. For these months, the batteries were nearly always at full charge.

TABLE 5.5 Current to Batteries (Amps) During Daylight Hours.

	Jun 87	Jul 87	Aug 87	Sep 87	Nov 86	Dec 86
Mean	0.20	1.13	1.12	1.04	0.15	0.08
Maximum	2.47	2.80	3.64	3.33	0.86	0.38
Minimum	0.02	0.04	-1.02	-1.16	-0.55	0.00
S.D.	0.28	0.76	0.87	0.90	0.18	0.06
f (logs/month)	337	219	404	518	426	502

Note: Negative values indicate daytime discharge

Figure 5.6 shows the energy flows to and from the batteries, each month. The ratio of discharge energy to charge energy gives a rough indication of the gross energy efficiency of the battery storage under these operating conditions.

Battery Energy Flows

by month

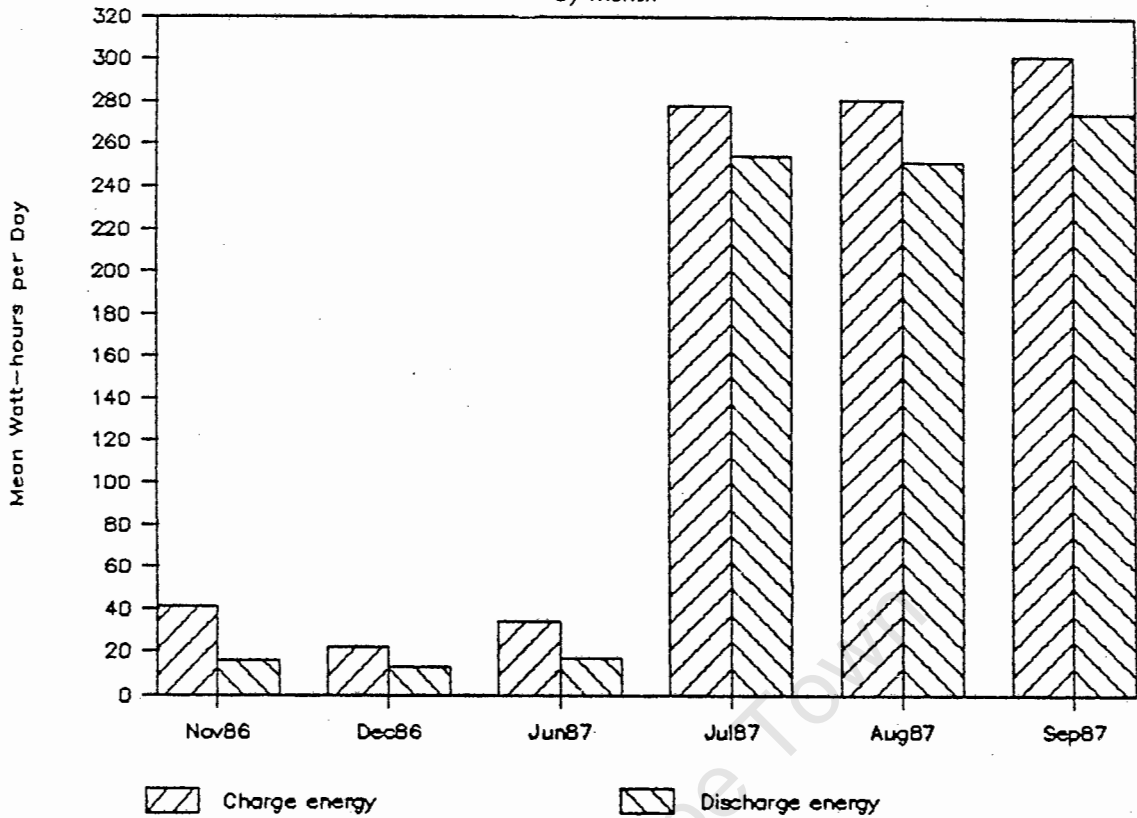


FIGURE 5.6 Average Monthly Battery Energy Flows

In the months November and December 1986, and June 1987, the mean daily energy flows to and from the batteries are low, as a consequence of insignificant load demand. The gross battery energy efficiencies are also seen to be low, with the following approximate values:

Mean battery energy efficiency

(= mean discharge energy / mean charge energy)

November 86	0.40
December 86	0.59
June 87	0.50

These low efficiencies merely indicate that the batteries were generally sitting at or near full charge, accepting a slow trickle charge, and were seldom discharged to load.

In the months July to September 1987, with an average daily load of 370 Wh/day, and variable weather, battery storage played a more active part in the system, supplying the nightly load and balancing out

occasional daily energy deficits.

TABLE 5.6 Battery Energy Supply to Load and Battery Energy Efficiency, July to September 1987.

	Mean daily energy supplied to load	Calculated mean battery energy efficiency
July 87	255 Wh/day	0.92
August 87	252 Wh/day	0.90
September 87	275 Wh/day	0.92

The calculated values for mean battery energy efficiency must be treated with caution, since small errors (milliamps) in recording load and battery currents can affect the fine balance between charge and discharge energy flows. The monitoring data do not provide for precise measurements of battery energy efficiencies, and the figures above should be regarded as indicative.

5.2.6 Photovoltaic array voltage and current

A univariate statistical summary of observed array voltages is difficult to interpret, because array operating voltage is a function of insolation levels, cell temperatures, and the effective load as seen by the array. The effective load, in turn, is a function of the applications load, battery state of charge, and Energy Management Unit behaviour. Variations in array voltage are therefore due to the interaction of many variables.

Recorded array voltages during daylight hours (POA insolation above 50 Watts/sq.m) were as summarised in Table 5.7.

TABLE 5.7 Observed Array Voltages, Daylight Hours.

	Mean	S.D.	Recorded maximum
Nov86	34.8	2.14	37.7
Dec86	35.0	2.06	37.7
Jun87	35.1	4.23	39.3
Jul87	30.8	2.41	35.8
Aug87	30.3	2.41	35.1
Sep87	29.5	2.43	35.2

The high variance in recorded levels for June is due to the high incidence of log periods when, at low and variable insolation levels, the array was not generating for the full log period, leading to fractional voltage recordings. For the same reason, the June mean is an under-representation of typical full-log values: 36 to 38 volts, with no load.

Otherwise, the variation in maxima observed between winter and summer (eg. between December and June, with equally low load demand) reflects the impact of cell temperature on array voltage; while the lower array voltage means in July, August and September reflect the impact of the controlled load demand on system operation during these months.

The maxima for November and December, when insolation levels were higher and load demand very low, provide an indication of array voltage at near open-circuit conditions. The recorded operating cell temperatures in the regions of these maxima (greater than 37.5 volts) ranged from 18 to 22 degrees C., while array currents were less than 50 milliamps.

The recorded cell temperatures in the region of the June maxima (greater than 39.0 volts) ranged from 6 to 10 degrees C., with array currents of less than 200 milliamps.

A principal factor affecting array voltage is the power acceptance of the Energy Management Unit (which depends on load demand and battery state of charge). With other variables constant, increases in

admitted array current bring down the operating array voltage. Figure 5.7 illustrates mean operating array voltages in different array current brackets, for all months, and for POA insolation levels greater than 150 Wh/sq.m.

Considerable variance in the array voltages thus compartmented is due to variations in insolation and cell temperature. The variance is indicated in the figure by curves one standard deviation away from the mean.

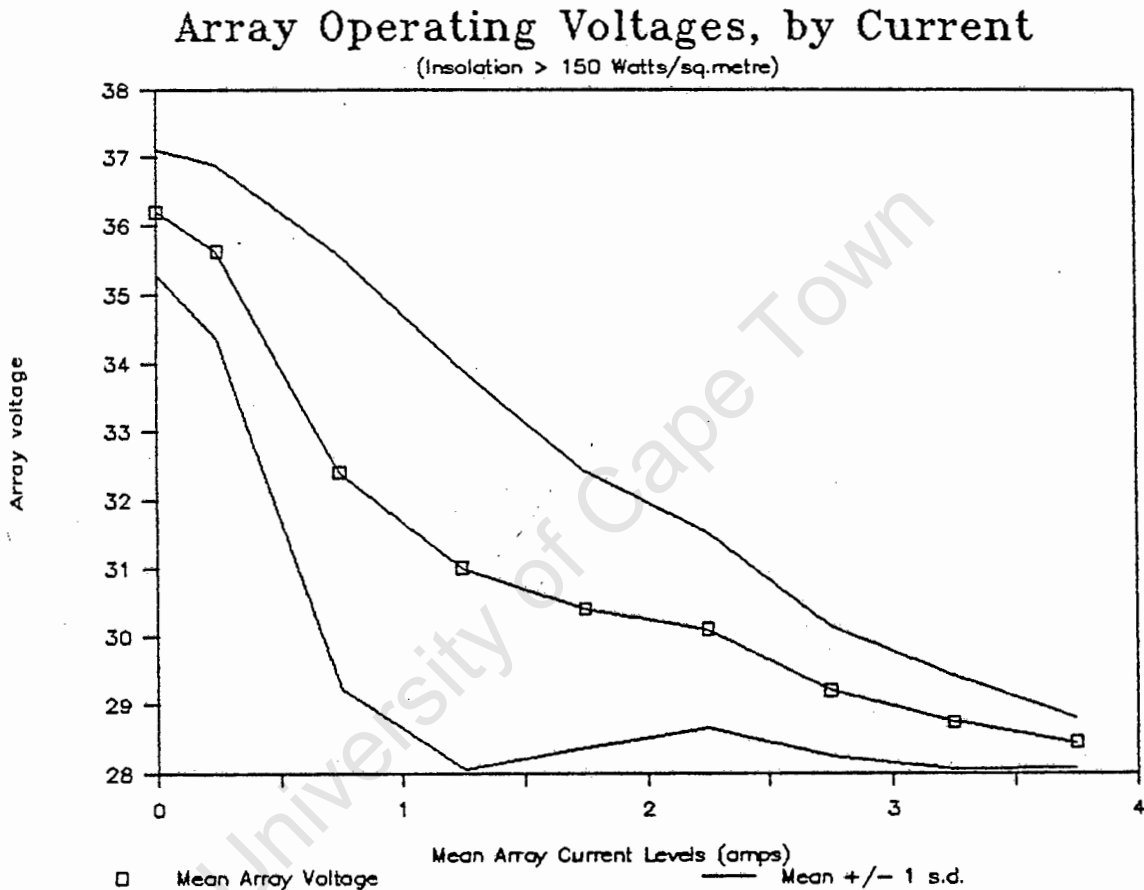


FIGURE 5.7 Array Operating Voltages, Compartmentalised By Array Current.

The frequency distribution of array voltages is typically bimodal, for months (and typical days) when there is load on the system, but when surplus array power is available. At times when the batteries are below full charge and/or the daily load is on, array voltages are brought down by the power demand. When batteries approach full charge, and there is no applications load, array voltage rises.

Figure 5.8 illustrates this for the month of September 1987, the month in which least surplus array power was monitored.

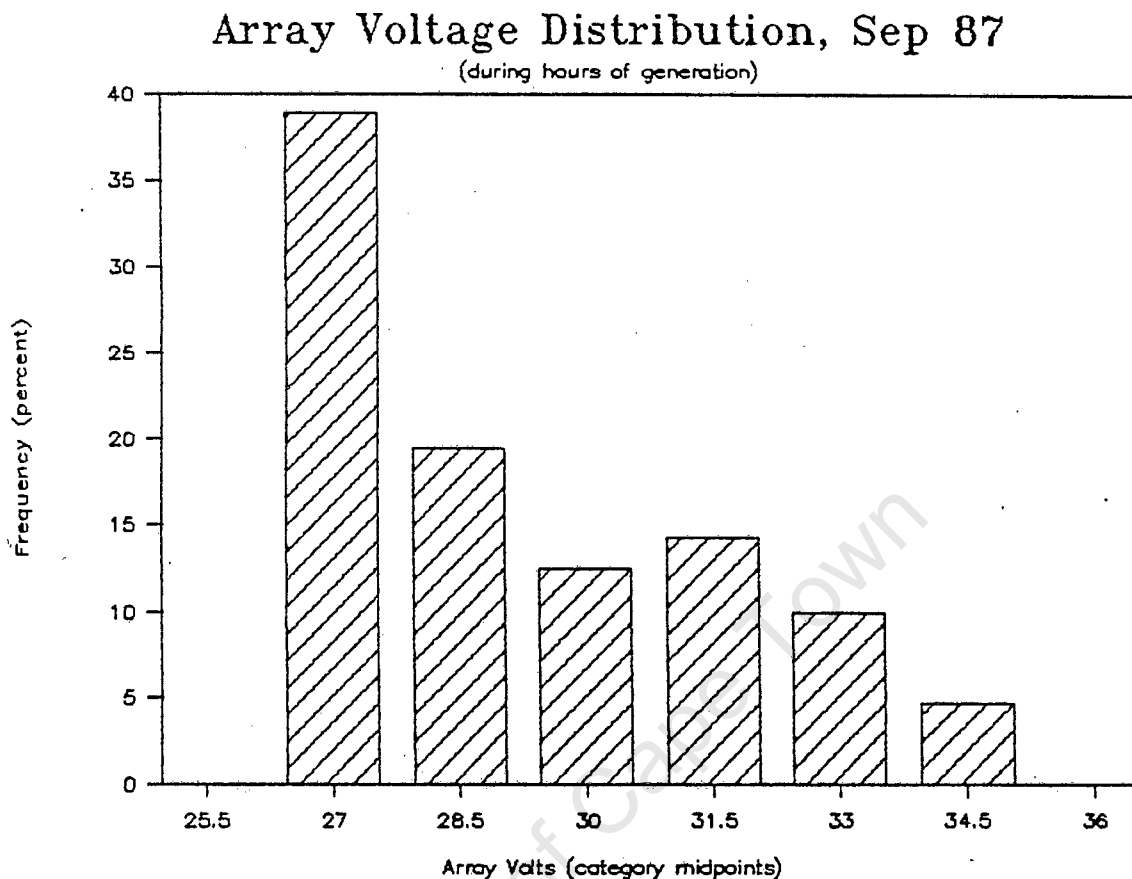


FIGURE 5.8 **Array Voltage Distribution, September 1987**

The tail of the voltage distribution in Figure 3.12 is an indicator of surplus/wasted array power, since the Energy Management Unit restricted voltage transmission to 27.6 volts during this period. Supply voltages higher than this were dropped across the Energy Management Unit. The incidence of higher array voltages corresponds to available array power in excess of system energy demands. The hump in the distribution around 31.5 volts indicates the September modal array voltage in such circumstances.

The frequency distribution of array currents is similarly bimodal. Figure 5.9 depicts this for all monitored months combined, for POA insolation levels greater than 150 W/sq.m. For roughly 50% of the log periods here, array current was less than 500 milliamps, corresponding with lack of system energy demand. Under energy demand conditions, the modal array current range was between 1.5 and 2 amps. Array current seldom exceeded 3 amps.

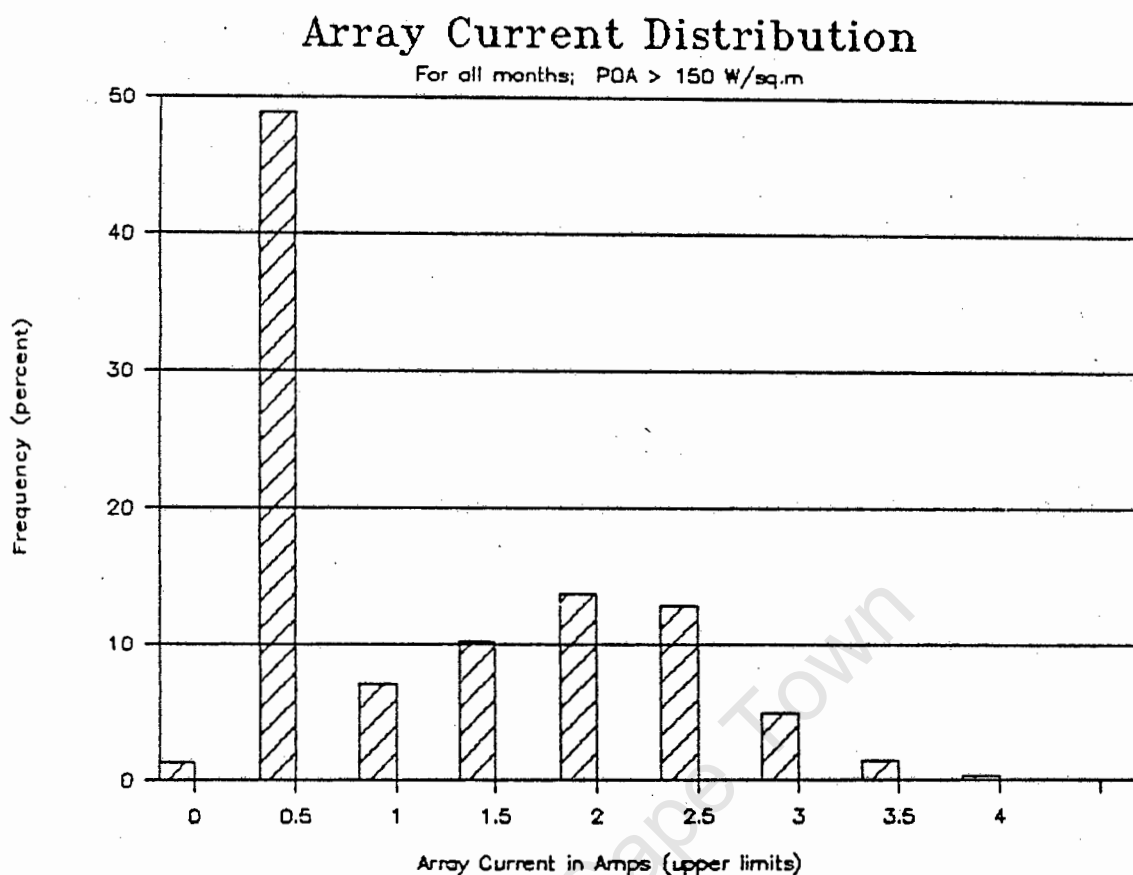


FIGURE 5.9 Array Current Distribution

The array power, obtained through multiplying array voltage by array current, is shown in Figures 5.10 and 5.11, in the form of frequency polygons. Figure 5.10 shows those months when there was a controlled load, averaging 370 Wh/day for July, August and September combined. Figure 5.11 shows months where load demand was negligible.

In each case, all valid log periods in which the plane of array insolation exceeded 50 W/sq.m constitute the monthly population. The vertical axis shows the percentage of these observations, per month, that corresponds with the shown levels of array power. To bring out the pattern of the distributions more clearly, array power levels have been grouped into categories of 12 Watt intervals.

Thus it is seen that in the lean months - as far as load demand is concerned (Figure 5.11) - observed array power was very low indeed. For 99% of December observations, recorded array power was less than 10 Watts, and only one half-hourly observation exceeded 20 Watts. A small minority of higher values were recorded in June and November,

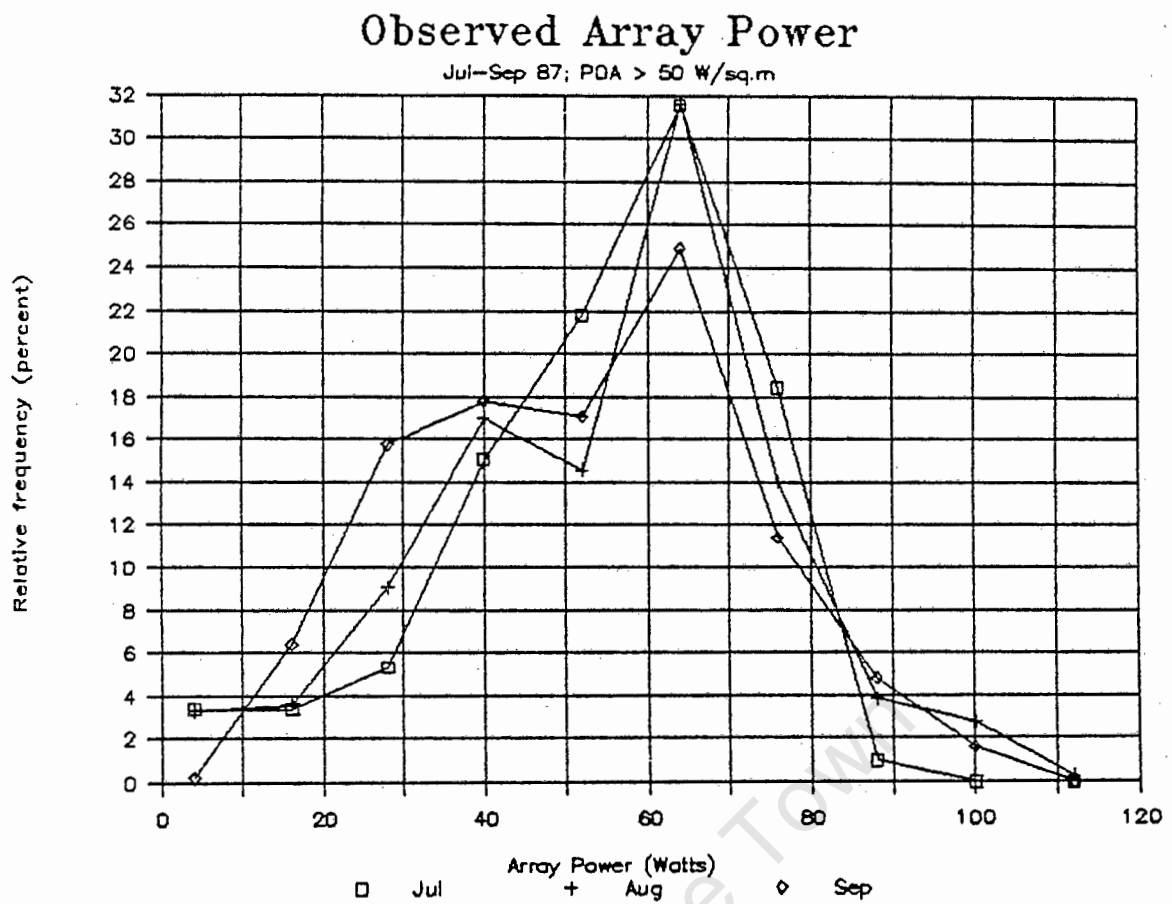


FIGURE 5.10 Observed Array Power, With Controlled Load

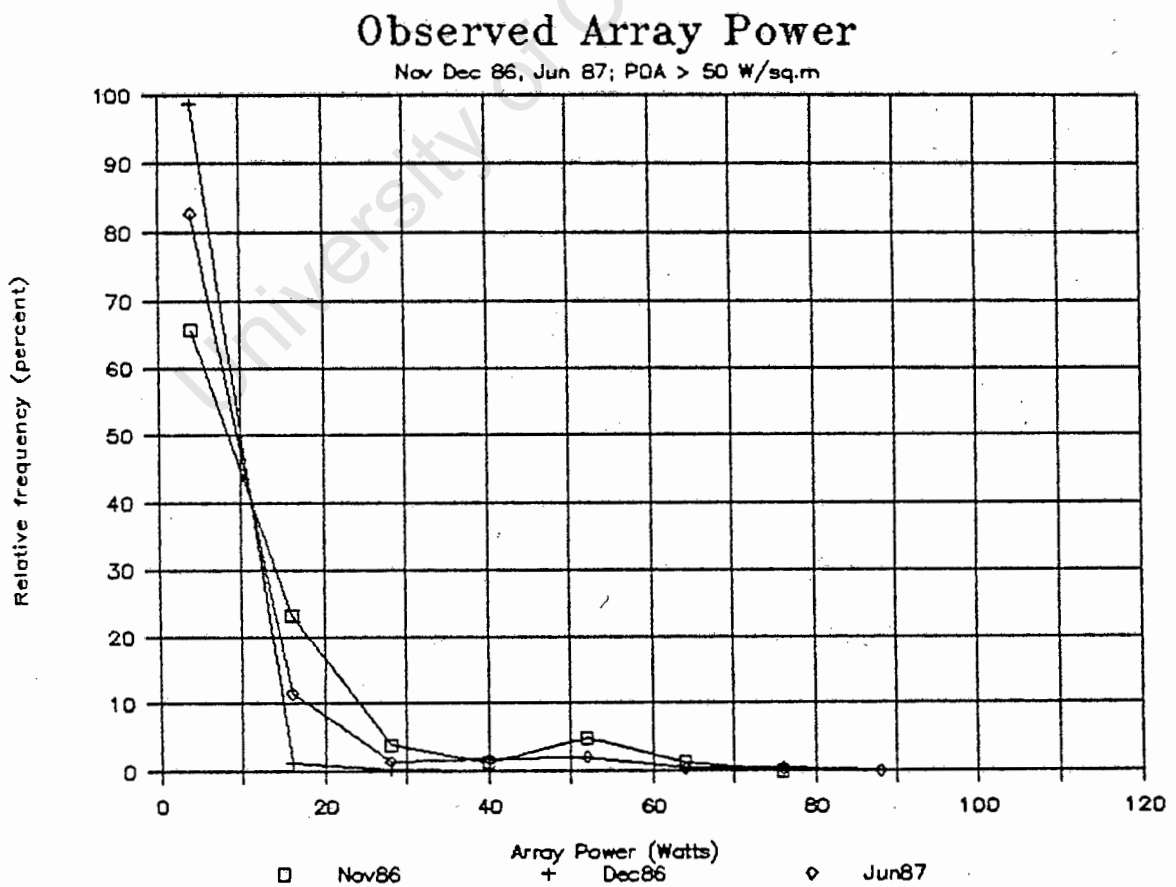


FIGURE 5.11 Observed Array Power, With Negligible Load

but the pattern is similar, with the great majority of observations below 20 Watts, and only one measurement exceeding 70 Watts.

These low values are of course a result of the lack of system power demand, and indicate conditions where the batteries are generally at full charge and the Energy Management Unit is consequently limiting power transmission to a negligible float charge. Note that the measurements of array power, in these conditions, are inaccurate due to the chopped waveform (as mentioned earlier, in Section 4.5). The actual array power output would be less than the measurements indicate. The pattern of the distribution, however, is not significantly affected by this qualification. It shows the extent of underutilisation in these months.

In July, August and September 1987 (Figure 5.10) it is seen that the modal category for array power for all three months occurs at a category midpoint of 64 Watts (ie. 58 to 70 Watts). In July and August, more than 30% of observations occurred in this range. A small percentage of observations exceeded 90 Watts and array power never exceeded 120 Watts.

Mean levels for array power, together with recorded mean POA insolation and mean daily load, are shown for these months in Table 5.8. Array power and insolation are averaged over periods where POA insolation was greater than 50 W/sq.m.

The mean recorded insolation in W/sq.m has been multiplied by the area of the two photovoltaic modules ($1.078 \text{ sq.m} \times 2$) to obtain the mean insolation on the array in Watts.

From these figures, the mean conversion efficiencies of the photovoltaic array can be calculated for these months (mean array output power divided by mean incident insolation power, where means have been taken over times when $\text{POA} > 50 \text{ W/sq.m}$). They range from 0.046 to 0.054 under these operating and climatic conditions.

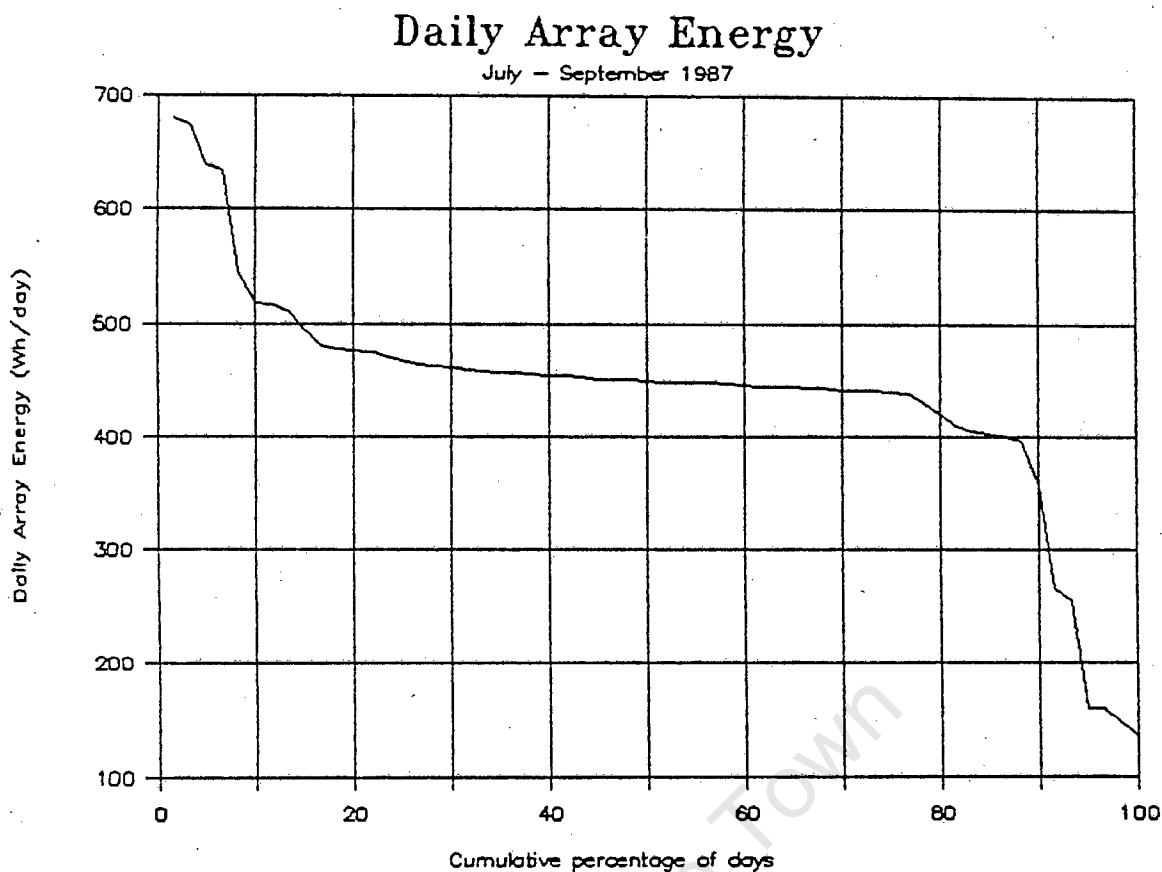


FIGURE 5.12 Array Energy Generated, Cumulative Frequency Distribution.

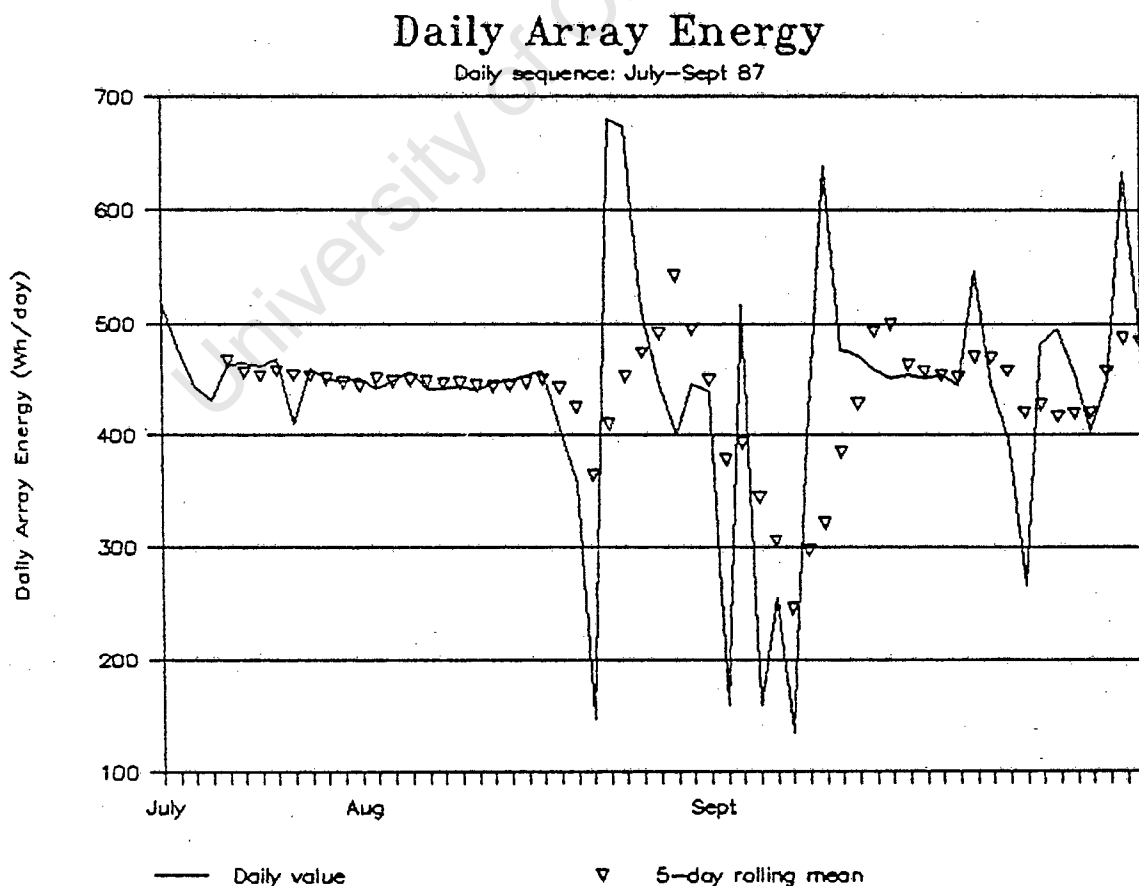


FIGURE 5.13 Array Energy Generated, Daily Sequence with 5-Day Rolling Mean

Effects of array energy deficits are only slowly cumulative in a system, such as this, which has a high battery storage capacity in relation to the daily load. Figure 5.13 includes an indication of the 5-day rolling mean of daily array energy values. This is seen to fall below 400 Wh/day for 9 days (8 of them in succession) and below 300 Wh/day on one day.

Since the system is generously designed for supporting a higher daily load (about 450 Wh/day) for 5 days in the absence of any insolation at all, the period of remarkably adverse conditions at the beginning of September did not pose any threat to system availability. The maximum depth of battery discharge recorded was only 25%.

It should be pointed out that the generated array energy is not the same as the energy delivered to the batteries and load. When excess array power is available, there is a voltage drop across the Energy Management Unit; and there is a further energy loss when the applications load is powered by the batteries, due to their imperfect energy efficiency. However, the difference between generated array energy and energy available to the load is minimised in adverse conditions, where excess array power is least frequent and where the partially depleted batteries are in their most efficient charge-discharge range.

5.2.7 Module cell temperature

Finally, the data for recorded module cell temperature is summarised in Table 5.9. Only values for daylight hours (POA insolation greater than 50 Watts/sq.m) have been included.

Relationships between cell temperature and other variables are discussed in Chapter 8.

TABLE 5.9 Module Cell Temperatures (degrees C), by Month:
Daylight Hours.

	Jun 87	Jul 87	Aug 87	Sep. 87	Nov 86	Dec 86
Mean	23.8	17.1	25.2	26.2	27.2	30.7
Maximum	39.6	41.9	44.3	48.7	49.9	50.6
Minimum	1.3	-7.6	-6.8	4.4	4.4	8.8
S.D.	8.1	14.8	9.4	9.7	9.3	9.2
f (logs/month)	337	219	404	518	426	502

Chapter 6

ASSESSMENT AND TREATMENT OF INSOLATION MEASUREMENTS

The insolation measurements logged at the site appeared low. These measurements were compared with historical and concurrent solar radiation records from the Forum weather station in Pretoria, and substantial discrepancies were indicated. This chapter describes the methods used for making the comparisons (including a comparison of methods for calculating irradiance on a tilted plane), tests conducted on the solar radiation instrumentation at the monitoring site, an analysis of sources of discrepancy, and consequent adjustments made to the monitoring data.

Reliable insolation measurement is clearly of vital importance in analysing the performance of a photovoltaic system, and the margins of uncertainty attached to such measurement carry through to any calculations of system efficiencies based upon incoming solar energy.

The problems encountered in this area have drawn attention not only to the uncertainties in measuring insolation in the present study, but also to more general difficulties in sizing photovoltaic arrays on the basis of insolation data (such as from weather station records) which are obtained using instruments which have a different spectral response from that of silicon photocells.

6.1 Comparing the Insolation Measurements with Weather Station Records

The closest weather stations which record hourly insolation are in Pretoria, approximately 40 kilometers from the monitoring site. The Pretoria-Forum weather station was selected, as the headquarters of the South African Weather Bureau, where instrumentation should be carefully maintained. Up to 22 years' records for Pretoria-Forum have been utilised in the comparisons, including hourly data for the months during which monitoring took place.

6.1.1 Sources of data for weather station records

Long-term monthly means for global and diffuse daily insolation, received on the horizontal, have been derived from Pretoria-Forum records and are published in:

- 1 CSIR Research Report, No. 243 (1971)
(using 9 years Weather Bureau data)
- 2 Eberhard, Tegen and Williams (1988)
(using 22 years Weather Bureau data)

Printed hourly records for global and diffuse insolation at Pretoria-Forum station were obtained directly from the South African Weather Bureau for the months in which monitoring took place.

In addition, ten years' raw data were extracted from South African Weather Bureau (SAWB) hourly records on magnetic tape, screened for errors and missing values, and used as input into a tilt-conversion program.

6.1.2 Methods for calculating insolation on a tilted plane

Insolation at the monitoring site was only measured in the plane of the array, ie. at a northwards tilt of 30 degrees from the horizontal. The weather station records, on the other hand, are of global and diffuse insolation received on a horizontal plane. In order to make comparisons, it was therefore necessary to calculate from horizontal measurements what insolation will fall on a tilted plane.

Two methods were employed for this.

Method A (isotropic)

Horizontal insolation is divided into direct and diffuse components. The angle of incidence of the direct beam on the tilted surface is calculated trigonometrically from the tilt angle and orientation of the tilt plane, the latitude of the site, the hour of day (solar time) and the julian date. This allows calculation of the component of the direct beam normal to

the surface of the tilt plane. Diffuse radiation is treated as isotropic, evenly distributed from the sky. The fraction of the sky to which the tilt plane surface is exposed is then taken as the fraction of horizontal diffuse insolation which the tilted surface receives. Reflected light is entered as a function of global insolation and surface reflectivity (taken as between .25 and .30 for the calculations below). The code for these calculations appears in Appendix C1. Computations are made either from hourly records (Method A1) or else from daily totals for horizontal global and diffuse insolation (Method A2). The latter entails a greater degree of approximation, from averaging cosine effects through the day, while both entail the approximating assumption of isotropic diffuse radiation from the sky's dome.

Method B (anisotropic)

For independent comparison, an anisotropic model for calculating tilt-plane insolation was employed. This was derived from the photovoltaic system simulation program authored by Menicucci and Fernandez (1985), available from Sandia National Laboratories, Albuquerque, N.M., called PVFORM. The subroutine for computing tilt plane insolation in turn derives from R R Perez of the State University of New York at Albany (cf. Perez, 1984), and differs from the above method in using empirical parameters to refine the calculation of diffuse insolation from different zones of the sky. Relatively higher diffuse radiation emanates from the circum-solar region, and a band around the horizon.

Validation studies are reported in Menicucci (1986b), from Sandia National Laboratories. Comparative studies of alternative anisotropic models (cf. Chowdhury and Rahman, 1987; Perez et al., 1986) have found the Perez model superior to others in predicting insolation on sloping surfaces.

The code from PVFORM Version 3.2 was adapted and rewritten to accept locally available insolation data (global and diffuse hourly records, as opposed to global and direct normal insolation records), and it is included in Appendix C2.

To some extent, the empirical parameters in the Perez model within the PVFORM simulation program are likely to be influenced by type of climate. However, Chowdury and Rahman (1987) tested the method against data in three widely different climatic situations, and found Perez model predictions most accurate out of four methods tested. Perez et al (1986) also report favourably on their evaluation of site dependency.

Applied to the same set of insolation data (hourly means, per month, derived from 22 years' Pretoria-Forum records) the two methods for calculating tilt plane insolation, at a tilt angle of 30 degrees and at the location of the monitoring site, yielded the following results:

Anisotropic calculations (Method B) as a percentage of isotropic calculations (Method A1)

June	July	August	September	November	December
102%	103%	107%	107%	104%	104%

(Months correspond to the months monitored)

The somewhat higher predictions of the anisotropic method are compatible with published validation studies, as cited above. The variation is greatest for months where there is a higher proportion of diffuse insolation recorded.

Since predicted insolation on tilted planes is central to photovoltaic system design, and local scrutiny is being given to alternative data treatments and tilt-plane calculations, Table 6.1 shows a more detailed comparison. The results of appropriate combinations of the two data sources and the different tilt-plane methods are compared. They are identified in the Table as:

Tilt plane method	Insolation records
A = isotropic model	1 = CSIR Report 243 (9 years)
B = anisotropic model	2 = Eberhard et al (22 years)
	3 = SAWB tape (10 years)

TABLE 6.1 Mean Daily Insolation, Per Month, Predicted on a
Plane Tilted 30 Degrees North from Long-term
Insolation Records for Pretoria.

JUNE	JULY	AUGUST	SEPTEMBER	NOVEMBER	DECEMBER
Mean daily tilt plane insolation, in Wh/sq.m/day					
Method (A2) Records (1)					
5794	5836	6508	6322	5934	5611
Method (A1) Records (2)					
5888	5938	6117	6261	5848	5977
Method (B) Records (3)					
5804	6065	6786	6776	6194	6062
Method (B) Records (2)					
5994	6086	6556	6670	6066	6189
Average of tilt-plane calculations on Pretoria records					
5870	5981	6492	6507	6011	5960
Greatest deviation amongst above calculations from average					
2%	2%	6%	4%	3%	6%

The deviations in the calculations incorporate variations in the weather records, and differences in the tilt-plane calculation method.

Depending on one's purposes, these deviations could be regarded as substantial. The largest ranges of $\pm 6\%$ are attributable primarily to the tilt-plane calculation method in the month of August, while in December there is a combined effect of the tilt-plane method and an apparent anomaly in the CSIR data for that month. If the aim is to develop critical photovoltaic sizing methods dependent on weather station records, then the extent of these variations suggests a need for further assessment and validation of insolation records and tilt plane computation.

For present purposes of assessing discrepancies in the monitoring data, however, the deviations above are of a relatively small magnitude in relation to the apparent discrepancies.

For comparing the measured plane of array insolation at the monitoring site with what would be expected on the basis of weather station records, the Perez anisotropic method for calculating tilt-plane insolation has been adopted, since there appears to be no disagreement that it is superior to an isotropic model; and the historical records used are those summarised in Eberhard et al (1988), since they cover a longer time span and have been subject to careful screening.

6.1.3 Discrepancies between monitored and expected plane of array insolation

Comparing the expected plane of array monthly mean insolation, based on long-term Pretoria records, with the monthly means derived from the monitoring data, substantial differences are evident. These are presented in Table 6.2.

TABLE 6.2 Monitored Plane of Array Insolation compared with Long-term Pretoria Records, Converted for Tilt.

JUNE	JULY	AUGUST	SEPTEMBER	NOVEMBER	DECEMBER
Monitoring data, monthly means, 30 deg tilt, in Wh/sq.m/day					
Jun87	Jul87	Aug87	Sep87	Nov86	Dec86
3876	5092	5116	4675	4500	5500
Expected monthly means from Pretoria long-term records, converted for 30 deg tilt, in Wh/sq.m/day					
5994	6086	6556	6670	6066	6189
Monitoring data means as % of calculated Pretoria means converted to 30 deg tilt, using long term records					
65%	84%	78%	70%	74%	89%

To take into account the particular weather during the actual months monitored in 1986 and 1987, and any variations from long-term means, insolation data from the Pretoria-Forum weather station for those months was compared with long-term means. This allows estimation of

the net discrepancy between the monitored data and the insolation which could be expected on the basis of Pretoria data.

TABLE 6.3 Monitored Plane of Array Insolation Compared With Expectations

Jun87	Jul87	Aug87	Sep87	Nov86	Dec86
Variation between Pretoria insolation records for the monitoring period and long term records					
+4%	+4%	-3%	-19%	-8%	+8%
Approximate net discrepancy of monitoring data from Pretoria expectations, taking account of 86-87 weather in Pretoria					
-37%	-19%	-20%	-14%	-20%	-18%

From foregoing tables, the following features are relevant to an assessment of the monitoring site insolation data:

- 1 Using different tilt-plane calculation methods, and different data sets for Pretoria insolation (but all derived from Pretoria-Forum weather station), a fair degree of agreement is achieved in calculating expected plane of array insolation. The largest discrepancies are of the order of + 6%.
- 2 Substantial variations in 1986/7 insolation from long-term means were recorded in Pretoria only in September 87 (19% lower than long-term means).
- 3 Taking recorded 1986/7 weather into account, the estimated discrepancies between monitored monthly means and Pretoria-based expectations ranged from -14% to -37%.
- 4 Discrepancies were greatest in winter months, sharply so in June, and least in the month of September. (In anticipation of later conclusions, it can be noted that September is the month when the sun's trajectory is most nearly perpendicular to the plane of the tilted array, at this latitude and tilt.)

6.2 Analysis of Discrepancies

A number of possible sources of error were considered, together with possible reasons for insolation at the site falling below calculated expectations.

Lower insolation could occur because of:

- climatic differences between the monitoring site and Pretoria
- air pollution at the monitoring site
- shading of the array and sensor

Errors of measurement could occur through:

- pyranometer error
- signal conditioning error

In addition, errors of analysis and computation were considered.

6.2.1 Climatic differences

In considering climatic differences between the monitoring site and the Pretoria-Forum weather station, somewhat greater cloud cover can be expected at the monitoring site in summer months, but not in winter months, when skies are predominantly cloudless in both locations. At Jan Smuts airport, which is closer to the monitoring site than Pretoria, hourly insolation records are unfortunately not kept. On the basis of sunshine hours for Jan Smuts, and absolute solar radiation, Tegen (pers.comm; and in Eberhard et al, 1988) has calculated insolation levels for Jan Smuts which are within 2 or 3 % of her empirically derived values for Pretoria, except for the month of December, where the Jan Smuts estimation is 6% below the Pretoria figure, reflecting more frequent cloud cover.

For each hour of the day, mean insolation values from the monitoring data were compared with Pretoria records for the same hours, per month. There was evidence of greater cloud cover at the monitoring site in the afternoons in November and December; otherwise, the comparison of mean daily profiles indicated no systematic differences in daily cloud patterns.

However, comparison of daily profiles showed that the percentage difference between monitored values and weather station values was greatest in the early hours of the morning and late hours of the afternoon, most notably in winter months. Figure 6.1 illustrates this, for two days in June. This feature is compatible with shading of the array, as discussed below, and any other hypothesis predicting reduced insolation or increased error at low solar elevations.

From day to day, variations in monitored daily total plane of array insolation followed Pretoria-Forum records for 1986/7 fairly closely.

After tilt conversions, for example, the correlation between daily totals from the two sets of data for the month of September 1987 was $R = .96$. Again, there was no evidence from this of significantly different weather patterns at the monitoring site, compared with Pretoria.

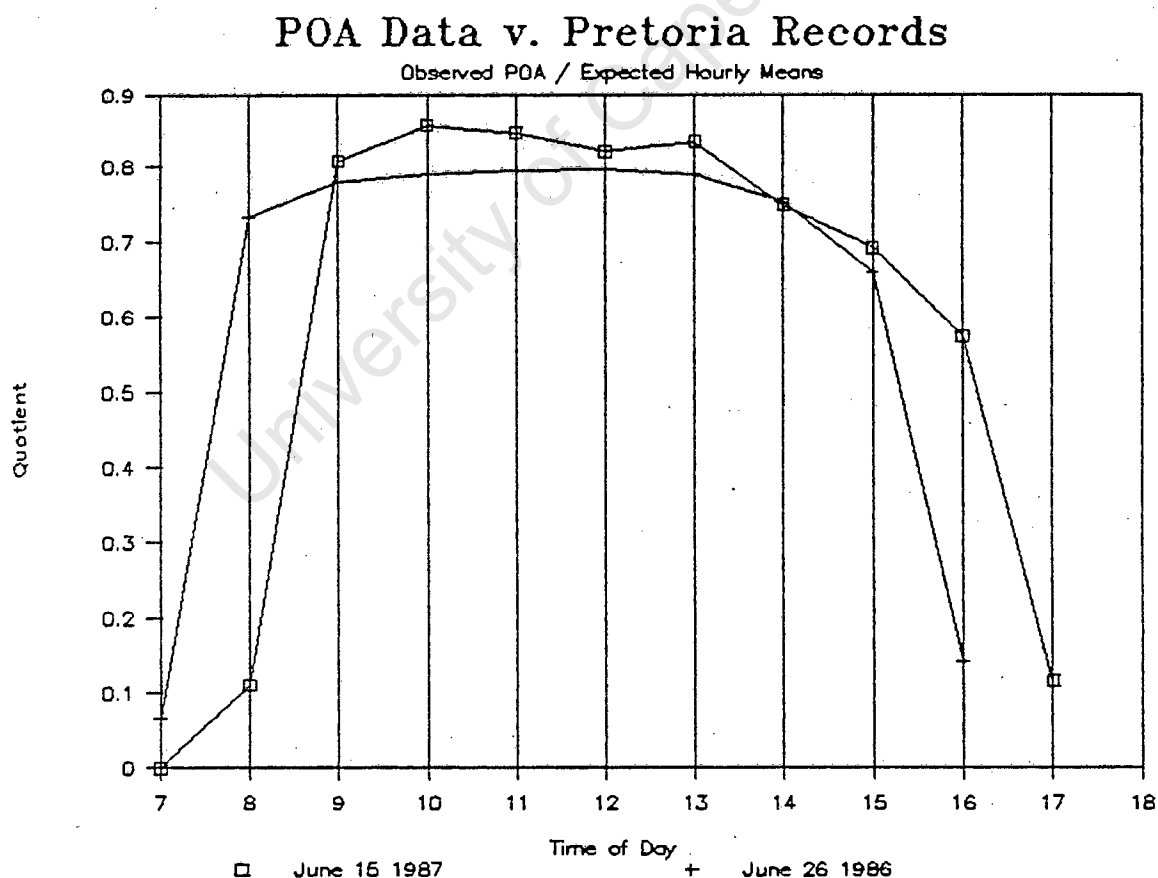


FIGURE 6.1 Comparison of Daily Insolation Profiles, Pretoria and Monitoring Site, for Two Days in June

6.2.2 Air pollution

There is considerable air pollution in the area of the monitoring site. Nearby sources of pollution are the Isando industrial area, Modderfontein, Jan Smuts airport itself and a large power station all within a radius of approximately 10 km. There are also smoke and dust in the immediate environment, from farm activities. The visible effects are greatest in winter. Haze extends into the middle of the day, while there is a characteristic reddening of the light in the mornings and afternoons. In winter, there is a more or less permanent high pressure cell over the Rand, which leads to inversion layers, trapping pollutants in the morning and later afternoon.

However, pollution is also substantial in Pretoria, and information is not available to judge whether the effects at the monitoring site are more severe. What appears more certain is that the extent of the pollution affects the spectral distribution of irradiation. This could occur at both locations, but (as discussed below) the pyranometer used at the monitoring site has a spectral response which is more selective than that of weather station instruments.

6.2.3 Shading

The array is mounted in a school courtyard, with the centre of the array just over 2 meters from the ground. The school roof rises 3 meters above this, at a variable distance from the array. The solar elevation below which the array is fully or partly shaded varies from 20 to 23 degrees for morning sun and 14 to 29 degrees for afternoon sun, depending on the sun's seasonal declination angle.

From trigonometric calculations for solar elevation and azimuth, and the geometry of the site, it was possible to calculate the periods of the day, at different times of year, when the array was fully or partly shaded. (See Appendix B2 for method.) Weather station insolation data then allowed calculation of the percentage of the day's total insolation (on the horizontal) occurring in such shaded periods. For the months monitored, the values were as follows:

Percentage of mean daily horizontal insolation subject to shading of direct beam:

JUNE	JULY	AUG	SEPT	NOV	DEC
12%	10%	8%	9%	10%	7%

The shading of the direct beam does not of course eliminate diffuse irradiation in these periods. Conversely, the effects of shading and shadow are not restricted to these periods, since they affect the proportions of diffuse and reflected radiation received at other times of day. The effects of shadows on the reflected component will be greatest in the middle of winter, while in general, approximately 8% of the sky's dome to which the array is exposed is obstructed by the school buildings, reducing the diffuse component at all times.

6.2.4 Factors leading to reduced insolation

There appear therefore to be factors leading to reduced insolation at the site:

- somewhat greater cloud cover in the afternoons, in November and December, compared with Pretoria, leading to a reduction in daily total insolation of perhaps 5% in December;
- shading of the array, with shadow period including up to about 12% of daily insolation in winter months; and with some further impact on diffuse and reflected light when the array is not directly in shadow;
- pollution, dust and smoke reducing insolation, especially in winter and in the mornings and late afternoons; but perhaps comparable with Pretoria pollution, so that spectral effects may be more salient, as discussed below under pyranometer error.

These factors contribute to the observed discrepancies from Pretoria-based expectations, but are not sufficient explanation.

6.2.5 Pyranometer error

Tests were conducted independently on the pyranometer and the signal conditioning circuitry. The pyranometer tests were conducted over two days at the site, again in Cape Town, and also under stable and clear solar and atmospheric conditions in semi-desert conditions in the Karoo.

The tests are described in greater detail in Appendix B1.

Essentially, readings from the Li-Cor pyranometer were compared with readings from a Kipp and Zonen solarimeter, under a limited variety of natural conditions. The Li-Cor sensor is a silicon cell pyranometer while the Kipp and Zonen is a thermopile instrument, as used for weather station measurements.

The tests showed a strong relationship between the angle of incidence of direct radiation on the sensors, and the discrepancy between Li-Cor and Kipp and Zonen measurements. In the Karoo tests, where spectral variations were minimised, and with a calculated air mass close to 1.5 (the value at which photovoltaic module specifications are typically given), the relationship was

$$d(LC/KZ) = - 0.00165 * I$$

$$R\text{-square} > .99$$

LC : Li-Cor measurements
KZ : Kipp and Zonen measurements
I : Incidence angle, in degrees from normal

It was checked to satisfaction that this relationship did not arise from tilt errors in KZ measurements.

In the site tests, varying angles of incidence were associated with the sun falling to lower elevations. The relationship between LC and KZ measurements was again a linear function of angle of incidence, although the goodness of fit was somewhat less, and the gradient of the function was higher:

$$d(LC/KZ) = - 0.00232 * I$$

R-square > .95

Tests in Cape Town yielded values inbetween these two relationships, which are depicted in Figure 6.2.

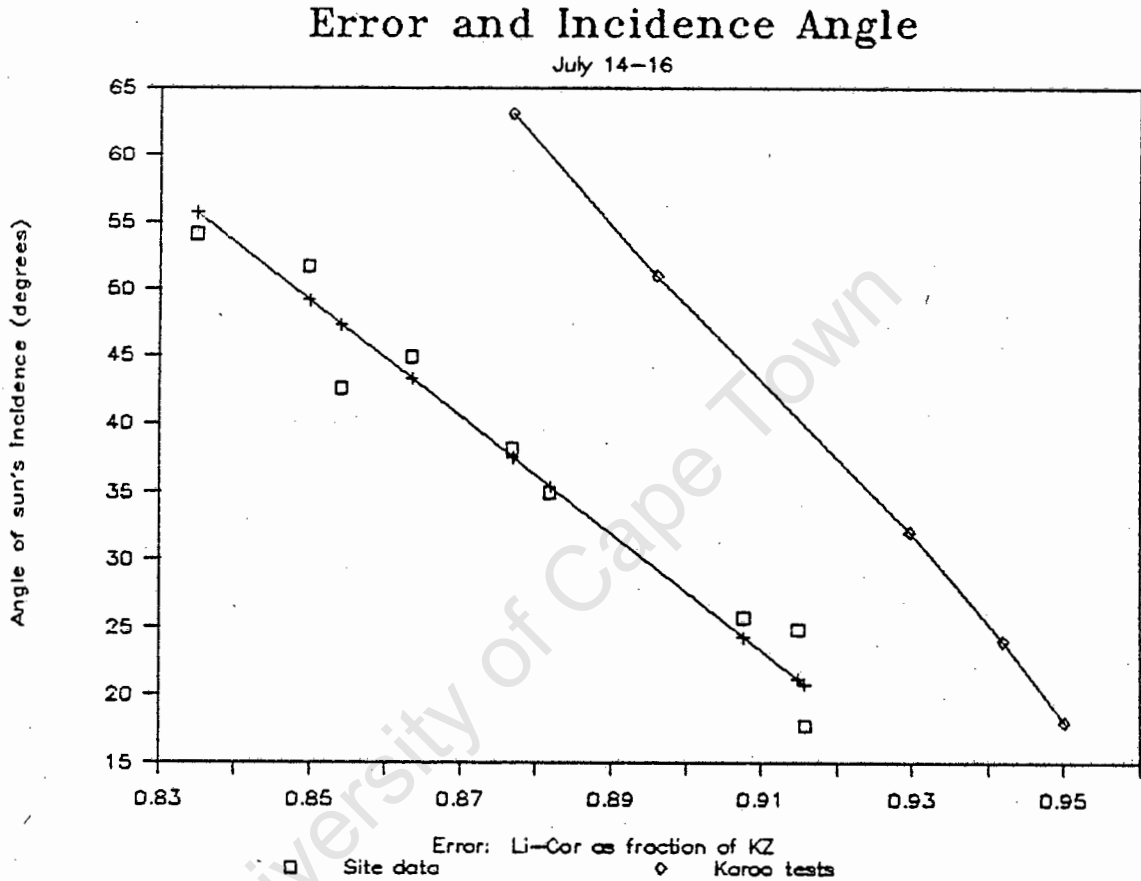


FIGURE 6.2 Tested Discrepancy Between Li-Cor and Kipp and Zonen Pyranometer Measurements, as a Function of Incidence Angle

The gradient of the function is independent of the calibration of the two instruments, and indicates that relative to the KZ instrument, the LC sensor increasingly undermeasures radiation at increasing angles of incidence.

Referring to Li-Cor pyranometer product information, the sensor is supposed to be cosine-corrected, through construction of its diffuser cap, such that direct radiation incident at angle I should be measured equivalent to the cosine of the same direct radiation received

normally. Deviations from this relationship are referred to as cosine error. Li-Cor specifications claim a cosine error for this pyranometer of typically less than 5%, up to 80 degrees incidence angle. The minimum cosine error indicated by the above tests was 0.165% per degree however, amounting to a 5% error at 30 degrees incidence, and more than 13% cosine error (if still linear) at an incidence angle of 80 degrees.

Kipp and Zonen solarimeters typically have a cosine error of less than $\pm 1\%$, up to 70 degrees incidence angle, according to the manufacturer (reported in Coulson, 1975:113).

The difference between the gradient of the functions in the site tests and the Karoo tests is most likely attributable to the fact that in the latter there was very little variation in the sun's position: different incidence angles were tested with the sun in approximately the same position. In the site tests, the higher incidence angles correspond with lower solar elevations, and the most probable additional factor here is spectral variation, with a shift towards longer wavelengths at lower elevations.

Li-Cor product information warns that measurements at low solar elevations can "show significant error because of altered spectral distribution with changes in atmospheric transmission". This is due to the selective spectral response of the sensor, which peaks at wavelengths around 950 nanometers, falling to 80% relative response outside the range 800 - 1000 nanometers. Figure 6.3 reproduces the relative spectral response curve supplied with the instrument.

By contrast, Kipp and Zonen solarimeters have an approximately flat response, in the range 320 - 2500 nanometers. An ideal spectral response for measuring terrestrial solar radiation would be flat in the range 280 - 2800 nm.

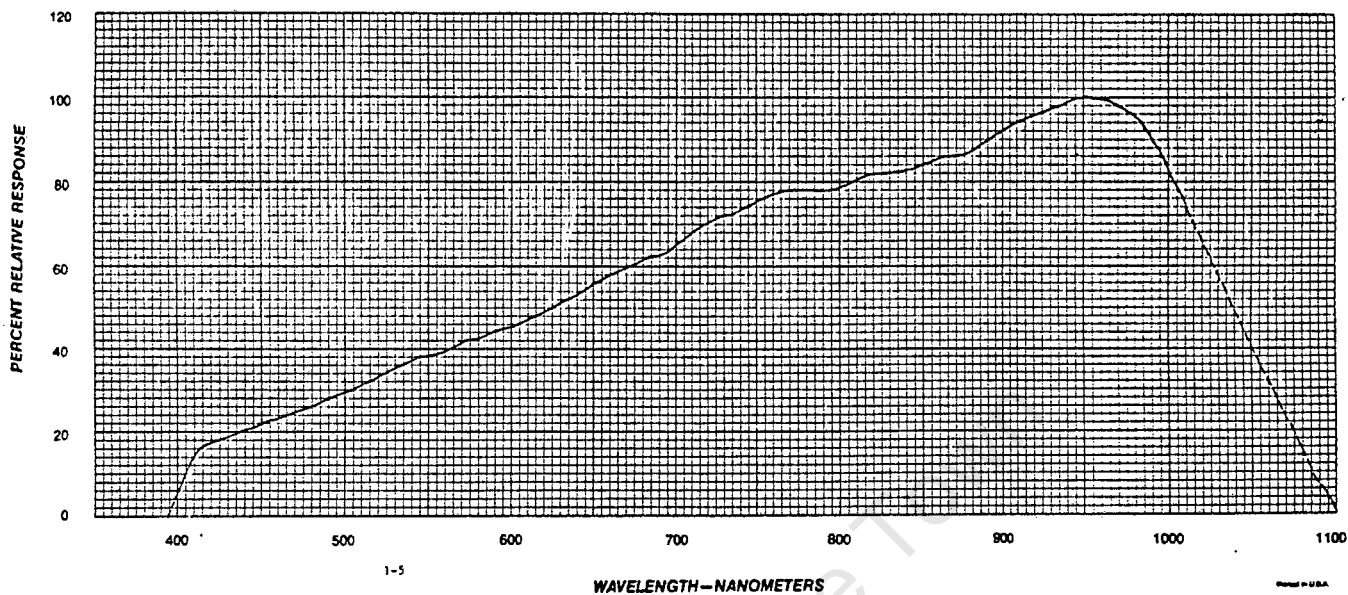


FIGURE 6.3 Relative Spectral Response of Li-Cor Pyranometer
[reproduced from Li-Cor product information]

Unfortunately, there is no way of systematically compensating for spectral response errors in the logged insolation data, since the extent of spectral variations on different days, with changing atmospheric conditions, and at different times of day, cannot be assessed from available information.

An important point, though, is that the silicon sensor of the Li-Cor pyranometer presumably has a spectral response more similar to the silicon cells in the photovoltaic array than the blackened thermopile receiver of the Kipp and Zonen solarimeter. Discrepancies between thermopile insolation measurements and silicon cell insolation measurements which are attributable to spectral effects therefore have direct implications for photovoltaic module performance. Modules can operate at lower than expected power, if expectations are based on weather station insolation records, when the spectral distribution of insolation diverges from that under which the output characteristics of the modules have been rated.

Turning now to the question of instrument calibration, as posed by the intercepts of the lines in Figure 6.2, there is an uncertainty here estimated in the region of $\pm 5\%$.

Li-Cor product information states that absolute error, resulting from the calibration process (against an Eppley Precision Spectral Pyranometer, traceable to the U.S. National Bureau of Standards, under natural daylight), is $\pm 5\%$ maximum, and typically within $\pm 3\%$, but that long-term stability is typically $\pm 2\%$ per year. The pyranometer used was calibrated by Li-Cor in 1985, which could introduce further error of up to $\pm 6\%$ by mid 1988.

The calibration has therefore rather been assessed by comparison with Kipp and Zonen solarimeters - the solarimeter used for the site and Karoo tests, and a second instrument of the same model at the University of Cape Town. Comparison of the latter instruments showed the first solarimeter reading on average 4% higher than the second. Relative to the magnitude of other discrepancies encountered, this disagreement was regarded as acceptable, and as a best guess, measurements taken with the test instrument were revised downwards by 2%.

Having done this, the regression line from the Karoo tests shown (before correction) in Figure 6.2 has a zero intercept, suggesting there would be insignificant discrepancies in measuring insolation, under these clear sky conditions and air mass 1.5, if direct radiation were normal to the instruments.

The regression equation for the July site test data, after the 2% correction to KZ measurements, was

$$LC/KZ = .984 - .00237 * I$$

$$R\text{-square} > .95$$

LC : Li-Cor measurements
KZ : Kipp and Zonen measurements
I : Incidence angle, in degrees from normal

Here, the non-zero intercept is difficult to interpret, since haze in the atmosphere could introduce a degree of spectral response error at any angle of incidence. The decision was therefore made, in applying a correction formula to the monitored data, not to attempt any average correction for calibration, nor to attempt any general correction for spectral response errors, but only to correct for the apparent cosine error of the Li-Cor pyranometer, using the least compounded relationship derived from the Karoo clear sky tests:

$$LC/KZ = 1 - .0017 * I$$

It would have been useful to check the calibration of instruments against the instrument used at the Pretoria-Forum weather station, but this was not achieved. As a less direct comparison, test measurements at the site were compared to corresponding records for Pretoria-Forum, for corresponding days of the year, and hour of day, from 1987 records. Very little variation in daily insolation receipts is recorded at this time of year (15-16 July). KZ measurements at the site averaged 4% higher than corresponding weather station records. It would seem that $\pm 5\%$ is a reasonable estimate of the uncertainty in calibration, independent of cosine error and spectral response error.

6.2.6 Signal conditioning error

Errors in setting the gain and offset of the amplifying circuit in the signal conditioning interface were possibilities.

The offset setting could not directly be tested at the end of the monitoring period, due to a second incidence of lightning damage which had rendered the IC inoperable in this circuit. It was still possible to measure the gain of the circuit, since this is essentially independent of a particular IC's characteristics.

Inspection of logged data showed a drifting zero offset, during nights, of about 0.2 to 0.9% of full scale readings, in the months July to September 1987. However, these drifts were not systematic, from day to day, and also varied during the hours of night, starting small. It was therefore not possible to deduce an offset error applicable to daylight hours.

In other months, including June 87, there was no evidence of drifting offset; and in these months the discrepancies were equal to or greater than the discrepancies in months where drift was observed. It is therefore unlikely that offset errors were a primary factor in accounting for the discrepancies. Offset errors could have contributed to slightly lower measurements in July to September, 1987. However, correlation of monitored data and weather station data for the same periods showed no evidence of systematic offset error.

The gain of the amplifier circuit was tested and found to be accurate within 0.8%, in relation to the multiplier setting of the datalogger.

Signal conditioning errors were therefore judged not to constitute a significant component of total errors.

6.2.7 Errors in statistical analysis of monitoring data.

To check, monthly means were computed in a variety of ways, including manually for some months. Results were consistent. In July and August, there were often missing values in the early morning hours, due to sub-zero temperatures which upset the datalogger. These missing values were interpolated. Further, by taking means for each hour, per month, then totalling these for the mean daily total, any errors from missing values were reduced. The consistency of results suggested computational errors were not a significant factor.

6.3 Adjustment of Monitoring Site Insolation Measurements

For the analyses which follow, a statistical adjustment has been made to insolation measurements, following the relationship found between angle of incidence and pyranometer discrepancy under clear skies. This correction for pyranometer cosine error introduces an adjustment to daily total POA insolation of between 4.5 and 6.8 % of recorded values, depending on the time of year.

$$\text{POA}(\text{adj}) = \text{POA}(\text{raw}) * (1 + .0017 * I)$$

where POA(adj): Adjusted plane of array insolation
 POA(raw): Recorded plane of array insolation
 I: Incidence angle, in degrees from
 normal to plane of array

To avoid the repeated computation of incidence angles for every data point, a simplified transformation was developed. This was fitted to the above relationship for all hours of the day, for mid-days of monitored months, achieving a goodness of fit of R-square > .99 for all months except June (.97) and December (.94).

Applied to recorded plane-of-array data, this transformation produced corrections to average daily POA insolation as follows:

JUNE	JULY	AUG	SEPT	NOV	DEC
5.5%	5.3%	4.8%	4.5%	6.2%	6.8%

Although a stronger relationship had been observed between instrument discrepancy and incidence angle at the site in July, it was judged that this included spectral response errors, which could not be systematically quantified for the monitoring period.

Comparing the above corrections with the initially estimated discrepancies between measured and expected POA insolation, and including the estimations for factors leading to reduced insolation at the site, compared with the Pretoria-Forum weather station, the remaining discrepancies are estimated in Table 6.4:

TABLE 6.4 POA insolation discrepancies after cosine-error adjustment and estimation of factors leading to reduced insolation at the site.

JUNE	JULY	AUG	SEPT	NOV	DEC
Initial estimate of deviation from Pretoria-Forum expectations					
-37%	-19%	-20%	-14%	-20%	-18%
Estimated shading factor (as % of expectations)					
12%	10%	8%	9%	10%	7%
Estimated cloud cover variation (as % of expectations)					
-	-	-	-	3%	5%
Average daily cosine correction (as % of expectations)					
5%	5%	5%	4%	5%	6%
Remaining deviation from expectations					
-20%	-4%	-7%	-1%	-2%	0%

For purposes of analysing gross system performance, the months July to September have been used, and the remaining estimated discrepancies for these months are within the region of uncertainties arising from tilt-plane calculations (maximum $\pm 6\%$ in August) and absolute error in instrument calibration (estimated as $\pm 5\%$).

It is difficult from the foregoing analysis to assign a reliable uncertainty estimate to such corrected measurements. Firstly, the uncertainty in the weather station records is not known. Secondly, the factors held to contribute to reduced insolation at the monitoring site are themselves estimates (eg. the shading factor) with unestablished uncertainty. Thirdly, the sources of error which have been considered are not necessarily independent of one another, but interdependence has not been quantified, so probabilistic combination of error components is not really warranted.

The analysis of discrepancies therefore only aids an educated guess about the probable magnitude of uncertainty in mean (or aggregate) insolation measurements during these months. This is estimated on the

basis of compounding the largest estimated remaining discrepancy (7% in the month of August) with an estimate of the major sources of uncertainty in comparing tests with weather station values ($\pm 5\%$ for absolute calibration, and $\pm 6\%$ for tilt-plane calculations), yielding $\pm 10.5\%$ for the square root of the sum of their squares, which is raised to $\pm 12\%$ to include other uncertainties not figured in this estimate.

For more precise estimation of system efficiencies, data has been used from the middle of July, 1987, where onsite conditions can well be expected to resemble those in mid-July, 1988, when instrumentation tests were performed. This allows use of the relationship derived from measurements in those specific conditions:

$$\text{POA}(\text{adj}) = \text{POA}(\text{raw}) / (.98 - .00237 * I)$$

where POA(adj): Adjusted plane of array insolation
 POA(raw): Recorded plane of array insolation
 I: Incidence angle, in degrees from
 normal to plane of array

In the conditions where this relationship is applied, the uncertainty of POA insolation measurements is estimated as $\pm 5\%$, attributable to absolute calibration of the thermopile solarimeter reference.

Although of no direct significance to the analysis which follows, the large remaining discrepancy between June measurements and expected values may be indicative of a number of factors associated with low solar elevations: the increased impact of shading on diffuse and reflected radiation; increased pollution in the lower atmosphere at this time of year, and an increased impact on transmission of solar radiation and on spectral distribution. The present study does not extend to the quantification of such variables; but they could be factors to consider in siting and sizing photovoltaic arrays in peri-urban areas.

6.4 Implications

The foregoing, rather laborious assessment of insolation measurements at the monitoring site has still left considerable margins of uncertainty. According to an official from the U.S. National Bureau of Standards (quoted by Biggs, 1984), "one could not expect less than 10 to 25% error in radiation measurements made under non-ideal conditions" - and this assessment has estimated uncertainties of measurement within that discouraging range.

Despite failing to resolve sources of uncertainty satisfactorily, the assessment has been necessary because of the implications for the analyses which follow.

In the present study:-

- 1 The margin of uncertainty is carried through to all calculations based on the incoming solar energy. Thus, observed system efficiencies, computed for different periods of the year, are subject to at least $\pm 12\%$ uncertainty.
- 2 When efficiencies are calculated from mid-July data, the corresponding uncertainty attributable to insolation measurement is estimated as $\pm 5\%$.
- 3 The same $\pm 5\%$ uncertainty is attached to solar radiation measurements during mid-July tests of the photovoltaic array's IV output characteristics. In comparing these tests with manufacturers' power ratings for photovoltaic modules, further uncertainty arises from the spectral distribution of the insolation in relation to the spectral response of the modules.

The assessment has also suggested possible problems which could have implications beyond the present study:

- 1 Instrumentation. While silicon cell pyranometers, such as the Li-Cor 200SZ pyranometer used in this study, have advantages of robustness, economy, and freedom from tilt-mount error (ie. do not need to be mounted in a horizontal position), are they sufficiently accurate for engineering tests and critical design

of systems where solar radiation is the prime energy source? This question probably hinges on the impact of their selective spectral response, and on prior testing of the cosine response of a particular sensor.

- 2 Tilt-radiance response of photovoltaic modules. The fact that the pyranometer displayed significant tilt-radiance (cosine) error alerts one to the likelihood that photovoltaic panels equally, and perhaps more strongly, have reduced response to radiation at higher incidence angles, through the characteristics of the silicon cell surface, angle of penetration of the direct beam through the active material, and through the increased reflection of the protective glass. Coulson (1975:124) indicates a drop to 85% relative response of bare silicon solar cells at an incidence angle of 60 degrees from normal. The impact of this on module performance needs to be assessed, for sizing non-tracking arrays, and it would be useful if manufacturers supplied specifications for the tilt-radiance response of their panels.
- 3 Spectral response of photovoltaic modules. Similarly, the spectral selectivity of the pyranometer raises the question of whether the spectral response of photovoltaic modules is a factor to be considered in sizing photovoltaic systems, especially when weather station records are used for insolation prediction and where substantial spectral variations are experienced in critical months. Again, it would be helpful if manufacturers' product information included details of spectral response, instead of typically only providing output characteristics under standard conditions. To make practical use of such information, however, would require additional knowledge of local spectral variations in insolation.
- 4 Adequacy of weather station records and accuracy of tilt-plane estimations. Using different tilt-plane calculation methods and different extractions of data from the same weather station produced a range in plane-of-array insolation predictions of as much as 12% in some months. It could be argued that the unpredictability, from year to year, of specific climatic conditions makes inaccuracies in this area of lesser importance;

are correspondingly lower in some months than mean values obtained using the Perez anisotropic method - although, in this instance, this would not affect system sizing if June is taken as the design month, since in that month there is no significant difference.

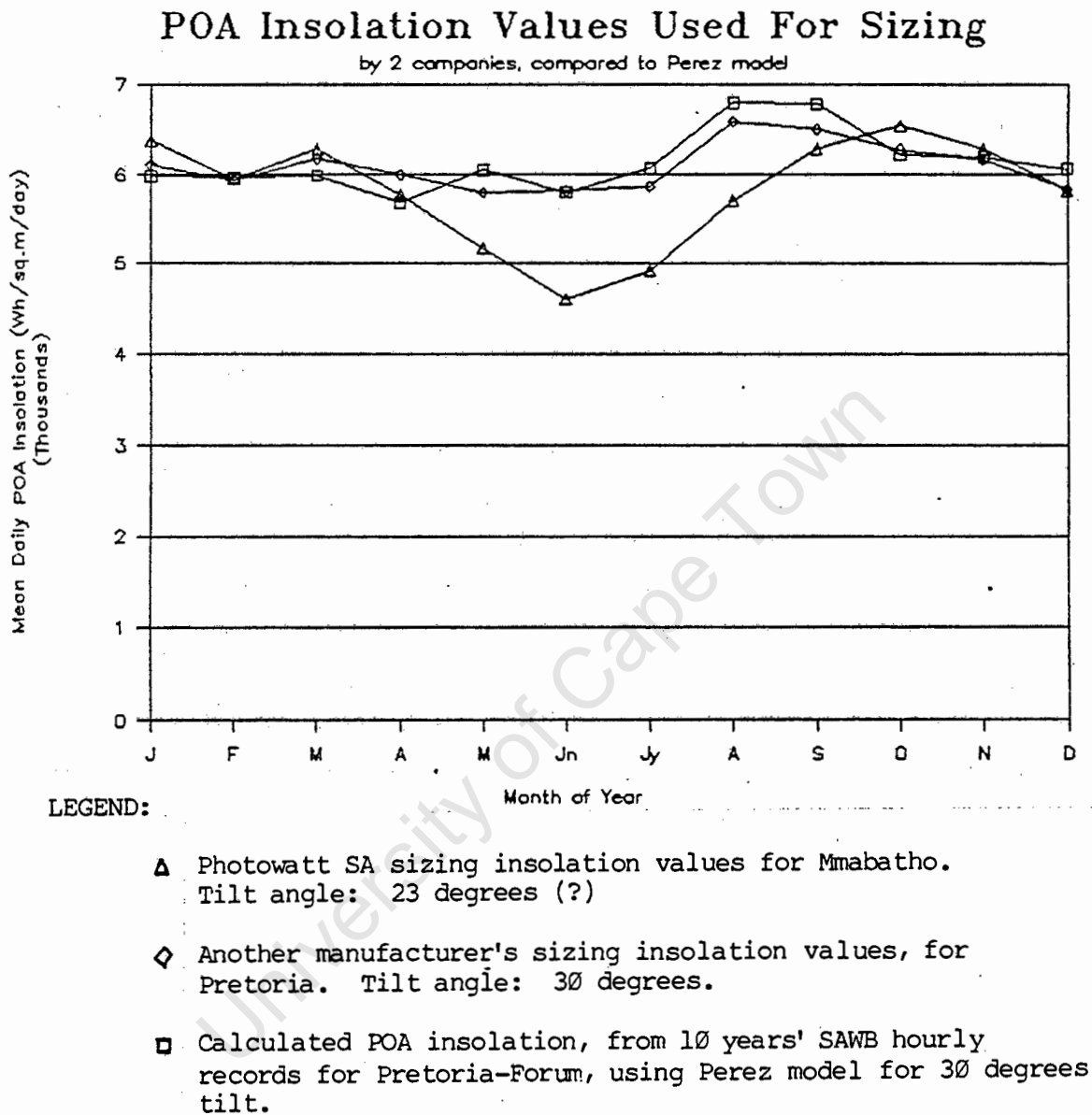


FIGURE 6.4 POA Insolation Values Used for System Sizing by Two Manufacturers, Compared With Perez Model Predictions

The Photowatt values for June are roughly 20% lower than the other June values in Figure 6.4. In Chapter 9 it is shown that the sizing of the photovoltaic arrays recommended by Photowatt was at least 20% above that required. This illustrates the practical importance of using reliable and locally valid solar radiation data in sizing photovoltaic systems.

Chapter 7

TESTED OUTPUT CHARACTERISTICS OF THE ARRAY, COMPARED WITH SUPPLIED (MONOCRYSTALLINE) MODULE SPECIFICATIONS

This chapter reports on supplementary tests to determine the current-voltage output characteristics of the photovoltaic array at the monitoring site, and compares the indications of these tests with the specifications which were supplied by the manufacturers of the modules.

7.1 Reasons for the Tests

Photovoltaic modules can be tested under natural sunlight, simulated sunlight, or artificial light of other specific spectral characteristics. Variation in the spectral distribution of irradiance on the modules has a considerable impact on measured performance. In general, the purpose of tests conducted under natural sunlight is to provide an accurate indication of expected performance in realistic conditions, (though operating conditions will typically also include periods where the spectral distribution of irradiance differs from test conditions.)

The performance specifications supplied by the module manufacturers, Photowatt SA, were for model PW-P 800 (monocrystalline) photovoltaic modules. The fact that these were the specifications provided to the supplier company, and were again the only specifications sent by Photowatt SA when requested for specifications for the PW-P 801 (polycrystalline) modules installed at the monitoring site, implied that the latter modules should have performance characteristics equivalent to model PW-P 800 modules.

Monitoring data had indicated that this was not the case. For instance, recorded array voltages in near open-circuit conditions were substantially less than PW-P 800 specifications for open-circuit voltages. It was therefore necessary to try to obtain current-voltage (IV) output characteristics for the array, through tests in natural sunlight. These tests were conducted at the site in mid-July 1988.

7.2 Method

The array was disconnected from load, and reconnected directly to a heavy-duty passive variable resistance. Array currents were measured by means of a current shunt in this circuit, calibrated for a voltage drop of 17.6 mV/amp, while array voltage was taken as array terminal voltage, both measured with digital voltmeters. These measurements should be accurate to within less than $\pm 1\%$.

Insolation was measured using a Li-Cor 200SZ pyranometer mounted between the two modules in the array, and a Kipp and Zonen thermopile pyranometer mounted on an adjustable table contiguous with the array. Output from these instruments was measured directly by digital multimeters. Currents from the Li-Cor silicon cell pyranometer were also checked across a 100 ohm resistance. The accuracy of the insolation sensors was discussed in the previous chapter, while the accuracy of measuring their output in these tests should be within less than $\pm 1\%$.

Open-circuit array voltage and closed-circuit array current were measured by respectively disconnecting and shorting out the variable resistance load.

Temperatures were measured with a thermocouple attached to one of the multimeters. Ambient temperature was recorded in the shade, near the array, while module cell temperature was measured by probing through an aperture in the back casing of one of the modules. Although stable readings were obtained, it is possible that actual cell temperatures at the surface exposed to sun could have been higher than those measured at the back of the cells.

Measurements were conducted in rapid succession, in order to minimise changes in the irradiance:

- open-circuit voltage
- closed-circuit current
- amps-volts pairs, for changing values of load resistance

The resistance values were variably stepped to provide adequate detail in non-linear portions of the IV output curve. The full range of measurements, for a given insolation level, took approximately 10 minutes, and insolation and temperatures were measured at the beginning and end of each measurement sequence, to check stability of conditions.

7.2.1 Climatic conditions during the tests

The latitude of the site is approximately 26 degrees South, and the tilt of the array is thirty degrees towards true north. Tests were conducted on 15 July, and angles of incidence of the direct beam on the array have been calculated.

The sky was cloudless, with a slight detectable haze, minimised at the times of measurement (early afternoon). Wind-speed was approximately 5 m/sec.

From calculated values for the elevation of the sun at times of measurements, the air mass of the solar path varied from approximately AM1.55 to AM2.40. (These calculations disregard the altitude of the location, 1600 m above sea level.) Angles of incidence of the direct beam on the array ranged from 23 to 48 degrees from normal.

7.2.2 Recommendations for module performance testing in natural sunlight

Draft recommendations for testing module performance in natural sunlight are available through the Asian Institute of Technology (in Lasnier and Gan Ang, 1988:211-236). The method of using total sunlight (direct plus diffuse) is proposed in conjunction with a module tilt of 37 degrees from horizontal and ground albedo of 0.2, at an air mass of AM1.5. The associated spectral characteristics are indicated as slightly stronger in short wavelengths and lower in longer wavelengths than the previous reference spectral irradiance distribution of ERDA/NASA 1022/77/16 for module performance rating, leading to a "more realistic" reduction in ratings of 2 to 3% compared with the previous spectral reference.

Specific procedural recommendations for tests in natural sunlight include:

- stable insolation ($< \pm 1\%$ fluctuation in test)
- irradiance $> 800 \text{ W/sq.m}$ (direct + diffuse)
- direct solar beam within 10° degrees of normal to module
- module shaded and at ambient temperature until beginning of test
- use of a calibrated reference cell for relating observed module performance to observed insolation conditions

The calibrated reference cell would be similar in material (hence spectral response) and mounting to the module cells. Calibration of this cell, in turn, should be done under somewhat more stringent conditions, with reference to a pyranometer:

- clear sunny weather
- total irradiance $\geq 900 \text{ W/sq.m}$
- air mass between AM1 and AM2
- turbidity coefficient $.265 \pm .185$ at wavelength 500 nm
- precipitable water vapour content $.4 - 2.6 \text{ cm}$

It is suggested that the latter two criteria should be adequately met if the ratio of diffuse to total irradiance is less than 0.25 .

7.2.3 Test procedure compared with recommended procedure

Limited access time necessitated some deviations from the recommendations presented above.

A reference cell of equivalent material was not used. Instead, the silicon cell of the Li-Cor pyranometer was used to fulfil this function. Spectral response may be somewhat different from the polycrystalline solar cells of the modules. The manufacturer's relative spectral response curve for these instruments is shown in Figure 7.1 together with a generic solar cell response curve provided in the recommendations referred to above (1988:233).

Relative Spectral Responses

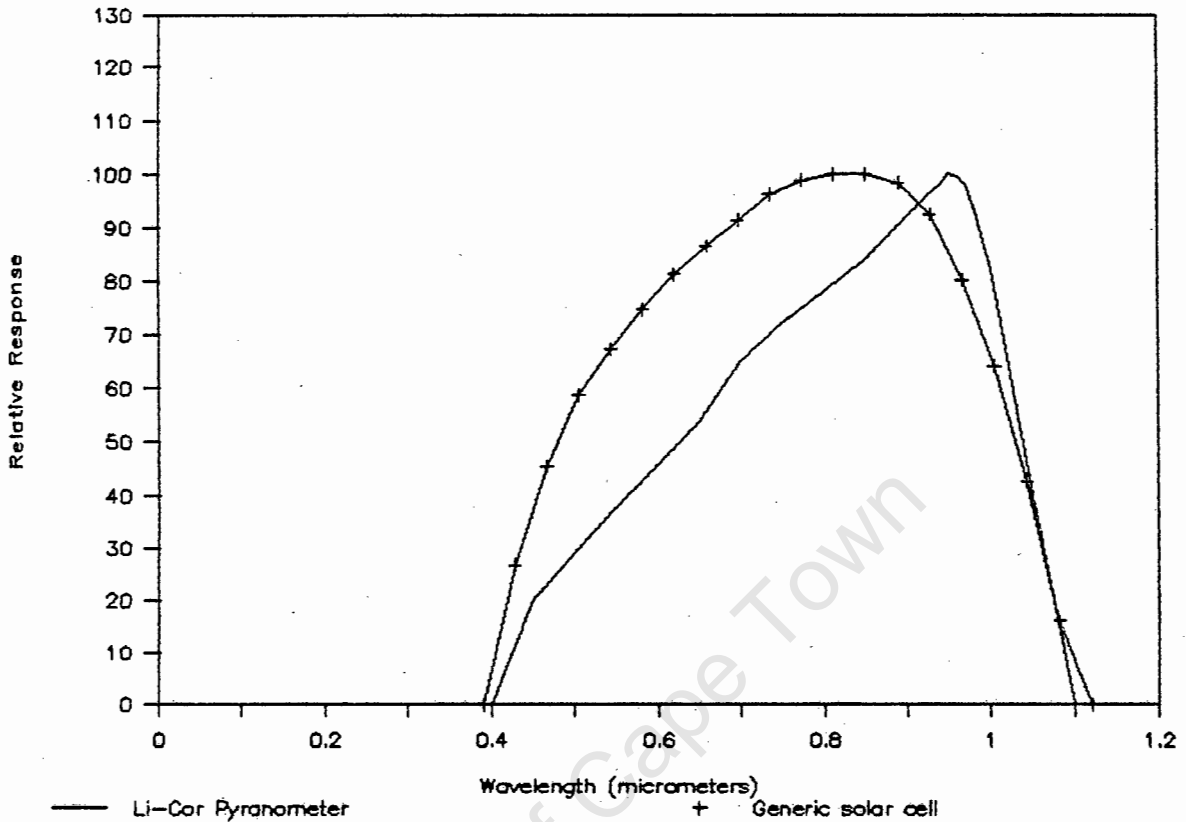


FIGURE 7.1 Relative Spectral Response of (a) Li-Cor Pyranometer and (b) Generic Solar Cell.

The recommended procedure entails calibration of a reference cell against a reliable pyranometer in more stringent conditions than those necessary for the actual performance tests. Corresponding to this, the calibration of the Li-Cor pyranometer was conducted against a Kipp and Zonen thermopile pyranometer under clear skies in the Karoo, with atmospheric conditions corresponding to the recommendations for reference cell calibration.

Spectral variations from these conditions, in the onsite tests, are therefore registered through the spectral response characteristics of the Li-Cor pyranometer, which resemble those expected of the modules more closely than the thermopile pyranometer. The effect is to compensate, albeit not completely, for the spectral characteristics of irradiance in the site tests, in order to assess what module performance would be under the more stringent calibration conditions.

(However, module performance under thermopile-registered irradiation at the site was also of interest, as an indication of diminished performance due to spectral selectivity of the modules.)

Further deviations from the recommendations above were:

- stability of insolation was less than recommended, with variation of approximately 5% from beginning to end of measurements at one insolation level (but since the variation took a steady course, calculated adjustments were possible to correct for this drift)
- in some of the tests, total irradiance exceeded 800 W/sq.m while in others it fell below these figures (with no detectable departure from linearity of closed-circuit currents, however)
- angles of solar incidence were greater than 10 degrees from normal, ranging from 23 to 45 degrees, partially compensated for as below

As discussed in Chapter 6, the Li-Cor pyranometer exhibited a degree of cosine-error, relative to thermopile pyranometer readings, measured as 0.17%/degree incidence, in steady spectral conditions. The effect of incidence angle on module performance is not known, but could be expected to be of at least the same magnitude as the pyranometer response to tilt-radiance. As partial compensation for the greater than recommended angles of incidence in the module tests, the cosine-error of the Li-Cor pyranometer has not been corrected, effectively derating the measured insolation by 4% at an angle of 23 degrees from normal, to give an improved indication of expected module performance at normal incidence.

7.3 Assessment of Accuracy

The following are estimates of uncertainty in measurements which related tested performance of modules to measured insolation. These estimates pertain to those tests selected for optimality of conditions.

UNCERTAINTY ESTIMATES IN MEASURING ARRAY $I=f(V)$ CHARACTERISTICS

thermopile pyranometer reference	$\pm 5\%$
absolute error	(see Chapter 6)
inter-pyranometer calibration	
signal measurement	$\pm 1.5\%$
silicon cell pyranometer / module	
spectral mismatch	$\pm 5\%$
silicon cell pyranometer / module	
tilt-radiance mismatch	$\pm 2\%$ at 23 degrees
pyranometer signal measurement	$\pm 1\%$
current measurement	$\pm 1\%$
voltage measurement	$\pm 1\%$
irradiance instability	$\pm 2.5\%$

At a given cell temperature, array $I \cdot V$ output characteristics are related almost linearly to insolation. In the measurement of these characteristics, the uncertainty of insolation measurements therefore predominates. The overall uncertainty of power measurements in relation to insolation is estimated as the square-root of the sum of the squares of the components, amounting to $\pm 8.1\%$.

For normalisation of measured IV characteristics to a reference cell temperature of 25 degrees C., transposition is required. The relationship used for this was derived from monitoring data (see Section 8.3) as

$$VOC(T_c) / VOC(25) = 1 - 0.0028 * (T_c - 25)$$

$VOC(T_c)$: Array open-circuit voltage at T_c

$VOC(25)$: Array open-circuit voltage at 25 degrees C.

T_c : Measured cell temperature in degrees C.

Array currents are negligibly affected by small variations in cell temperature, so the normalisation based on this relationship is approximated by increasing measured voltages by 0.28% / degree C. for recorded cell temperatures above 25 degrees.

In the tests, recorded cell temperatures did not exceed 33.1 degrees, leading to a maximum voltage adjustment of 2%. The impact of possible errors in measuring cell temperature (due to thermocouple location) is reduced by using a temperature coefficient derived from monitoring data, based on equivalent cell temperature measurement. Leaving that aside, if a cell temperature measurement in the tests was low by 5 degrees C., the consequent error in voltage adjustment would be less than 1.5% of measured voltage.

Including this uncertainty allowance, overall uncertainty in power measurements in relation to insolation is estimated at $\pm 8.2\%$.

7.4 Results

Due to the dry weather, dust had accumulated on the photovoltaic modules. Tests were conducted before and after cleaning the surface. In each set, the linearity between closed-circuit currents and insolation was preserved, while open-circuit voltages were not affected. The dusty surface had the effect of reducing array currents, and hence power, by 5.5%.

Tests were conducted at POA insolation levels ranging from over 800 W/sq.m to under 600 W/sq.m. Figures 7.2 and 7.3 show sample curves at a measured irradiance of 810 and 723 W/sq.m. and at the cell temperatures stated.

These irradiance levels are as recorded by the Li-Cor silicon cell pyranometer. Corresponding measurements by the Kipp and Zonen thermopile pyranometer were higher, by 8.5% and 13.6% respectively. This provides an indication of tilt-radiance and spectral effects registered by the silicon cell pyranometer. These effects are also presumed to reduce module performance, relative to thermopile-measured insolation.

Measured Array IV Characteristics

at 810 W/sq.m $T_c=30.3$ degrees C.

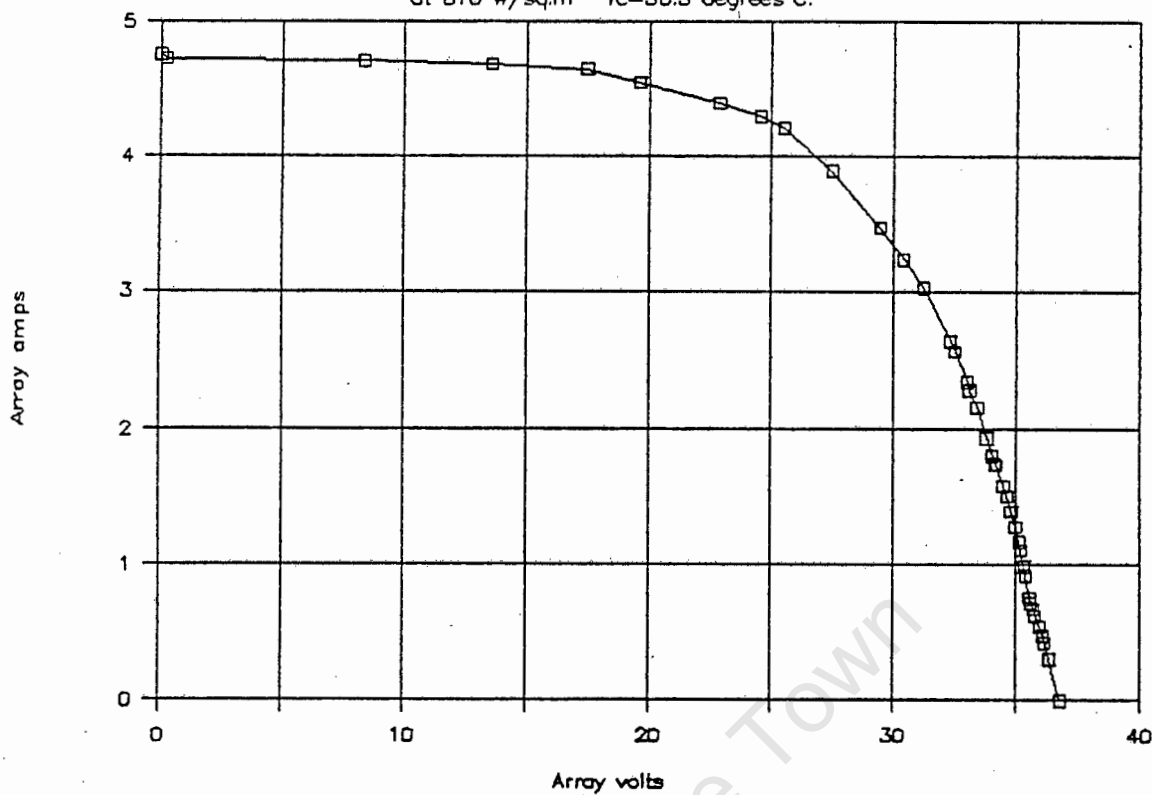


FIGURE 7.2 Recorded Array IV Characteristics at 810 W/sq.m

Measured Array IV Characteristics

at 723 W/sq.m $T_c=33.1$ degrees C.

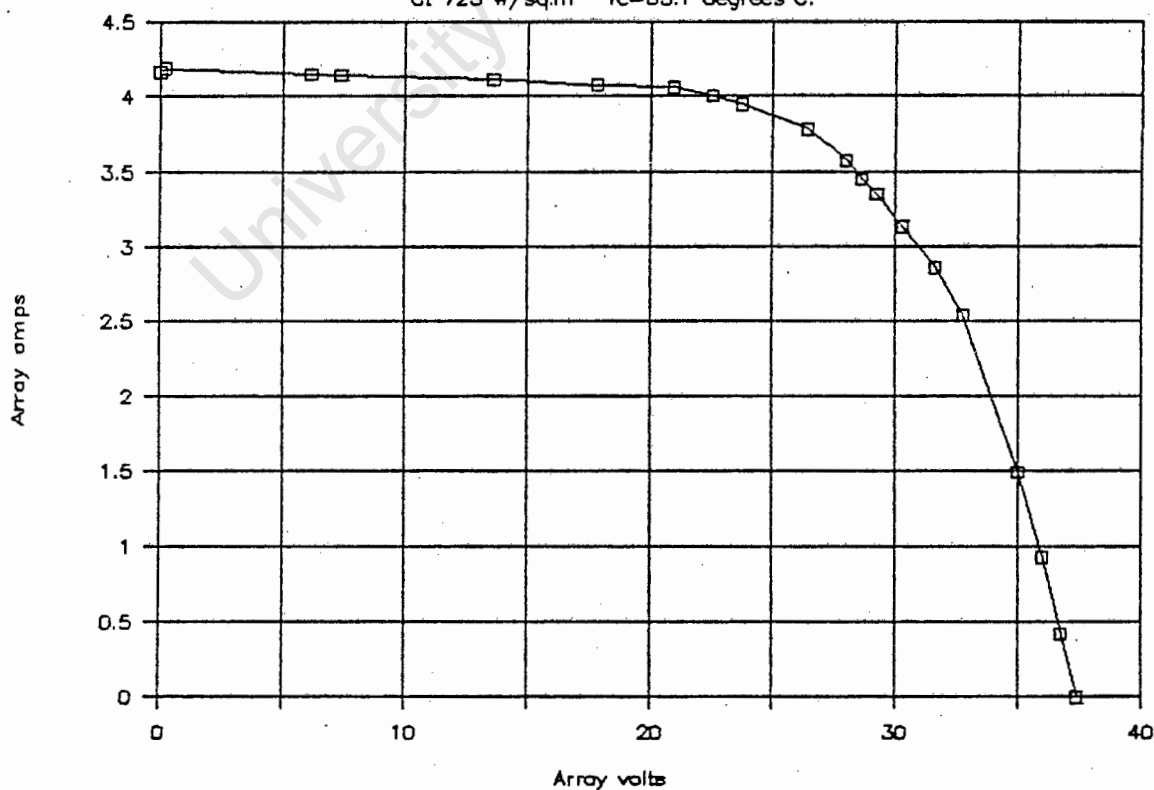


FIGURE 7.3 Recorded Array IV Characteristics at 723 W/sq.m

The measurements taken at 810 W/sq.m have been used for the transposition of array IV curves to insolation levels of 1000 and 800 W/sq.m, and a cell temperature of 25 degrees C., as shown in Figure 7.4. The conditions for this test most closely fit the recommendations referred to above, and are summarised:

Air Mass:	AM 1.55
Tilt of array:	30 degrees from horizontal
Incidence angle of direct beam on array:	23 degrees from normal
Measured cell temperature:	30.3 degrees C.

In Figure 7.4 voltages have been adjusted to correspond to a cell temperature of 25 degrees C., while currents have been transposed as a linear function of insolation.

Constant power curves have been superimposed, to illustrate that under these conditions of measurement and transposition, the peak power of the array is indicated to be 135 Wp at 1000 W/sq.m insolation.

Since the array consists of two modules, average module power is indicated as 67.5 Wp.

The surface area of each module is 1.078 sq.m (outer dimensions) giving an optimum module conversion efficiency of 6.26% at a cell temperature of 25 degrees C.

The uncertainty associated with these measurements was estimated as $\pm 8.2\%$.

Array IV Characteristics, From Tests

For Cell Temperature 25 degrees C.

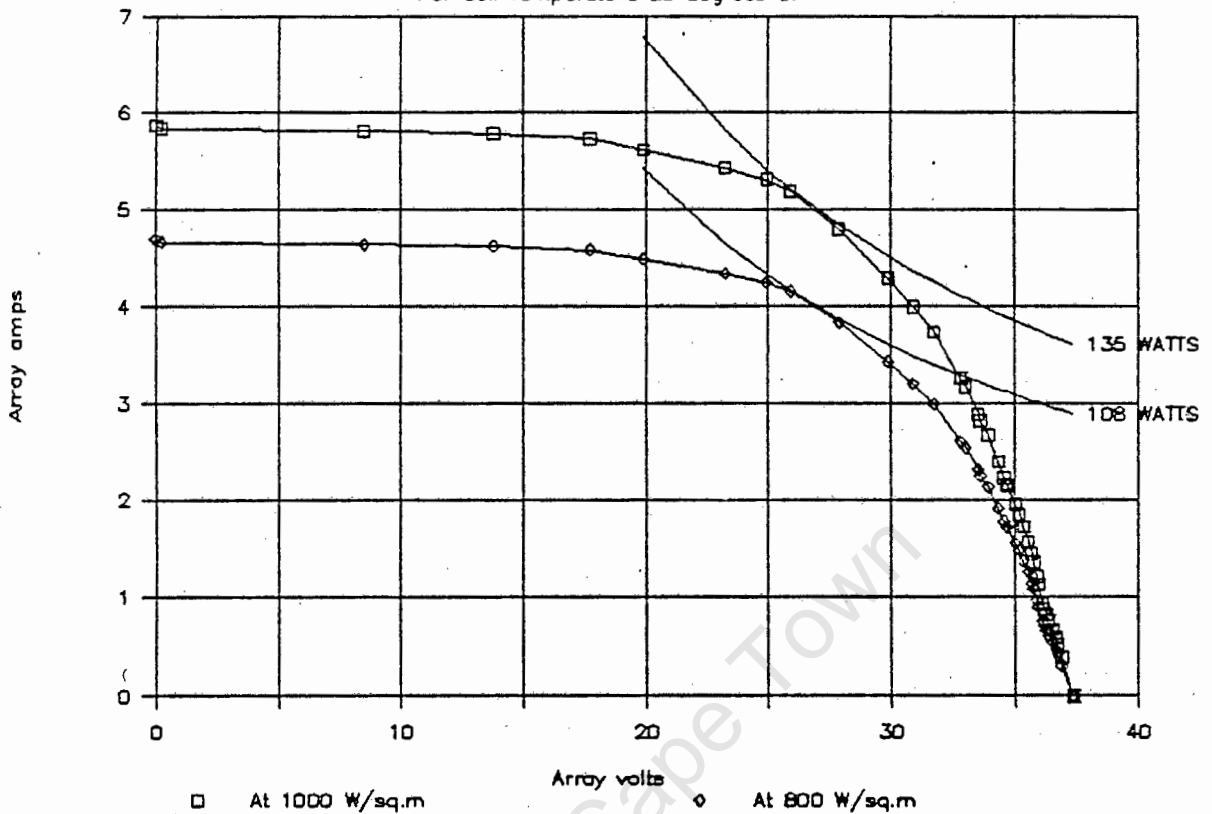


FIGURE 7.4 Array IV Characteristics Derived From Tests
(for two PW-P 801 modules in parallel)

7.5 Comparison Between Test Results and PW-P 800 Specifications

Comparisons are now made between the performance characteristics of PW-P 800 modules (as obtained from Photowatt specifications) and the tested characteristics of the PW-P 801 modules in the array at the monitoring site.

As mentioned earlier, in Section 2.5, two sets of specifications were obtained for PW-P 800 modules. The first set, on which the original system sizing was apparently based, is referred to below as SPECS#1. The second set, made available in February 1988, indicates lower performance, and is referred to below as SPECS#2.

Salient performance indicators are summarised in Table 7.1.

It should be borne in mind that the PW-P 800 values are given for "typical" modules (at $\pm 12.5\%$), while the PW-P 801 values are for two particular modules tested in combination in the monitoring site array, under the specific conditions described above.

TABLE 7.1 Comparative Performance of PW-P 800 and PW-P 801 Photovoltaic Modules

	PW-P 800		PW-P 801
	SPECS#1	SPECS#2	as tested
	(from Photowatt specifications)		at site
At irradiance 1000 W/sq.m and cell temperature 25 degrees C.			
Maximum power	82 Wp	73 Wp	67.5 Wp
Current at max power	2.41 A	2.15 A	2.5 A
Voltage at max power	34 V	34 V	27 V
Short-circuit current	2.67 A	2.40 A	2.9 A
Open-circuit voltage	42.4 V	42.4 V	37.4 V
Optimum module conversion efficiency	0.0835	0.0743	0.0626
Module area (outer dimensions)	0.982 sq.m	0.982 sq.m	1.078 sq.m
Total cell area (approx)	0.565 sq.m	0.565 sq.m	0.720 sq.m
Packing factor	0.57	0.57	0.67
Fill factor	0.72	0.72	0.62
Average maximum cell conversion efficiency at 25 deg C.	0.145	0.129	0.0937

Table 7.1 includes values for the "packing factor" and the "fill factor" of the modules.

The packing factor is simply the proportion of module area occupied by photovoltaic cells. The PW-P 801 modules have a higher packing factor since the square polycrystalline cells are arranged more densely than the circular single-crystal cells of a PW-P 800 module. In combination with the slightly larger module dimensions, this allows for a larger cell surface area in the PW-P 801 module (1.27 times greater), which largely compensates for the lower cell conversion efficiency of the polycrystalline cells. Despite this, the PW-P 801 modules still appear to have a significantly lower peak power delivery.

The fill factor of a module is defined as

$$\text{optimum power} / (\text{short circuit volts} * \text{open circuit current})$$

and essentially it is an index of the shape of the $I=f(V)$ output characteristics of a module. It is regarded as an indicator of cell quality, since imperfections contribute to a more rounded IV curve and a correspondingly lower fill factor. In Lasnier and Gan Ang (1988:61) it is suggested that modules with high quality cells should have a fill factor greater than 0.7. The PW-P 800 specifications meet this criterion (fill factor 0.72), but the tests on the PW-P 801 panels indicated a fill factor below this level (0.62).

Judging by this comparison between PW-P 801 tests and PW-P 800 specifications, it is easy to believe that the PW-P 801 version was intended as a rough equivalent for the monocrystalline PW-P 800 module, presumably employing a cheaper production process.

The PW-P 801 modules have a higher current output (owing to their larger cell area), and much lower voltage characteristics (by virtue of the impaired transmissivity of polycrystalline silicon). An attempt at approximate equivalence is suggested, but with an element of arbitrary design (72 monocrystalline cells of 100 cm diameter in one case, 72 polycrystalline cells 100 cm square in the other). Due to the lower fill factor of the polycrystalline modules, the net result is a reduced optimum power output, 82% or 92% of PW-P 800

ratings (depending on whether original or latest specifications are used for the comparison).

This is a hefty margin of difference, bearing in mind that the original sizing of system components, provided by Photowatt SA to the supplier company, was apparently based on original PW-P 800 rated module performance of 82 Wp per module. According to their sizing advice, these modules had been "specially selected" for the task.

However, the substitution of PW-P 801 modules, according to analysis later in this study, has had fortunate implications for optimisation of the monitored system and the systems installed in Bophuthatswanan schools. It has not been established why the local supplier company made use of the polycrystalline PW-P 801 modules rather than the monocrystalline PW-P 800 modules originally recommended by Photowatt SA. Nor is it known whether they were fully aware of the different performance characteristics of the PW-P 801. But according to the analysis in Chapters 8 and 9, the latter modules represent a technically better choice for the task in hand. This is because:

- 1 An array of modules with the peak power capacity of PW-P 800 modules (as originally rated) would be substantially oversized in relation to the design load and prevalent climatic conditions. This point casts doubt on the manufacturers' sizing procedures (at least in this instance).
- 2 The higher voltages of PW-P 800 modules, when operating at optimum power, according to specifications, would be considerably in excess of system take-off voltages, when batteries are charging, leading to wastage of available array power. The PW-P 801 voltage characteristics are better matched for battery charging, under expected local temperature conditions. This point also casts doubt on the procedures by which the manufacturers sized and selected components in their recommendations to the local suppliers.
- 3 In addition to having an apparently lower power capacity, the polycrystalline modules tested have differently shaped, more rounded $I=f(V)$ output characteristics. While this is associated with lower cell conversion efficiencies, it has the fortunate

effect that the deviations from optimum voltage generation which will occur in such a system have a reduced impact on power output, compared with the specified characteristics of monocrystalline PW-P 800 modules.

The two latter points help to offset the tested failure of the monitored array to deliver 160 Wp, which is the power rating made in the supplier company's specifications. Indeed, technically, the installed systems seem to represent a superior, more critically sized design than that originally recommended by the manufacturers - but for economic optimisation, one would also need to know the price differential between the two models of module.

These points, together with other observations made in the course of testing the $I=f(V)$ characteristics of the array at the monitoring site, raise considerations which may have more general implications for sizing such photovoltaic systems:

- 4 How reliable are manufacturers' specifications for photovoltaic module performance? In this instance there was an unexplained revision in PW-P 800 power ratings from 82 Wp to 73 Wp, while specifications for "equivalent" PW-P 801 modules could not be supplied. What is the extent of variation in actual performance, according to manufacturing batches? The PW-P 800 performance figures were given "at $\pm 12.5\%$ ". If such a margin is valid, and needs to be taken seriously, this introduces an uncomfortably large margin of uncertainty into critical photovoltaic systems design.
- 5 How well do manufacturers' performance specifications, measured under controlled conditions, correspond with actual performance under realistic operating conditions? In particular, for system sizing, should module specifications be derated for the angles of incidence of direct irradiation, and for spectral variations in expected insolation?
- 6 To what extent are local suppliers, or local agents of module manufacturers, dependent on "invisible" product knowledge and sizing methods, without being in a position to scrutinise the assumptions made by the manufacturing company? It appears that

local system sizing is often dependent, directly or indirectly, on manufacturers' proprietary software, which may incorporate contestable assumptions about photovoltaic system optimisation as well as about module performance characteristics.

- 7 In sizing a photovoltaic system, and also in judging the merits of system design (as for instance where a number of competing tenders are being assessed), the peak power rating of the photovoltaic array is not necessarily a reliable indicator of array generating capacity. Apart from the margins of uncertainty attached to manufacturers' specifications, and the deviations from specifications which are probable in realistic operating conditions, there are also questions about the shape of array output characteristics and the matching of these characteristics to what the load requires. This has been highlighted by comparing roughly equivalent monocrystalline and polycrystalline modules. Chapter 8 includes a more detailed discussion of these issues.

Finally, the questions and the implied criticisms raised in this chapter were generated by the results of tests of array current-voltage output characteristics which are themselves subject to critique, focussing on the measurement of irradiance and the effects of spectral distribution on module performance. For perspective, the following quotation underlines the difficulties of representatively measuring module performance characteristics, and encourages caution in applying manufacturers' specifications:

"The main problem in photovoltaic performance measurement arises from the fact that solar cells have a highly selective spectral response and are, therefore, very sensitive to the spectral composition of the incident radiation. Outdoors, this varies considerably with location, weather, time of year and time of day. Indoors, it depends on the type of simulator used... Performance ratings of the same module by different laboratories have been known to disagree by as much as 20%."

(from "International Test Procedures for Photovoltaic Modules", in Lasnier and Gan Ang, 1988:211)

Chapter 8

SYSTEM EFFICIENCIES

This chapter reports on observed system efficiencies in the monitored system, and then analyses circumstantial, probabalistic and design factors which affect the efficiencies of such a stand-alone photovoltaic installation. These theoretical considerations are then applied in an analysis of the efficiencies of the monitored system, with special attention to matching array output characteristics to load characteristics.

8.1 Observed System Efficiencies

Observed system efficiencies are evaluated, in this section, in three ways. The schematic in Figure 8.1 shows corresponding measurement points.

(a) MODULE CONVERSION EFFICIENCY

The ratio of electrical energy output from the array to the insolation energy incident on the array (points B and A in Figure 8.1).

(b) DELIVERED ENERGY EFFICIENCY

The ratio of electrical energy delivered to battery and load, over the incident insolation energy (points C and A). This incorporates energy losses across the charge controller.

(c) CONSUMED ENERGY EFFICIENCY

The ratio of electrical energy consumed by the applications load to the incident insolation energy (points D and A). This can incorporate further energy losses through the energy storage cycles of the batteries.

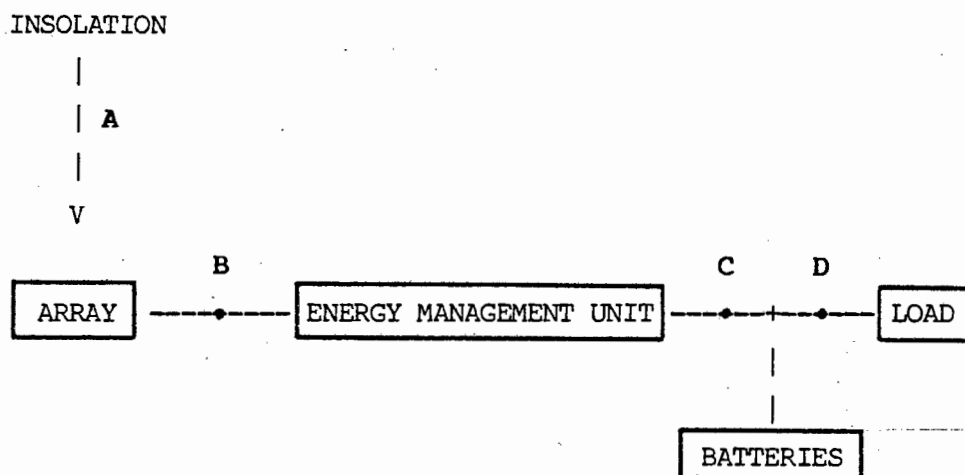


Figure 8.1 Measurement Points for Efficiency Measures

8.1.1 Observed module conversion efficiencies

It should be pointed out that the module conversion efficiency is not the same as the conversion efficiency of a single photovoltaic cell in the modules. This is because the incident insolation energy is calculated as insolation incident on the total area of the modules. Outer dimensions for the modules have been used for this calculation (including the frame), giving a surface area of 2.156 sq.m. for the two modules in the array.

Secondly, a qualification must be made about the measurement of module conversion efficiencies at low currents (and low recorded efficiencies) when the Energy Management Unit is acting as a charge regulator. As discussed in Section 4.5, the multiplication of recorded array voltage by recorded array current does not accurately reflect the array output power in these conditions. The effect here is that recorded values in the low efficiency range are somewhat inflated.

Figure 8.2 shows the recorded module conversion efficiencies for the months July, August and September 1987. In these months, the average daily load on the system was 370 Wh/day.

The graphs show cumulative frequency distributions over time. The horizontal axes show the cumulative percentage of generating hours recorded for each of the months.

To avoid inaccuracies at low insolation levels, generating hours are defined here as log periods where the recorded POA insolation was greater than 250 W/sq.m. The insolation measurements used here, and for the remainder of this study, incorporate the statistical correction for pyranometer cosine error described in Chapter 6.

The vertical axes show the maximum observed module conversion efficiencies corresponding to the cumulative percentage of generating time. For example, Figure 8.2 shows that in July 1987, recorded module conversion efficiencies varied from 1.5% to 6.2%. The median value was 4.5% (50% of the time the observed module efficiency was less than this value, and 50% of the time it was greater). For 90% of the time the module conversion efficiency was less than 5.7%.

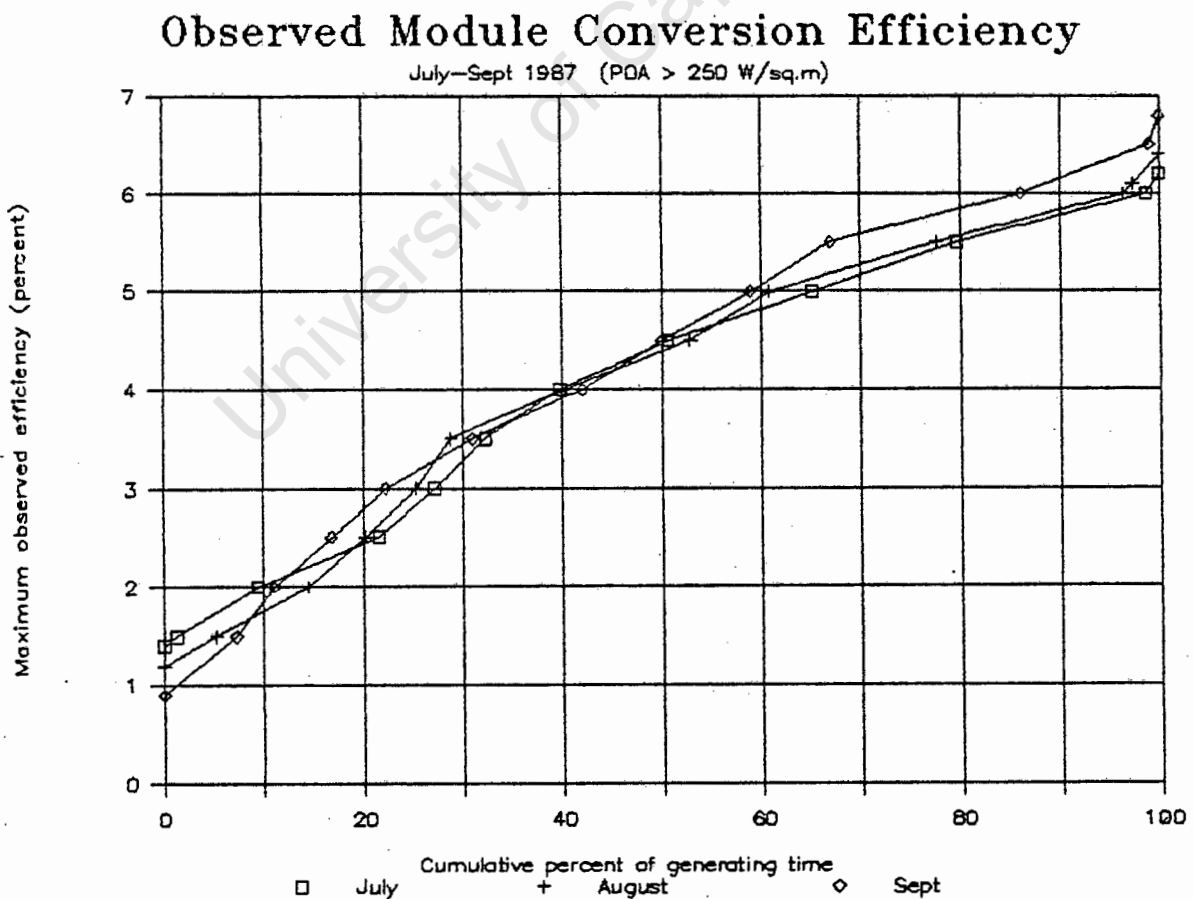


FIGURE 8.2 Observed Module Conversion Efficiency, July–Sept 1987

The curves for July, August and September are very similar. Slightly higher module conversion efficiencies were recorded in September, with a 90-percentile value of 6.2%, and few isolated maxima greater than 6.5%. Since the latter are outliers they are regarded with caution. The median module conversion efficiency in this month was unchanged at 4.5%.

The uncertainty of the insolation measurements used here has been estimated in Chapter 6 as $\pm 12\%$, which is of such magnitude that other sources of uncertainty in the efficiency calculations can be neglected.

Within this latitude of uncertainty, there is good agreement between the maximum monitored module conversion efficiencies, and the optimum module conversion efficiency established in the supplementary module performance tests reported in Chapter 7.

The latter tests indicated an optimum module conversion efficiency of 6.3% at a cell temperature of 25 degrees C.

While cell temperature at this stage has not been brought into consideration, the cumulative frequency distributions show that the array was capable of operating in the region of optimum module conversion efficiencies, but that these high efficiencies were restricted to a small proportion of generating time.

The monitored months November and December 1986 and June 1987 are depicted in Figure 8.3. Data for these months have been combined, since load energy demand was negligible. As a consequence, module conversion efficiencies were very low. For 90% of the time, the conversion efficiency was less than 1%. For only 5% of the time, efficiencies exceeded 2%, with recorded values again asymptotic to the expected maximum of just over 6%. Since the system was never stretched during these latter months, they are disregarded for the remainder of this section.

Observed Module Conversion Efficiency

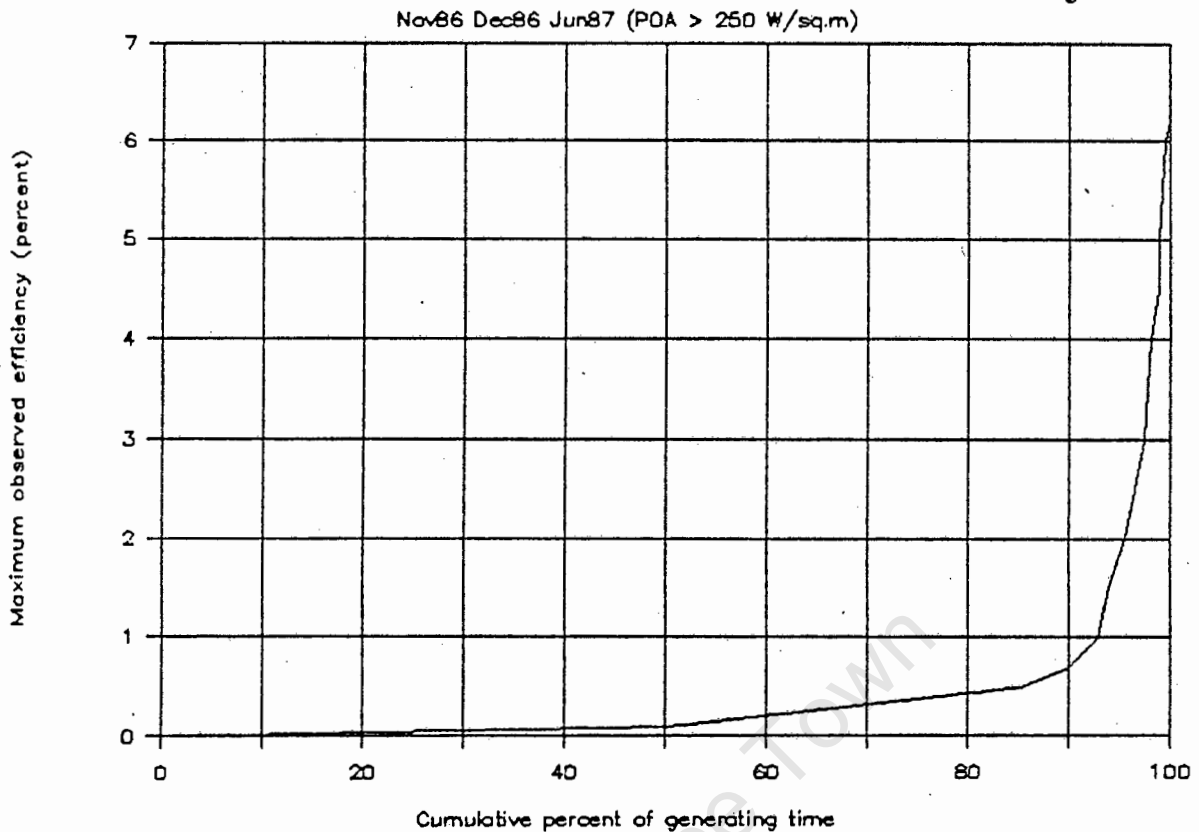


FIGURE 8.3 Observed Module Conversion Efficiencies in Months of Negligible Load Demand.

These graphs have shown that the system is capable of operating close to maximum predicted module conversion efficiencies, but seldom does. The main reason for this is that the array is capable of delivering more power than the system demands, most of the time, under observed operating conditions. The Energy Management Unit is usually therefore restricting the power admitted from the array.

To an extent, this is to be expected in a stand-alone photovoltaic system which is sized for reliability in adverse conditions. Higher load energy demand, or a smaller array, or lower insolation levels, would result in higher average module conversion efficiencies, but could affect system availability. These relationships are discussed in later sections, and modelled in Chapter 9.

The question of whether an array is operating in its optimum power voltage range is also deferred to later sections.

8.1.2 Delivered energy efficiencies

Delivered energy efficiencies are lower than module conversion efficiencies because there is a voltage drop across the the charge-controlling Energy Management Unit.

At a minimum, the voltage drop is the voltage across the FET switch and its protecting Schottky diode during power transmission. While values as low as 0.6 to 0.7 volts are observed for this voltage drop in the monitored data, such minima over a half-hour log period may include times when the EMU is not transmitting, and a safer estimate of low values is 0.9 to 1 volt. These values were typical at times of high demand, and represent a power loss, across the Energy Management Unit, of less than 5%.

When available array power exceeds system demands then the voltage drop is made greater by the pulse-width-modulation charge controlling circuitry. As a percentage of array voltage, the voltage drop across the Energy Management Unit was observed to range up to 28%.

Lowest values are typical when the system is stretched - when batteries are depleted, and/or insolation levels low in relation to energy demand. High values occur when batteries are fully charged and there is no load energy demand. Under such conditions, the power attenuation is even greater than the voltage attenuation, because the chopping action of the FET allows current flow only for the portion of the waveform where the switch is closed.

The difference between module conversion efficiency and delivered energy efficiency therefore depends on the balance between available array power and current energy demand.

Figures 8.4 shows the cumulative distributions of delivered energy efficiency for the months July to September, 1987. (Measurements are again restricted to log periods when POA insolation was greater than 250 W/sq.m. and the estimated uncertainty of insolation measurements is again $\pm 12\%$.)

Delivered Energy Efficiency

July–Sept 1987 (POA > 250 W/sq.m)

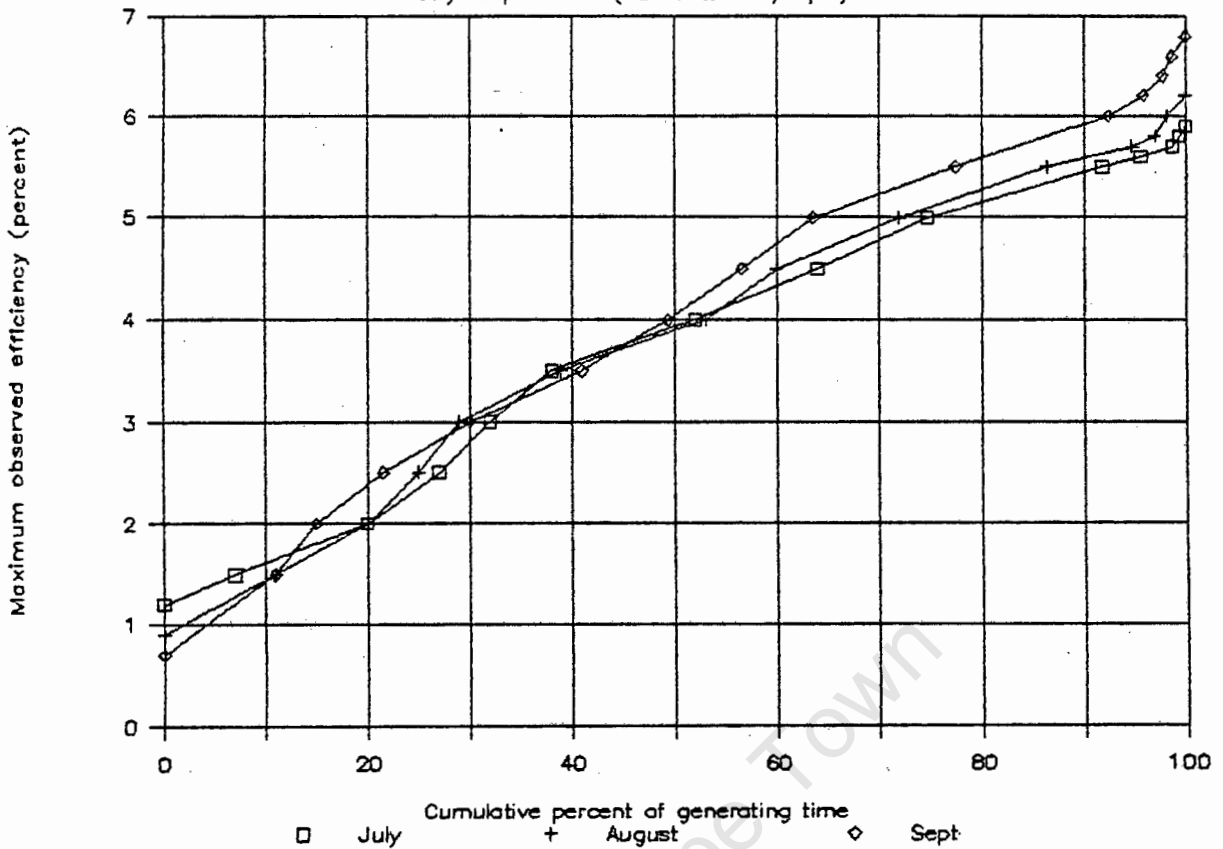


FIGURE 8.4 Delivered Energy Efficiency, July–Sept 1987

Medians for these months were:

July	3.6 %
August	3.8 %
September	4.0 %

For more precise evaluation of maximum delivered energy efficiencies, data from the month of July was analysed, employing a more detailed statistical correction to pyranometer readings which is applicable to clear-sky days in mid-July. This correction, described in Chapter 6, makes allowance both for cosine errors and spectral response errors in the silicon-cell pyranometer in relation to a thermopile reference. (Under these conditions, the uncertainty in corrected insolation measurements was estimated as $\pm 5\%$.) Using this correction, the maximum observed delivered energy efficiency was recorded on the day of July 20 1987 at a value fractionally under 6%, as shown in Figure 8.5. The recorded cell temperature corresponding to this maximum was 12.5 degrees C.

Delivered Energy Efficiency

July 20 1987

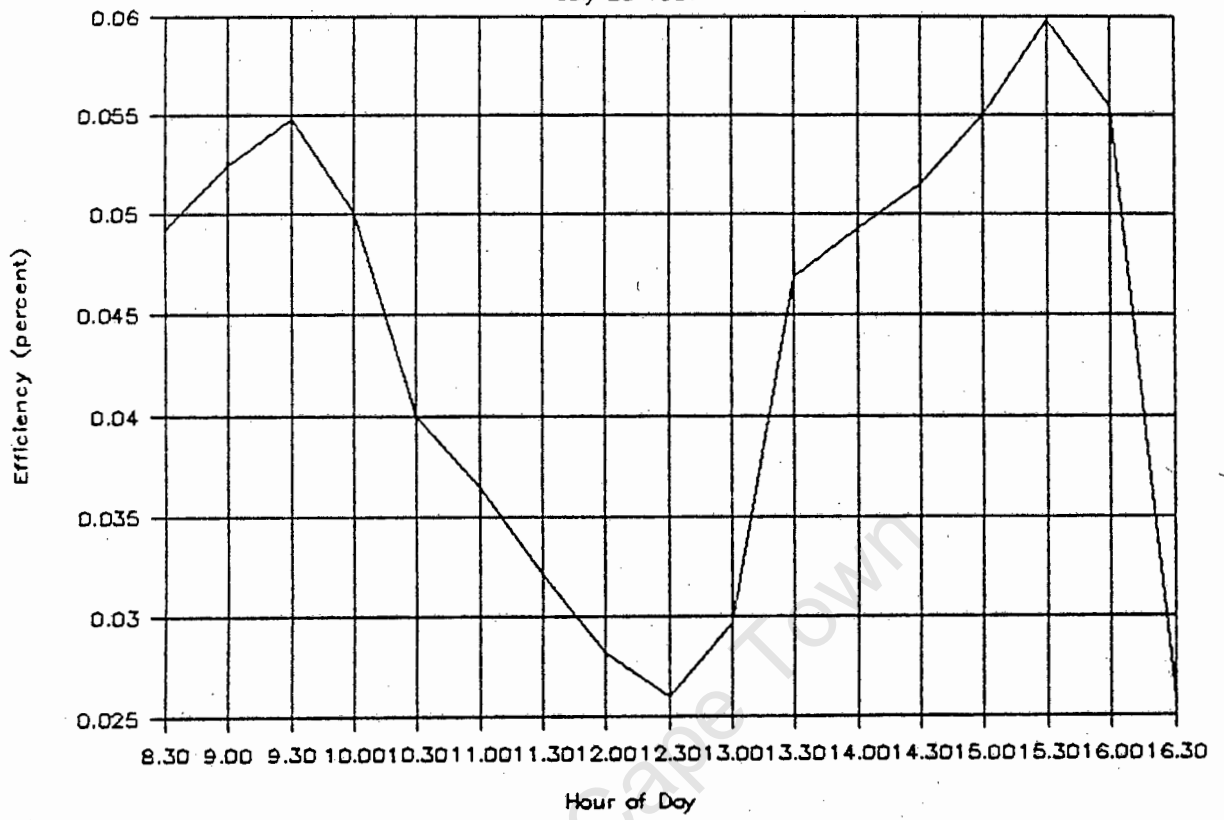


FIGURE 8.5 Delivered Energy Efficiency, July 20 1987

8.1.3 Consumed energy efficiency

Monthly means for the "consumed energy efficiency" (energy consumed by the load divided by insolation energy incident on the array) are calculated as follows:

TABLE 8.1 Mean Consumed Energy Efficiencies, July to September 1987.

	July	August	September
Mean POA Insolation (Wh/sq.m/day)	5620	5480	4961
Mean Insolation Energy on Array (Wh/day)	12117	11815	10696
Mean Load Energy Consumed (Wh/day)	372	378	362
Mean Consumed Energy Efficiency	3.1%	3.2%	3.4%

The mean consumed energy efficiency depends on load energy demand in relation to insolation received, and was therefore negligible in months November, December and June.

At the system design load of 425 to 450 Wh/day, the consumed energy efficiencies would have been higher than those observed, namely:

July 3.5 to 3.7 %
August 3.6 to 3.8 %
September 4.0 to 4.2 %

These figures are based on the assumption that the system could support such a design load, under observed climatic conditions. This assumption is discussed in Chapter 9. The factors affecting system efficiencies are discussed in the following section.

8.2 Factors Affecting System Efficiencies

A variety of interacting factors affect the system efficiencies of a stand-alone photovoltaic system with battery storage. In this section, the principal factors are assessed, both from a theoretical point of view, where appropriate, and also in practical relation to the monitored system.

The factors can be grouped as follows:

a) CIRCUMSTANTIAL FACTORS

Primarily the energy demand profile put on the system by users' utilisation patterns.

b) PROBABILITY FACTORS

Primarily weather: insolation levels, and to a minor extent ambient temperatures.

c) DESIGN FACTORS

The sizing of the array, in relation to expected weather conditions and system utilisation; orientation of array; balance between array size and battery storage capacity; balancing array output characteristics and load input characteristics; choice of components; component efficiencies; method of charge regulation / power conditioning.

If efficiency is viewed more broadly as efficient provision of the service of the applications load, then of course the energy efficiency of the applications equipment is of major importance.

One factor not considered in the following discussion is the level of photovoltaic technology employed in the modules, with the exception that certain comparisons are made between the performance of monocrystalline and polycrystalline modules. Apart from this, it is assumed that modules employing different technologies are competitively priced, such that cost effectiveness in Peak Watts per Rand is more or less independent of make of module. (If this is not

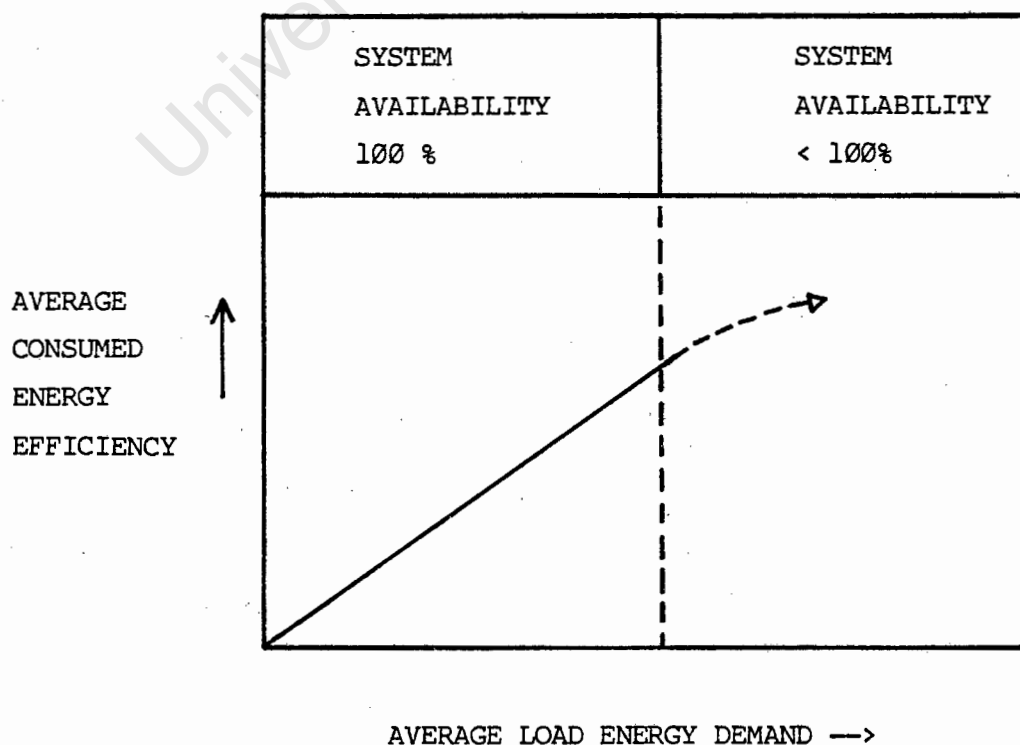
the case, then the cost optimisation of the array size to battery storage ratio would be affected; but in other respects the factors affecting system efficiencies remain broadly the same.)

8.2.1 Circumstantial factors

It was seen in the previous section that system efficiencies depend strongly on levels of utilisation. If a system is designed to support a certain load energy demand, and actual load energy demand is much less than this, then system efficiencies will be very low. Available array power is not fully utilised.

Conversely, if utilisation exceeds an accurately determined design load, system efficiencies will be higher on average, but there will be a probability of periodic down-time.

The average consumed energy efficiency of the system is directly proportional to load energy consumed, for given insolation conditions, up to a point where performance is interrupted by system non-availability in adverse conditions. Beyond this point, average consumed energy efficiency is still likely to increase, up to a point, but at the cost of periodic non-availability due to insufficient insolation.



The "cost" of interrupted system availability depends on the application. If the costs incurred are high, as for example in a chain of interdependent solar-powered repeater stations, then it is sensible to oversize the photovoltaic systems to achieve very high reliability. In non-crucial applications, however, it would seem wise to size a system for a definite probability of occasional non-availability, since the gains in efficiency and reductions in capital cost could outweigh the costs of possible interruptions of service in exceptional weather conditions.

A problem, however, is that accurately predicting actual load energy demand is virtually impossible for applications where utilisation depends on the choices and circumstances of users. This is why load energy demand here is regarded as a circumstantial variable.

In the Bophuthatswana Edutel project, actual utilisation of the televisions/video in schools depends on a complex of factors, including teachers' attitudes, availability of educational software, timetable and classroom scheduling. Perhaps if schools regularly followed a regular daily broadcast programme of educational television then load energy demand could be reasonably assessed; but certainly while distributed videotapes remain the main medium of television instruction, actual utilisation levels could hardly be predicted in advance.

It was therefore necessary to design for somewhat notional system requirements, and these were generously set (10 hours television use per day, including 5 with use of VCR, during school terms). Actual utilisation levels at this time have not yet been established by a representative survey of schools in Bophuthatswana, but based on viewpoints of informed observers who visit a cross-section of schools, it is safe to say that average actual utilisation levels are considerably below the maximum for which the systems are designed.

The resulting spare capacity has the effects of enhancing system reliability, and of allowing for future expansion of usage. But average system efficiencies will of course be depressed as long as utilisation levels are lower than the design load levels. In Chapter 9 estimations are presented for system efficiencies, and associated probabilities of non-availability, at varying load energy demand levels.

The seasonal and daily profiles of load energy demand also have a bearing on system efficiencies. If demand profiles corresponded closely with the availability of insolation energy over the course of a day and over the course of the seasons, efficiencies could be maximised. This is generally not the situation for stand-alone photovoltaic applications (with possible exceptions, such as water-pumping applications). Discrepancies between load profiles and insolation profiles bring the requirement for battery storage, and for sizing the array large enough to support the load in the worst months of the year.

The proportion of the load energy demand which occurs at night requires that amount of short-term energy storage from the batteries. This proportion of the load is met at a lower efficiency than daytime loads, because of the batteries' less than perfect energy efficiency. Of greater consequence are discrepancies which occur as a result of day to day, and seasonal fluctuations in weather. These require medium-term battery storage to cope with runs of adverse weather, and array size sufficient to cover any seasonal fluctuations.

If the load energy demand profile is assumed to be constant at different times of year (as essentially was the case in designing the present systems) then the tilt plane of the modules is generally chosen to optimise insolation received in the worst insolation month of the year. If load energy demand were higher in months of higher insolation, efficiencies could be improved, as less surplus would be wasted.

In the case of the Bophuthatswana installations, however, there are no grounds for expecting important seasonal variations in utilisation, with the exception of the Christmas period when school usage is likely to be low. Similarly, variations in daily load profiles (ie. in the proportion of night-time usage) are unlikely to be a major factor, since most intended usage should be during school hours.

In summary, it is probably fair to say that **levels of load energy demand are likely to be the most important determinant of system efficiencies** in the Bophuthatswanan school installations. If actual utilisation at a school is only say six hours a week, instead of the

design load of 70 hours a week (during school terms), then average consumed energy efficiencies will be less than a tenth of what could be achieved at the design load levels. Such variation in utilisation is easily possible, and beyond the control of system suppliers. No other design factor has a similar magnitude of impact on efficiencies.

This points to the importance, despite the difficulties, of making best possible estimates of likely load energy demand levels. In a situation of such uncertainty as the introduction of new technology into teaching, it may be worthwhile to begin with more conservative specifications than in the Edutel project, and rather to provide for modular expansion of the power subsystem when higher levels of load energy demand are demonstrated.

8.2.2 Probabalistic factors

Photovoltaic system design is made more complex by the probabilistic nature of the primary source of energy, received insolation.

A comedian once pointed out that, since the success rate of BBC weather forecasts was less than 50%, it would make more sense to expect the opposite of what was predicted. This is not quite true, since a multiplicity of deviations could count as "opposites"; and fortunately predictions for average conditions over a longer stretch of time have a better chance of accuracy than short-term forecasts; but it underlines the point that weather is uncertain, and hence received insolation can at best be predicted only as a probability distribution.

The impact of the probabalistic distribution of insolation on the efficiency of a stand-alone photovoltaic system occurs primarily through the need to oversize the array, and to supply sufficient battery storage, to allow continued supply to load in adverse weather conditions. Ideally, if weather probabilities are known, this can be done in such a way as to predict the probability of system failure due to extremes of adverse weather. More usually, rules of thumb and safety margins in design are used for deciding the degree of oversizing required.

In either case, a system designed to survive periods of low insolation will be oversized for periods of high insolation, if the average load demand is constant, and the impact on average consumed energy efficiencies will be the same as if the system were underutilised, as discussed above.

In principle, the degree of oversizing can be reduced if the probable variance in locally received POA insolation, from day to day, from month to month, and from year to year, is low. To some extent, this depends on latitude and local climatic patterns, which are of course outside the control of the system designer. However, mean seasonal variations in POA insolation can be manipulated by changing the tilt-angle of the array. The tilt angle is usually selected to optimise POA insolation in the worst month of the year (assuming steady load energy demand throughout the year).

To optimise the degree of oversizing, good information would be needed about insolation probabilities for the site. Ideally, this should include information about the statistical probability of insolation levels over runs of days, since this is what determines continuing system availability over time. Such information is generally not available. (Using historical weather data for Pretoria, this kind of information has been generated for system modelling in Chapter 9.)

The lack of information about insolation probabilities is a constraint on determining the optimal degree of oversizing needed to achieve a specified probability of system availability through bad weather conditions. To the degree that a system approaches such optimality of oversizing, average consumed energy efficiencies will be increased, and installed costs thereby minimised.

Compared with insolation, ambient temperature has a less crucial but nonetheless significant impact on system efficiencies. Along with insolation levels, it is a co-determinant of operating module cell temperature, which affects optimum module conversion efficiencies, and optimum-power array voltages. It can also affect battery performance.

Photowatt specifications for PW-P 800 modules indicate that the optimal module conversion efficiency is diminished by a factor of approximately 0.4% for every degree C. above the reference of 25 degrees C.

module cell temperature. In principle, then, an array of such modules operating at say 60 degrees C. could optimally produce in the region of 8% less power than one operating at 40 degrees C. cell temperature.

While this appears to be a substantial margin, the impact is reduced in a system where (a) there is no optimum power tracking, and (b) the array operating voltage at times of high demand is effectively set by battery charging voltage. This is because the dominant effect on array performance of increasing cell temperature is to lower the voltage at which the array can generate. Array open-circuit voltage is reduced, and the voltage at which the array produces its maximum power output is similarly reduced. But as long as the optimum-power voltage of the array remains above the battery charging voltage, there is little impact on the power which can be delivered to the batteries. This is discussed in greater detail in Section 8.2.3, as it raises the design issue of how to match array output characteristics to load input characteristics, taking into account the expected range of array operating temperatures.

The effect of ambient temperature on **battery performance** is primarily concerned with the fact that battery capacity and battery terminal voltages increase at higher operating temperatures, due to increased rates of electrochemical activity. (Correspondingly, battery lifetime is expected to be less at higher operating temperatures, other conditions being equal.) Battery temperature will depend on ambient temperatures, on where the batteries are housed, and on charge and discharge current rates. Within the range of expected battery temperatures for the monitoring site, it is not felt that variations in battery temperature enter as a significant efficiency factor. A sudden rise in battery temperature can lead to the anomaly that it can discharge more energy than it received under charge at lower temperatures, but this would of course be a short term effect, and of no importance over a period where batteries are regularly cycled and where battery temperatures change slowly.

With regard to system design, the main concern to do with battery temperature is the setting of charge and discharge voltage limits. Higher charge voltages are recommended for lower electrolyte temperatures. This information is generally supplied by the manufacturers. Sizing calculations which entail assessment of

available installed battery capacity require estimation of battery electrolyte temperatures in conjunction with the setting of the lowest permitted discharge voltage.

In the monitored system, battery electrolyte temperature was not measured. Since the batteries are stored indoors in an enclosed cabinet, and discharge and charge currents are small in relation to battery capacity, it has been assumed that the monthly mean ambient temperature is a good enough estimation of battery cell temperature.

8.2.3 Design factors

The operating module cell temperature was noted above as one determinant of module conversion efficiencies, related to the probabilistic distribution of climatic conditions. However, of far greater impact upon system efficiencies in a typical stand-alone photovoltaic system are considerations based on the sizing of the system, in relation to expected load energy demand and expected POA insolation. The relationships at work here are most readily seen by considering the output characteristics of photovoltaic generators.

The output characteristics of PV modules resemble those of a current generator source, rather than the more familiar case of constant voltage generation (as exemplified by grid electricity supply or, approximately, by battery supply). The PV generator has similar characteristics to a diode, where gate voltage is the photovoltage induced by insolation. For a given insolation, and cell temperature, the cell, module or array will attempt to output an almost constant current, proportional to the photovoltage. Inconstancies arise from the effects of series and shunt resistances in the actual cell, module or array. (The effects of these are increased by agglomeration, so that the output characteristics of an array are less close to those of a perfect current generator than the output characteristics of a single cell.)

The input energy to the array cannot sustain constant current output under any conditions. When connected to a load of infinite impedance, no current will flow. More generally, the characteristic output current of a photovoltaic generator remains nearly constant up to a certain load impedance, after which it falls swiftly to zero.

This is illustrated in Figure 8.6 which shows the form of photovoltaic output characteristics when load impedance is varied from zero to infinity. The three curves represent output characteristics at three insolation levels, while cell temperature is held constant. (Data for these curves was derived from Photowatt PW-P 800 specifications. The curves do not accurately represent the output characteristics of the installed PW-P 801 modules, which are discussed in Section 8.3.)

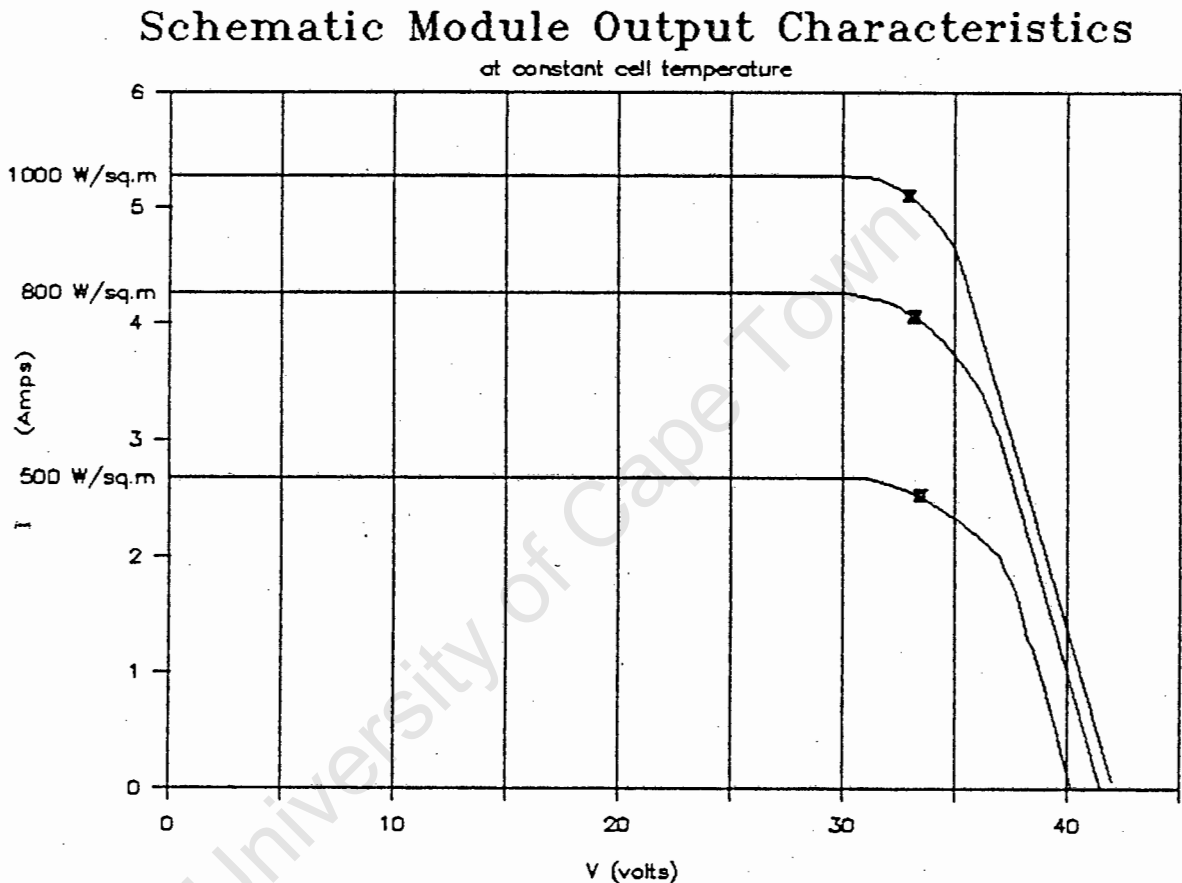


FIGURE 8.6 Example of PV Module Output Characteristics at Constant Cell Temperature and Varying Insolation

The power which can be obtained from a photovoltaic generator, at a given insolation and cell temperature, depends on the impedance of the load to which it is connected. Optimum power is delivered when output voltage multiplied by output current is maximised. Because of the shape of the PV $I=f(V)$ output curves, this value is maximised on the "knee" of the curve, when the load impedance reduces the output current somewhat below the short-circuit value, while avoiding the steep decline associated with higher voltages. Approximate optimum power points are marked in Figure 8.6.

When an array is connected to a load, the operating points on the array output curves will depend on the apparent impedance of the load. If the load impedance is independent of what the array is doing, then "load lines" can be superimposed on the same graph to show the $I=f(V)$ input characteristics of the load. Array operating points are then predicted as the points of intersection between array $I=f(V)$ output curves and the load $I=f(V)$ input characteristics.

For example, a purely resistive load has a straight load line which passes through the origin, since $I = 1/R * V$ for a resistive load R . Loadline A in Figure 8.7 provides an example of such a resistive load, and it is seen that connecting such a load to such an array would result in operating points well away from the maximum power points of the array, as insolation varies.

IV Characteristics and Sample Loadlines

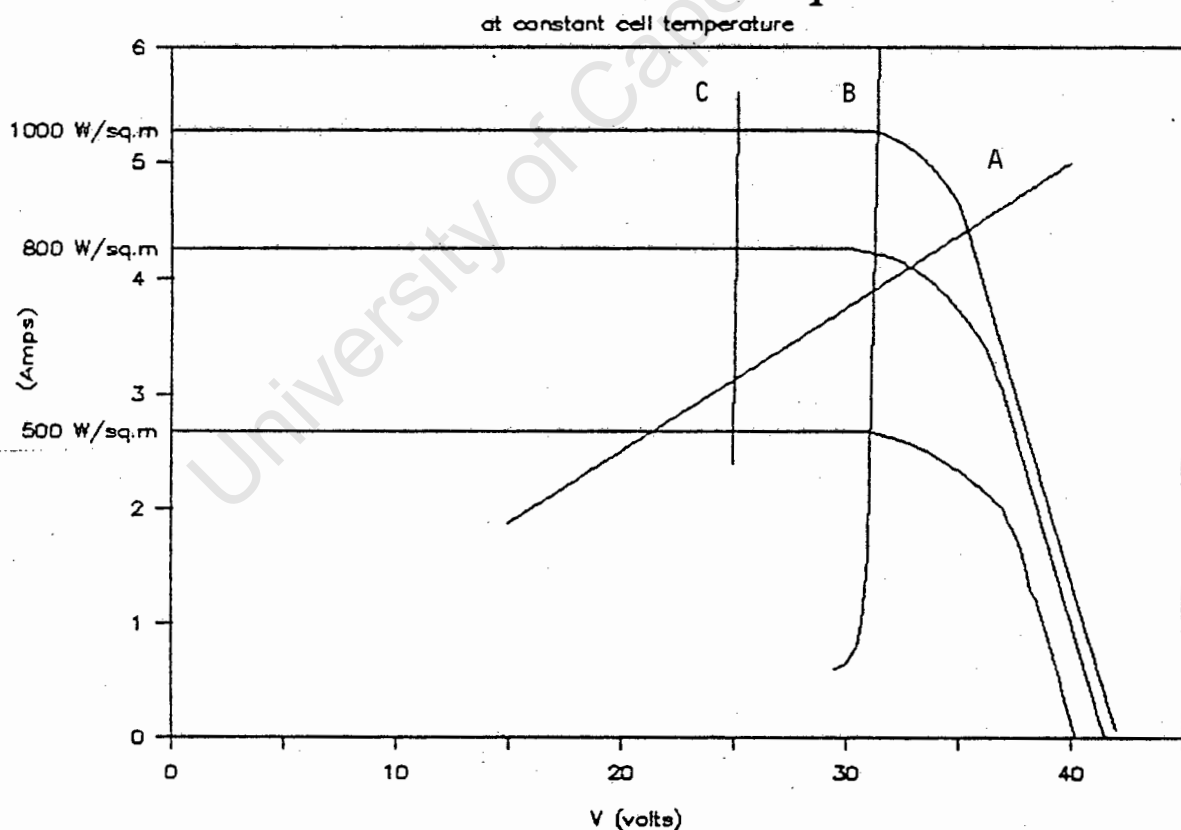


FIGURE 8.7 Module IV Curves and Sample Loadlines

A better match is obtained when the array is charging a battery, providing the optimal voltage range of the array is close to the

It should be emphasised, though, that while an optimum power tracker can maximise available array power, whether the available energy is in fact utilised will depend on system energy demand. If energy demand were always greater than available array energy (as for instance in a photovoltaic generator connected to a grid which will receive any surplus power) then optimum power tracking would deliver its potential benefits. But in a stand-alone system with battery storage, this need not be the case.

For example, in a stand-alone system where array voltage was adequate for battery charging, and where the array/battery combination was substantially oversized in relation to load energy demand, there would be little purpose in optimum power tracking, because there would be no call upon the extra potential power made available. The storage batteries would simply spend more time at high charge (with some benefit to battery life expectancy).

This illustrates the interdependence between two sets of design issues. The one concerns matching energy demand (over time) to the energy which can be supplied by the array and associated energy storage in prevailing climatic conditions. Providing the array characteristics are reasonably suited to charging the batteries, the primary design variables here are the size of the array and the capacity of the batteries, which need to be calculated in relation to energy demand and climatic conditions. (Chapter 9 deals with this.)

The second set of design variables concerns optimising the performance characteristics of power generation. Here the matching of array output characteristics with load input characteristics is of primary concern. A well matched combination will allow for higher generating efficiencies, and thus enable a more economical sizing of the array and batteries. However, if a system is oversized in relation to energy demand over time, then improved component matching will be of minor interest.

Thus the improvements in system performance which could be obtained through use of optimum power tracking in a stand-alone battery-charging system are only likely to be of significance in a critically sized system, which could be defined for present purposes as a system where there is a definite but acceptably small probability of system

non-availability due to insolation shortfalls in exceptionally adverse climatic conditions. If an optimum power tracker significantly increased the available array power in such critical conditions, it could provide a lower probability of loss of power, or alternatively allow the same probability of loss of power with a reduced array/battery combination.

In this situation, the comparative benefits of optimum power tracking electronics would depend (inversely) on how well the array output characteristics can be matched to the load input characteristics in the absence of such power conditioning.

This leads to a discussion of the variables which principally determine the matching of array output characteristics and load input characteristics, in a critically sized system.

Where storage batteries are in parallel with the applications load, the load input characteristics in critical conditions (batteries undercharged) will be dominated by the batteries' loadline at that state of charge. The high energy acceptance and low internal resistance of the batteries produce an input loadline which is effectively set by the battery charging voltage at that state of charge. This will vary only slightly with variations in array current output at changing insolation levels. (Any voltage drop across charge-regulating circuitry will be added to the batteries' charging voltage, to set an approximately vertical loadline.)

On the array side, the $I=f(V)$ array output characteristics will be mainly a function of module design, insolation and operating cell temperature. Insolation (energy flux and spectral distribution) has little effect on optimum-power array voltages for a given design of module, compared with cell temperature. The match (or mismatch) between critical loadlines and array optimum-power voltages is therefore determined primarily by the choice of module and by the operating cell temperatures.

Figure 8.8 illustrates the principles of matching array characteristics to battery charging characteristics, in the absence of an optimum power tracker, taking into account variations in battery charging voltage and operating cell temperatures.

Matching IV Characteristics to Loads

Battery Charging & Temperature Effects

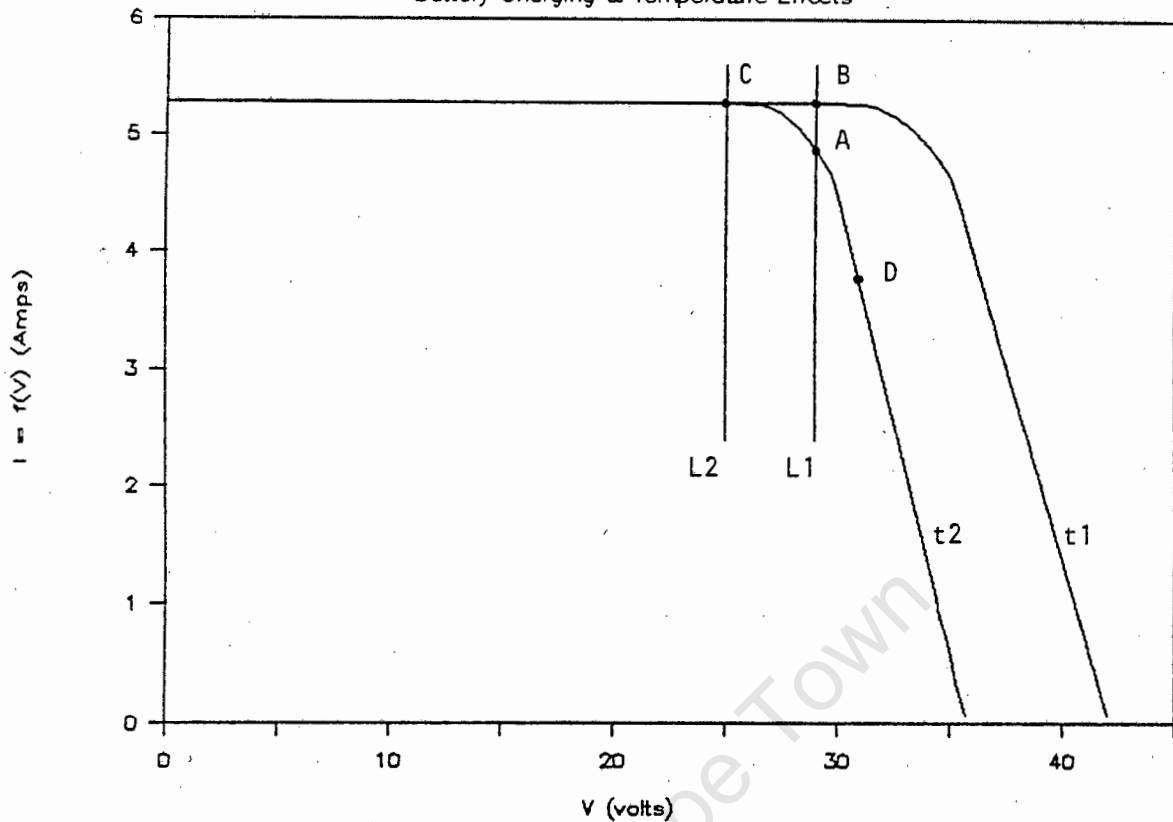


FIGURE 8.8 Matching Array Output Characteristics to Battery Charging Input Characteristics

Suppose the two array $I=f(V)$ curves shown above represent array output characteristics, for an arbitrary level of insolation, at low and high expected operating cell temperatures, t_1 and t_2 . (The schematic emphasises the effect of cell temperature on array voltages, while ignoring the small increases in array current associated with higher cell temperatures.)

The two loadlines represent battery charging loadlines at a high battery state of charge (Line L_1) and at a low battery state of charge (Line L_2), ignoring any variations in battery electrolyte temperature, but notionally including any voltage drop across charge-regulating circuitry.

Considering loadline L_1 , it can be seen that if the array is designed to provide a sufficiently high optimum power voltage at high cell temperature to charge the battery at high state of charge (Point A), then there will be a deviation from optimum power voltage when the array operating cell temperature is lower (Point B).

Considering loadline L2, where the battery is at a low state of charge, there is an even greater deviation from optimum power array voltage (Point C). The deviation is greatest with respect to the low temperature (t_1) output characteristics of the array.

The extent of maximum deviation from optimum power voltages is therefore determined, in this case, by (i) the range in battery charging voltages, and (ii) the range in operating array cell temperatures in conjunction with the temperature-voltage coefficient of the array.

Unfortunately, periods of maximum energy demand might be expected to incur the greatest power losses through deviation from optimum power array voltages. This would be the case if critical periods, when batteries approach their lowest state of charge, are also associated with low array cell temperatures, eg. in winter months and at low insolation levels.

An optimum power tracker would remove this problem, and might be preferred in a critically sized system when there is a large range in expected operating cell temperatures, and where lowest cell temperatures are incurred in periods of maximum energy demand.

Alternatively, generating efficiency in critical periods (loadline L2) could be improved by using modules with lower optimum power voltage characteristics, in effect relatively moving the loadlines to the right, closer to low temperature optimum power voltages.

The danger here would now come at high operating cell temperatures. Loadline L1 (high state of charge) if moved to the right would intersect the t_2 array output curve on its sharply descending tail, for example at Point D. The currents which the array can generate would be sharply reduced, and might be insufficient to bring batteries to full charge, with cumulative harm to battery life. (The danger to battery plate life would be greater in the case of lead-antimony than lead-calcium batteries, the latter having less requirement for boost charging to prevent sedimentation and acidification.)

Without an optimum power tracker there must be an inevitable compromise in array generating efficiencies. However, the compromise

which can be made, and the cost of that compromise in terms of power generated, is also dependent on the shape of the array $I=f(V)$ characteristics.

The characteristics used in Figure 8.8 were derived from Photowatt PW-P 800 specifications, and show typical characteristics for modules with a fairly high fill factor. The optimum power voltage is fairly well defined, and the power losses associated with deviations from optimum power voltages are as shown in Figure 8.9 below. But modules with a lower fill factor, such as the polycrystalline PW-P 801 modules installed at the monitoring site, do not incur such high power losses as a result of deviations from optimum power voltages. This is particularly so for operating voltages which are higher than the optimum power voltage. This is also illustrated in Figure 8.9, where positive values on the horizontal axis indicate operating voltages in excess of the optimum power voltage. The vertical axis shows the corresponding percentage of optimum power lost.

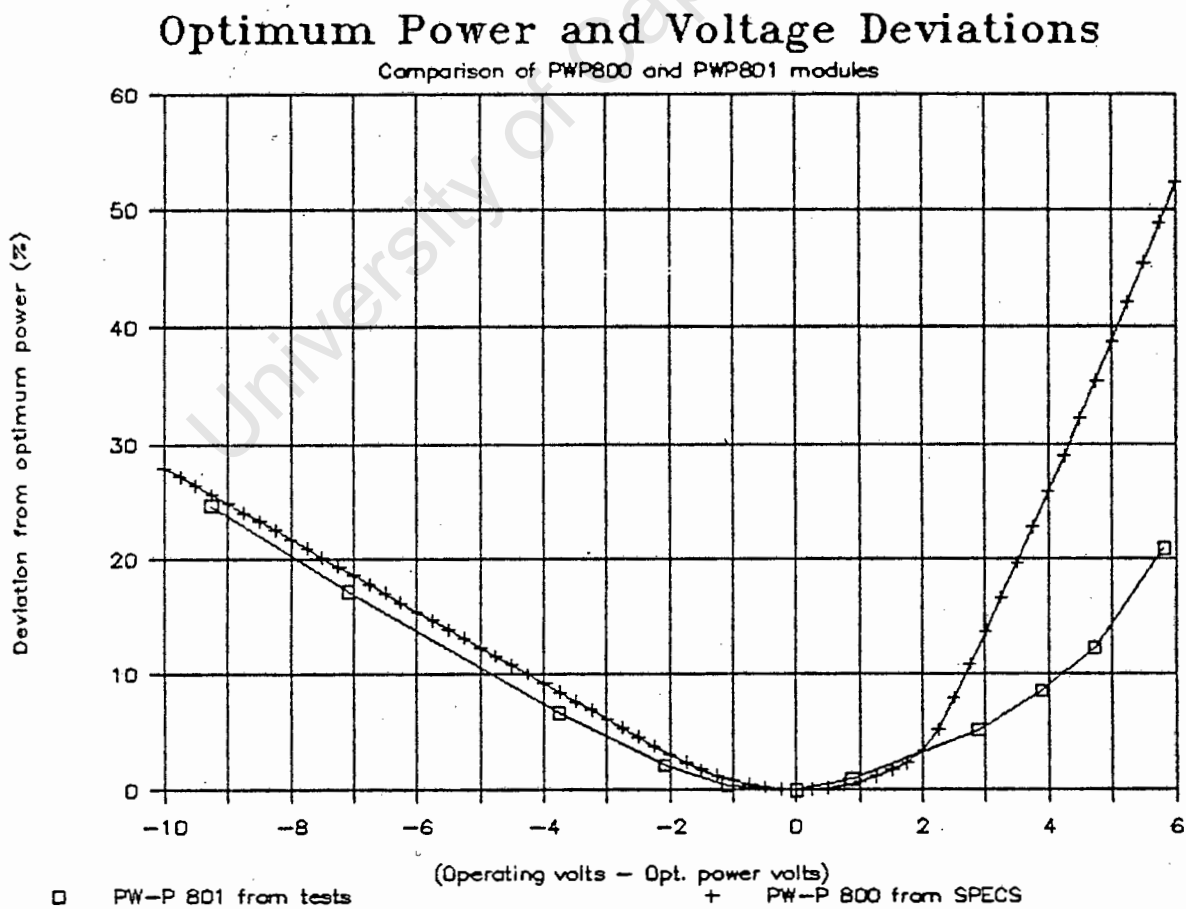


FIGURE 8.9 The Relationship Between Optimum Power and Optimum Voltage Deviations For Two Photovoltaic Modules

Figure 8.9 indicates that, to the extent that manufacturer's specifications for PW-P 800 modules and tested characteristics for the PW-P 801 modules can be relied upon, there is greater opportunity for useful compromise in the case of the latter polycrystalline modules. They can be allowed to operate in a wider voltage range with least cost to optimum power generation than is the case with the monocrystalline PW-P 800 version, and in particular, if required to operate at voltages higher than their optimum power voltage, the power losses will not be as acute.

This means that modules with the latter characteristics could be used to charge batteries at a charging voltage higher than the modules' optimum power voltage. For instance, intersection with a loadline three volts higher than the optimum power voltage of the modules would lead to a reduction in power of only 5%, compared with a reduction of 15% in the case of PW-P 800 modules. Such a situation could be matched to expectations for high states of charge of the battery, and high operating cell temperatures, without endangering system performance.

The benefit of this would be that in critical conditions, when batteries are at low state of charge and when cell temperatures are likely to be lower, the deviation between optimum power array voltage and take-off voltage will be reduced. In these conditions, if the loadline fell to a voltage three volts lower than the corresponding optimum power array voltage, the loss of potential power would again only be 5%.

The voltage deviations cited here, and as they appear in Figure 8.9, are all relative to a 24 V nominal configuration. The aim has been to indicate the magnitude of power losses which could be achieved through suitable balancing of array and load characteristics, in the absence of an optimum power tracker. Losses in potential power are reduced if modules have a lower fill factor. To achieve minimum power losses, the absolute value of optimum power array voltages must still be matched to load voltage characteristics. Other determining variables are the range in permitted battery charging voltages and the range in expected operating array cell temperatures. Optimum power tracking will be of greater advantage when these ranges are high, when modules have a high fill factor, and only if a system is critically sized.

8.3 Analysis of Efficiencies in the Monitored System

The foregoing approach is now applied in an analysis of efficiencies in the monitored system. Array output characteristics are assessed in relation to observed loadlines. Comparisons are also made between the monitored system and efficiencies which would be expected if PW-P 800 monocrystalline modules had been installed. These comparisons are of interest firstly because the original system design was based on the latter modules, and secondly because they illustrate the extent of efficiency losses which could be incurred through poor component matching.

8.3.1 Observed loadlines

Loadlines have been statistically extracted from the monitoring data, for selected system states. The datapoints represent combinations of array voltage and array current, at varying insolation levels, corresponding to the selected system states.

In states of low energy demand, ie. when the Energy Management Unit is performing a charge-limiting function, there is no singular loadline, since it is then functioning as an active device, variably limiting power transmission in response to insolation, cell temperature and battery voltage.

In states of higher energy demand, the loadlines are relatively well defined, and are then independent of array cell temperature, being set by the load input characteristics.

Insufficient range in operating conditions was observed (particularly with respect to low battery states of charge) to establish input characteristics for a full range of system states. However, regularity in the observed loadlines allows extrapolation to non-observed system states.

The loadlines have been portrayed as BMDP scattergrams, to provide an indication of variance in the data points. The horizontal axes show recorded array voltage (before the Energy Management Unit) while the vertical axes show the current delivered to batteries and/or television load (ie. array current).

In these scattergrams, the numbers/letters indicate the frequency of data points at a given position. (When more than 9 datapoints coincide, BMDP uses letters to continue the numbering, so that "A" represents a frequency of 10.)

Definition has been somewhat reduced by the multivariate analysis, primarily the need to bracket ranges of system states to obtain sufficient datapoints.

Figure 8.10 shows input load characteristics for states of low energy demand. Here the batteries were at or close to full charge, and there was no applications load. While these input characteristics are of little design interest, they are shown here in order to illustrate the impact of the Energy Management Unit (EMU).

Figure 8.10(a) corresponds to the period when the EMU was inoperative, probably following lightning damage. It is seen that the loadline is fairly well defined, in comparison with the spread of amps-volts pairs in Figure 8.10(b).

Figure 8.10(b) shows the impact of the EMU when batteries were at a charge voltage greater than 27.5 volts (close to maximum permitted charge voltage). It is seen here that the EMU makes varied adjustments to power transmission, and hence apparent input impedance, to achieve its regulating function in varying insolation and temperature conditions.

Fig.8.10(a)

Batteries
fully charged

EMU failure

No
applications
load

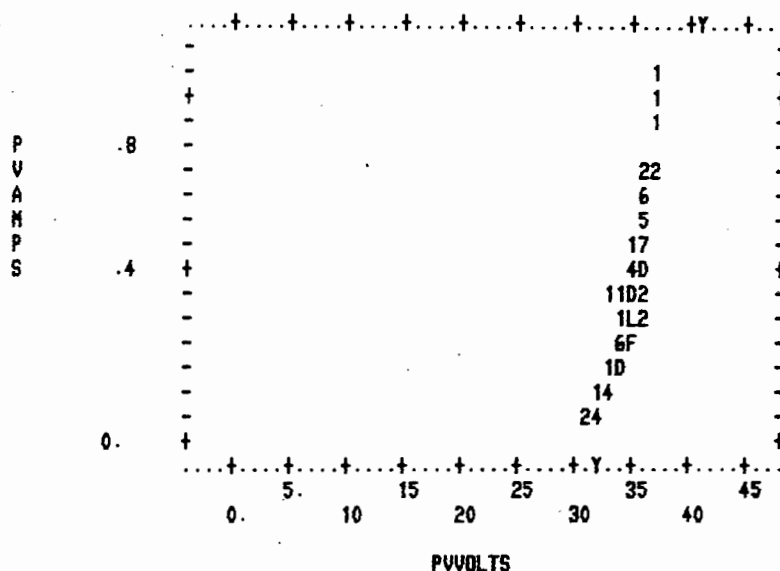


Fig.8.10(b)

Batteries >
27.5 volts

EMU
operating

No
applications
load

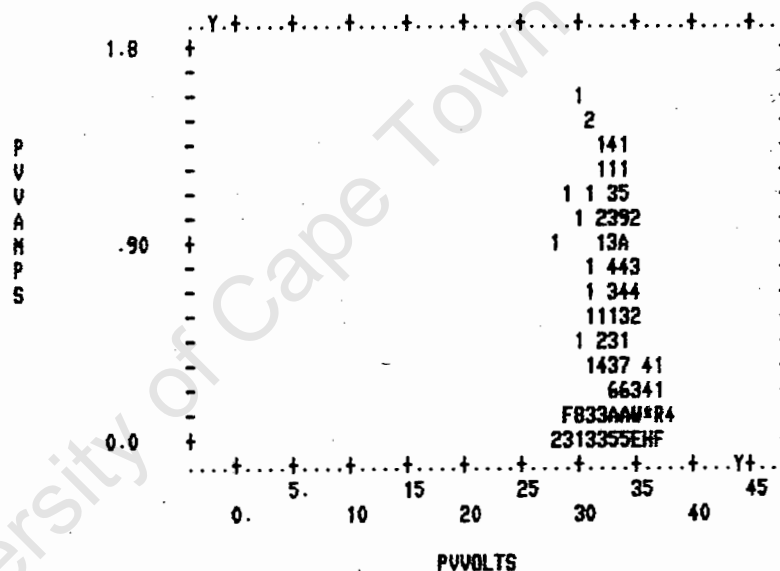


FIGURE 8.10 Input Load Characteristics in States of Low Energy Demand

The loadlines become more defined when there is greater system energy demand in relation to array power, reducing the variability and extent of EMU power limiting. Figure 8.11 corresponds to states where the batteries were again at a charge voltage greater than 27.5 volts, but where the television load was on. In these conditions, recorded array operating voltage ranged from 29 to 32 volts.

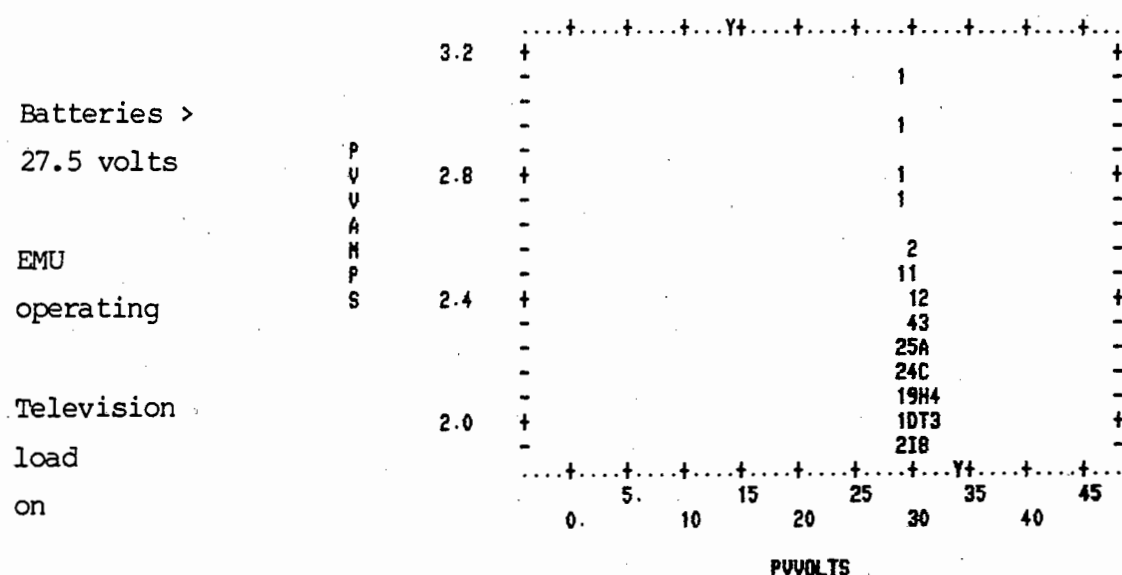


FIGURE 8.11 Input Load Characteristics With Batteries at High Charge, and Television Load On.

When batteries are at lower states of charge, there is increased power acceptance, and array operating voltages are brought down closer to battery charge voltage. Figure 8.12(a) shows the case for battery charge voltage between 26.5 and 27 volts, with no applications load, while Figure 8.12(b) shows the loadline for the same battery voltage range, but where the television was also switched on. In both cases, array voltage is fairly well defined, in the region of 28 volts. More detailed analysis shows the array voltage range for these two system states was 27.6 - 28.5 volts (no TV) and 27.8 - 28.0 volts (with TV on).

Datapoints become sparse for lower battery states of charge, but the pattern remains the same. At a battery charge-voltage range of 26 - 26.5 volts, recorded array voltages ranged from 26.7 - 27.8 volts (no TV) and 26.9 - 27.5 volts (TV on).

Fig.8.12(a)

Batteries
between 26.5
and 27 volts

No
applications
load

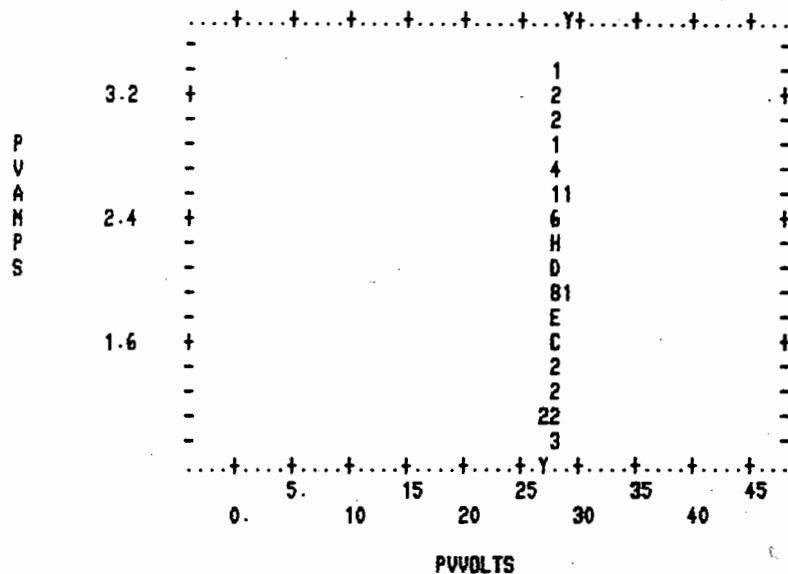


Fig.8.12(b)

Batteries
between 26.5
and 27 volts

Television
load
on

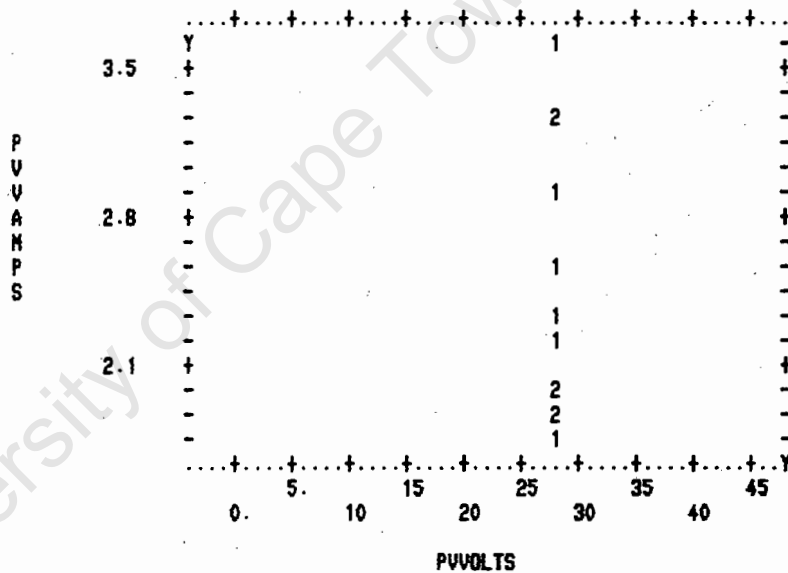


FIGURE 8.12 Input Loadlines at Lower Battery States of Charge

Comparison of these loadlines shows that, as expected, the regulating action of the EMU introduces greatest indeterminacy of input characteristics when batteries are near full charge. In situations of higher energy demand, the load lines are nearly vertical, at a voltage level approximately 1 volt above battery charge voltage. In principle, this characteristic is favourable to efficient array operation, since array optimum power points, at varying insolation levels (and constant cell temperature), are also close to vertical. The question remains whether the array is matched to these load input characteristics.

8.3.2 Array output characteristics

Array output characteristics were measured in the tests reported in Chapter 7, and the results are used here to assess the optimality of matching between the array and the load.

Array output characteristics, at varying insolation levels, were also extracted from the monitoring data, through multivariate analysis. Recorded pairs for array volts and array amps were statistically adjusted for recorded cell temperature, to bring them to estimated equivalents at cell temperature 25 degrees. Then these pairs were compartmentalised for POA insolation bands of ± 50 W/sq.m and array voltage bands of ± 0.5 volts. The mean temperature-adjusted array current was computed for each POA-volts cell. These mean values constituted datapoints for plotting array output characteristics.

However, due to the limited range in observed operating conditions, the curves obtained from monitoring data were restricted to an array voltage range of between 27 and 37 volts. The full $I=f(V)$ curves from Chapter 7 are therefore used in preference.

Both procedures entailed making adjustments for cell temperature. The relationship used for this purpose was derived from the monitoring data, as follows.

It was not possible from the monitoring data to obtain a direct measure of how cell temperature is related to optimum power points in the array's output characteristics. This is because the influence of battery charging voltage on array operating voltage masks the influence of cell temperature.

The best indicator of the impact of recorded cell temperatures on array voltages was obtained by correlating these variables in conditions approaching zero current flow (ie. in conditions approaching array open circuit). Data from two months in mid-summer and mid-winter was combined for this purpose.

The regression relationship was:

$$VOC(T_c) = VOC(25) * (1 - 0.0028 * (T_c - 25))$$

$$R\text{-squared} = 0.81$$

T_c : Module cell temperature (degrees C.)

$VOC(T_c)$: Open-circuit array voltage at cell temperature T_c

$VOC(25)$: Open-circuit voltage at cell temperature 25 deg C.

The temperature coefficient of open-circuit voltage obtained in this way was used as the temperature correction factor for all voltages on the array IV curves. The derived value of $-0.28\%/degree$ for the monitored PW-P 801 modules is somewhat lower than that derived from PW-P 800 specifications, which is $-0.38\%/degree$.

The cell temperature coefficient of module current has not been taken into consideration in assessing the matching of array and load characteristics. It could not be derived from the monitoring data, but from theoretical considerations it can be expected to be in the region of $+0.1\%/degree$, while PW-P 800 specifications indicate a coefficient half this magnitude. Higher cell temperatures are accompanied by slight increases in array current, but this has negligible effect on the optimum power array voltage at a given cell temperature. Temperature effects on current were also not considered in normalising the tested IV characteristics in Chapter 7, since the small temperature range would have introduced an estimated correction of only 0.5% to array currents, negligible alongside other sources of uncertainty. However, the theoretical temperature coefficient of current is included in later optimum power calculations where a large temperature range is considered.

To assess the matching of array and load characteristics, it is necessary to identify the expected range in operating cell temperatures. The summary of monitored data in Chapter 4 showed that the recorded cell temperature in daylight hours averaged between 17 and 30 degrees (winter to summer), with maxima ranging from 40 to 50 degrees, depending on season. Minima fell below zero at times, but at times of insignificant insolation, and more representative minima for generating periods were in the range 10 to 15 degrees C.

The expected operating cell temperature band for this site is therefore taken as the range 10 degrees to 50 degrees C.

Loadlines can now be combined with the monitored array's tested IV characteristics, making voltage adjustments for this expected range in operating cell temperatures.

The two loadlines which are superimposed make use of the finding that in situations of energy demand, loadlines were approximately vertical, and approximately 1 volt above battery charging voltage. Loadline A represents the state of system when the batteries have a charge voltage of 24 volts (23.8 volts is the lowest permitted discharge voltage) while Loadline B represents the state where batteries are fully charged but there is remaining demand from the applications load (as in Figure 8.11 above).

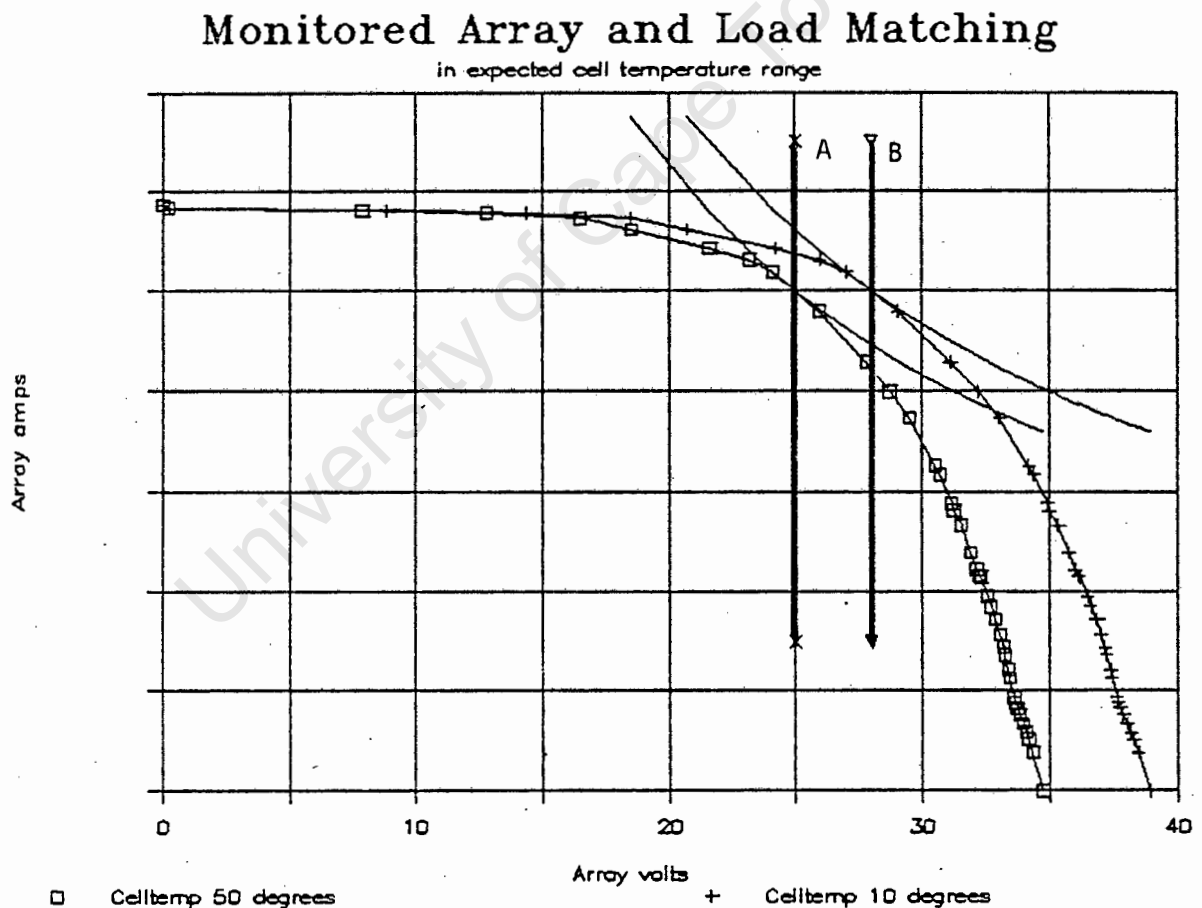


FIGURE 8.13 Matching of Array and Load Characteristics for the Monitored System, at Expected Operating Cell Temperatures

The array IV curves in Figure 8.13 are for an arbitrary insolation level, since by the assumptions made, the insolation level does not significantly affect voltage matching of array and load characteristics.

The intersection of the maximum and minimum voltage loadlines with the array IV curves at minimum and maximum expected operating temperature show that this array appears to be very well matched to the load characteristics.

The voltage of Loadline A virtually coincides with the optimum power voltage of the array at cell temperature 50 degrees, while the voltage of Loadline B coincides with the optimum power voltage of the array at cell temperature 10 degrees. The worst cases indicated are where the batteries are discharged (Loadline A) and cell temperature is low, and where batteries are charged (Loadline B) and cell temperatures are high. In the first case, operating voltage is approximately 3 volts lower than the optimum power voltage. In the second case, it is approximately 3 volts higher.

For this range of operating conditions, therefore, the voltage matching could hardly be improved upon, and given the rounded shape of the IV characteristics of this array, the same can be said in terms of optimum power deviations. Figure 8.13 earlier showed that the deviation from optimum power associated with a 3 volt deviation from optimum power voltage, for this array, was only 5% (whether 3 volts higher or 3 volts lower than the optimum power voltage).

This ideal matching provides a good illustration of how available array power can be optimised in a stand-alone photovoltaic system where batteries dominate the input load characteristics. With maximum expected deviations of 5% from optimum power generation, it is unlikely that an optimum power tracker could significantly improve performance.

This would not have been the case if monocrystalline PW-P 800 modules had been installed. Their higher fill factor and higher optimum power voltages would have led to serious mismatching.

To illustrate this, Figures 8.14 to 8.16 portray the main relationships needed to make the comparison.

Figure 8.14 shows the optimum power voltages of PW-P 801 and PW-P 800 modules, as a function of cell temperature. (The relationships are derived from monitoring data and specifications respectively.)

The shaded rectangle indicates the expected range in operating cell temperature (horizontally) and the expected voltage range of battery loadlines (vertically).

The maximum expected deviations from optimum power voltages are given by the vertical distance from the modules' optimum voltage lines to the furthest corner of the shaded rectangle.

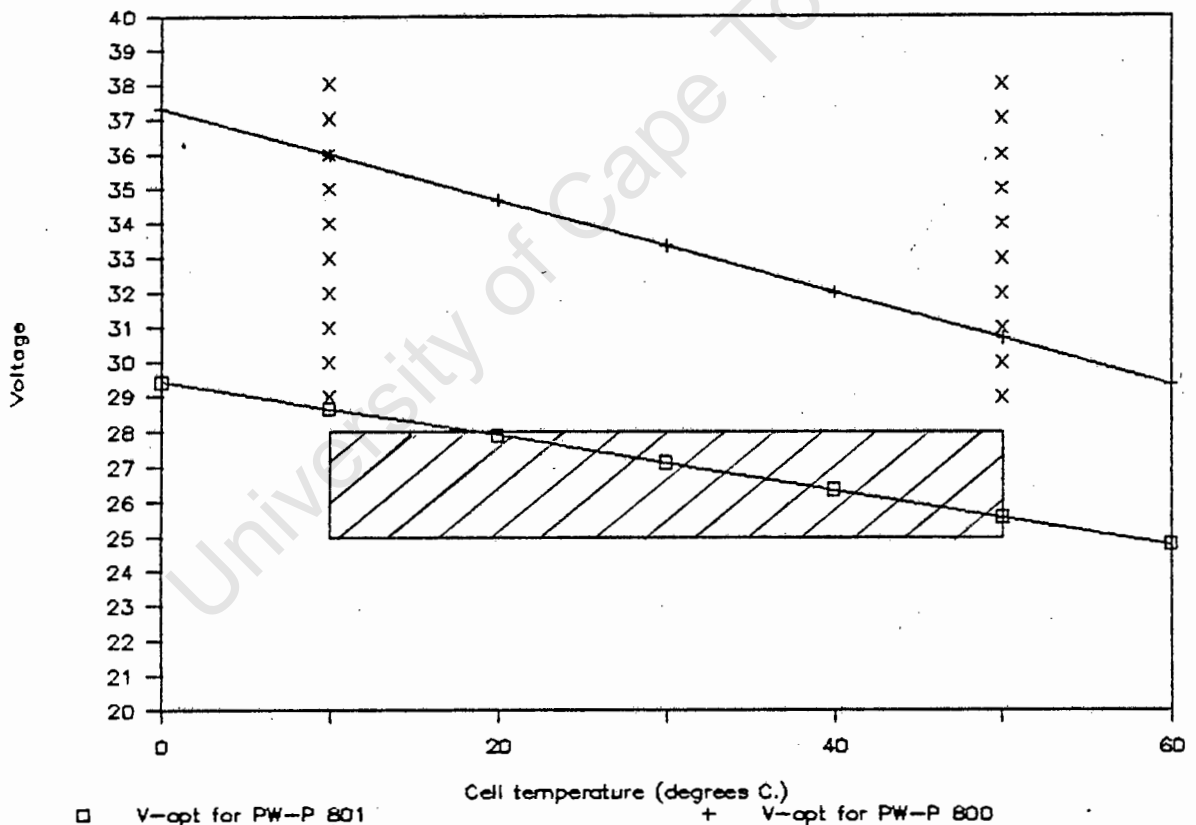


FIGURE 8.14 Optimum Power Voltage Deviations for PW-P 800 and PW-P 801 Modules In Relation To Expected Cell Temperature and Loadline Ranges

This shows the deviations for PW-P 801 modules more accurately, with maximum deviations of -3.5 and +2.5 volts from optimum. For the PW-P 800 modules, however, the voltage deviations would be more severe.

The deviation would be -6 volts, with highly charged batteries (plus TV load) and a cell temperature of 50 degrees; and -11 volts with a depleted battery and a cell temperature of 10 degrees.

Figure 8.15 reproduces the relationship between optimum power voltage deviations and optimum power deviations used earlier, based on the form of the IV characteristics for the two types of module. The maximum voltage deviation for PW-P 801 modules of -3.5 volts indicates a 6% maximum loss of optimum power, at cell temperature 10 degrees, while at 50 degrees cell temperature the maximum loss is 5%.

The maximum optimum power loss for PW-P 800 modules would be 14% at a cell temperature of 50 degrees, and (although a -11 volts deviation is off the scale in Figure 8.15) approximately 30% at cell temperature 10 degrees C.

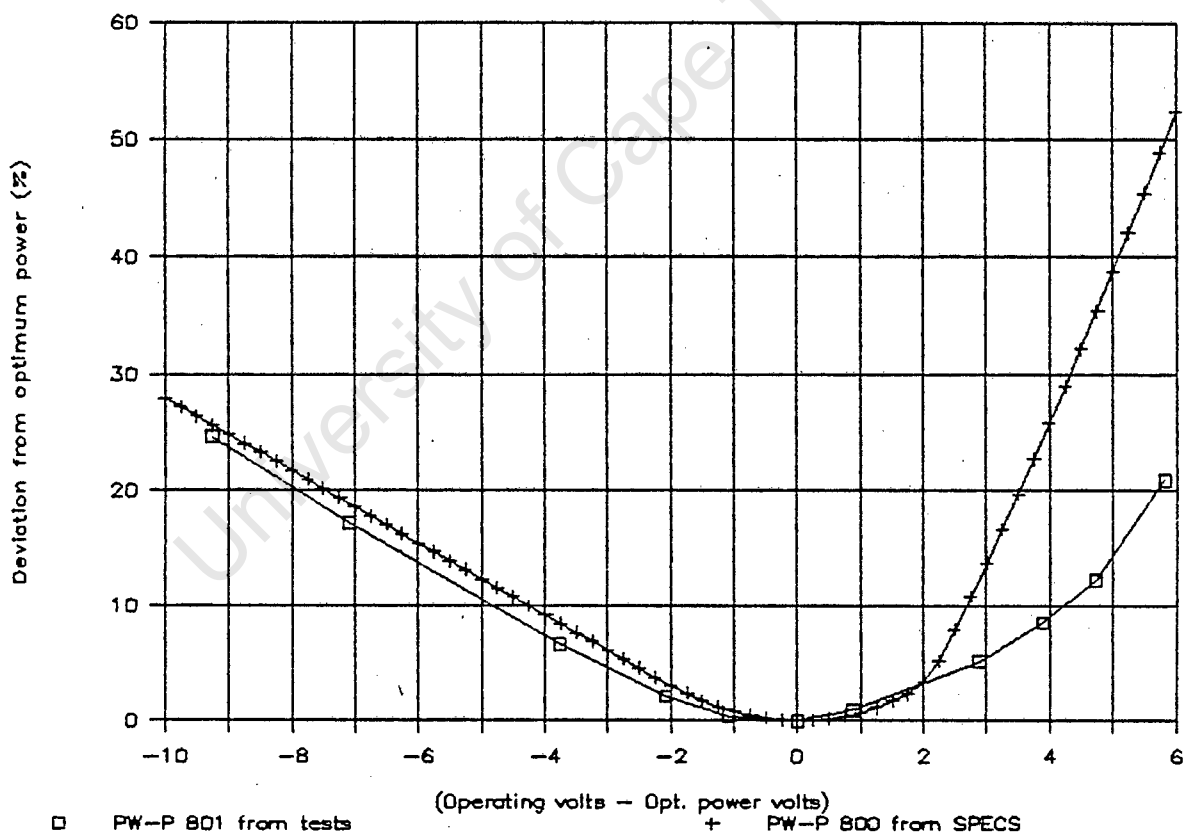


FIGURE 8.15 Optimum Power Loss As A Function Of Deviations From Optimum Power Voltages, for PW-P 800 and PW-P 801 Modules

This maximum power loss of up to 30% could unfortunately occur in critical conditions, associated with low battery state of charge, low

insolation and low ambient temperatures in winter months; and in terms of system availability, this loss in generating efficiency through voltage mismatch would counteract the higher peak power rating of the monocrystalline modules, in the absence of optimum power tracking.

Figure 8.16 in conjunction with these estimates allows for a comparison of available power from the two types of module. Their optimum power ratings (multiplied by two, for two modules in an array) are depicted as a function of cell temperature, for a nominal insolation level of 1000 W/sq.m. The PW-P 800 optimum power line is derived from original specifications, while the PW-P 801 power line is derived from tests and monitoring data. These power lines incorporate adjustment for temperature effects on array currents as well as array voltages.

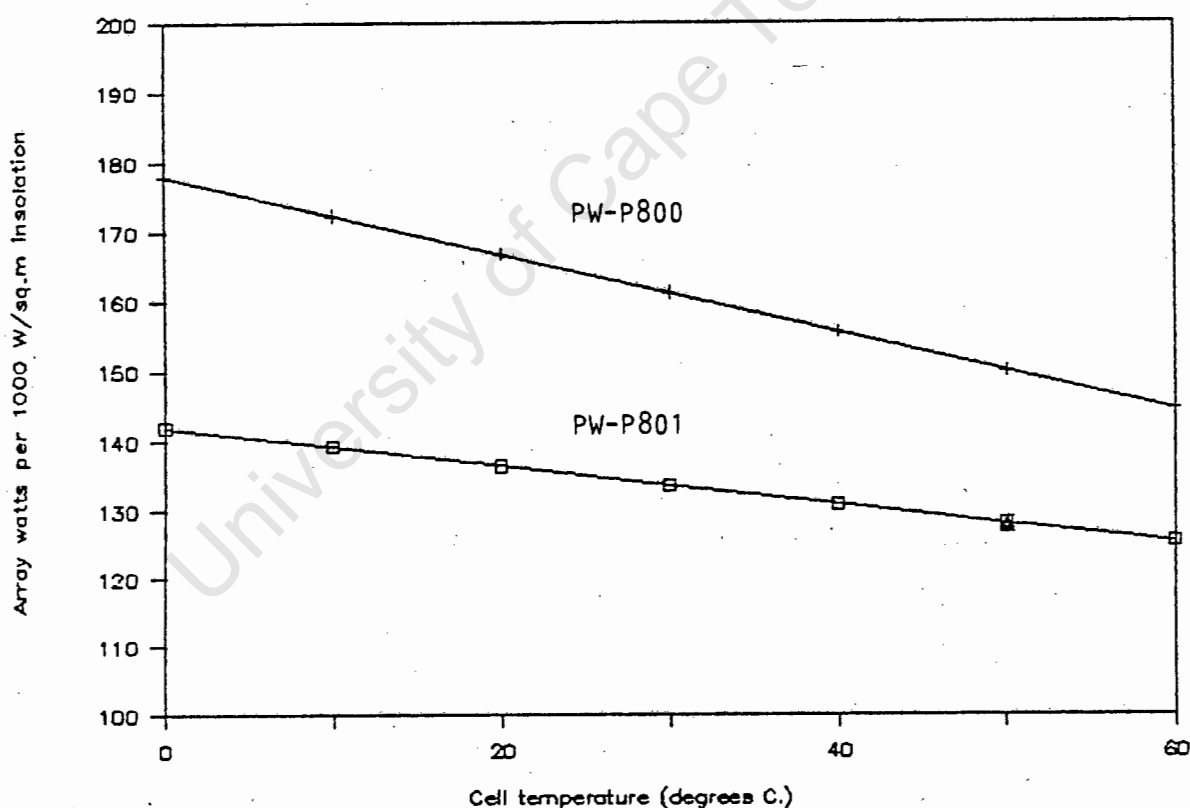


FIGURE 8.16 Optimum Power for an Array of Two PW-P 800 and PW-P 801 Modules, Per 1000 W/sq.m POA Insolation, As A Function Of Cell Temperature

When the rated optimum power, at the corresponding cell temperature, is derated by the estimated loss in optimum power at that temperature, it is calculated that in the worst cases these two types of module

would deliver nearly the same power. The results of these calculations are in Table 8.2, for a wider range of cell temperatures. PW-P 801 modules are calculated to deliver slightly higher power at low cell temperatures, due to the mismatch of PW-P 800 modules in this situation.

TABLE 8.2 Comparative Power Output of PW-P 801 and PW-P 800 Modules, Taking Account Of Array/Loadline Matching

PW-P 801 (polycrystalline) modules

Two in array

Tested Peak Power: 135 Wp at 1000 W/sq.m and 25 degrees C ($\pm 8.2\%$)

Available Array Power Output, per 1000 W/sq.m

Array/Loadline Match:		BEST CASE	WORST CASE
CELL TEMPERATURE: (degrees C.)	10	140 W	132 W
	20	136 W	129 W
	30	133 W	130 W
	40	131 W	128 W
	50	128 W	122 W
	60	126 W	118 W

PW-P 800 (monocrystalline) modules

Two in array

Specified Peak Power: 164 Wp at 1000 W/sq.m and 25 degrees C ($\pm 12.5\%$)

Available Array Power Output, per 1000 W/sq.m

Array/Loadline Match:		BEST CASE	WORST CASE
CELL TEMPERATURE: (degrees C.)	10	138 W	121 W
	20	139 W	122 W
	30	141 W	122 W
	40	142 W	128 W
	50	145 W	128 W
	60	142 W	134 W

8.4 Conclusions

Conclusions relating to the optimality of matching array output characteristics to load input characteristics are as follows:

- 1 The installed PW-P 801 modules are well matched to the system load input characteristics. Maximum power loss in expected operating conditions, due to operating away from maximum power points, is estimated as 6%. This represents an unavoidable loss, in the absence of an optimum power tracker, and could not be significantly reduced. The low fill factor of the modules, while concomitant with low cell conversion efficiencies, contributes to minimisation of this power loss, in combination with nearly ideal matching of array and loadline voltages.
- 2 For comparison, the predicted mismatch of PW-P 800 modules, as originally recommended by Photowatt SA and according to their original module specifications, could have resulted in losses of up to 30% of optimum power output, in the absence of optimum power tracking. This is primarily due to the higher voltage characteristics of these modules.
- 3 The PW-P 801 modules were apparently intended as a polycrystalline equivalent for monocrystalline PW-P 800 modules. According to tests, they had considerably lower peak power, but due to superior matching to load characteristics in the present application, should have equivalent power performance in mid-range conditions, and slightly superior performance in critical conditions when cell temperatures are low and batteries are depleted.
- 4 The higher voltage characteristics of PW-P 800 modules would suit them for battery charging in very hot conditions (desert or tropical), or for operation with an optimum power tracker, in which case their higher optimum power could be utilised.
- 5 The comparison between these two module designs has illustrated that peak power ratings of an array (even if they were accurate) may not be a sufficient guide to expected array performance. Matching of array and load characteristics must be considered.

Conclusions relating to average system generating efficiencies, over time, are deferred to Chapter 9, except to repeat that:

- 6 The efficiency gains which can be achieved through the matching of array output characteristics and load input characteristics, or through optimum power tracking, will only be of significance if a system is critically sized, ie. if energy generated over time is critically adjusted to the course of energy demand over time. Conversely, the optimality of critical system sizing is dependent on optimising array generating characteristics in critical conditions.
- 7 In stand-alone installations where energy demand over time is determined by user preferences, this is likely to be the greatest and the most unpredictable determinant of average generation efficiencies, particularly if these preferences lead to underutilisation of potential energy generation.

Chapter 9 takes up the problem of how to assess the power of an array and battery storage capacity in relation to a design load, climatic probabilities and chosen levels of expected system availability.

given load profiles.

Secondly, a more reductive approach was considered, where system performance is predicted only for critical conditions, that is to say, operating and climatic conditions leading towards system non-availability. This approach requires statistically condensed weather data, in order to predict the probability of system failure at selected load levels.

For present purposes, the second approach has been preferred.

9.1.1 Full simulation

A fairly full simulation model can be achieved by developing algorithms for the following functions. The state of system variable is the State of Charge of the batteries, recalculated hourly by means of these functions operating on hourly weather data and load profiles.

- 1 Power delivered to load and/or batteries
as a function of POA insolation, ambient and cell
temperature, load current, battery SOC, battery temperature.

This function in effect gives the intersection points of array IV output characteristics (dependent on insolation and cell temperature) and the input load lines of the system, including charge controller. The former can easily be mathematically fitted, but the latter is a complex function (especially at higher battery states of charge), depending on battery SOC, and on charge controller behaviour at that SOC, load level, and array power. Such load lines could be established through bench tests for the present system (the monitoring data has insufficient range for load currents and battery SOC to establish this function) but would not easily be generalisable to other systems, due mainly to differing means of power regulation.

- 2 Charge rate $d/dt(\text{SOC})$ of batteries
as a function of charge current, battery SOC and battery
temperature.

- 3 Discharge rate $d/dt(\text{SOC})$ of batteries
as a function of discharge current, battery SOC and battery temperature.
- 4 Battery energy efficiency (charge cycle)
as a function of charge power, SOC and battery temperature.
- 5 Battery energy efficiency (discharge cycle)
as a function of discharge power, SOC and battery temperature.

Again, temperature controlled battery bench tests would be needed to establish these functions accurately. Results could be generically specific to type of battery tested.

Subsidiary functions include: Module cell temperature as a function of insolation, ambient temperature and power delivery; Battery temperature as a function of ambient temperature, charge/discharge current, and battery SOC.

Battery SOC figures as the dependent and as a determining variable. Each hour, the present calculated value has a determining influence on the next hour's calculated value, together with other determining variables. When battery SOC falls below a set value, the system fails, while at full charge, excess array power is wasted.

Such a model, if accurate, would have a number of advantages:

- Full modelling of system performance offers time-continuous response to continuous weather-record input data. By inputting sequential data for many years, long-term performance probabilities can be derived without the errors of statistical reduction of weather data.
- Validation of the model against monitored data is aided by continuous capability. Any observed weather and load conditions can be used as simulation input data, and simulated results can be tested against monitored performance.

- Simplifying assumptions about the performance of components in the system are reduced, and replaced where necessary by empirically derived functions, providing a more accurate basis for assessing the accuracy costs of simplifying the model.

Disadvantages in the present context are:

- Establishing some of the functions requires additional bench tests.
- Empirical functions derived from bench tests can be component specific, so that a representative range of tests would be needed to establish generalisable functions.
- The proposed simulation model would be costly of computing time (estimated as about 8 hours processing for 1 year's data, on standard PC), reducing the time available for mapping sets of options across many years' input data.

This approach would be favoured as a building stage in a project aimed towards careful development of heuristic sizing methodologies suited to the Southern African region. Development of the model would require additional empirical work, program development and testing, validation of the model against data from monitored PV installations, and consequent modifications. Once validated, the model could provide predictions against which simplified sizing methods could be evaluated.

A similar project has proceeded at Sandia National Laboratories, Albuquerque, New Mexico, under the funding of the US Department of Energy. It is probably wiser for technologically peripheral countries to wait for such research to be done in the centres rather than to spend R&D funds on similar research. However, the research output of the advanced countries does not always embrace the concerns of developing areas.

The simulation model developed at Sandia is available as a program called PVFORM, authored by David Menicucci and James Fernandez (1985). It follows an hourly energy accounting approach very similar to the form proposed above, but contains a crucial assumption which, at

present, is generally not applicable to most photovoltaic installations in developing areas. This is: that the system being simulated has optimum power tracking electronics.

This assumption enables prediction of available array power without reference to interaction of array IV curves and load lines. The optimum module conversion efficiency, adjusted for cell temperature, and POA insolation are then all that is needed to predict array output.

The structure of the simulation code in PVFORM depends upon this assumption, and an alternative model for array generation which took account of interaction between array output characteristics and continuously changing load lines could not be substituted into the existing program.

David Menicucci, on request, advised that in the absence of an optimum power tracker, prediction errors would typically not exceed 15%, but agreed that a different approach to modelling array generation would be required to achieve greater accuracy.

Optimum power trackers may be standard equipment in sizable photovoltaic installations in the advanced countries, but at present optimum power tracking is generally not widely employed in small installations in developing areas.

A less exhaustive but elegant simulation model developed by Yaw-Juen Wang, at the Asian Institute of Technology, Bangkok (Wang, 1987) takes the step of modelling array IV curves, but then incorporates the assumption that power takeoff is at a constant voltage, eg. 12 volts for a 12 volts nominal system. This is equivalent to assuming a constant and vertical load line. The effect is that array power would be somewhat underestimated, by up to 15% if applied to the present system, though by a smaller amount in critical conditions of low insolation levels and low battery SOC.

9.1.2 Reductive model for critical conditions

Here the approach taken is to ask: what is the minimum information needed to predict the probability of system loss of power (due to energy deficit) under specifiable climatic and operating conditions?

Instead of predicting system performance continuously for a full range of climatic conditions and system states, attention is restricted to periods of energy deficit - where more energy is consumed by the load than is delivered by the array. As daily energy deficits accumulate, they bring the system towards its cut-out point, where batteries are depleted to their lowest permitted State of Charge.

Since the model now is based on integrated energy flows, over a timescale of runs of days, leading to depletion of system reserve energy storage, it is possible to avoid hourly energy accounting and instead to use daily or longer-runlength totals and averages for insolation income and load energy demand. By restricting attention to energy deficit periods, certain simplifying assumptions can be made about system performance, and in fact the modelling burden shifts rather to the statistical treatment of insolation data.

9.2 Form of the Model

The aim is to produce two sets of curves, sharing a common horizontal axis, which represent respectively

- 1) The minimum average insolation energy per day required to keep the system above its cut-out point, given array size, battery capacity, and average daily load.
- 2) The minimum expected average daily Plane of Array insolation, over runs of days from 1 to n, at selected probability levels.

Intersections between the two sets of curves allow prediction of the probability of system loss of power, due to accumulated daily energy deficits.

9.2.1 POA insolation energy demand curves

Critical conditions, leading to system loss of power, are likely to be characterised by

- low insolation levels
- relatively low module cell temperatures

States of system during a run of such critical conditions are likely to be characterised by

- depleted batteries
- high energy demand relative to available array power

Consequences are that as the system approaches a loss of power point, it is likely to be operating in a convergent efficiency range.

Optimum module conversion efficiencies are increased at low cell temperatures, corresponding to low insolation levels. For the present system, monitoring data show typical cell temperatures in the 15 to 20 degrees range during such periods, and observed module conversion efficiencies slightly above the tested value of 6.3% (corresponding to 25 degrees module cell temperature).

In general, cell temperature is strongly correlated with ambient temperature and insolation. In this study, regression of cell temperature on these variables yielded a multiple R-square of 0.99 (all monitored months included) and recorded cell temperature could be well predicted as equal to ambient temperature plus $0.015 * \text{POA}$ insolation, where POA insolation is in W/sq.m and cell temperature is in degrees C. The exact relationship would depend on module thermal characteristics and method of array mounting, but it indicates that relatively low cell temperatures can be expected when insolation is low, especially in winter months.

Delivered energy efficiencies can be expected to converge in critical conditions. Two opposing effects are predicted.

The voltage loss across the Energy Management Unit is expected to move to minimum values, due to high system energy demand in relation to

available array power. From the monitoring data it was found that the voltage drop across the EMU correlated highly ($R=0.95$) with system energy demand in relation to available insolation, using, as an index for the latter, delivered energy divided by POA insolation. In high demand conditions, the voltage drop across the EMU converged in the range of 0.6 to 0.9 volts, representing a maximum power loss in these conditions of 4% of array power. For purposes of the model, a figure of 5% is adopted for the power loss across the charge regulator in critical conditions.

However, losses due to the array operating away from optimum power points are expected to increase in critical conditions, since battery charging voltage is reduced, and since the modules are expected to be operating at a lower range of cell temperatures, increasing optimum power array voltage.

The extent of the latter losses will depend on the difference between array optimum power voltages and battery charging voltages, and depends therefore on the modules employed and the expected cell temperatures during a critical run. For the present system, in the cell temperature range 20 to 30 degrees, losses of between 1 and 5% are predictable (from Section 8.3) as the batteries decline from full charge to minimum permitted state of charge. In a decline, from full charge to full discharge, a mean value of 3% is estimated for the average loss due to deviations from optimum power points.

The estimated average delivered energy efficiency is then

$$F_d = F_m * F_c * F_p \quad (1)$$

F_d : Average delivered energy efficiency
 F_m : Average module conversion efficiency
 F_c : Average charge regulator efficiency
 F_p : Average optimum power loss-factor

and values for the present system are taken as

$$\begin{aligned} F_d &= 0.063 * 0.95 * 0.97 \\ &= 0.058 \end{aligned} \quad (2)$$

This allows estimation of the average daily delivered energy, when array area is A sq.m and average daily POA insolation is P Wh/sq.m/day.

$$E_d = A * P * F_d \quad (3)$$

E_d : Average delivered energy per day (Wh/day)
 P : Average daily POA insolation (Wh/sq.m/day)
 A : Area of array (sq.m)

The delivered energy is the energy available for charging the batteries and/or powering daytime loads. The portion which is used directly for powering daytime loads does not suffer further efficiency losses (although the power consumption of the load may depend on delivery voltage). The portion which is used to charge the batteries, for later consumption by the load, is subject to the energy efficiency of the batteries' charge/discharge cycle. Thus the energy available for powering the load is

$$E_c = E_d * (1 - f * (1 - F_b)) \quad (4)$$

E_c : Average energy available for load consumption (Wh/day)
 f : Fraction of this energy cycled through batteries
 F_b : Average energy efficiency of battery cycling

It was noted earlier that the monitoring data do not allow for accurate determination of battery energy efficiencies, and that the observed gross values (in the region of 0.9) should be regarded with caution. There is also little help from the literature on photovoltaic system sizing. Estimations vary. A representative figure would be about 0.8, but evidence is seldom cited for the estimates used. In the PVFORM simulation program, the default settings for battery energy efficiency in the range 20-90% SOC give a value of 0.72. This is for lead-antimony flooded batteries. The value is user-settable, and evidence is not to hand for the initial default value. Chapman (1987) uses a value of 0.75 in his proposed sizing methodology. Buresch (1983:146) adopts a value of 0.85. In the professional sizing program reviewed in Section 9.5 below, the coulombic efficiency for Delco batteries is set as 98%, compared with

96% for deep cycle lead antimony batteries. Coulombic efficiency is a component of battery energy efficiency.

Battery energy efficiencies can be expected to be higher when charge and discharge currents are small in relation to battery capacity (as is the case in the present system), and when batteries are not above 90% SOC. Since both are true in the energy deficit conditions being modelled, battery energy efficiency is estimated as 0.85 in these conditions, somewhat below the monitored values but above more conservative estimates.

The fraction of delivered energy which is cycled through the batteries depends partly on what proportion of the load is at night. Night loads definitely require battery-stored energy. Daytime loads also require battery-stored energy when available array power is less than the load power consumption. In order to sustain the night and day loads in adverse and variable conditions, more than the night-time load energy will need to come from battery storage, on average. But the fraction of daytime load also requiring cycled energy is unpredictable, depending on the daily timing of the load and daily insolation profiles.

In the present system, major usage of the school television and video is assumed to occur during daylight hours. At the specification load of 10 hours' average usage per day, during school terms, it could be assumed that at least 6 hours would be during daylight, giving a night-time load proportion of 0.4. This proportion is conservative. However, some of the daylight load will require power assistance from the batteries in adverse conditions, so the proportion is raised to 0.6 for the average proportion of delivered energy cycled through the batteries.

The average daily energy available to power the load then becomes

$$\begin{aligned} E_c &= E_d * (1 - 0.6 * (1 - 0.85)) \\ &= E_d * 0.91 \end{aligned} \tag{5}$$

Combining equations (5),(3) and (2),

$$\begin{aligned} E_c &= A * P * 0.058 * 0.91 \\ &= A * P * 0.053 \end{aligned} \quad (6)$$

The average daily POA insolation required to supply this amount of average daily energy to the load is therefore

$$P = E_c / (A * 0.053) \quad (7)$$

It is now possible to calculate the minimum average daily POA insolation which is required to sustain the average daily load, in critical conditions, over run-lengths of duration 1 to n days.

This function depends on the installed battery capacity, which is defined as the discharge energy available from the batteries when they are discharged from their maximum permitted SOC to their minimum permitted SOC, at expected discharge current rates and expected operating temperature.

If the installed battery capacity is C Wh, and if the average daily load is L Wh/day, then the system has C / L days "autonomy". That is to say, starting from full charge, the batteries could support the load without any power from the array for C / L days.

For the first C / L days in any run, then, zero power is required from the array to support the load. However, if the system is to survive another day without loss of power to load, then it must have gained another L Wh of available energy along the way, through array generation.

Using Equation (7) to convert this energy requirement from the array to the corresponding insolation requirement,

$$P = L / (A * 0.053) \quad (8)$$

Thus for each day of continued operation beyond C / L days, the system requires an additional L Wh of available energy, corresponding to $L / (A * 0.053)$ Wh/sq.m/day POA insolation.

To survive for N days, the total POA insolation required is

$$(N - C / L) * L / (A * 0.053)$$

$$\text{for } N > (C / L) \quad (9)$$

and the required minimum average daily POA insolation is

$$P = ((N - C / L) * L / (A * 0.053)) / N$$

$$\text{for } N > (C / L) \quad (10)$$

P: Minimum average daily POA insolation (Wh/sq.m/day)

N: Run length in days

C: Installed battery capacity (Wh)

L: Average daily load (Wh/day)

A: Area of array (sq.m)

This constitutes the basic model for POA Insolation Energy Demand curves. Figure 9.1 illustrates the form of the function for a fixed daily load, and varying battery capacity. Figure 9.2 illustrates the function for a fixed battery capacity and varying loads.

Sample POA Demand Curves

Fixed Load, Varying Battery Capacity

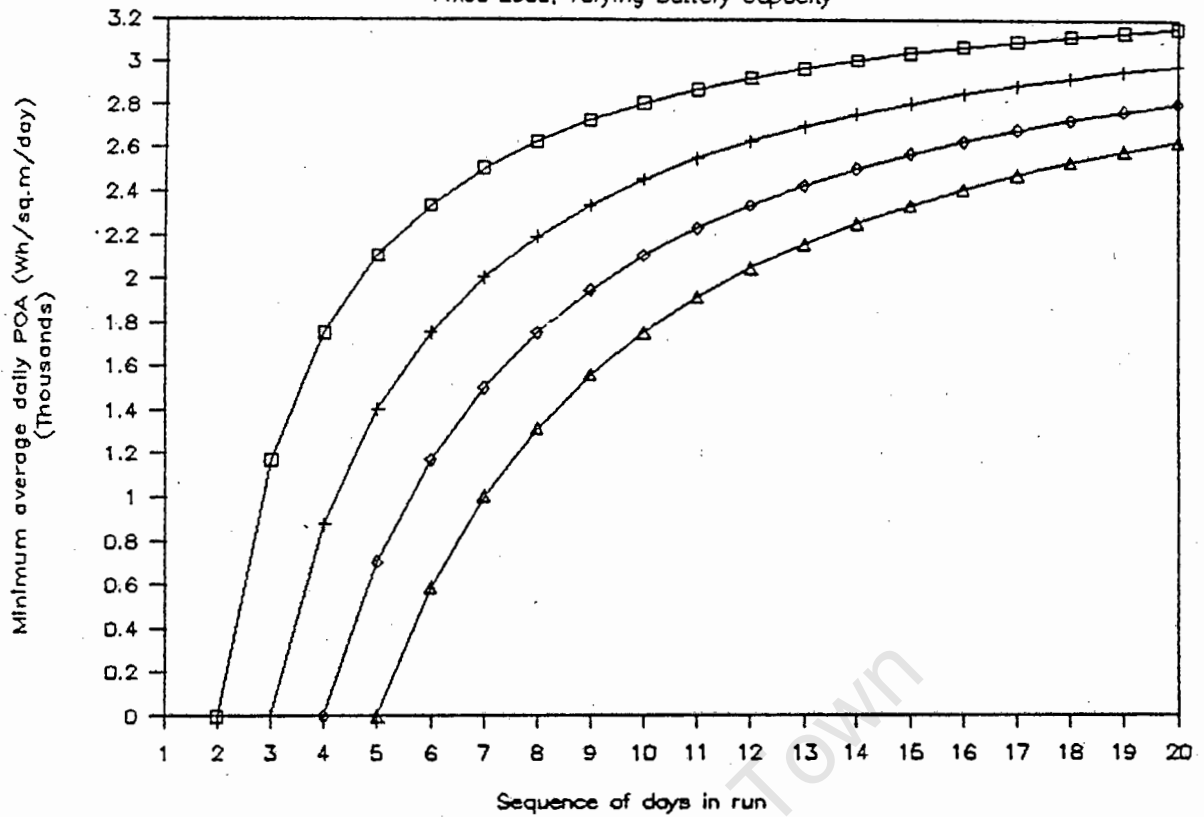


FIGURE 9.1 Sample POA Insolation Demand Curves for Fixed Load and Varying Battery Capacity

Sample POA Demand Curves

Fixed Battery Capacity, Varying Load

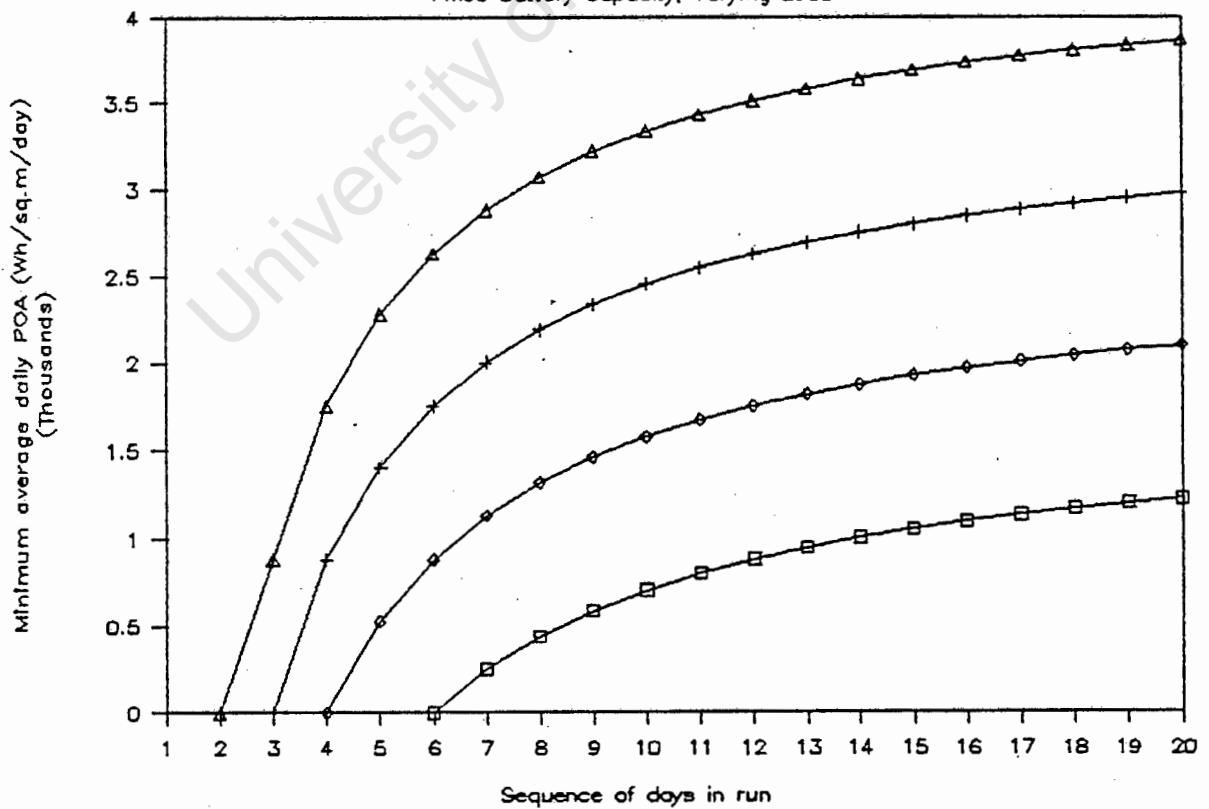


FIGURE 9.2 Sample POA Insolation Demand Curves for Fixed Battery Capacity and Varying Load

9.2.2 Probability curves for POA insolation

To intersect with the POA Insolation Energy Demand curves, a set of curves is required which show the expected minimum average daily POA insolation, over day runs of length 1 to n, at selected probability levels.

These probability curves will be location specific, and the method adopted for generating them made use of historical weather data. Hourly records for global and diffuse insolation for 10 years (1966 to 1975) were obtained from South African Weather Bureau records for the Forum weather station in Pretoria. Pretoria was selected as the climatically closest centre to Bophuthatswana, which provides hourly insolation records. A reasonable assumption is that, in general, and allowing for microclimate, areas of Bophuthatswana to the West of Pretoria will tend to receive similar or higher average insolation.

The following steps were taken:

- Hourly data were extracted from SAWB tape, and reformatted for PC processing.
- Records were screened for error codes and missing values. (Errors were treated conservatively, with limited monthly-hourly means replacement for sporadic errors; otherwise for multiple errors in a day, that day's records were omitted.) Records were rewritten in hourly sequence. The code used for this appears in Appendix C3.
- A tilt angle of 30 degrees from the horizontal, inclined true north, was selected for calculating insolation incident on a tilted plane. Previous computations using aggregate data had indicated this orientation was close to optimal for maximising worst-month mean POA insolation. Surface reflectivity was set at 0.25.
- All data were run through a model for calculating hourly tilt-plane insolation, adapted from the anisotropic tilt-plane model used in the PVFORM simulation program. Total daily POA insolation was derived for each day over ten years. The code

used for this appears in Appendix C2.

- Daily POA values were transferred to the mainframe for statistical analysis. The principal method was to calculate the average daily POA insolation for all runs of days, with run length 1 to 20 days, in the ten years data, and then to obtain cumulative frequency distributions of these values. The BMDP runstream used for this appears in Appendix C4.
- The probability of obtaining a minimum average daily POA insolation of P , for run-lengths of N days, was associated with the observed percentile in the cumulative frequency distributions over ten years. Thus, if 99.9% of observed values for run lengths of 5 days were found to exceed an average daily POA insolation P , the probability of receiving less than P in a 5-day run was taken to be 0.1% or 0.001.

More strictly, then, these "probability" levels are retrospective observed percentiles over the ten years analysed. The results for probability levels 0.001, 0.005 and 0.01 are depicted in Figure 9.3.

For example, the 0.001 probability value for run-lengths of 8 days is seen to be roughly 3000 Wh/sq.m/day. This indicates that for 99.9 % of all run-lengths of 8 days in the ten year period, the average daily POA insolation over 8 days was greater than 3000 Wh/sq.m/day.

Another way of expressing this is that the 8-day rolling average fell below 3000 Wh/sq.m only 0.1% of the time.

It was felt that this rather cumbersome and computer-hungry method of generating the curves was the most reliable. It is an accurate representation of probabilities over the ten years analysed (subject to the accuracy of the weather data, and tilt-plane computations). Long term representivity could be enhanced by analysing more years' weather data, or by investigating the probable errors in projecting from such a subset of years.

Minimum POA/day for Runs of Days

10 yrs Pretoria records; Tilt 30 deg.

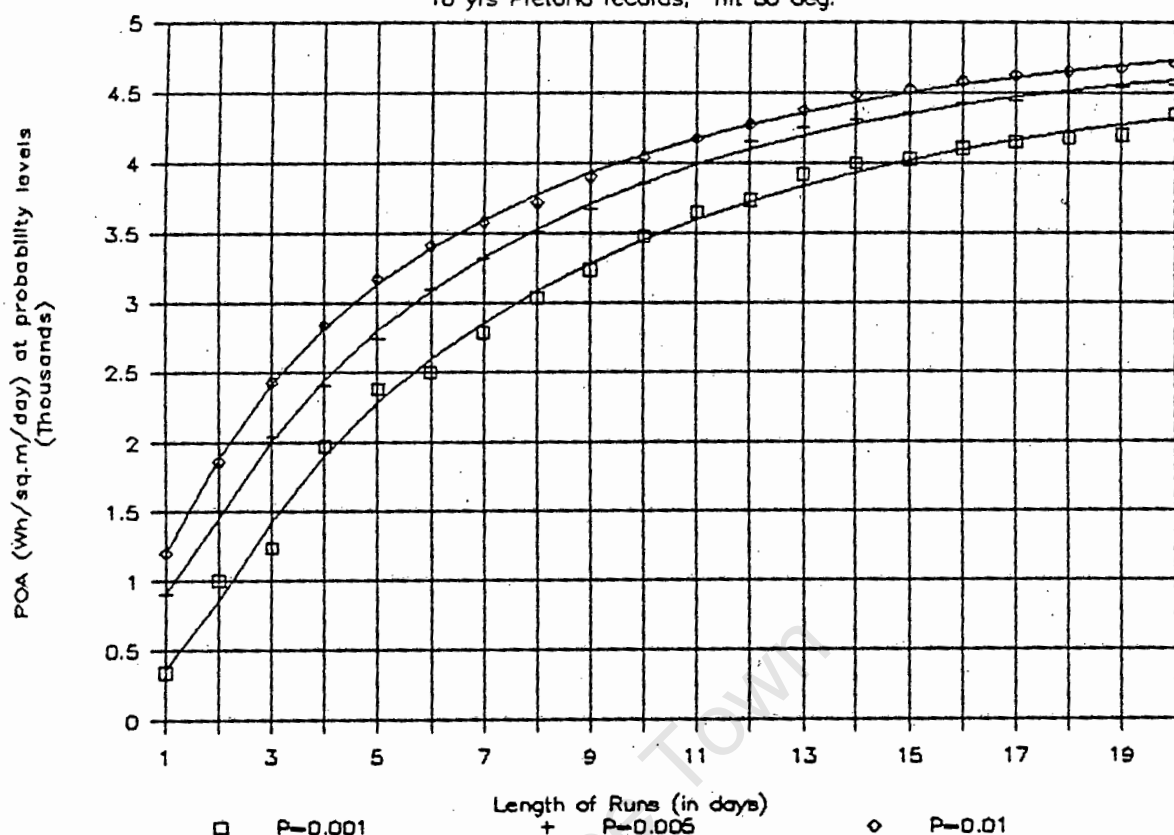


FIGURE 9.3 POA Insolation Probability Curves for Pretoria
(from 10 years' records, at 30 degrees tilt)

The location of percentile levels in large data sets requires greater computation time than calculating parameters such as the mean and standard deviation. It could therefore be of interest to ask whether such POA insolation probability curves could be modelled from more speedily computed statistical parameters.

If, for run-length N , POA insolation were normally distributed about the run-length mean, the run-length standard deviation could be used with z coefficients to locate selected probability levels. However, run-length POA insolation distributions are skewed, with long tails at the lower end (low insolation runs). Thus the empirically observed percentiles in this region are substantially lower than corresponding normal curve percentiles. Figure 9.4 illustrates this, comparing observed percentiles at the 0.01 or 1% level with values computed from day-run means, day-run standard deviations, and the z coefficient for 0.01 one-tail probability.

With increasing run-length, the difference systematically diminishes, as would be expected. (Kurtosis is reduced as run-length is increased.) It should therefore be possible to model such observed percentiles from run-length location, dispersion and kurtosis parameters¹. There is no need for this in the present context. It could be a useful simplification if the method were intended to be applied more generally, for statistical condensation of weather data from many stations. A prior study point would be the degree to which the kurtosis of day-run distributions is site specific. It is expected to be sensitive to type of weather regime.

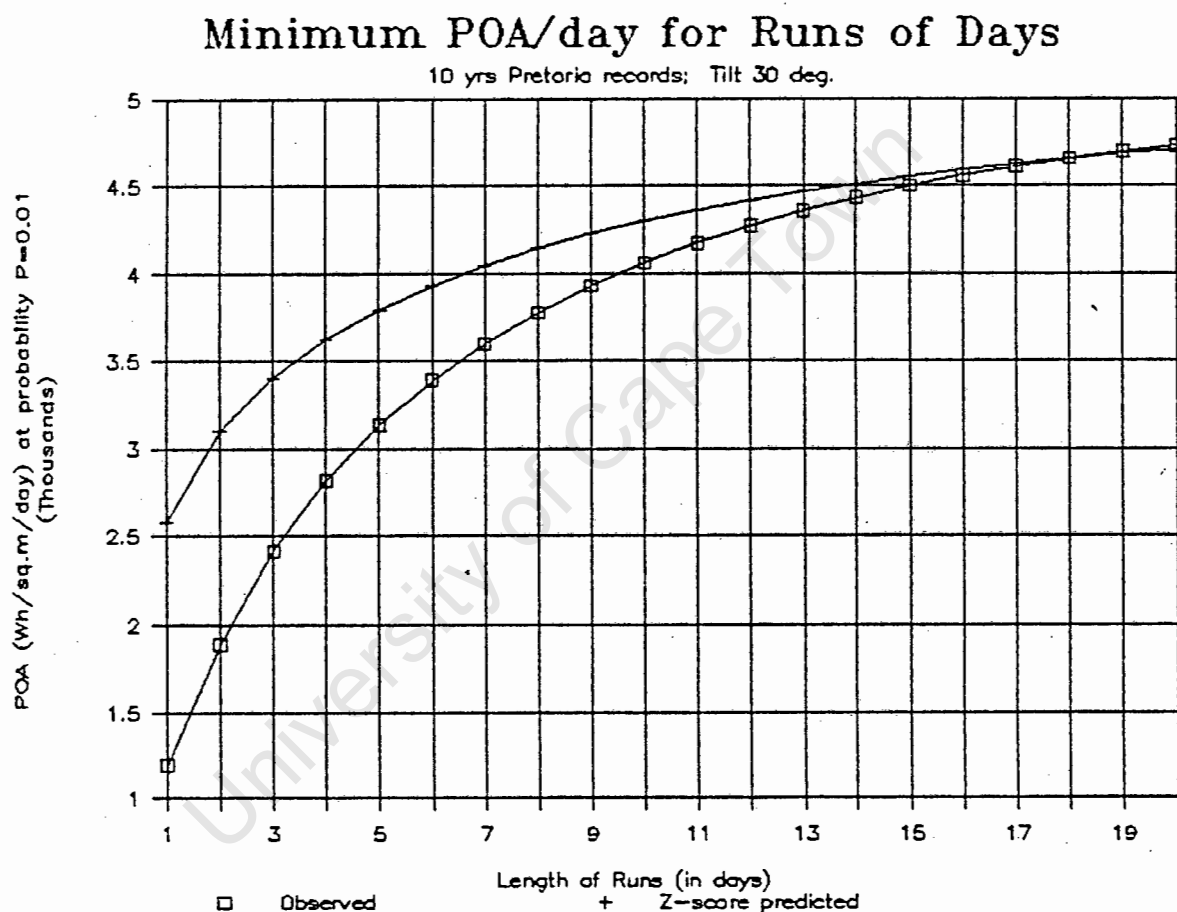


FIGURE 9.4 POA Insolation Probability Curve Compared With Lower Confidence Bound of Day Run Means Using Z-Coefficient for $P=0.01$

¹Some PV sizing methodologies (cf. Macomber et al, 1981; Rosenblum, 1982; Borden et al, 1984) estimate loss of power probabilities on the assumption of normal distribution of daily insolation. Figure 9.4 indicates scope for inaccuracy from this assumption, at low percentile levels, particularly for shorter run-lengths. A practical consequence of assuming normal distribution could include undersizing of the battery storage required to attain a selected loss of power probability.

Projecting observed percentiles from historical weather data into the future entails uncertainty, which could be partially evaluated. If long-term trends in climate are insignificant in relation to variations from year to year (and the accuracy of solar radiation measurements), historical data can be regarded as a sample from a population which includes the future, and confidence intervals could be constructed around estimates derived from that sample.

Two points of view in this respect could be put forward.¹ One is that observed percentiles should be taken for what they are, and simply used as the best estimates for the future. Further estimates of uncertainty will themselves be subject to estimation uncertainties. The other point of view would see value in at least constructing confidence intervals around the percentile estimates derived from the sample data. This would allow better judgement about the stability of estimated percentiles, and allow better informed evaluation of how much data is required to establish different insolation probability levels with acceptable confidence.²

To obtain such confidence intervals theoretically appears a difficult task, given auto-correlation in daily insolation, and variably skewed distributions. The favoured approach would be to use "bootstrap" methods (cf. Efron and Tibshirani, 1986), generating empirical confidence intervals by Monte Carlo resampling of the sample data.

For present purposes of demonstrating the approach and method of the proposed Loss of Power Probability sizing model, POA insolation percentiles obtained from empirical weather records have been accepted as the basis for judging photovoltaic system sizing and performance, without statistical evaluation of further prediction uncertainties. If the model were to be used as the basis for a more generalised sizing methodology, then bootstrapping the observed percentiles would be a recommended future step.

¹These views were suggested by W Zucchini, Professor of Mathematical Statistics, University of Cape Town (pers. com., 1989).

²Klein and Beckman (1987) question the stability of $P < 0.01$ estimates from historical weather data. Bootstrapping empirical run-length distributions could aid the enquiry.

9.2.3 Modelling the POA probability curves

To assist computation of Loss of Power Probabilities, the curves were fitted as mathematical functions of run-length.

For run-lengths 1 to 20 days, fairly good fit can be obtained from the simple logarithmic function

$$\text{POA} = a + b * \ln (\text{run-length}) \quad (11)$$

Using this function, R-squared values for the regression of fitted predictions on observed values exceeded 0.99 for this range of run-lengths. However, this form of function misrepresents the asymptote of the dependent variable, and leads to over-estimation at higher run-lengths.

All the curves are finally asymptotic to the mean daily POA insolation for the 10 years' weather data (mean daily POA = 6130 Wh/sq.m/day, for run-length 3652 days) and ideally a fitted function intended to model any run-length should reflect this.

But the Loss of Power Probability model aimed at here is intended for critical sizing calculations, and it is felt that deficit run-lengths greater than 1 month should not be considered. The reasons are

- assumptions in the model may be strained, if applied over so long a period
- such long deficit run-lengths, if determinant of system sizing, would indicate gross oversizing of battery capacity: battery storage would be fulfilling a seasonal adjustment function, rather than a short term storage function
- in such a situation, batteries would be at low SOC for extended periods, instead of for short durations due to non-seasonal weather variations, and battery life would be jeopardised

Accordingly, a conservative approach is adopted for modelling the POA probability curves:

- high accuracy of fit is sought for run-lengths 1 to 20 days
- conservative extrapolation for run-lengths 21 to 30 days
- an imposed POA probability ceiling for run-lengths greater than 30 days¹

These criteria are fulfilled by functions of the form

for Probability p and Run-length N ,

$$\text{Daily Minimum Mean POA } (p, N) = a + bN + c/N + d(\ln(N))$$

where for $N > 30$, $N = 30$ (12)

Regression values for the goodness of fit (R-squared), constants, and coefficients for this fitted function were:

For $N = 1$ to 20

Probability level, p	R-squared	Constant	Coefficients			
		a	b	c	d	
0.010	0.999	30	-64.253	1230	1975.75	
0.005	0.999	-1170	-87.414	2174	2468.29	
0.001	0.996	-2134	-87.411	2589	2692.51	

The equations given by (12) are written in Appendix C5 (optimisation program). They have been used for the curve-fitting in Figure 9.3 and are used for subsequent system-sizing calculations.

¹ If economical battery storage was available, that was not subject to the stratification dangers of prolonged states of discharge, the assumptions leading to this constraint should be revised.

9.3 Combining the Curves for Loss of Power Probabilities

POA Energy Demand curves from (10) can now be superimposed on the POA probability curves from (12). The combined curves are now referred to as Loss of Power Probability (LOPP) curves, since the purpose is to indicate the probabilities of system loss of power to load, due to insufficient insolation energy, given system parameters. Figure 9.5 illustrates this, using the following values for array area, average daily load and battery capacity in (10):

Array area: 2.156 sq.m
 Average daily load: 450 Wh/day
 Installed battery capacity: 3530 Wh

These values correspond to the system monitored, and to its design load. (Note: an adjustment is made below to battery capacity).

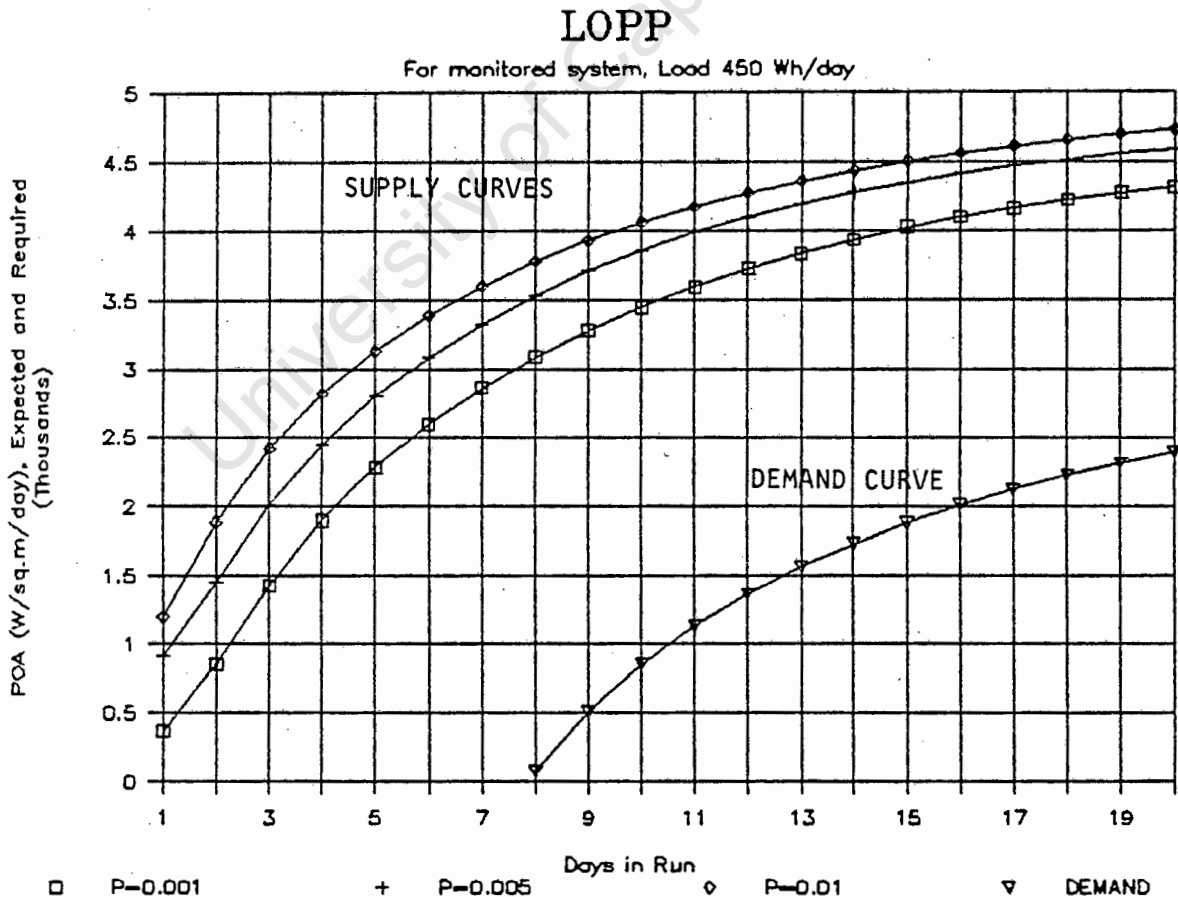


FIGURE 9.5 Loss of Power Probability Curves for the Monitored System at Design Load

Figure 9.5 shows that the POA energy demand curve, for sustained system power to load, is considerably below the POA supply probability curves, for any length of run in the range 1 to 20 days. This would indicate that with this average daily load, the system has a negligible chance of failing under Pretoria insolation conditions.

The large battery capacity provides over 7 days autonomy. Because of this degree of autonomy, and the array size in relation to the design load, it is indicated that starting from fully charged batteries, the system could survive a 20-day run with a minimum average daily POA insolation of about 2400 Wh/sq.m/day. The POA probability curves show that there is a negligible chance of such low average daily POA insolation over any 20-day run. The minimum expected at a probability of 0.01 is over 4700 Wh/day for a 20-day run.

9.3.1 Adjustment to battery capacity

The question might be asked: will the system start off with fully charged batteries at the beginning of any deficit run?

- 1 Two (or more) consecutive POA deficit runs will be subsumed under a deficit run of greater run-length, unless in between the shorter deficit runs there is sufficient POA energy to make up for the deficits. Thus, for example, two successive 5-day deficits, separated by say 5 days of surplus, will feature as a 15-day deficit, unless the 5 days surplus is sufficient to make up for the 10 days of deficit.
- 2 However, in recovering to full charge after a deficit, system efficiencies can be expected to deviate from the assumptions which were made for critical conditions. Specifically, as the batteries approach full charge, system energy acceptance decreases.

It is possible then that over a period of non-deficit, although sufficient POA insolation is predicted to make up for included deficit runs, this energy will not be all converted at the efficiencies used in the model for critical conditions. Efficiencies will be significantly lower as batteries approach full charge.

A simple adjustment is therefore introduced in the model, based on the premise that significantly lower efficiencies occur when battery capacity exceeds 90 % SOC. To account for this, and for progressive slighter drops in efficiency below this SOC, the assumption is made that charging efficiencies for $\text{SOC} > 90\%$ are zero.

It could be objected that battery charging efficiencies above 90% SOC will not be zero, and will only approach zero as SOC approaches 100%. The rationale for introducing this adjustment is as follows. At higher states of charge (perhaps $\text{SOC} > 85\%$) it can be expected that battery charging efficiency will be a function of state of charge, strongly so at very high states of charge. Unfortunately, the model cannot provide a prediction of the probability that batteries will cycle temporarily in this region, and that uncertainty could be significant (a) in the case of longer critical runs which include sub-runs of surplus POA insolation, and (b) as a carry-over from marginal non-deficit runs.

There are further uncertainties in battery electrochemical behaviour, which cannot be fully modelled. For example, battery charging efficiencies, full-charge battery voltages and full-charge capacity are variably affected by electrolyte temperature and by immediate and longer-term battery history.

Since the model is aimed at predicting the minimum required POA insolation to sustain power to load, rather than average performance (where greater latitude is implied for such deviations), it seems reasonable to avoid these uncertainties at the cost of introducing a boundary condition, within which the model assumptions can be expected to apply.

The boundary at $\text{SOC} > 90\%$ for battery charging efficiency is equivalent to derating the available battery capacity in any run, in Equation (10). The amount by which the battery capacity is derated depends on the maximum permitted depth of discharge used in setting the batteries' installed storage capacity. For the present system, batteries are permitted to cycle between 30 % and 100 % SOC. By effectively reducing the upper limit to 90 % SOC, the installed battery capacity is reduced by a factor of $(90 - 30) / (100 - 30)$, or approximately 0.86.

The function for the POA Energy Demand curve thus becomes

$$P = ((N - C_1 / L) * L / (A * 0.053)) / N$$

$$\text{where } C_1 = C * 0.86$$

$$\text{for } N > (C_1 / L)$$

(13)

P: Minimum average daily POA insolation (Wh/sq.m/day)

N: Run length in days

C: Installed battery capacity (Wh)

L: Average daily load (Wh/day)

A: Area of array (sq.m)

This function is used for subsequent LOPP calculations.

For comparison, Figure 9.6 shows the effect of this adjustment to the POA demand curve, using the same system parameters as before. The upper demand curve incorporates the adjustment to battery capacity.

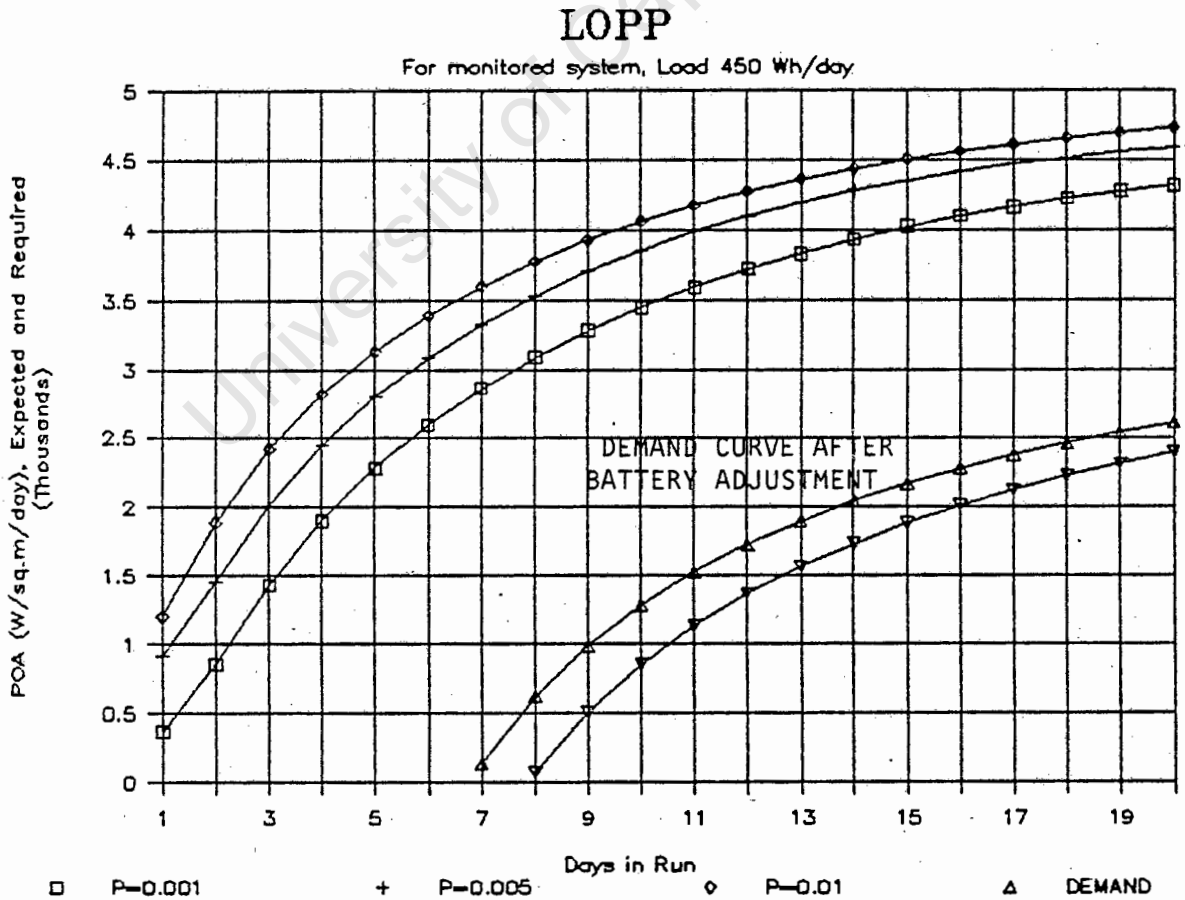


FIGURE 9.6 LOPP Curves for Monitored System Before and After Battery Capacity Adjustment, at Design Load

9.4 LOPP Predictions for The Monitored System

The following questions can now be addressed:

- What average daily load could the present system support at a specified Loss of Power Probability?
- In order to support the design load, with existing array size, what battery capacity is required for a specified LOPP?
- Could array size be reduced?
- What combinations of battery capacity and array size are predicted to satisfy a specified LOPP for the design load?

The predictions which follow are based on Pretoria weather records, an array tilt-angle of 30 degrees, ground surface reflectivity of 0.25, and the assumptions for system efficiencies described above.

Allowances for component degradation, and other design margins, are treated as post-sizing factors.

Predictions are made for a selected Loss of Power Probability of 0.01. This is equivalent to saying that on average over the years, the system would be expected to fail to supply the load on about 3.7 days per year. It is proposed that this is a suitable level for system availability in the current application of powering schools television, in view of the non-crucial nature of the application, and the economic savings of such a design criterion.

However, predictions are also included for a LOPP of 0.001, to show the design costs of achieving this higher level of availability (average 3.7 days downtime in 10 years' operation, for predicted performance without degradation). It should be noted that the uncertainties of prediction for such low LOPP levels will be greater than at higher LOPP levels.

9.4.1 Maximum predicted daily load

Figure 9.7 shows POA demand lines when the average daily load is increased while other system factors remain unchanged (array area 2.156 sq.m; installed battery capacity 3530 Wh).

It is seen that if the average daily load is raised to 690 Wh/day, the demand line intersects the $LOPP=0.01$ POA supply curve at a run-length of 20 days. But as can be judged from the gradient of the demand line, long term failures are predicted at this load level: for run-lengths greater than 20 days, the required POA energy exceeds the expected POA supply at probability 0.01.

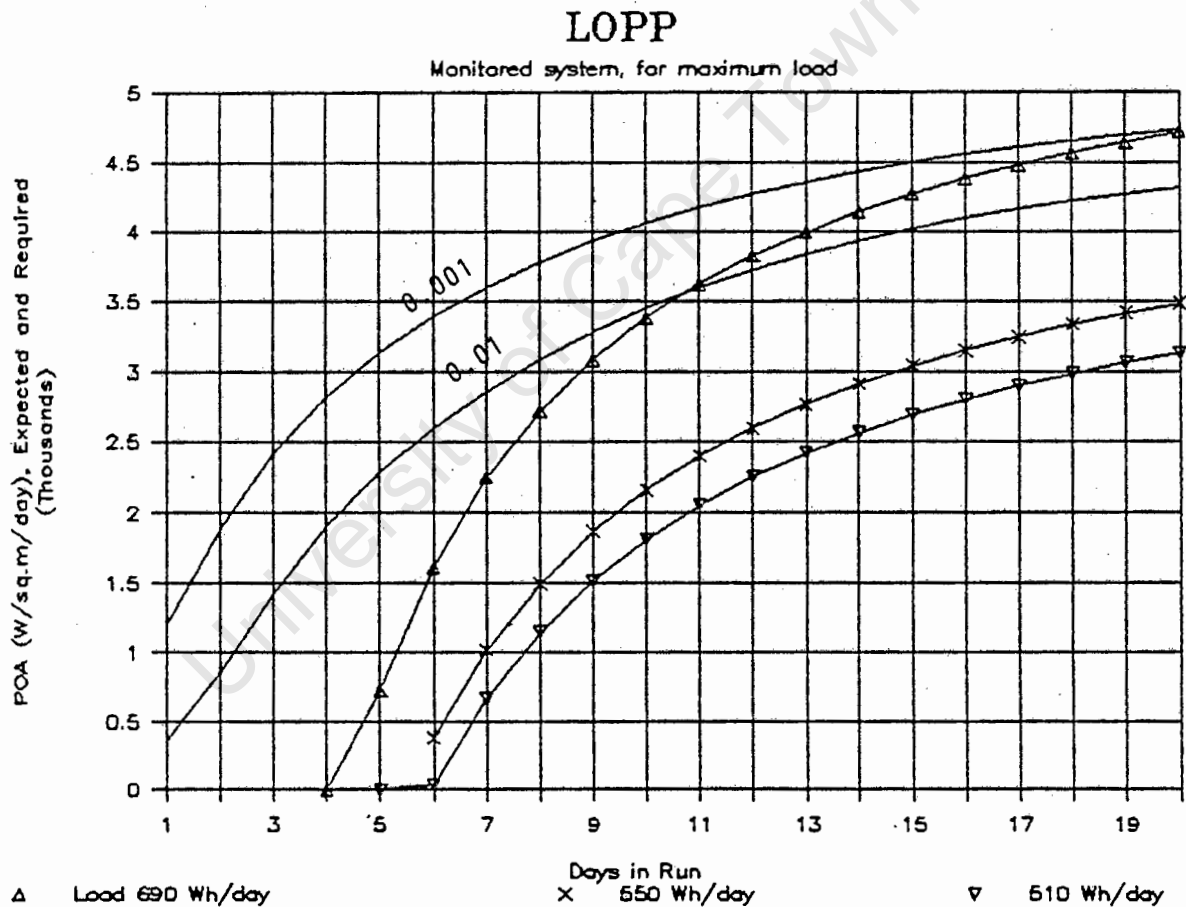


FIGURE 9.7 LOPP Predictions of Maximum Load Demand for the Monitored System

Realistic values for the maximum load which the present system could support are not convergent in the range shown in the graph. They are convergent with expected POA supply at very high run-lengths. This is

because the present system has excessive battery capacity in relation to the array size.

For example, according to the model, a load level of 550 Wh/day would survive long-term runs at a 0.01 probability. A load of 510 Wh/day would survive long term runs at a 0.001 probability. These curves are also shown in Figure 9.7. They almost converge with the POA probability curves at very high run-lengths (> 90 days).

In the model, conservative assumptions are made about such long run-lengths, expressed in the ceiling which is imposed on expected minimum POA for run-lengths greater than 30 days.

It is therefore suggested that the system could safely support a load of 550 or 510 Wh/day at the respective LOPP levels. These would be regarded as maximum loads for the system. (Note that degradation factors have not been included in the computations yet.) However, the fact that convergence is not reached for shorter run-lengths indicates that the battery capacity is oversized. The combination of array size and battery size does not allow for critical sizing, within the assumptions of the model.

Practical consequences are:

- If the system were operated at the maximum load which it could support, at $LOPP=0.01$ or $LOPP=0.001$, then batteries would be fulfilling a long-term storage function, and would be expected to cycle at diminished states of charge for extended periods. Another way of putting this is that the array power would not be sufficient to achieve full recovery of the batteries, over extended periods, at maximum load levels. This could be expected to be detrimental to the useful lifetime of the batteries.
- If the system is operated at a sub-maximum load (as presently designed, with a design load of about 450 Wh/day) then surplus array and battery capacity is available. This has the effect of extending the lifetime of the batteries, and/or providing a margin for degradation, but at the expense of somewhat higher initial capital cost per Wh/day load.

As will be seen below, the model predicts that both battery capacity and array size could be reduced, to support the design load.

9.4.2 Could battery capacity be reduced?

Figure 9.8 shows the predicted minimum battery capacities required for $LOPP=0.01$ and $LOPP=0.001$, at the existing array size of 2.156 sq.m and design load of 450 Wh/day.

If battery capacity is reduced to 1100 Wh (installed capacity) then the POA energy demand line has tangential convergence with the $P=0.001$ expected POA supply curve. Similarly, an installed battery capacity of 610 Wh is indicated as sufficient to achieve a $LOPP$ of 0.01.

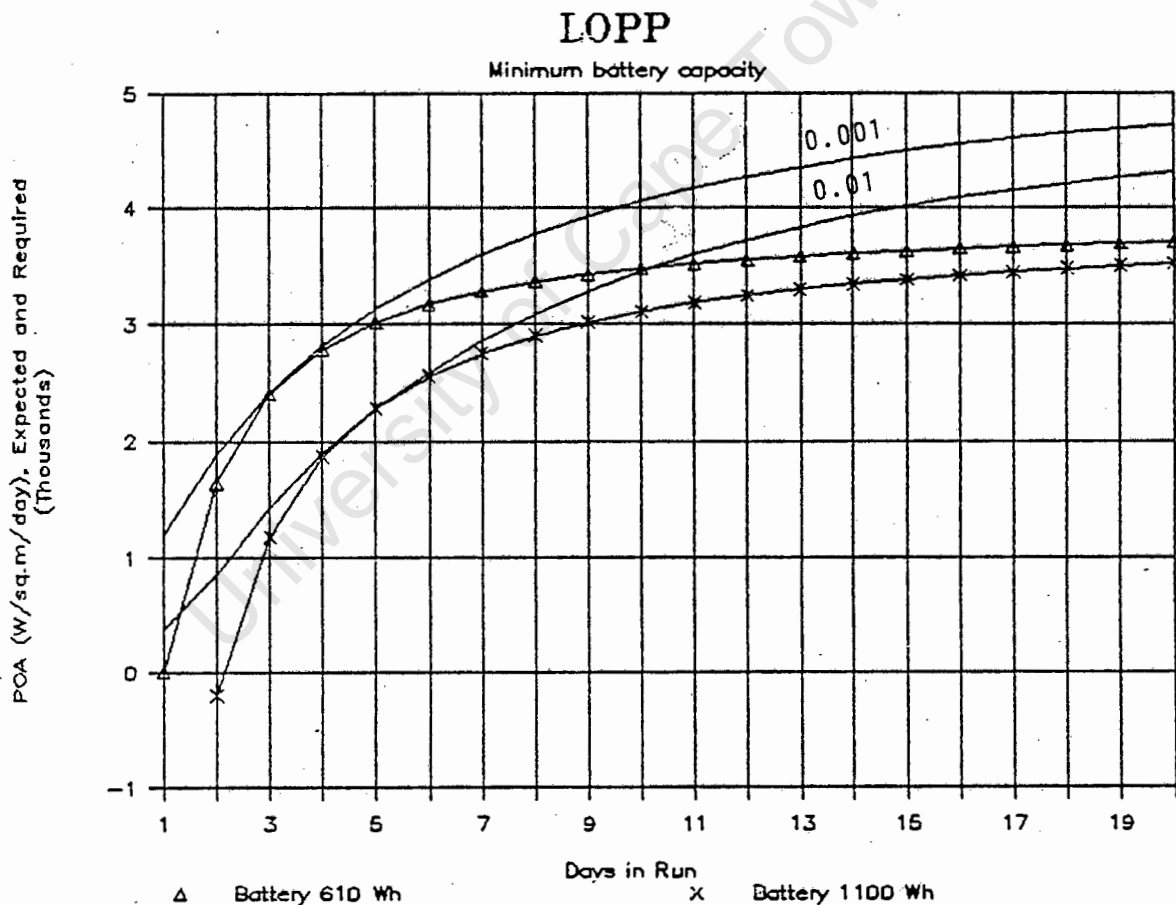


FIGURE 9.8 LOPP Predictions of Minimum Battery Capacity for the Monitored System

If battery operating conditions are the same as at present, installed battery capacity is about 70 % of rated battery capacity, so these figures correspond to about 1570 Wh and 870 Wh rated capacity, or

about 65 and 36 amp-hours respectively.

These values are very low. They would be treated with caution, and would not be recommendable.

Firstly, caution is called for because the model has less accurate definition at such low extremes. The extremes are reached because the present array size is somewhat large, in relation to the design load; a reduced array area would bring the model towards a more apt critical sizing region. (It should be noted again that degradation factors are introduced into this sizing approach after calculating Loss of Power Probabilities. The actual sizing of the installed system of course incorporates such design margins.)

Secondly, even if the predictions were reliable, economising to such a degree on battery size could be uneconomic for two reasons:

- the continual deep-cycling of the batteries would drastically shorten battery life
- the relative cost of battery storage in relation to the cost of photovoltaic modules is such that it is cheaper to reduce array size close to a minimum rather than to minimise battery capacity

Optimal combinations of battery and array size are discussed below in Section 9.4.4.

9.4.3 Could array size be reduced?

Figure 9.9 shows POA demand curves for different sizes of array, when battery capacity is maintained at 3530 Wh and the load is 450 Wh/day. (For comparison, the existing array area is 2.156 sq.m.)

An array size of 1.3 sq.m leads to failure within the range of the graph, for $LOPP=0.001$ - but, as was the case with maximising the load, consistent longer-term failures would be predicted: the demand and supply lines are intersect and diverge at greater run-lengths.

As with maximising the load, tangential convergence is only achieved at long run-lengths, due to the large battery capacity in relation to the design load. For example, array sizes of 1.75 sq.m and 1.90 sq.m produce demand curves which meet the supply curves at very long run-lengths. These could be regarded as minima for $LOPP=0.01$ and 0.001 , before adding any margin for degradation. The curves are shown in Figure 9.9. But again, such a system would not be optimally sized, since battery capacity could still be reduced. In order to arrive at more advantageous combinations of array power and battery storage capacity, it is necessary to vary both variables.

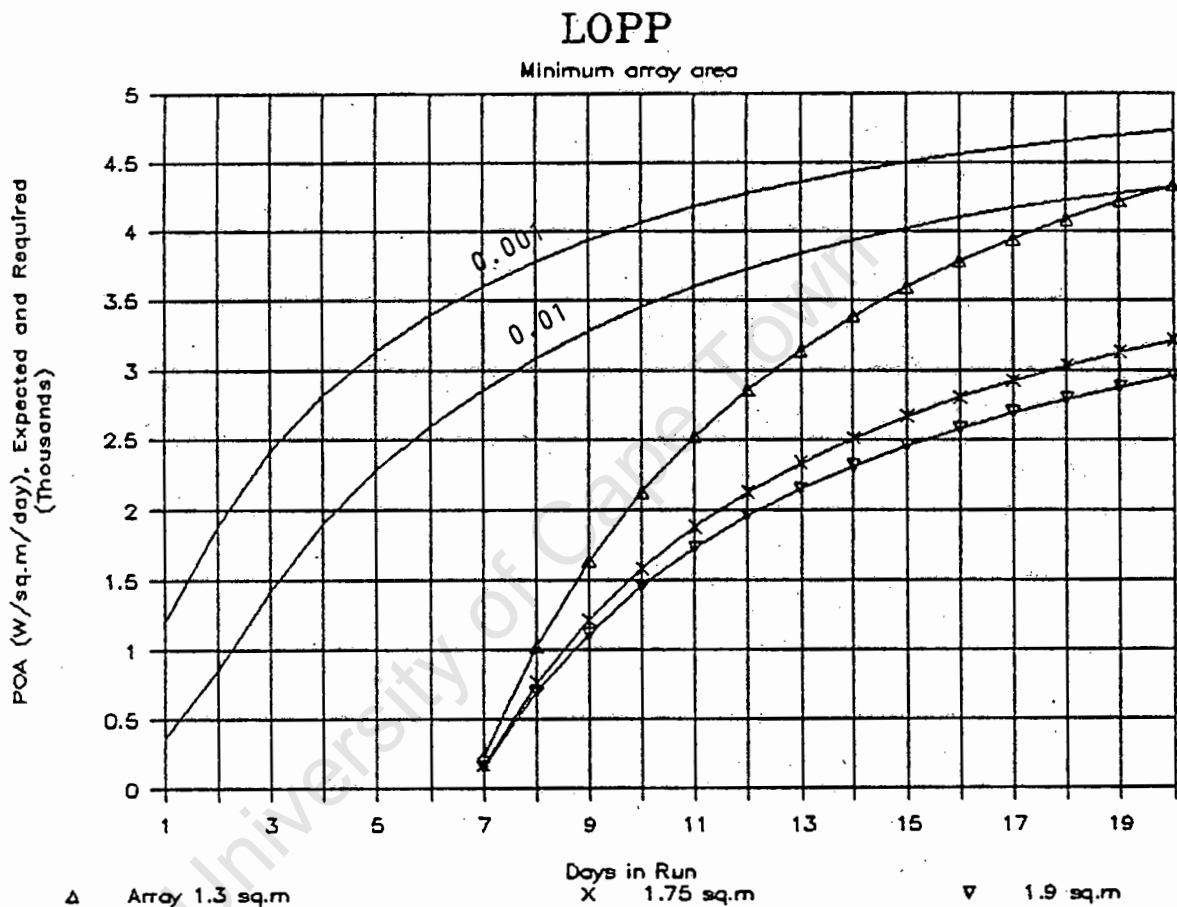


FIGURE 9.9 LOPP Predictions of Minimum Array Size for the Monitored System

Beyond this point, as battery capacity increases, the predicted array area approaches an asymptotic minimum. This asymptote is accentuated by the assumptions of the model (a ceiling on expected POA supply), and is used as the criterion for terminating the loops.

Results of these computations are depicted in Figure 9.10 and Figure 9.11, which show combinations of array power and battery storage capacity predicted to satisfy the design load (450 Wh/day) at LOPPs of 0.01 and 0.001 respectively. Array area has been converted to array Peak Watts, to give a more general indication of the sizing combination options.

(Array area calculations were based on tested Photowatt PW-P 801 module efficiencies; deconversion to general module Peak Watts uses the same specification power to area ratio in reverse.)

The figures show that there is a choice of combinations of array and battery size which are predicted to satisfy the load at these LOPP levels. For example, an array of power 140 Wp needs an installed battery capacity of 1050 Wh to attain $LOPP=0.001$, while the same array needs 570 Wh battery capacity to attain $LOPP=0.01$ for the design load of 450 Wh/day.

An array of 110 Wp attains $LOPP=0.01$ with installed battery capacity 950 Wh, while Figure 9.11 indicates that such an array is too small to achieve $LOPP=0.001$.

For system design, the choice of optimum combination entails firstly the selection of LOPP level, and then a choice from the battery/array ratios predicted for that LOPP level. Design margins can then be added to allow for degradation and unpredicted deviations.

It was suggested earlier that a LOPP of 0.01 should be suitable for rural schools television. This predicts average non-availability (excluding component failures) of 3.65 days a year. Because this is an average, there will be years when there are a greater number of days non-availability. This level of availability is likely to be greater than the availability of rural grid supply, but it might still be preferred to aim higher, in which case the 0.001 level might be selected. There would be little in favour of sizing non-crucial

systems for a higher availability than this.

When the LOPP level has been selected, the choice of which point on the curve to select as the design point would depend primarily on the relative cost of battery Wh versus array Wp. If only initial costs of components are considered, at current prices the substitution line is steep. Using present retail prices for Delco batteries and competitively priced modules, installed battery capacity costs are about R 0.27 / Wh and module costs are about R 17 / Wp. The substitution line therefore has a gradient of about -63 Wh/Wp.

If life-cycle costs are considered, then the gradient of the substitution line will be less, since batteries can be expected to need replacement during the life expectancy of the array. The reduction in gradient will depend on the relative expected lifetime of batteries and array, and on the discount rate (assuming future payments are converted to present value).

The cheapest point on the LOPP combinations curve is where the gradient of this curve is equal to the gradient of the substitution line.

In terms of initial installation costs, for both LOPP curves portrayed, this occurs at a well defined point: at the kink in the curve, where the model brings in a rapid array asymptote. Moving from this point to larger array sizes, the gradient of the LOPP curve is always less than the gradient of the substitution line.

This is also the case, according to calculations, when life-cycle costs are considered, providing batteries need to be replaced less than 5 times in the lifetime of the array (assuming 10% real discount rate, and stable prices), or less than 4 times (at a discount rate of 5%).

If these conditions are met, then the kink in the LOPP curves will again indicate the economic optimum for choosing the array/battery combination.

Array/Battery Combinations, LOPP=0.01

Pretoria weather; Load 450 Wh/day

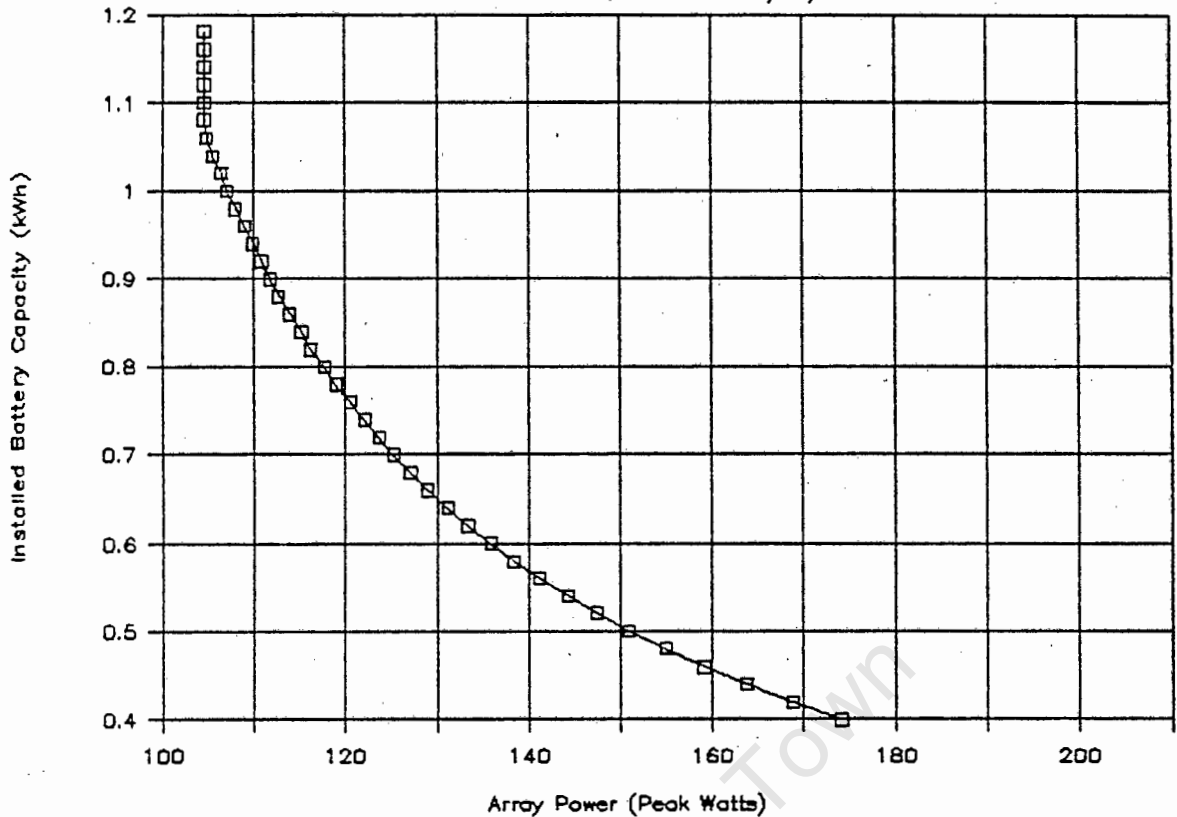


FIGURE 9.10 Array/Battery Combinations Predicted to Satisfy LOPP=0.01 for the Design Load in Pretoria Weather

Array/Battery Combinations, LOPP=0.001

Pretoria weather; Load 450 Wh/day

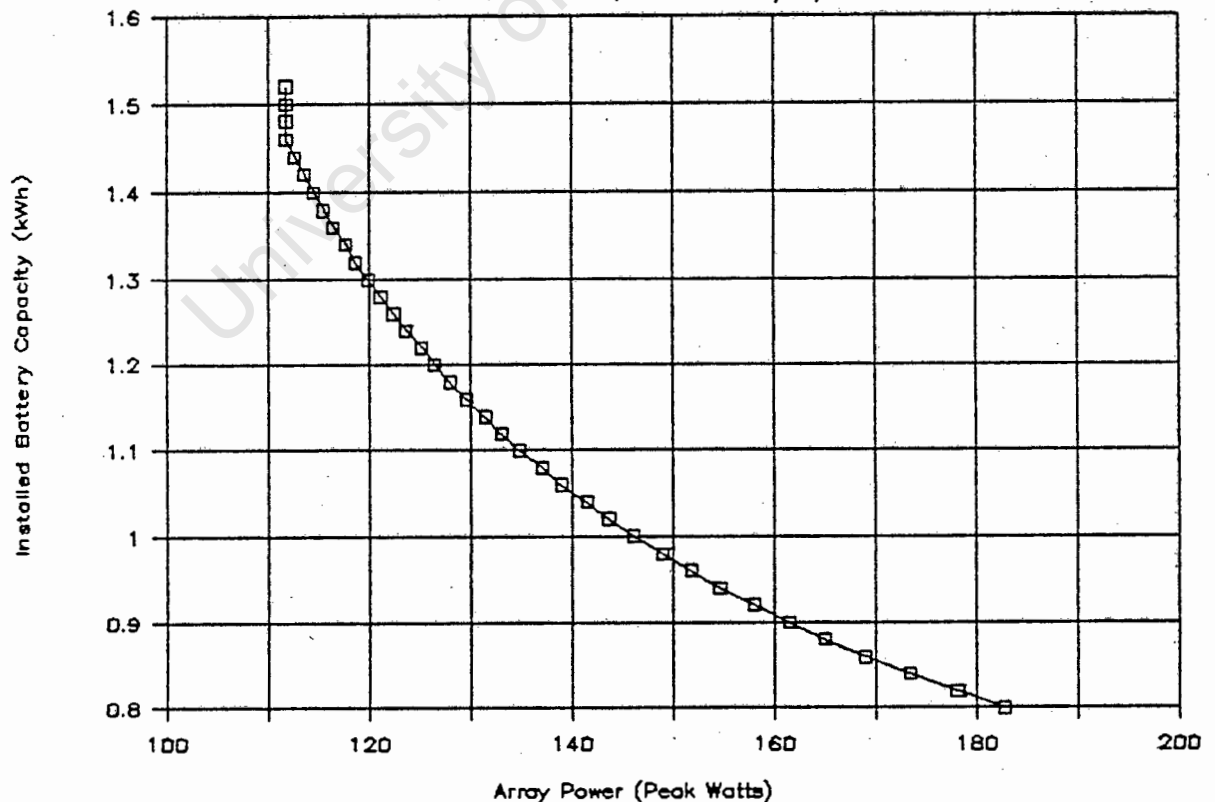


FIGURE 9.11 Array/Battery Combinations Predicted to Satisfy LOPP=0.001 for the Design Load in Pretoria Weather

If the above battery lifetime expectations were not met, then the optimal choice would lie further down the LOPP curves, and modelling life-cycle cost optimisation would be more complex: for example, battery life expectancy is itself partly a function of the array/battery combination, so substitution lines would not be linear, but convex; and they would be different for different LOPP levels, since a lower LOPP implies less frequent deep cycling of the batteries.

In either event, available components (modules and batteries) are not continuously variable in size, so combinations further down the curve could be selected, depending on the discrete size of available components, after incorporating design margins. Substitutions close to the optimal point would incur very little added cost, unless substitution lines were significantly convex.

For present purposes, it has been assumed that the kink in the curves can be used as the critical sizing reference point, with subsequent adjustments to be made for degradation factors and for giving consideration to enhancing battery lifetime.

The kink in the curve is accentuated by the assumptions of the model, but represents a predicted discontinuity in the storage function of the batteries. This can be seen by examining in Table 9.1 the critical run-lengths at which critical sizing combinations are obtained.

It is seen that short runs of bad conditions are determining, up to a certain battery capacity. For $LOPP=0.001$ and battery capacity up to 1460 Wh, the critical run-length is up to 7.2 days. Above this battery capacity, short runs are no longer as much of a threat to availability as long term runs (> 50 days), as predicted by the model. This is the sizing region, therefore, where the batteries are predicted to change from a short run storage function to a long run storage function, at this probability level. If the assumptions of the model are acceptable in application to a critically sized system which does not have optimum power tracking, then the arguments presented earlier for avoiding this long-term battery storage function apply. (The avoidance is of course itself a probability estimate, at the selected LOPP level.)

One feature of this model-predicted breakpoint in critical run-length is that it points to parsimonious guidelines for Loss of Power Probability system sizing in conditions equivalent to those modelled.

The salient conditions are:

- 1) The system to be sized has the same average array-to-load path efficiencies as the system modelled, over critical run-lengths.

This is not dependent on the module optimum conversion efficiency, which will vary for different makes of module, if array size is measured in rated peak watts. But it may be sensitive to the mode of power conditioning/charge regulation, and to the matching of array output characteristics to load input characteristics, as discussed in Chapter 8.

The model assumes no optimum power tracker, but it should be noted that the system modelled represents a particularly well matched system. (For comparison, calculations are repeated in Section 9.4.7 for less well-matched modules.) In general, the average array-to-load path efficiency will be sensitive to the optimum-power voltage of a given array, at expected deficit run average module temperatures, in relation to average battery charging voltages.

- 2) The array is oriented to true north at a tilt angle of 30 degrees, and is not shaded.
- 3) Weather probabilities are the same as those derived from ten years' Pretoria weather station records.
- 4) The average daily load is sufficiently steady, or contained, not to exceed the average daily design load over critical run-lengths.

Of these factors, as has been pointed out in other sizing studies (cf. Chapman, 1987:36) the dominating factor is variability in insolation, by location and over time. Application of condition (3) above would have to be circumspect, with regard to local conditions and strength of prediction.

If the conditions above are met, then the model predicts the following guidelines for system sizing. The predictions here include post-sizing allowances for performance degradation. Array power is derated by 15%, and installed battery capacity is derated by 15%. (The rationale for these margins is discussed in Section 9.4.6 below.)

TABLE 9.2 Rules of thumb for judging PV sizing in Highveld conditions (based on Pretoria weather)

If average daily load is L Wh/day,

	Design margin includes
For $P=0.01$ chance of failure	for degradation:
ARRAY POWER = $L * .275$ Wp	(15% allowance)
BATTERY = $L * 2.8$ Wh	(15% allowance)
(installed capacity)	
For $P=0.001$ chance of failure	
ARRAY POWER = $L * .30$ Wp	(15% allowance)
BATTERY = $L * 3.8$ Wh	(15% allowance)
(installed capacity)	

- Note:
- 1 Local solar radiation is the most unpredictable factor
 - 2 If more than half the load is at night, battery capacity should be increased
 - 3 System efficiencies equivalent to monitored system

Using the same derating factors, the model indicates the following array/battery sizings for the monitored system, to support an average daily load of 450 Wh/day, for Pretoria weather conditions:

$LOPP=0.01$

Array power	124 peak watts
Installed battery capacity	1247 Wh
Delco 2000 equivalent	74 amp-hours @ 24 volts
(70% max depth of discharge)	

9.4.6 Uncertainties in the model, and degradation allowances

Some of the main areas of uncertainty in the model are as follows:

- a) The long term stability of climatic patterns. While it can be accepted that ten years' weather station data may not be a large enough sample to obtain satisfactory representivity, it needs to be known whether a sufficiently long series of weather station records could be adequately predictive, how long such a series would have to be, and whether available solar radiation data in the region could approach this requirement. The expected inaccuracies from using available records in a statistically based LOPP sizing methodology could then be assessed relative to alternatives (such as the use of monthly mean data). A method for assessing the statistical uncertainties of prediction was suggested in Section 9.2.2 above.
- b) The accuracy of weather station records for solar radiation. As argued in previous chapters, measurement of solar radiation is easily subject to error, and the accuracy of any photovoltaic sizing methodology which makes use of local records will be subject to the accuracy of these records.
- c) The impact on photovoltaic module performance of changing spectral composition of irradiance, the extent of spectral variations, and the consequent differences between module power output and what would be anticipated on the basis of broad spectrum solar radiation measurements, such as weather station records. Since this LOPP model is based on minimum expected insolation receipts over runs of days, and since spectral variations may be more pronounced in such adverse conditions, it is felt that some allowance must be made for modules operating at lower efficiencies due to spectral selectivity.
- d) Similarly, a critical sizing model based on periods of insolation deficit may be more subject to error through losses in module efficiency at higher incidence angles of direct irradiation (eg. in winter months and in early hours of the day) or the angular incidence of totally diffuse irradiation. To provide some allowance both for this possibility and the possible spectral

effects in (c) above, an additional derating of 5% has been added to the conventional module lifetime degradation factor.

- e) An avoidable loss of module efficiency can occur through dust on the panel surface. For instance, the tested array showed 5.5% lower power before the surface was cleaned of dust. Although avoidable, there is a probability of some performance degradation through soiling, especially in long dry seasons, and if operating conditions warrant it, a further allowance should be added for this soiling factor. But it is not included here in the design margin.
- f) Atmospheric pollution (industrial, or dust) is not allowed for, nor particular effects thereof on spectral composition of irradiance: it would have to be assessed as a local adjustment to expected insolation.
- g) Expected module lifetime degradation. There appears to be little firm evidence on which to base an estimate for performance degradation of photovoltaic modules, and a conventional allowance of 10% has been made for this factor. This would presumably include an allowance for expected cell mismatches occurring within an array, which have the effect of limiting array current generation, particularly if many modules are in series.

The factors above, where taken into account, contribute to adopting a design margin of 15% for the photovoltaic array. This is higher than normal practice. The estimate includes the conventional lifetime degradation factor of 10% (which is in line with the guarantee by some module manufacturers that their modules will deliver at least 90% of rated power over a specified period), and then adds a further 5% for spectral and tilt-radiance efficiency losses, which could affect module performance particularly in those adverse operating conditions on which the model is based.

The degradation allowance of 15% for the batteries is based on the convention that a battery's useful lifetime has passed when it has fallen to about 80% of its initial rated capacity. If the aim of the sizing method is to predict the minimum size of components which will satisfy a selected loss of power probability over system lifetime, it

is important to allow for expected battery degradation before replacement. A margin of 15% does not fully cover expectable degradation, but should ensure the required availability of power to load over most of the batteries' life.

These proposed design margins are considerable. They may even seem to undermine the aims and rationale of a critical sizing approach. In part, they reflect remaining areas of uncertainty (notably in regard to the accuracy of module performance specifications and the effects of spectral composition and tilt-radiance on operating efficiencies). But they also reflect two competing present objectives.

One is to investigate in principle the savings which could be possible through loss of power probability photovoltaic system design, and to propose a suitable ~~method~~ for critical system sizing.

The other is to provide a fair engineering assessment of the sizing of the monitored systems. For this purpose, conservative margins have been included to allow for unresolved uncertainties in the sizing predictions of a theoretical model.

When the model predictions are compared with other sizing methods in Section 9.5, comparisons are made clearer by omitting the various derating factors employed in different methods; but for purposes of judging the sizing of the installed systems, the design margins above have been included in the comparison.

**TABLE 9.3 Comparison of LOPP Sizings for Modules with
Differing Output Characteristics**

[CONDITIONS THE SAME AS IN TABLE 9.2]

	Module characteristics as for monocrystalline PW-P 800	Module characteristics as for polycrystalline PW-P 801
LOPP=0.01		
Array power	143 peak watts	124 peak watts
Installed battery capacity	1247 Wh	1247 Wh
Delco 2000 equivalent (70% max depth of discharge)	74 amp-hours @ 24 volts	74 amp-hours @ 24 volts
 LOPP=0.001		
Array power	152 peak watts	132 peak watts
Installed battery capacity	1718 Wh	1718 Wh
Delco 2000 equivalent (70% max depth of discharge)	102 amp-hours @ 24 volts	102 amp-hours @ 24 volts

It can be seen that the critical array size would have to be increased, by a factor of approximately 15%, to achieve the predicted LOPP levels, using modules with the characteristics of PW-P 800 modules. This is due to power losses occurring through mismatch between expected loadlines and module optimum power voltages.

It can be noted, though, that the original Photowatt recommendation for sizing this system (using two PW-P 800 modules with total specified power of 164 peak watts) would have still been in excess of the LOPP=0.001 sizing prediction of 152 peak watts, even taking the optimum power losses into account. It would appear, then, that the original recommended system would have been both poorly matched and oversized.

9.5 Comparing Model Predictions With Other Sizing Methods

It is interesting now to compare the predictions of the model - and the sizing of the monitored systems - with the sizing indications of other sizing methods.

In this section, three other sizing methods are examined, in application to the monitored system. Two of these follow the LOPP concept, although their method is somewhat different. The third is a commercial program from a major photovoltaics company, designed for international applications, such as would be used by local representatives of this parent supplier/manufacturer.

9.5.1 Method 1

This method is the most recent to hand, and is authored by Richard Chapman in association with Sandia National Laboratories, New Mexico, (Chapman, 1987). It makes use of a highly simplified system simulation model, which is tested for validity against the full PVFORM simulation program (Menicucci and Fernandez, 1985); and then Loss of Load Probabilities derived from this model are generalised, observing simplifying assumptions about insolation probabilities (cf. Liu and Jordan, 1960; Klein and Beckman, 1987).

The simplified system model used for generating Loss of Load Probability functions in this method ("LOLP" is equivalent to LOPP) is based on hourly energy accounting at the battery, assuming constant values for component efficiencies. Chapman suggests that, providing suitable values for these efficiencies are chosen, the loss of accuracy is within an acceptable range. A further simplifying assumption is that all energy generated by the array passes through battery storage. He states without elaboration that this does not introduce inaccuracy in the calculation of LOLPs. These simplifying assumptions allow a very trim simulation program.

Using hourly weather station insolation data, LOLPs were calculated for a variety of conditions and the predictions compared against the predictions of PVFORM, which is considered a validated simulation model. Both programs made use of the Perez model for calculating the diffuse component of POA insolation.

The errors, in the order of $\pm 50\%$ in predicted LOLPs, were considered acceptable and "within the uncertainty associated with the LOLP values given by this sizing technique" (Chapman, 1987:39).

Twenty dispersed American weather stations were used, each providing twenty or more years of hourly insolation data, to generate LOLP functions for each site.

Chapman then makes simplifying assumptions about weather probabilities, drawn from the work of Liu and Jordan (1960) and Klein and Beckman (1987) respectively:

- the distribution of daily total insolation is not significantly dependent on types of climate
- the persistence pattern of weather is not significantly dependent on types of weather or locality

The LOLP functions for each site are derived from the hourly weather records used for the simulation for each site. However, using the two assumptions above, Chapman finds it possible to eliminate the need for any distributional information about local insolation.

Instead, all that is used, by way of insolation data, to model LOLP functions for any site is the mean daily insolation (G) in the winter solstice month, for that site.

In order to achieve this reduction, Chapman in effect fits a third-order polynomial of (G) to the data-derived LOLP functions. This is done separately for different array tilt-angles. Parameters for the polynomial are chosen such as to minimise the deviations amongst sites between fitted and data-derived LOLP functions.

Through such fitting, it was possible to achieve "very small" deviations amongst sites (1987:40). No measures of goodness of fit are provided, but this information may be available in an earlier paper (Chapman et al, 1986).

The product of this approach to photovoltaic system sizing is a series of nomograms, from which the prospective sizer should be able to

derive the optimum combination of array size and battery capacity, and the optimum array tilt angle, which will satisfy a stipulated load demand at a given location with a selected Loss of Load Probability.

Chapman suggests that the predictions should be valid for any location, for any daily load demand profile, and for monthly variations in average daily load which do not exceed $\pm 10\%$.

Using the sizing model

To operate this sizing method, one first specifies the site latitude and the mean daily horizontal insolation at the site for June (southern hemisphere) or December (northern hemisphere). These values are then applied in twenty separate nomograms, to obtain the "design insolation" corresponding to four groups of "size sets" and five selected array tilt angles.

The "design insolation" is a quantity peculiar to the model, which represents compartmentalised relationships between the site insolation, the array tilt angle, and four combinations of battery/array ratios which will satisfy subsequent LOLP calculations. The four "size sets" denote these battery/array combination compartments.

Next, the number of days' battery storage required to achieve a selected LOLP is derived from a further four nomograms (one for each size set). Each size set represents a battery/array-ratio compartment. Within each compartment, battery capacity is therefore taken as the determinant of LOLP.

After these steps, which are mechanical if laborious, the system sizer must now supply:

- a) the average insolation-to-storage efficiency of the system during the design month (June, for the southern hemisphere), and
- b) the average storage-to-load efficiency for this month

These are required to be real-time averages, in the design month, for system states where battery SOC is less than 100 %. The second is

relatively simple to estimate, but the first requires an assessment of the daily average interaction effects between array IV curves and the varying load, and the varying efficiencies of intervening components such as power conditioners and charge regulators.

Under the assumption of constant efficiency of the charge regulator, and presence of an optimum power tracker with constant efficiency, and batteries which operate in a SOC region where constant roundtrip energy efficiency is a reliable assumption, this estimation would be simplified. (These assumptions are made in an example offered for guidance in Chapman's sizing handbook, and they are also effectively built into the PVFORM simulation which was used to test the assumptions of this sizing method.)

In difficult situations, it is suggested that a "typical day" should be constructed, made up of monthly-averaged hourly insolation values for the design month, and then interacting component efficiencies should be calculated across that day, then averaged.

Normally, however, the sizing method would be used with gross estimates for system efficiencies, as is now done, with reference to the monitored system:

For Pretoria:

Latitude	26 degrees S
Mean June horizontal insolation	3900 Wh/day
Surface reflectivity	irrelevant to model

Tilt angles considered	30 degrees considered optimal for maximising worst-month mean POA insolation; but model only allows 26 and 36 degrees, so 26 degrees selected

After setting these initial parameters, the sizer is told to use a number of nomograms to calculate the Design Insolation and the Storage Capacity necessary for the selected LOPP level. This is to be repeated for the four "size sets".

Unfortunately, although this method is intended to be applicable to any site in the world, Pretoria insolation levels for June are outside the range of the nomograms offered, and so extrapolation is necessary. Definition is very low, and this may be why the nomograms are curtailed.

Approximately,

		LOPP=0.01
	Design insolation	Days' storage
Size Set 1	) 6 kWh/day	1.5 days
Size Set 2	) 6.1 kWh/day	2.3 days
Size Set 3	) 6.3 kWh/day	3.0 days
Size Set 4	) 6.3 kWh/day	3.8 days

This represents Stages 2 and 3 in the sizing process, after setting the site-specific parameters. The lack of definition is apparent in the values for design insolation obtained from the nomograms.

For Stage 4, efficiencies are estimated. Values derived from the monitoring data are used:

Average daily insolation-to-storage efficiency =

Average module conversion efficiency at average
 module cell temperature 30 degrees¹: 0.062 *
 Average regulator efficiency in June: 0.95 *
 Average deviation from optimum power points: 0.97 *
 Average charge-energy efficiency of batteries: 0.85

$$= .062 * .95 * .97 * .85$$

$$= .049$$

¹The observed time-averaged module cell temperature for June was 23.8 degrees C in daylight hours (from Table 5.9). However, for present purposes one should presumably use an energy-averaged value, so the higher value of 30 degrees has been estimated.

It could be difficult to make accurate and valid estimates for some of these component efficiencies; it helps to have the benefit of monitored system performance data, but even so, since the component efficiencies are intended to be averages for all periods in the design month when batteries are not at full charge, there is scope for error of estimation.

Average storage-to-load efficiency is easier to estimate, on the assumption that battery capacity is reckoned as available energy to load:

Battery discharge efficiency: 1.0
 Load consumption efficiency (allowing for difference between battery voltage and load voltage regulation): 0.96

These estimations allow prediction of the array and battery size combinations (four) which will satisfy the design load at a probability of LOPP=0.01.

Array area is given by the equation

Array Area = Load / (Design Insolation * eff(in) * eff(out))
 where eff(in) = 0.049
 eff(out) = 0.96 [by above estimations]

while the accompanying battery storage, depending on "size set" is

Days storage * Load / (permitted % depth of discharge)

The results, for the design load of 450 Wh/day, are:

	FOR LOPP = 0.01		Rated battery capacity at 70% DOD	
	Array area	Array Wp	(Wh)	(A-h at 24 volts)
Size Set 1	1.59 sq.m	100 Wp	964 Wh	40 A-h
Size Set 2	1.57 sq.m	99 Wp	1479 Wh	62 A-h
Size Set 3	1.52 sq.m	96 Wp	1929 Wh	80 A-h
Size Set 4	1.52 sq.m	96 Wp	2443 Wh	102 A-h

variations are independent of climate. The optimum tilt angle must depend on climate over the seasons if minimum long term LOLP is to be achieved. The method, if applied for all tilt angles offered by the nomograms, would predict a greater than optimal tilt angle for Pretoria conditions. June POA insolation would be maximised, but significantly lower POA insolation would be received in other months than in June at this tilt angle. It appears that

- (a) using midwinter as the design month is not a generally reliable approach
- (b) the derived relationships for LOLP functions may be weighted towards locations where winter clearness indices are substantially lower than in Pretoria (and much of South Africa).

4 In any simplified sizing model, the estimation of component efficiencies is likely to be subject to uncertainties and error. However, the problem is exacerbated in this case, because the estimated efficiencies must be valid average values for the whole range of system operation. Of course, if the right values can be found, the assumption of constant component efficiencies will "work"; but these right values are not necessarily indicated by information easily accessible to the system sizer. Even long term monitoring data will not be of great assistance, since average system efficiencies depend on the sizing of the system, (which is what is being sought). It is felt that the critical run LOPP approach suggested earlier in this chapter makes less dangerous assumptions about system efficiencies, since attention is restricted to critical runs, where component efficiencies are expected to be convergent towards more accurately predictable values.

5 The assumptions of constant efficiencies, and the device of forcing all array energy through battery storage, which are crucial to the elegant mathematical simplicity of the simulation model used for generating the LOLP functions, were held to be validated by comparing predictions against the PVFORM simulation model. This is not entirely convincing, since (a) the validation

tests included the assumption, on both sides, of optimal power tracking (PVFORM does not simulate systems without optimum power tracking); and (b) PVFORM was set to run for a typical residential demand profile. This would increase the proportion of load outside daylight hours, and could reduce any errors arising from the device of forcing all array energy through battery storage

- 6 It is felt that the observations of Liu and Jordan (1960) may not justify the starkly simplifying conclusion that insolation-distribution-dependent factors in the model can be adequately regressed on December/June mean daily insolation for any site. Briefly, Liu and Jordan's presented evidence (1960:10-12) indicates the possibility for considerable distributional divergence between sites at lower insolation percentiles, which are the insolation levels most likely to determine system Loss of Load. This question is raised in Appendix D1.

In conclusion, one would like to be able to recommend Loss of Power Probability sizing methodologies for general application in photovoltaic system sizing. The conceptual approach suits the probabilistic nature of the primary energy source, and would provide a basis for critical sizing to achieve a specified level of availability. However, it is not possible to recommend the method described above with full confidence. It is elegant and innovative in its simplifications, but is unlikely to be accurate for application in a full range of local conditions.

Chapman (1987:36) sums up the problem well (although with a more confident conclusion):

"The usefulness of the sizing nomograms depends on two factors; the accuracy and applicability of the simulation model. If the model is accurate, but only valid for one system, the nomograms are of little use. The same result holds if the model is applicable to any system, but is grossly inaccurate. Normally, as a performance model becomes more generic, it becomes less accurate. There is, however, an acceptable compromise."

9.5.2 Method 2

The next method examined also follows a loss of power probability approach, and is again an attempt at a unified methodology to size stand-alone photovoltaic systems with battery storage for a selected LOPP level. It derives from Borden et al (1984) and was published by Jet Propulsion Laboratories as a recommended sizing method for the U.S. Department of Energy.

At the heart of this method is a single sizing nomogram which economically portrays relationships between (a) the degree of array oversizing necessary, and (b) the corresponding battery storage required to sustain the load at a specified LOEP. LOEP denotes Loss of Energy Probability, and the recommended LOEP which defines the nomogram is 0.1 for the design month.

The design month is selected as that month of the year when the ratio of average POA insolation to average daily load is lowest. This will depend on the tilt angle of the array, which is selected to maximise this ratio in the worst insolation-to-load month of the year. For the present system, the optimal tilt by these criteria is very close to 30 degrees, and the corresponding design month is June.

The method only provides for sizing for a LOEP of 0.1 in the design month, ie. for a predicted average long-term probability of loss of power to load of 10% in that month. There is no direct way of assessing the probability of failure in other months, although the authors offer the suggestion that a design-month LOEP of 0.1 should correspond to a long-term average annual LOEP of about 0.02 to 0.04. In this estimate, Borchers (1989) suggests they are following earlier estimates by Rosenblum (1982). The selected design-month LOEP of 0.1 is put forward as providing a reasonable basis for comparing photovoltaic supply with alternatives such as genset supply, at comparable availability levels.

The sizing nomogram is reproduced in Appendix B7. Each curve portrays a relationship between "array sizing factors" and "battery storage sizing factors". These can be converted to required array power and battery capacity through a knowledge of average efficiencies of system components in the design month, and the average daily load.

All that is required to select a curve (or to interpolate between curves) is the average daily POA insolation for the design month.

Further selection of a particular point on the curve, representing a specific array-battery combination, can be done through costs analysis. (For initial guidance, a "lowest system capital cost" dashed curve is imposed on the nomogram; but for greater accuracy, life-cycle costs using local component prices would need to be calculated to find the optimal combination.)

This method therefore presents a simple and fairly rapid means of finding array-battery combinations to satisfy load demand at a design-month LOEP of 0.1. Before applying the method for the present system, it is useful to note some of the assumptions.

The fact that curve selection from the nomogram only requires one item of information - average daily POA insolation for the design month - draws attention to simplifying assumptions about climatic probabilities and associated photovoltaic system performance.

These assumptions include (a) that the distribution of daily insolation is relatively independent of location and type of climate, and that the distributional characteristics can be adequately correlated to monthly mean insolation for any month; (b) that it is adequate for purposes of probability analysis to assume that insolation is normally distributed (see Macomber et al, 1981, referenced by Borden et al, 1984). Macomber's approach to estimating LOEP's made use of normal curve probabilities, set by the mean and standard deviation of the expected insolation distribution. The condensation of this approach, in Borden et al, finds it unnecessary to know even the standard deviation. Borchers (1989) provides a fuller account of the development of Borden's sizing method from the earlier work of Macomber et al (1981) and Rosenblum (1982), and the assumptions held in common by these authors.

Such assumptions could be expected to lead to some inaccuracy in LOEP predictions, according to location and climate. To illustrate the kind of climatic variations which could lead to deviations from the fitted model: the worst insolation month for Pretoria can be calculated as June, if an optimum tilt angle of 30 degrees is adopted,

and if monthly mean POA insolation is the quantity to be maximised. However, according to analysis of weather station data, the variance in daily insolation is considerably lower in June than in some other months, due to generally cloudless Highveld winters; and in other months, where mean POA insolation may be fractionally higher, there is a higher probability of runs of low insolation days. This suggests that an oversizing factor which accurately represented June array requirements would be likely to misrepresent weather probabilities in other seasons, and vice versa. More generally, it is likely that the relationship between the design-month LOEP and annual LOEP would vary according to climate.

Applying the method

Applying this method to the monitored system, the month of June, for Pretoria and a tilt angle of 30 degrees North, provides a mean POA insolation level close to 5.80 kWh/sq.m/day. (This value, chosen from Table 6.1, corresponds with the data and tilt calculations used in the critical run LOPP predictions of Section 9.4, and is most suitable for these sizing comparisons.)

From the sizing nomogram (Appendix B7) the following array and battery sizing factors can be obtained, for a design-month POA insolation of 5.8 kWh/sq.m/day:

Array sizing factor:	4.9 kWh/sq.m/day
Battery sizing factor:	1.3 days storage

This combination coincides with the lowest system capital cost curve supplied in the nomogram. More precise economic optimisation could be performed using local substitution rates, but for present purposes this intersection is sufficient. (Morris, 1988, has modelled the relationships expressed in the nomogram, and the economic optimisation of array-battery combinations using local prices for life-cycle costs: with this refinement, the sizing indicated does not differ significantly from that obtained below.)

The array sizing factor is equivalent to a derated POA insolation expectancy, which indicates the degree of oversizing of the array required for the specified LOEP. To convert this value to the

required array power, the following system performance characteristics are needed:

Mean values for design month	Estimates for monitored system
Daily load energy demand:	450 Wh/day
Fraction of load energy passing through battery:	0.5
Power regulator efficiency:	0.95
Battery energy efficiency:	0.85
Module conversion efficiency at 25 degrees C:	0.063
Module efficiency temperature coefficient	-0.0028 /degree C
Mean operating module temperature	30 degrees C

Assuming all power to load passes through the Energy Management Unit (average efficiency 0.95) and 50% of consumed power passes through battery storage, the combined array-to-load efficiency is

$$0.95 * (0.5 * 0.85 + 0.5 * 1.00) = 0.88$$

and the array power indicated to meet the load (before temperature correction) is

$$\begin{aligned} \text{ARRAY POWER} &= \text{LOAD} / (\text{ARRAY SIZING FACTOR} * 0.88) \\ &= 450 / (4.9 * 0.88) \\ &= 104.4 \text{ Wp} \end{aligned}$$

After temperature correction for expected mean module operating temperature in June, this rises to 106 Wp.

It is recommended to include an array degradation factor. Assuming a conventional factor of 10% for array degradation, the indicated array power for this load at LOEP 0.1 is then 118 Wp.

The battery storage sizing factor of 1.3 days is converted to installed battery capacity:

$$\begin{aligned}\text{INSTALLED BATTERY CAPACITY} &= \text{LOAD} * 1.3 \\ &= 585 \text{ Wh}\end{aligned}$$

and, assuming a maximum depth of discharge of 70%, this can be converted to the rated battery capacity required:

$$\begin{aligned}\text{RATED BATTERY CAPACITY} &= 585 / 0.7 \\ &= 836 \text{ Wh}\end{aligned}$$

At 24 volts nominal, this is equivalent to 35 A-h rated storage.

Comparing the LOEP sizing of this method with the LOPP=0.01 sizing in Section 9.4, the LOEP array size is very similar, before derating and degradation margins are included (106 versus 105 Wp). The difference of about 5% in final recommendations can be attributed to different degradation estimates. For the LOPP model, a further 5% margin was added to the conventional 10% degradation factor, to allow for derated array performance in critical conditions due to spectral variation and incidence angles of POA insolation.

However, there is greater difference in the battery capacity indicated (35 A-h rated capacity for the LOEP prediction, and 63 A-h for the LOPP=0.01 prediction, assuming 70% depth of discharge and omitting degradation factors in each case). It should be borne in mind here that the LOEP sizing is for a higher probability of average long-term failure, in line with the authors' suggestion that a design month LOEP of 0.1 should correspond to a long-term average LOEP of about 0.02 to 0.04. This higher probability of loss of power could then be associated with the reduced battery capacity of the LOEP sizing.

The degree of indeterminacy of long-term annual LOEP could be considered a weakness in this sizing method. In this regard, it is interesting to apply the critical run LOPP model of Section 9.4 to predict the long-term average loss of power expected from this LOEP sizing of 106 Wp array power and 1.3 days battery storage.

For this purpose, system efficiency assumptions have been made as compatible as possible (see Appendix B8 for method), and the empirical data from 10 years' Pretoria weather records, statistically condensed as in Section 9.2.2, have been used.

Table 9.4 shows the results for runs of days from 1 to 16 (Column A). The minimum POA insolation per day required to sustain the load of 450 Wh in critical conditions, for the LOEP system sizing, has been calculated for each run-length (Appendix B8). Columns B and C show the percentage of day-runs, over ten years, which fall below these required POA insolation levels.

Since shorter run-lengths are subsumed under longer run-lengths, the maximum values in Columns B and C predict the relative frequency of loss of power to load over these ten years.

Column B values follow the full LOPP model assumptions of Section 9.4. In Column C, the "battery capacity correction factor" introduced in 9.3.1 to allow for reduced efficiencies near full states of charge has been dropped, to compare the effect of this safeguard in the model.

The results in Table 9.4 indicate that, according to the predictions of the critical run LOPP model, the sizing method of Borden et al (1984) applied to the present system would deliver levels of reliability within the estimates which the authors propose (between 0.02 and 0.04 long-term average LOEP). Over ten years, based on local empirical data, the model predicts an average loss of power to load of 3.4%. If the conservative "battery capacity adjustment factor" is dropped from the LOPP model, the corresponding incidence of loss of power to load would be 0.028.

This degree of correspondence between the proposed LOPP model and the Borden sizing method does not of course constitute an adequate cross-validation of either approach. The methods could be compared for a range of climatic conditions, to establish the variation in predictions; and independent validation against a reliable full simulation of photovoltaic system performance would be desirable.

TABLE 9.4 Model-Predicted Loss of Power for Method 2 Sizing,
Using Pretoria Weather Data

Load: 450 Wh/day Array: 106 Wp
Battery: 1.3 days storage
(24.4 A-h installed capacity)

Post-sizing design margins excluded

RUNLENGTH	RELATIVE FREQUENCY OF SUB-MINIMAL POA INSOLATION RUNS, OVER 10 YEARS	
[A]	[B]	[C]
1	0.0 %	0.0 %
2	1.4 %	0.9 %
3	2.8 %	1.8 %
4	3.3 %	2.4 %
5	3.4 %	2.7 %
6	3.4 %	2.7 %
7	3.4 %	2.8 %
8	3.4 %	2.8 %
9	3.3 %	2.6 %
10	3.2 %	2.7 %
11	3.1 %	2.7 %
12	2.9 %	2.4 %
13	2.8 %	2.2 %
14	2.6 %	2.0 %
15	2.4 %	1.7 %
16	2.2 %	1.5 %

From the comparison above, however, certain advantages for the proposed critical run LOPP method can be suggested:

- 1 The method of Borden et al (1984), as published, allows only for sizing at one LOEP level, a design-month LOEP of 0.1. This reduces flexibility of application. In sizing hybrid systems, for instance, one may be interested in sizing for higher probabilities of failure, while for applications where high availability levels are preferred (eg. for vaccine refrigeration) lower LOEPs would be of interest. The critical run LOPP model is readily adapted for variable LOPP levels. As shown above, it can be used to predict the LOPP of a given system configuration, as well as used to size system components for a selected LOPP.
- 2 The long-term LOEP associated with a design-month LOEP of 0.1 in the Borden method is only approximately indicated, and the relationship may vary with climate. A long-term LOEP of about 0.03 as predicted in the example in Table 9.4 might be considered unacceptable, depending on the application: it represents an average of 11 days failure per year, at the design load, and in any single year could substantially exceed that average. If one can only estimate the long-term LOEP as between 0.02 and 0.04, that latitude brings extra uncertainty to reliability decisions.

Perhaps such latitude is not unrealistic, in view of the limited statistical accuracy of predictions from historical weather data, especially at low percentiles. However, the proposed critical run LOPP model provides a firmer empirical base from which to make best predictions, and the method allows for statistical evaluation of the confidence of predictions, at various LOPP levels, through empirically based bootstrap resampling methods.

- 3 The assumptions contained in the Borden method, that insolation distributions are independent of climate type, and that probabilities can be derived from normal distribution theory, may lead to inaccuracies. The single comparison above provides no evidence of significant inaccuracy, relative to the predictions of the proposed LOPP model. It has been suggested earlier, however, that such inaccuracies would be most likely to occur at low percentiles, since this is where skewness in insolation

distributions causes greatest deviations from normality. The Borden method may partly escape such inaccuracies by selecting higher percentiles (10-percentile in the design month) as the basis for sizing estimates. The proposed LOPP model, however, makes no assumptions about theoretical distributions of insolation, nor the degree of correlation between mean monthly insolation and distributional characteristics. It should therefore provide a firmer basis for predicting system size for lower LOPPs than in the Borden method.

- 4 The great attraction of the Borden method lies in its presentation as a universal system for approximate system sizing, requiring minimal input data, and in being "paper-based" rather than requiring computer calculations. By contrast, the present critical run LOPP approach could offer advantages as the basis for a local microcomputer sizing tool. The model's run-length approach requires substantial pre-processing of local weather data, but this could be done centrally with batch mainframe programs, after which very few parameters are needed to model the run-length characteristics of local weather for various probability levels. The modelled insolation data could then be readily incorporated in an efficient and flexible LOPP sizing method, to run on a PC.

9.5.3 Method 3

It is interesting now to examine the system sizing options obtained from a professional photovoltaic system sizing program, used by a major international company in this field. This software was made available for scrutiny by local agents. It is probably prevalent practice for local agents, and independent local suppliers of photovoltaic systems, to make use of such software, either directly, or (as in the case of the systems monitored in this study) by referring sizing enquiries to the module manufacturers.

Three points are of main interest here:

- Since the sizing software examined has presumably stood the test of widespread commercial applications, it is unlikely that it should lead to undersizing of photovoltaic systems, for given applications. The sizing predictions should therefore serve as a conservative criterion by which to judge the Loss of Power Probability sizing estimates presented earlier in this section.
- The sizing of the monitored systems followed recommendations to the local suppliers from the module manufacturers, Photowatt SA, France, presumably using their own sizing software. It is interesting to compare the recommendations of one major manufacturer with those of another.
- It would be interesting to assess the assumptions and method on which such a sizing program is based. However, this can only be done in a limited way, since the available software is in compiled form, and the sizing method can only be inspected through inputs and outputs to the programs.

The software examined provides a sophisticated and quick aid to system design. With minimal user inputs, the designer can investigate alternative combinations of modules and batteries predicted to support the specified load, in local conditions. No detailed input data are required, and the programs run on a PC.

User inputs can be described in three categories.

First, basic specification is required of the geographical location, and the load profile for which the system is to be designed. A spread of locations throughout Africa is offered (in the version examined), which the user can denote by name or choose through entering the latitude and longitude of the site, followed by choice of nearest offered location. System loads can be specified as constant or variable, and as dc or ac. Minor site specifications, such as ground reflectivity, can be entered, or defaulted.

Second, the user can select the type of modules and batteries to be used for the sizing. The range of modules available are of course those produced by the company, while a range of commercial batteries, as well as "generic" battery types, in smaller units, are offered for selection.

Third, there are options for the designer to add flexibility to the sizing process, for instance through overriding default values for several aspects of component performance, through entering user data in place of the sizing program's database, or through changing the optimisation procedure used in the program.

The sizing calculations will depend on the site-selected weather data, held in the weather database provided, or optionally supplied by the user. The weather data used for sizing consist of average daily horizontal insolation, per month, and monthly ambient temperatures (minimum, mean and maximum) for the selected site. No data for climatic variance, within months or between years, is processed.

It is not known whether the insolation data for the wide variety of African sites has been obtained from weather records, from theoretical calculations, interpolations, or a combination of these; but the values stored for Pretoria monthly insolation were virtually identical to the 10-years' averages derived from weather station data, as published by the CSIR (1971), so empirical origin is likely.

While no information is provided, or solicited, for variations in local weather, other than the course of the monthly means, the program advises users that system performance at the installation site will "vary dependent upon weather conditions". More concretely, an ad-hoc assessment of weather variability is invited in the user-set choice of

the days of autonomy of the batteries. The default is three days autonomy, as a set guideline by which the program seeks an economic optimisation of array/battery combinations. But users are told that "Five (5) is safer" and that the choice depends on local weather, availability of back-up power, site accessibility, etc. Fine tuning of the reliability of the system is therefore left in part to the user's judgement of local conditions.

The default mode of arriving at recommended combinations of module power and battery capacity, for the specified conditions, is that of "economic optimisation" - presumably choosing the array/battery combination which will meet the load at cheapest capital cost. It is not known whether battery replacement costs are taken into account here, but that seems unlikely since no data are stored for the life expectancies of different makes of batteries.

Minimisation of capital costs for alternative combinations of array power and battery capacity of course depends on component prices. These are held as data, which can be altered within limits by the program user. (Attempts to change the manufacturers' module price algorithms were unsuccessful!). The ratios of battery prices to module prices, in local application, would be susceptible to exchange rates and other economic and industry variables, so the optimal combinations indicated by the program would not necessarily be cheapest at current local prices. However, for present purposes, it is interesting to know the range of array/battery sizes indicated as sufficient to support a specified load.

The program was run for location Pretoria, specifying a steady daily load of 18.75 amp-hours at nominal 24 volts dc. This corresponds to a design load of 450 Wh/day. 30% of the average load was stated to occur at night. Ground reflectivity was set at 0.2. The supplied weather datafile for Pretoria was used.

Multiple runs of the program were conducted, to search for optimisations and to judge the criteria in the sizing procedure.

The most striking outcome was that for a relatively small system, the sizing of components is strongly dependent on the choice of components.

This is because of the "lumpiness" of commercially available components. If one selects photovoltaic modules of certain size (optimum-power amps, volts) and a certain make of battery (of set rated capacity) the sizing software will possibly oversize the system. For instance, if one of the selected battery-type is not enough to provide the required battery capacity, then two will be indicated, even if the excess required was only a few percent. Simultaneously, if one module of a selected type provides slightly too little current, then two modules in parallel will be indicated.

Selecting modules of similar optimum-power current to those employed in the monitored system, and selecting Delco 2000 batteries (as used in the monitored system), the program predicted a sizing combination as follows:

Module power: 147 Wp
Batteries: 2 * Delco 2000 = 105 amp-hours @ 24 volts
(rated capacity)

This sizing incorporates a 0.9 module derating factor, and compares with Photowatt's original sizing recommendation of 164 Wp array power and 210 A-h rated battery capacity.

The lower array power indicated appears mainly attributable to selecting a module type which has a lower optimum-power voltage than the Photowatt PW-P 800 modules (32 volts versus 34 volts).

The program appears to assess the required module power on the basis of amp-hours supplied to load (for dc loads) while checking that optimum power voltages at prevailing ambient temperatures are sufficiently high to exceed the batteries' recommended float charge voltage, again adjusted for ambient temperature. Because of this approach, it could be expected that the indicated array power would be higher if modules of slightly higher optimum-power voltage were selected. If modules of optimum-power voltage 34 volts (at 25 degrees) were selected, having similar amps output, the array sizing would then come very close indeed to the Photowatt recommendations: approximately 156 Wp.

The associated battery requirement, according to this sizing, is half the Photowatt recommendation, at 105 A-h rated capacity. (In terms of installed capacity, the reduction is even greater, because the data stored in this program for Delco 2000 batteries restricts them to 50% maximum depth of discharge.)

However, the danger of arbitrary decision here is illustrated by the fact that when the design load was specified only 3% higher (19.3 A-h instead of 18.75 A-h) the program indicated a requirement for 210 A-h rated battery capacity - the same as the Photowatt recommendation. This shows how the "lumpiness" of components could lead to oversizing, if the selected modules or batteries have large unit power/capacity relative to specified system load demand.

Subsequent runs of the program indicated that the array power could be substantially reduced by selecting modules of more suitable unit size. Various combinations were investigated, but the savings are most simply illustrated by the device of scaling up the load demand, to reduce the lumpiness of selected components. When the average daily load was multiplied by 100 and set at a value of 1875 A-h, keeping all other factors equal (the same modules, batteries and nominal system voltage) the following combination was indicated:

Module power: 11858 Wp

Batteries: $2 * 107 * \text{Delco 2000} = 11235 \text{ amp-hours @ 24 volts}$
(rated capacity)

In the sizing program, it appears that line losses, etc., are treated as voltage losses, so by keeping the system voltage steady, the sizing combinations should be scale neutral. It is possible that the database prices for modules are scaled for quantity, which could affect the economic optimisation, but if anything this would have the effect of increasing the array to battery proportion indicated. It is therefore reasonable to regard the combination above as a more critical sizing estimate, when scaled down again.

Scaled back to the design load of 18.75 A-h/day, the required array power is indicated as 119 Wp (27% less than the original Photowatt sizing) while the rated battery capacity of 112 A-h is slightly over half the Photowatt recommendations (47% less).

Compared with the installed system, as tested, the sizing program indicates a somewhat smaller array (12% less peak power) and the same 47% reduction in battery capacity.

Compared with the LOPP model predictions in Section 9.4, the component sizes indicated by this sizing program fall between the $LOPP=0.01$ and $LOPP=0.001$ predictions, if derating factors are omitted, and if installed rather than rated battery capacities are compared. (The sizing program includes a 10% derating factor for array performance, and restricts the batteries to 50% depth of discharge.)

EXCLUDING DERATING FACTORS			
Critical Run LOPP Model:	<u>Array</u>	<u>Battery Capacity</u>	
	<u>Power</u>	Installed	Rated
LOPP=0.01	105 Wp	44 A-h	63 A-h (70% DOD)
LOPP=0.001	112 Wp	61 A-h	87 A-h (70% DOD)
Commercial Sizing Program:	107 Wp	56 A-h	105 A-h (50% DOD)

In all cases, the sizing program indicated an optimum array tilt angle of 30 degrees.

This sizing program does not follow a loss of power probability approach. It would seem, also, that it does not account for variations in deviation from optimum power points as battery charge voltage declines, although variations in module conversion efficiency due to cell temperature are taken into account. (Power take-off from the array appears to be programmed as the batteries' temperature-dependent float charge voltage multiplied by the array current corresponding to monthly weather conditions - though full features of the program here cannot be assessed from the outside.)

The present comparison suggests that the sizing program can predict array power in a range very close to other (loss of power probability) methods, providing unit module size is carefully considered.

Drawbacks are that the choice of battery capacity appears to be guided first by arbitrary decision (3 or 5 days autonomy, user-settable, around which the program seeks economic optimisation) and that there is no direct indication of the availability of power which can be

expected from the final choice of battery capacity.

The comparison has also suggested how using such a program could be economically detrimental to the buyers of relatively small stand-alone photovoltaic systems. This could occur if the system designers select components, either the modules to be used, or the batteries to be used, which are of large unit size relative to the design load. Significant rounding surpluses can result, and the program would indicate a sizing combination which is wastefully large.

This would not be a fault of the program, but of its application. At the same time, manufacturers may have an interest in selling a particular module, or may not manufacture ideally sized modules for a full range of small system load demands. There could be further technical or business reasons for recommending a particular make of battery. And there are installation advantages if systems consist of a small number of larger components, rather than a larger number of smaller units. These kinds of considerations could promote such oversizing of small systems.

Since the photovoltaic modules constitute the largest cost in a typical stand-alone photovoltaic system, independent system suppliers would be recommended to investigate a wide range of modules, of different power ratings and appropriate voltage, from several manufacturers, when selecting the optimum array size for powering small loads.

9.5.4 Summary of sizing comparisons

Table 9.5 summarises comparisons between the battery and array sizes predicted by the critical run LOPP model developed in this chapter, the sizes indicated by three other sizing methods, the original Photowatt sizing recommendations for the Bophuthatswana installations, and the actual sizing of the monitored system (as tested). Figure 9.12 presents the same information graphically.

The initial aim was to assess whether the Bophuthatswanan systems had been oversized for their design load, and if so to what degree. Given the probabilistic nature of solar radiation received, and uncertainty about the applicability of generalised sizing methods for local applications, this led to the development of a sizing model which could accept local empirical weather data, and predict loss of power probabilities on that basis for varying system configurations.

As an aid to judging the reliability of this model, its predictions have been compared with other sizing methods, and the combined indications of various sizing methods have been used to assess the sizing of the Bophuthatswana systems.

The comparisons in Table 9.5 and Figure 9.12 lead to the following observations:

- 1 There is very close agreement between the various sizing methods as to the required array power for the design load, if derating factors are left out of account. Chapman's method indicates lower array requirements; the critical run model indicates higher array requirements for the higher availability level of $LOPP=0.001$; otherwise, the discrepancies are remarkably small, with predictions between 105 and 107 Wp.
- 2 If post-sizing design margins are included, to allow for array lifetime degradation and other derating factors, there is a greater range in recommendations. Where other methods adopt a conventional 10% lifetime degradation allowance, the critical run LOPP model recommendations include a further 5% derating factor for the selective spectral response of modules, and power losses at higher angles of incidence of light, which could reduce module

**FIGURE 9.12 Summary of Array and Battery Sizing Indicated
By Different Sizing Methods**

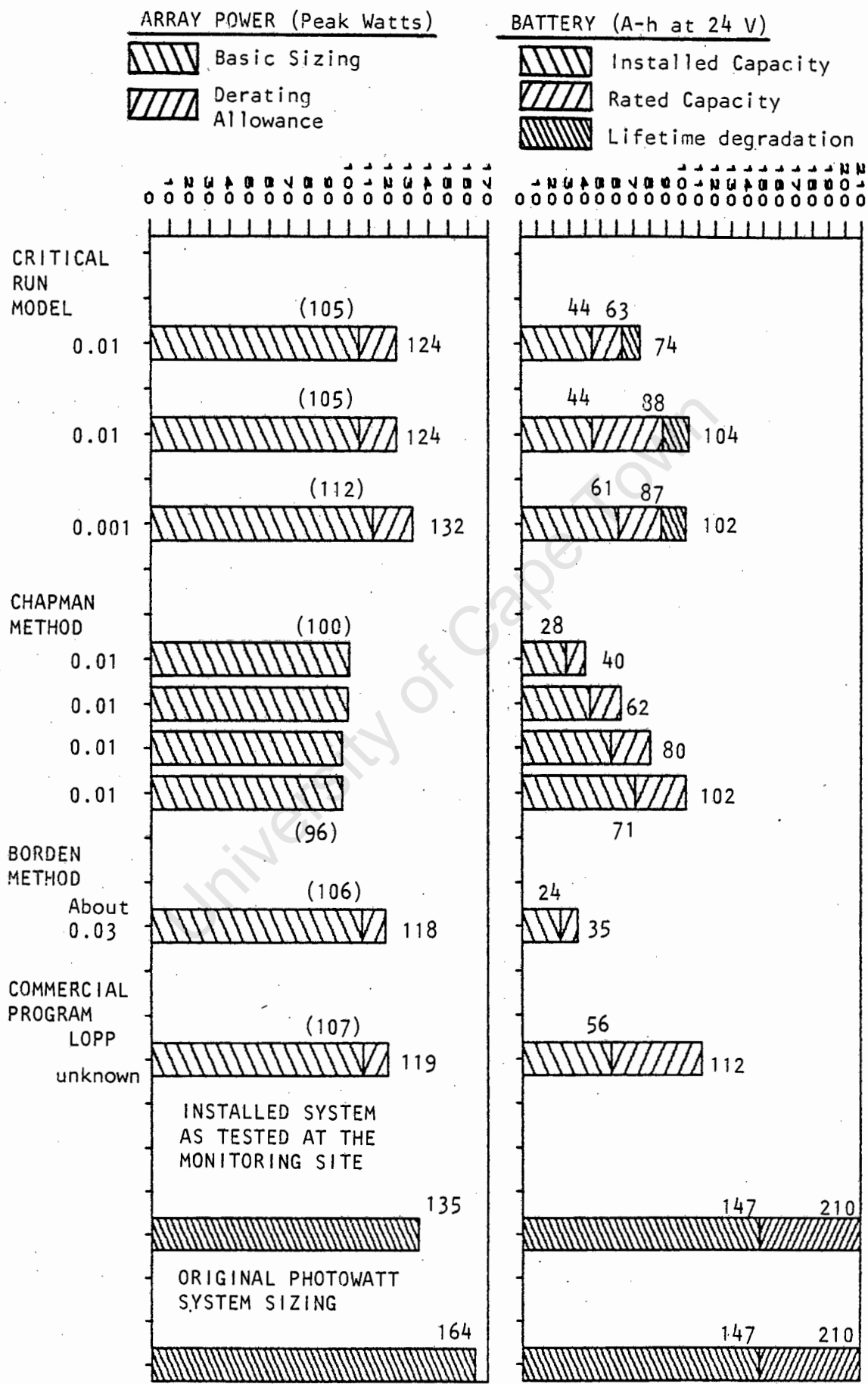


TABLE 9.5 Summary of Array and Battery Sizing Indicated
By Different Sizing Methods

LOSS OF POWER PROBABILITY	ARRAY POWER (Wp)			BATTERY CAPACITY (A-h at 24 V)			
	Excluding derating allowance	Recommended		Installed ----- (no degradation)	Rated -----	Recommended rated capacity	
	[derating]			[DOD] [derating]			
Critical Run LOPP Model							
0.01	105	124	[15%]	44	63	[70%]	74 [15%]
0.01.	105	124	[15%]	44	88	[50%]	104 [15%]
0.001	112	132	[15%]	61	87	[70%]	102 [15%]
Chapman (1987) method							
0.01	100	-	-	28	40	[70%]	- -
0.01	99	-	-	43	62	[70%]	- -
0.01	96	-	-	56	80	[70%]	- -
0.01	96	-	-	71	102	[70%]	- -
Borden et al (1984) method							
0.1 in design month ¹	106	118	[10%]	24	35	[70%]	35 -
Commercial Sizing Program							
LOPP unknown	107	119	[10%]	56	112	[50%]	112 -
BOPHUTHATSWANA SCHOOL TELEVISION SYSTEMS							
Original Photowatt sizing							
		164					210
Installed systems							
		135 (as tested)					210

Note 1: Corresponds to estimated annual LOPP of about 0.03

conversion efficiencies in adverse conditions. The validity of these assumptions needs further investigation, in conjunction with assessment of applicability of manufacturers' performance specifications under such conditions.

The aims of critical system sizing, the main purpose of improved sizing techniques, can be undermined by adding uncertain margins to basic sizing predictions. One purpose, however, in including cautious margins in the critical run LOPP recommendations was to provide a fair comparison for judging the conservatively engineered monitored system.

- 3 Greater variation is evident in the required battery storage predicted by different sizing methods. Again omitting degradation allowances, the minimum installed battery capacity varies from 24 to 71 A-h at 24 volts, and it is in this respect that the sizing methods differ most. Given the convergence in array power predictions, this variation in predicted storage requirements indicates that varied availability levels could be expected from the different sizing methods.
- 4 Recommended rated battery capacity varies from 35 to 112 A-h, according to method. The recommendations depend on maximum permitted depth of discharge (as shown in Table 9.5), and in the case of the critical run LOPP method, a lifetime degradation factor of 15% has been included to ensure that the required storage is available for most of the batteries' service life (battery replacement is assumed to take place when initial capacity has fallen to 80%).
- 5 The predictions of the critical run LOPP model are consistently in the range of other methods' predictions.

Except for Chapman's method, the $LOPP=0.01$ prediction for array power (before derating) is essentially the same as other methods; but the model also has the flexibility to predict array power for other loss of power probabilities (eg. 112 Wp for $LOPP=0.001$).

The **battery predictions** of the critical run LOPP model are within the range of other methods (installed capacity, for $LOPP=0.01$)

but avoid the lowest values of the Borden and Chapman methods. The Chapman method values appear internally inconsistent. The Borden minimum of 24 A-h is associated with a higher loss of power probability level (0.1 in the design month, which was estimated earlier to represent an annual LOPP of about 0.03). In the case of the commercial sizing method, the LOPP is indeterminate, and battery capacity seems subject to arbitrary decision.

The critical run model appears to provide a more rational and more empirical basis for calculating the battery capacity required for a selected LOPP, than other methods reviewed. Given the suitable form of the model for incorporation into a PC-based sizing method, and its flexibility, it may merit further investigation and development. Chapter 11 includes suggestions for doing this.

- 6 The original recommended Photowatt sizing for the monitored systems stands out as a clear outlier, with both array power and battery capacity considerably above the indications from a variety of other sizing methods. Possible reasons which have been considered include (a) doubtful validity of the solar radiation data used for the Photowatt sizing, (b) the sizing methodology used, and (c) possible inattention to the "lumpiness" of components, perhaps related to a prior choice of 82 Wp module units and 105 A-h battery units.
- 7 The sizing of the monitored system (and of the systems installed in Bophuthatswana schools), however, is less excessive than the original Photowatt recommendations. By comparison with the critical run LOPP model predictions, and now including post-sizing degradation allowances, the installed array power is suitable for providing a loss of power probability of approximately 0.001. The battery capacity appears unnecessarily large, and could be halved without incurring a LOPP > 0.001. It can also be suggested that such a high level of predicted availability is not essential in the present schools television application, and that a LOPP=0.01 level would be more suitable. This would permit a further saving (according to the model) of about 8% on array size.

Chapter 10

PHOTOVOLTAIC-POWERED SCHOOLS TELEVISION IN BOPHUTHATSWANA: SOCIAL, EDUCATIONAL AND ECONOMIC ASPECTS

Previous chapters have taken up technical issues generated in the monitoring study. Part of the reason for devoting most attention to technical issues in the evaluation of the monitored system was that these enquiries may have scope for generalisation, pointing to problem areas, and directions for further research, in photovoltaic system design for local applications.

Returning now to the specific application of solar-powered schools television in Bophuthatswana, the present chapter presents a broader socio-economic assessment of this attempt at educational innovation.

When considering the "appropriateness" of a particular technological intervention, the technical appropriateness of the hardware is one important ingredient. In earlier chapters, it was concluded that the photovoltaic generators, with associated applications equipment, provided an effective technical solution to the problem of equipping off-grid schools with video and television facilities. The systems promise reliable service, high levels of expected availability of power, facilities for easy maintenance, and features which make the equipment easy to use by inexperienced operators. Furthermore, the power source is renewable, silent and ecologically sound.

The technical appropriateness of hardware, however, while it may be a necessary ingredient, is not a sufficient condition for the success of a technological innovation. This comes through very clearly in such a complex and ambitious application as schools television. A host of social, organisational, educational and economic factors intervene. Such factors are pre-eminent in affecting the course of a programme such as the Bophuthatswana Edutel project.

For this Chapter, the information which has been obtained about the social actuality of Edutel is of a different status from the physical measurements underlying the technical evaluation. Firstly, the information includes subjective appraisals, made by educationists,

media specialists, Edutel planners and others (mainly from central observing positions in Mmabatho/Mafeking), as well as from a small haphazard sample of school teachers and pupils in other areas of Bophuthatswana. To a degree, subjectivity is inescapable in social enquiry - subjective opinions, and how they are formed, are in fact part of the enquiry - but it is necessary to be aware that particular interests of informants may colour their viewpoints or even condition their access to knowledge.

Secondly, both objective conditions and subjective opinions can be expected to vary according to time and location, so the information required is therefore distributed in nature. It was desirable to canvass a wider spectrum of viewpoints - fewer than 50 informants were interviewed (mainly in 1986/1987) - but certain obstacles prevented this: time constraints, resistance to enquiry amongst some officials, and a withholding of permission to conduct research at schools. A representative survey of schools was planned, both to collect a representative cross-section of teachers' opinions and also to gather reliable, representative information about more objective indicators, such as quantitative levels of utilisation of the facilities in schools. Permission to proceed was not granted by the Bophuthatswana Secretary for Education, who referred the research proposal to the Bophuthatswana cabinet for their decision. After lengthy delay, permission was refused.

10.1 Motivation for the Edutel Project

A broad context of attempts to reform Bophuthatswanan education, in the period following acceptance of "independence" from South Africa, formed the decision-making environment for the Edutel initiative. A documented landmark in this process was the publication of the "Popagano Report" (Rep. Bophuthatswana, National Education Commission, 1978), which proposed a unifying indigenous educational philosophy, as well as a number of practical steps towards restructuring Bophuthatswana's inherited educational system.

Amongst other elements in the Popagano philosophy, there was a stress on education for emerging nationhood - a common theme in newly independent African state philosophies, but perhaps complicated in this instance by Bophuthatswana's ambiguous nation-status, having accepted independence from South Africa, but lacking international recognition as a sovereign state. A pre-occupation with the quest by the government to gain measures of international recognition appears to have influenced the Edutel project, as noted below.

Despite Bophuthatswana's considerable continuing dependence on the South African economy and state, there is little doubt that the acceptance of formal independence opened opportunities for limited autonomy in development decisions. Besides embarking on a number of national-symbolic prestige projects, funds were also allocated to crucial development areas, amongst which education was prioritised. As De Clercq (1984:23) has argued, (with qualifications): by accepting independence as a "National State" in 1977, Bophuthatswana gained a relative freedom to introduce educational innovations, breaking with the philosophy and largely by-passing the bureaucracy of South African "Bantu Education". The Edutel initiative emerged in this context of educational innovation and repair.

Key problems faced in the educational system were a shortage of suitably qualified teachers, a shortage of adequate school facilities, and rapidly increasing school enrolments.

School enrolments at secondary level had increased from 16 000 in 1972, to 66 000 in 1977, and to 146 000 by 1984, when Edutel was initiated (De Clercq, 1984:36-37; Rep. Bophuthatswana National

Assembly Debates, 1984:336). The 1984 figures include a change in the composition of "secondary schools", since by that time, following recommendations of the Popagano Report, secondary schooling had been broken down into "middle schools" (standards 5 to 7) and "high schools" (standards 8 to 10). These middle and high schools were to be the target for educational television.

10.1.1 Educational motives

Increasing school enrolments, resulting from demographic and socio-economic factors, had increased the strain on educational resources. Between 1977 and 1983, the average teacher-pupil ratio in secondary schools had worsened from 1:34 to 1:38, while the percentage of secondary teachers without a Senior Teaching Certificate had risen from 50% in 1977 to 60% by 1982 (De Clercq, 1984:36-37). In middle schools alone, the teacher-pupil ratio had increased to 1:45 by 1984. Some schools had to operate double shifts. Underqualified primary school teachers were moved into middle schools, while expatriates were being employed to fill the acute qualifications gap at senior levels, especially in science, mathematics and English (Rep. Bophuthatswana, National Assembly Debates, 1983:799; 1984:336).

Educational television was put forward as a means of alleviating some of the problems of an overstretched education system. The goal was to bring standardised, high quality educational programmes into the classrooms, not to replace teachers, but to provide pupils with additional learning facilities, including expert presentations of subject matter in areas where teachers' qualifications or expertise were lacking. Simultaneously it was hoped that educational television could contribute to in-service upgrading of existing teaching staff, by setting good examples of teaching methods, as well as by extending teachers' substantive knowledge.

Qualified teachers were not the only shortage facing Bophuthatswanan educational development. Improved physical facilities, notably more schools and more classrooms at existing schools, were urgently required. Many schools needed improved basic amenities, such as water supply; most lacked electricity - about 80% of middle and high schools (as estimated by the photovoltaic supplying company) were not connected to the grid.

Other deficits at schools included books, libraries, teaching aids and laboratory equipment. To some extent, according to the 1986 Acting Director of Edutel, it was envisaged that school television could help meet some of these further needs, by opening a window to a world of richer educational resources, and by "bringing laboratories into the classroom".

There were therefore coherent educational motives for embarking on a school television project - or to express this more cautiously, the circumstances prevailing in Bophuthatswanan schooling provided a rationale for introducing educational television.

The precise ways in which the project was initiated have been difficult to establish. The initial impetus is commonly ascribed to one person, working at the time in educational technology at the University of Bophuthatswana (UNIBO), who subsequently became the first director of Edutel, before moving to commercial television in South Africa. There are suggestions that the initiative was, to a degree, technology-led, rather than based on a rounded assessment of educational needs. Bophuthatswana had recently acquired its television broadcasting station, and equipment was on the market for solar-powered television and video for remote areas. Over two decades, educational television projects had already been tried in a number of developing countries (with mixed consequences - critical commentators suggest that the lessons learnt in other countries had not been adequately heeded by the planners of Edutel). At least from a technical point of view, leaving aside the production of software and the social organisation of the Edutel project, the proposed scheme was feasible. In addition it carried a number of political and commercial attractions.

10.1.2 Political and commercial motives

Obvious commercial attractions derived from the scope of the proposed project. From the outset, the intention was to equip virtually all middle and high schools in Bophuthatswana with television/video facilities. The systems, in the event, were installed at a unit price of R7 500 (1984/85 prices) in more than 350 schools, amounting to a contract worth in the region of R2.6 million for school installations.

Political attractions of the project have been suggested at two levels, regional and international. At both levels, the theme of "nation-building" is prominent. It is difficult to assess whether political motives actually predominated in the implementation of the Edutel project. Two centrally placed informants, with access to government policy, claimed this to be the case.

Bophuthatswana is a geographically fragmented territory. At the level of regional politics, the geographical fragmentation of Bophuthatswana aggravates problems of political unification, and of the dissemination of government policy and services to scattered populations. Judging by Assembly Debates, broadcasting in general has been viewed by politicians as a powerful and prestigious way of representing the Bophuthatswanan nation to its people. This political attraction, which played a considerable part in the President's 1983 decision for urgent acquisition of a television service, seems to have extended to educational television as well. The geographical scope of the proposed schools television project would have added to its appeal, promising reception of central messages across the entire territory. Amongst others, Minister C K Sehume, responsible at that time for broadcasting, gave expression to this point of view in 1984:

"The development of television will enable the Government to establish a closer relationship with the Batswana wherever they reside, television being the great communicator... [T]he service will also proceed apace ... until the bulk of the people will be able to watch television even in the remote areas, where electricity will be a problem for some years, through the use of solar-powered receivers, perhaps viewing under community circumstances, in village centres or schools."

(Rep. Bophuthatswana, National Assembly Debates, 1984:531)

At the same time as Mmabatho politicians wished to exploit broadcasting as the "mouthpiece of the Bophuthatswana nation" (Rep Bophuthatswana, National Assembly Debates, 1985:170), another dimension of political demand came from regionally based politicians and chiefs, calling for a more equal distribution of resources to their constituent areas. Specifically with regard to the school

television proposals, regional representatives were happy to be assured by central government that the Edutel project would extend to all areas of Bophuthatswana. The promise of equally distributed, centrally supplied, high quality educational television made some amends for existing regional inequalities in educational provision (such as provision of classrooms).

Such politically-based aspects of the motivation behind the Edutel project are of some relevance to the path it took. For example, they contribute part of the explanation for the decision - widely criticised by educationists - to start the project from the outset on such a large scale, without pilot investigations. Experience from a number of other developing countries has indicated that it is wiser to proceed in careful stages (cf. Schramm, 1977:153), and that to mount a successful educational television project which would reach all middle and high schools and be directed at all school standards within those schools, would require far greater resources than Bophuthatswana has had at its disposal.

Interestingly, American Samoa, which was the early flagship for educational schools' television beginning in 1964, also proceeded at headlong pace, targetting all elementary schools in its first year of operation and all secondary schools the following year. While judging this in retrospect as a procedural mistake, Schramm notes (1977:152) two sources of motivation for being "in such a hurry": firstly political reasons of incorporation, secondly a Samoan egalitarian ethic whereby it would have been distasteful to favour some children with the new service and not others. These observations could equally be applied to the Bophuthatswana venture.

International politics also entered into the combination of motives leading to schools television. It has been claimed that the project was

"...all tied up with politicians, trying to set up relationships with the French. Bophuthatswana isn't internationally recognised. By signing business deals with French businessmen, maybe influential in government, this led to a later establishment of a trade mission in France... "

This observation was made in confidence (in 1986) by a centrally placed official¹, and the suggestion was independently supported (in 1988) by another informant with access to government policy and decision-making. It is notable that preceding the inception of Edutel, both the President and the Minister of Education travelled to France. Their visit gained applause from the Bophuthatswana Assembly, where it was felt that progress was under way towards achieving a measure of international recognition.

As one Assembly member put it:

"[W]e have not achieved recognition, but we have connections with leading countries in this world. When we have connections with countries like France and our leaders go to France and are welcomed by France and these are shown to us, this is showing that we are going to be recognised. The future of our recognition is very bright by touching these individual countries that make up the United Nations. Steadily and softly we have connections with the Five great powers that run the security of the United Nations."

(Rep. Bophuthatswana, National Assembly Debates, 1984:548)

The vulnerability of regions like Bophuthatswana to international commercial overtures, owing to their national aspirations, form of government and ambiguous sovereignty, has been demonstrated to unfortunate effect in other South African "National States" and "homelands". Sales of technology for third world development,

¹ Methodological Note: In general, informants have not been identified by name, except if their statements have been published elsewhere. Where information was offered on an implicit understanding of anonymity, or where it could be judged to have potential for harming the informant, informants have been identified in a sufficiently general way to avoid personal attribution. This caution is regretted, as it limits opportunities to assess the context and origins of information, but it is considered advisable on ethical grounds.

including solar technology, have figured in obscure deals made at highest levels and without adequate assessment of local needs. In the Republic of Ciskei, for example, an Israeli proposal for solar-powered lighting, television and refrigeration for rural centres led to an untendered contract with an Israeli-based company for over-priced equipment, inappropriate for local needs, which in any case did not work satisfactorily.

The latter example contrasts with the technical superiority of equipment, purchased from French manufacturers, and the efficient operation of the local supplying company, in the Edutel project. But more general points survive the comparison. There is the potential for influential decisions to be made by relatively isolated political leaders, often without adequate depth of local technical support to judge, size and select what is offered, and often without adequate assessment of needs, potentials and infrastructural/ organisational requirements associated with successful implementation of development initiatives.

With what degree of justification one cannot be sure, but opinions have been expressed both by Edutel staff and by informed observers that the Edutel project is something of a political inheritance, brought into being for other than purely educational motives, and that the remaining task of trying to make Edutel serve an educational function is a remedial one.

This is not to imply that political motivations have no place in commissioning development projects. Especially in developing countries, they are likely to be central. Schramm (1977:171), in an evaluation of factors promoting success in educational television ventures in third world countries, has identified the commitment of top leadership to such projects as centrally important. What is of concern, in evaluating the course of the Edutel project, is the articulation between political motivations and educational motives, and the implications of the mixture for the way the project was set in motion.

McAnany (1978:18-19), in a similar evaluative survey of third world communication-technology projects, observed that typically "the

promoter of the project sells his ideas on a political or long-range criterion and the implementors and evaluators often concentrate on a short term educational goal." This observation corresponds well with sentiments expressed by Edutel implementors as well as critical observers: from Edutel, a feeling that the scheme had been set up by decisions outside their control, "...and then we had to make it educational"; from critics, the opinion that centralised top-down decision-making had prevailed, with insufficient consultation, research and forward planning, leading not only to difficulties in realising the potential of the educational technology, but even creating blocks to short term educational goals.

Robin Welsh, the principal promoter of schools television in Bophuthatswana, as interviewed by Roodt (1984:30), envisaged in advance of the project that Edutel would develop over 4 to 5 years to a point where educational programmes would be broadcast for 53 hours each week.

Initially, for schools not within the range of television reception, pre-recorded videotapes would be distributed by post, by circuit inspectors and by maintenance teams. Local production of educational software would be in the hands of three production teams, each producing about 4 to 5 hours' material per month. In the early stages, there would be three script-writers (recruited from the teaching profession) advised by programme committees, and five "utilisation officers" responsible for producing manuals and guides, arranging utilisation workshops, and providing feedback from schoolteachers to the production teams.

In addition, two fulltime researchers would monitor and explore the course of the project.

According to the new acting director of Edutel at the end of 1986, and information from other observers in subsequent years, these ambitious broadcasting and organisational aims have not been and seem unlikely to be attained.

First, Edutel has had to rely heavily on the physical distribution of videotape cassettes. Educational programmes were obtained from overseas, mainly from America and Britain, and equipment was purchased for simultaneous duplication of videotapes (fifty at a time), typically containing a variety of educational/instructional material suitable for different school levels in various subjects. One of the recurring areas for criticism of Edutel delivery has been the quality and suitability of the imported software, while local production of programmes for schools has been severely constrained by economic and organisational factors discussed below.

Broadcasting could be a cheaper means of distribution than reproducing and distributing videotape cassettes, but constraints here have included the infrastructural expense of extending microwave links, or gaining a satellite link, in order to extend broadcast reception to all areas in Bophuthatswana. In 1987, the Minister of Broadcasting announced the inception of telecasting to schools for an hour each morning and in an afternoon slot at 16h00, while videotape distribution was continuing to "the 485 Middle and High Schools in the country" (Rep. Bophuthatswana, Assembly Debates, 1987:551); but judging by published programme guides, broadcast delivery has fluctuated. Beginning in June 1989, a regular Edutel broadcasting slot has been advertised from 15h00 to 17h00 on weekday afternoons.

In the same budget speech, the Minister noted that of the R45 million requested that year for broadcasting services, only R25,7 million had been allocated, necessitating cutbacks in many areas. Top priority was being given to moving all broadcasting facilities to a new prestige building. R5 million for this move had to be obtained at the sacrifice of other developments in the broadcasting service, including educational television and staff training. "The transferring of these funds from the entertainment and educational television programmes will by necessity mean a reduction in the amount of local programmes which can be produced during the current financial year" (Rep. Bophuthatswana, Assembly Debates, 1987:550).

With regard to Edutel staffing, the nominal staffing structure in 1986/87 was characterised by gaps and vacancies. In the important Utilisation section, responsible for liaison between Edutel and schools, five appointments had been made. A need was expressed for a further five, to cover all areas, but of the original appointees (according to one source, in 1987) several resigned, partly through finding the lines of communication too unidirectional: they found the feedback they communicated from schools was not sufficiently taken into account. In the Production section, no staff were employed in 1986. The Research section similarly had no staff; a previous appointee had left. The Technical function, responsible for repairing television sets, etc., appeared at this stage to devolve on maintenance support from the supplier company. The original Director of Edutel first moved to take responsibility for entertainment programming in Bophuthatswana Television, adding to his commitments

and leaving less time for Edutel, and then left altogether to join commercial television in South Africa. The Acting Director at that stage therefore lacked adequate organisational support.

Limitations of finance no doubt played a part in holding back the staffing of Edutel, but further problems arose through the lack of sufficiently qualified and skilled recruits. To aggravate the situation, an informal policy of separation from the University had prevented Edutel from making full use of the relative concentration of media, production and educational expertise at UNIBO. (According to one source, for example, Utilisation Officers had been instructed to have no dealings with university personnel.)

Three reasons have been suggested for the restricted communication between Edutel and UNIBO. One was that university educationists and media people tended to be critical of the process and planning of Edutel, and were therefore not viewed as supportive. Another was that university staff would prefer to keep some autonomy and "not get constricted in the political imperatives". Finally, it was suggested that concerns about status and qualifications had led to a degree of defensiveness amongst less well-qualified staff in parastatal posts. From this point of view, university academics could be perceived as a threat to status.

Inadequate production studio facilities available to Edutel were also claimed, by observers with production experience, to add to the problem of producing local programmes. Such locally commissioned programmes as have been made, have generally been contracted out to independent commercial production companies, drawing on South African professionals.

Experience in other countries has indicated that the financial and organisational resources required for mounting a schools television project are considerable. For instance, two of the countries which undertook such projects, which were cited as examples by Edutel motivator Robin Welsh (in Roodt, 1984:30), were Niger and the Ivory Coast.

Niger began with a production team of about fifty people - skilled specialists from France (Schramm, 1977:144) - a capital budget of about some \$1.5 million, and a recurrent budget of more than \$500 000.

per year, in 1964 currency. Ivory Coast, starting in 1971, drew on international aid to a value of approximately \$18 million over five years, made use of an elaborate organisational structure within Ivory Coast, and made use of further French assistance for programme design and production, and evaluation (Valerien, 1981:11-14). By comparison, the financial and organisational resources available to Edutel, as a minor subdivision of the broadcasting service, have been of small magnitude, and appear insufficient for undertaking such an ambitious project. Both Niger and the Ivory Coast progressed more slowly than Bophuthatswana attempted to do, addressing only one school grade per year.

It could be argued that, to the extent that Bophuthatswana is able to make use of imported rather than locally-tailored software, financial and organisational needs could be reduced. However, as already noted, the imported software has been reported as a major reason for dissatisfaction with Edutel's delivery to schools.

10.3 Utilisation

Any evaluation of the benefits of the Edutel project would require reliable knowledge about the extent to which the services are actually being used in schools. More qualitative information would then be needed, to evaluate the quality of the service and its educational contribution. However, quantitative levels of utilisation are a necessary baseline for enquiry, and (assuming teachers are free to make use of the service, or not) a primary indicator of levels of acceptance of the educational technology.

Unfortunately, reliable information about utilisation levels in Bophuthatswanan schools has so far not been obtained. An attempt to conduct a representative survey of schools in selected education circuits was halted when permission to proceed was withheld by the Secretary for Education, who said he was obliged to submit the research proposal for cabinet approval. This could indicate sensitivity about the origins of the Edutel project, and its progress to date (including low utilisation levels), or simply bureaucratic caution following the attempted coup d'état in 1988. It is also understandable that organisations would prefer to conduct their own research, and control the research findings, rather than entrust independent researchers with possibly sensitive information.

In the absence of a representative survey, available information about utilisation levels is not encouraging.

Although company representatives estimated that some 80% of schools were making use of the equipment within six months of installation, no estimates were obtained either from the company or from Edutel officials about the extent of usage within schools which make use of the facilities. Company maintenance records could provide some indirect evidence. On maintenance reports, after the technical condition of equipment has been checked, school principals (or delegates) are invited to make comments. From inspection, by courtesy of the supplier company, these records include a proportion of appreciative comments from school principals, and a smaller minority of frankly negative comments. The majority of responses however appeared either to be non-committal, or else the maintenance reports had merely been signed without comment.

Educationists and media specialists from UNIBO, who have observed the project, expressed uniformly sceptical views about actual levels of utilisation. One, who regularly visited a cross-section of schools in the region, reported never having seen the sets in use for classroom purposes, after the project had been operational for over a year, although teachers had sometimes been observed watching the television in off-duty moments.

Both company personnel and Edutel staff expressed the opinion that there is considerable variation in utilisation from school to school, depending to a great extent on the approach of the school principal. Other observers have also suggested that there are regional variations, pointing out that some areas experience greater difficulty in obtaining videotapes, and that intentional damage to the equipment and theft of components has been more prevalent in certain areas of Bophuthatswana.

Informal interviews (by Setswana-speaking interviewers) with teachers and pupils from a small haphazard sample of rural and peri-urban schools have provided no evidence of substantial utilisation. Due to the small non-systematic sample however, this information cannot be regarded as representative, and is merely suggestive. Pupils interviewed reported watching videos as infrequently as once a year. A few teachers pointed out that although they had very rarely shown videos, they had signed forms saying that they had. This suggests that central records held by Edutel are unlikely to be a reliable indicator of actual utilisation levels. An independent survey would be desirable.

From the available evidence and opinion, it seems almost certain that average utilisation levels are considerably lower than those for which the systems were designed (10 hours television/video use per day). Average levels could be of the order of hours per month rather than hours per day. On the one hand, this would have implications for the technical design of the systems, and the cost-effectiveness of the equipment installed, as discussed in Section 10.6. On the other, low utilisation levels would preclude any widespread delivery of the intended benefits of the educational television project.

10.4 Problems and Constraints

A number of problems have been identified to account for limited utilisation in schools, and these are now discussed. It should be repeated that the status of the information in this section is that of subjective opinions, expressed by a number of key informants (as described at the beginning of this chapter). Most of these opinions were gathered at the end of 1986, with selected informants re-interviewed in 1988. The bulk of the information was therefore current in 1986, and would need further research to bring it up to date.

In most cases, the problems which are discussed below were raised independently by several informants, giving an indication of perceived generality. However, it is likely that the experiences of educational television in schools would vary across the schools of Bophuthatswana. The problems and perceptions of teachers would therefore need to be representatively surveyed to provide a firmer basis for generalisation.

10.4.1 Educational software

The value of having TV/video facilities in schools depends very much on the quality and appropriateness of available educational software. This has been a central area for concern in the set of opinions gathered from educationists and teachers in Bophuthatswana.

As previously discussed, Edutel has relied principally on reproducing and distributing videotape material obtained from overseas suppliers. Several difficulties have been identified in making effective use of such material in local classroom teaching.

Some of the recorded complaints were directed at the general quality of the available video programmes.

For instance, charges were laid against the "faded 1950's-style American presentation" of some of the programmes; (but since software was procured from several sources in America and Europe, such a criticism must be restricted in application). An Edutel representative, commenting on the variable quality of software

obtained, classed the American material as generally stronger in professional presentation, while software bought from British sources tended to be superior in content. A number of informants, however, shared a belief that at least the initial procurements of video material had been guided more by opportunity and expedience than by a coherent educational strategy.

Still at this general level of criticism, it was suggested that the purchase of educational software had failed to take into account distinctions between **instructional television** and **educational television** programmes. As a consequence, the material purchased was difficult to apply systematically in a classroom environment. Some programmes had been designed for directive instruction, while others were rather of "general" interest. It was felt that this unevenness could confuse and frustrate teachers, especially if they had little means of knowing in advance whether a given programme would function as a substitute for a lesson, as a supplementary component within a lesson, or perhaps as supplementary material of educational interest but not directly related to syllabus teaching.

In an interview, the acting director of Edutel in 1986 shared these misgivings and said that a forthcoming goal was to pay more attention to the "methodology" of using material more effectively, drawing more careful distinctions between different categories of software - for example, programmes which would facilitate drill learning, those which carried forward or amplified the set syllabus, and programmes of more general educational interest. To what extent this goal has been effectively achieved is uncertain. The comments from certain school pupils, informally polled in 1988, that they only watched videos when one of the teachers was sick, suggest that there are at least cases of schools where the available video programmes are lumped together as "educational extras".

A number of observers commented about the unsuitability of the **language**, in imported programmes, for use in local schools. One problem here was the accents of presenters, "too British or too American ... for our pupils to follow." American pronunciation was counted especially difficult for Tswana pupils to understand. For the majority of pupils, English is a second language, and the English they encounter in their lives is not based on American pronunciation.

Apart from the accents, it was felt that the vocabulary employed by presenters was too advanced for most Tswana pupils. Hence pupils could sit through a whole programme comprehending almost nothing. It was felt that locally produced programmes, with native Setswana speakers, even if of lower technical standard, would be much more comprehensible to local pupils, and would also serve as a more useful role model for local teachers.

The issue of **environmental congruence** (cf. Michel and Thomas, 1985:251) was raised by a number of commentators. They pointed out that the imported programmes frequently used illustrations which would be totally foreign to pupils in rural schools, even at such simple levels as talking about a fish as if every member of the audience should be familiar with what a fish looks like. Or as one observer pithily put it: "An American voice says, 'Now go outside and turn over a leaf and look at it...' In this climate! Our pupils will be lucky if they can find a leaf anywhere - the best they could do would be to study some ants!"

At a less obvious level, the modes of presentation, self-expression and interaction of overseas presenters could be jarring to Tswana pupils, accustomed to different norms of polite behaviour (cf. Gana, 1980:15 for parallel observations about how children respond to "Sesame Street" in Nigeria).

All such comments point to a degree of inevitable mismatch between the intentions of overseas programme design and what would be received from the programmes by pupils living in quite different physical and cultural environments. At the same time, there is a partial counter-argument, in that one intention of the educational television service was precisely to expose school pupils to information which would otherwise remain outside their experience.

Company representatives gave the opinion that programmes in subjects which were less context-sensitive, such as mathematics, science and perhaps biology, were generally more successful than subjects which needed greater local content (geography and history were suggested as instances of the latter).

In recent years, Edutel has gradually increased its locally produced software resources, beginning with production of a useful local history series, and further investigation would be required for a more current evaluation of the degree to which software problems continue to be a source of dissatisfaction. With limited resources, however, it seems that Edutel could at best play a supplementary role in providing educational aids, and perhaps (within the present framework) intervene most effectively by focussing its production and distribution resources around selected school subjects and at selected school levels.

10.4.2 Scale of implementation

Criticisms of the scale of the Edutel project have already been mentioned above. The issues are explored further in this section. Some of the relationships between the scale of technological innovation, the choice of technology, and the peripheral status of rural education in an underdeveloped region will be discussed in Section 10.5.

Three arguments were commonly put forward to support the contention that Edutel began on too ambitious a scale. The first was simply that Edutel lacked the financial and human resources to take on a full-scale schools television scheme successfully. By spreading available resources over such a large target area, overall quality had to suffer, thereby hindering acceptance of what was offered.

A second line of argument was that overcommitment from the beginning severely restricted the ability of Edutel to learn from and adapt in response to emerging experience. Introducing schools television on a more exploratory scale could have allowed Edutel to refine its aims and methods in the course of growth.

Allied to this argument, some observers (reflecting a popular current theme in the international educational media literature) pointed to the different philosophy and practice expressed in "formative" and "summative" evaluation respectively. Summative evaluation would represent an assessment of achievements and failures once the project was substantially in place, by which time options for change might be greatly reduced, the costs of change increased, vested interests

entrenched, and teachers' attitudes perhaps adversely set in place. Formative evaluation, on the other hand, would entail finding out, at each stage in the process, how teachers and pupils responded to what could be offered, and building these discoveries into subsequent directions for development.

Any comprehensive form of formative evaluation could be both time-consuming and expensive, perhaps restricted to such huge and well-funded ventures as the production of the American "Sesame Street" series. To this extent, the appeals for formative evaluation in Edutel's development could be idealistic; but they do clearly point to the concern, amongst these educationists, over the relatively unguided transplant of technology and imported commodity software into local schools.

The third common argument was concerned with the dynamics of spreading an educational innovation. By offering schools television across the board, in middle and high schools, and throughout the region, little scope was entertained for spontaneous organic growth by demand.

The Bophuthatswana "Primary Education Upgrading Programme" (eg. see Holderness, 1986) has frequently been held up as an example to show how new methods in education should, and can, disseminate organically in response to growing demand. This Programme, which has been widely acclaimed both locally and internationally for its achievements, expanded from a kernel of education activists, almost contagiously, as teachers in other primary schools became aware of and excited by the achievements and morale of school teams which were already taking part in the Programme. The implementation of Edutel was seen as a sharp contrast to this model: the over-extension and under-delivery of the Edutel project, from a centralised office, was viewed as inhibiting teachers' enthusiasm and participation. Related points of criticism included the charge of "technology-dumping", and of following a "solution-based" strategy instead of finding out and responding to teachers' felt needs. To quote one observer,

"To get projects like this going successfully, they must start off slowly and on a small scale, and then if they are seen to be valuable, they will spread by themselves. I like to make a distinction between a problems-based approach and a solution-

based approach. With a problems-based approach you find out first what teachers say their needs are, and then you try to respond to these needs - and in a flexible way. You don't present them with a package and say 'this is your solution'. You might have to try out various different options, and the best options themselves might change over time... I understand that a solution-based approach is more convenient to people at the top, and to companies selling equipment. The companies of course want to sell their products and as many as possible - they like things to be simple and they like them to move fast. This of course is typical of capitalism. I don't blame the companies for what they do - that's their business and we should know what their business is. The trouble comes when decision makers do not take the trouble to set out all the options offered. When we see advertisements saying 'Drink Coca-Cola for a good life' we don't necessarily run off to the store to buy Coke."

Important ingredients in the dissemination and adoption of an innovation such as schools television could include

- the role of individuals who act as prime movers
- the development of demand for a facility that has not previously been part of users' experience, and is therefore imperfectly understood
- the ability to adapt the innovation to particular needs
- the receptiveness of different sections of the target population
- the development of a feeling, amongst users, that they "own" the facilities and are responsible for their creative use

It can be argued that blanket dissemination from a central source would tend to act against these potentially important dynamics.

Individual prime movers cannot effectively motivate new users on such a wide scale, especially when they are geographically dispersed and channels of communication are limited. (It is notable here that the initially appointed "utilisation officers", whose task was partly to motivate and train teachers in schools, were reported to find their work unsatisfying due to shortage of time at each school, but were then instructed to cut their time and travelling costs even further because of Edutel budget pressures.)

The growth of demand for what schools television could offer, due to systematic installation of sets throughout the region, could really only take form after the sets had already been installed in schools. It is debatable whether demand grows more strongly when people lack something they know they want, or when they are provided with something when they are not sure that they want it. There is a possibility that facilities which have not been used before could generate their own demand, once teachers find out what can be done with the equipment. The alternative, though, or at least a powerful complementary factor, would be the communication of interest and enthusiasm through example. If one school in an area had demonstrated the use of television to good effect, others might more strongly want to follow. Further, it is reasonable to expect that some schools, their principals and staff and pupils, would offer more fertile ground than others for making use of educational television. Blanket dissemination could obscure the more fertile routes for adoption of the technology.

A complicating factor in the generation of well-founded demand, in this particular case, is that television itself (along with somewhat similar technologies, such as radio and hi-fi) is a popular consumer demand. On the one hand, this engenders a superficial level of demand for something like schools television, since television itself is seen as a desirable technology. But there are misleading differences, since in the case of schools television the unit of consumption (and control) is not the household or other established consumer unit, and of course the service is different in appeal from entertainment television. Subject to income levels, it is relatively easy to market domestic commodities, such as solar-powered music centres. To market a communal facility such as schools television in a demand-led commercial way would be more difficult. There are further economic reasons against the viability of piecemeal dissemination which are discussed presently.

The issue of who controls, or who "owns", a technological innovation appears to be central to acceptance and utilisation, over a wide range of application areas, and no less so in the field of educational technology. It is possible that blanket dissemination of a centrally-controlled project could reduce teachers' feelings of power and

responsibility, and take on the aspect of an imposed choice. From the authorities above (according to Edutel and the supplier company) it was made clear that schools could decide whether or not to purchase the TV/video facilities, but judging by the perceptions of some teachers interviewed, there were effective pressures to join the scheme, if not in the first round of installations, at least subsequently. The reported practice mentioned earlier, of teachers signing forms saying they had used the facilities when they had not, also points to a perception of pressures and expectations from Edutel or the Department of Education authorities. Lines of control within schools, from school principals downwards, could further affect teachers' and pupils' subjective and objective "ownership" of the facilities.

Some of these considerations would have been affected by the style and scale of implementation of the project. However, it needs to be added that issues of control within schools, and within classrooms, and of control from education authorities, are also structured into the education system, extending well beyond the terrain of the Edutel initiative.

More narrowly, it appears that teachers generally did not have control over introduction of the technology, and they do not have control over the software available, but they do have effective control over how much they use the equipment. In commenting on utilisation of educational television in developing countries, Potts (1979:26) claimed: "Teachers want the same things the world over, regardless of whether they make up their own curriculum or whether it is laid down by central government. They want to be in charge of the situation in the classroom." For a variety of reasons, some of which are discussed further in the following section, it may be that teachers do not see the television facilities as contributing to this want, and this may in turn contribute to low average levels of utilisation.

10.4.3 Teacher and pupil attitudes

Evaluative reports of educational/instructional television in other countries have frequently stressed the issue of teacher resistance to the innovation. In comparing television projects from different countries, and their progress over time, there appear to be a number

of variables which can influence acceptance or resistance. For example:

- (a) The status of teachers prior to the innovation. Where teachers have diminished status, or are clearly too few or too underqualified for the educational tasks in hand, resistance is likely to be less.
- (b) The degree to which schools television is instructional (largely replacing traditional teaching, or a pivotal component in new styles of teaching) or rather educational (serving as a supplement to traditional instruction). Where television plays a greater role in dictating classroom procedures, resistance from experienced teachers is likely to be greater.
- (c) Consultation and training. Where teachers are brought into close consultation about the planning and implementation of a project, resistance is likely to be less. Additionally, where teachers are offered special training in utilising the medium within their practice, resistance may be less.
- (d) Educational level. It appears that teachers at primary school levels are generally more open to the innovation. (A number of studies have also suggested that pupils are more accepting of school television at primary levels.)
- (e) Changes over time. A number of possible interrelated effects have been noted whereby initial levels of acceptance may tend to diminish over time.

In Niger, for example, the problem of resistance from experienced teachers was by-passed by employing inexperienced "monitors", after six weeks' training, to oversee television instruction in primary grades. This appeared to work well (cf. Schramm, 1977) except that progressively the lack of integration of trained teachers and integration into the ministry of education undermined national support for the project (1977:158).

In the Ivory Coast, great emphasis was placed not only on serving the expansion of primary schooling, but also on teacher training aided by

television. In the initial expansion period, from 1971 to 1977, nearly 40% of broadcasting time was allocated specifically to teacher retraining (Valerien, 1981:13) as part of a coordinated drive to increase the quantity and quality of available teachers. During this time, broadcasting rose to over 400 programmes per year, thereafter levelling off to about 300 programmes per year, up to 1980. Primary enrolments rose from 20 000 to 650 000 in this period. However, after 1980, educational television broadcasting in the Ivory Coast dropped to less than 20 hours per year, and part of this sudden decline was associated with increasing teacher resistance. "[T]eachers who are increasingly better-qualified react against a pedagogy which imposes many constraints" (Valerien, 1981:15). Also, "secondary school teachers openly criticise teaching by television, accusing it of giving lessons to pupils who are not sufficiently-prepared, who are too active and who lack discipline" (1981:15). These themes, of increasing resistance from teachers as they gain in their qualifications, and increased resistance at more advanced school levels, are echoed by a number of other writers.

Schramm (1977) notes that in response to such changes in attitude over time, it is likely that television projects would contract, that the medium would be used more sparingly and discriminatingly, adapting more to a supplementary than instructional function. Hawkrigde (1982) makes the same comment, less positively. "[M]any projects which began using television for direct instruction in the classroom have been modified to provide supplemental or enrichment content. Such transitions may reflect changing needs in the system. It is more likely, however, that utilisation problems eroded the effectiveness of the direct instruction projects. Recognition of this erosion may have produced a drift to supplemental or enrichment content simply to salvage something from a system which continues."

A further compounding factor, however, in the progress over time of third world educational television projects is the availability or otherwise of supporting resources. In many cases, projects have fallen by the wayside, or undergone sharp transitions, following the withdrawal of overseas aid or expertise. Thus, even if as Schramm suggests there might be a natural course of expansion and contraction, this may be pre-empted by other factors.

In the Bophuthatswana Edutel project, no firm evidence has been obtained about the nature and extent of teachers' resistance to schools television. Diverse opinions which have been collected largely coincide with the points raised above.

The acting director of Edutel dismissed teacher resistance as a significant obstacle (1986 interview). His opinion was that teachers did not view schools television as a threat. "If they were equally strong they might see it as a threat, but since they are not, only a very few see it as a threat - rather as an aid." This could be linked with the way in which television was put forward as a supplementary aid to teachers rather than as an instructional replacement for them. However, other observers were less sure, and attributed greater importance to teacher resistance. The following extended quote from an educational media specialist is representative of this and related concerns:

" ... a certain amount of resistance is inevitable with any innovation - but this can be minimised and overcome if teachers are well consulted and drawn into the project, and if they can see that the innovation really helps them. But the teachers weren't drawn in at the beginning, and now anyway they are very frustrated with the material which is made available to them. In general, they find it very hard to fit this material into the syllabus they are teaching. Edutel never made or understood the distinction between educational and instructional television... And they went to obtain material, they were not clear about this difference, and most of it should be classified as educational television - it may be of general interest to the pupils, to the extent that they can get anything out of it, but it doesn't help them with their syllabus and exam work."

Apart from the claim of inadequate prior consultation with teachers, this opinion also suggests that Edutel could be falling between two stools. Almost certainly, an imposed programme of fully-fledged instructional television would have incurred strong resistance from existing teachers in secondary schools; and this probability is avoided by offering a supplementary rather than instructional service. However, teachers who feel strongly constrained to teach within the prescribed syllabus find it difficult to incorporate educational video

material which is not coherently related to their syllabus teaching.

This frustration is said to be compounded by timetable-scheduling problems, and sometimes by space constraints.

School timetables are already tightly filled with the existing curriculum, and only in exceptional circumstances (like staff illness) are teachers amenable to diverting time for activities outside the syllabus curriculum. Secondly, it has been suggested that the television/video facility can compete for space in schools which are already desperately short of accommodation. A few educationists observed that in some schools the set was housed, for security reasons, in a special room, which could not then be used for general classroom teaching.

It is probable that such problems would be felt more strongly in secondary than in primary schools. Judging evidence from a number of other countries, Hawkrige (1982) noted that "the sequence of changing classes in secondary schools complicates scheduling problems in using broadcast materials. The primary teachers, who usually have responsibility for a single class during the entire day, have much greater flexibility in fitting broadcast materials into their teaching schedule."

Further problems contributing to unfavourable attitudes amongst secondary teachers concerned disciplinary contact between teacher and class.

At a milder level, it was suggested that the contact between pupils and the television set is too passive and uninvolving to keep pupils alert and interested. Factors such as high temperatures in the classroom, too many pupils viewing one screen, and inability to follow the language, were said to lead to pupils losing concentration and falling asleep. More strongly, it was suggested that some teachers regarded the intrusion as a threat to their authoritarian disciplinary control, in as far as programme material could show or imply deficits in the teacher's expertise, or illustrate teacher-pupil relationships which were less authoritarian and more participative. Such teachers, already feeling over-extended, would then have to expend greater efforts to recover and maintain their authority in the classroom.

In this context, the views of an external commentator are of interest. An educational media specialist with the South African Department of Education and Training (D.E.T.) in Pretoria was interviewed for his opinions about Edutel in Bophuthatswana and possibilities of a similar venture in South African "black" schools administered by the D.E.T. Speaking in his personal capacity, he noted the problems which Edutel had experienced with educational software, and observed that software production was an area currently being contested within the South African Broadcasting Corporation and the D.E.T. He believed that innovations such as educational television would have a greater chance of success at primary school level, partly because more primary school teachers were women and because primary teachers in general were less concerned about maintaining an authoritative, disciplinarian stance in the classroom. A further advantage of introducing the medium at primary school level was that pupils' attitudes and expectations at that stage would be less moulded by the existing authority patterns. By being exposed to pedagogical approaches which encouraged greater participation and questioning, pupils might then enter secondary education with greater expectations of their teachers and a greater inclination to question what teachers taught and the style of teaching. The new generation of pupils might then help to transform the character of secondary school teaching by demanding more from teachers.

It can be assumed that this viewpoint would not be fully shared throughout the D.E.T. in view of well-demonstrated preferences for tight discipline and controlled syllabus teaching. It could also be expected that strong differences of opinion would be expressed in conflicts about who should produce South African educational software and how its content and pedagogy should be controlled.

Returning to the Bophuthatswanan case, pupils' attitudes towards schools television could not be adequately assessed without careful research in a cross-section of school populations. The information collected in this preliminary study only provides some incidental indications.

Supplier company representatives suggested that on the whole, pupils were enthusiastic, and at times frustrated by not receiving enough

from the television facilities; that pupils at times exert pressure on teachers to show more videos. A somewhat different interpretation, offered by several critics (and some pupils and teachers) is that in "community schools" where the television equipment had been paid for by funds collected from the school community, there was anger that the community had been pressured to pay for expensive equipment and then received very little benefit from it. Further comment, at this broad level of overall attitudes towards the innovation, was that in more politicised schools (specifically urban and peri-urban schools close to Pretoria) the equipment was taken as a symbol of an educational authority and state authority to which pupils were opposed, this being a reason for intentional damage to the conspicuous photovoltaic panels. It is clear that fine-grained research would be required to separate out the complex factors affecting pupils' attitudes towards the innovation.

Finally, a common theme in negative assessments of schools television was that compared with other pressing needs in schools, it could not be regarded as a high priority need. Other material needs which were mentioned included more classrooms and better accommodation; improved water supply and sanitation; books and libraries; simple teaching aids, such as maps and charts; laboratory equipment; and electricity supply for a range of applications, including lighting, rather than a dedicated supply just for television/video. Competing needs are not only a problem for planners choosing priorities. Teachers, pupils and parents also have views about priority needs, and if solutions offered do not correspond with their evaluation of what is most needed, this can contribute to negative attitudes.

Educationists further suggested that the primary need was for a sufficient supply of teachers, suitably qualified, to sustain Bophuthatswana's educational expansion and reforms. They expressed scepticism that this problem could be leapfrogged by replacing teachers or teachers' skills with a limited television offering. They felt that the resources should rather have been devoted to teacher training. A commitment to teacher training and the provision of schools television are of course not mutually exclusive, although they may involve a degree of competition for resources.

10.5 Aspects of "Appropriateness"

It is readily apparent that an assessment of a technologically-supported innovation such as solar-powered schools television cannot be limited to a narrow assessment of the technical appropriateness of the hardware. The value of the technology used is dependent on project implementation. The course of the project, in turn, is contingent on a complex range of individual, organisational, structural and historical factors. Evaluation and analysis are made difficult both because of the variety of determining variables and because of their interconnections.

The focus of this study has been on the photovoltaic power-supply, which plays a crucial role in enabling off-grid schools to use television/video equipment. Beyond that, the photovoltaic component has a rather minor impact in determining the appropriateness of the overall enterprise. However it is interesting to take up some themes which, on the one hand, are often present in debates about appropriate development initiatives, and which, on the other hand, reflect upon the characteristics of the technology used in Bophuthatswanan schools television.

10.5.1 Centralisation versus decentralisation

One of the interesting "tensions" in the Edutel project has been the interplay between centralised planning and decentralised end-use. This tension is mirrored in the technology itself. Photovoltaics offer a decentralised power source, especially suitable for local small-scale applications. Broadcasting technology is, of course, generally centralised technology. As mass media, the purpose of broadcast television or mass-distributed videotapes is to distribute information widely from central facilities.

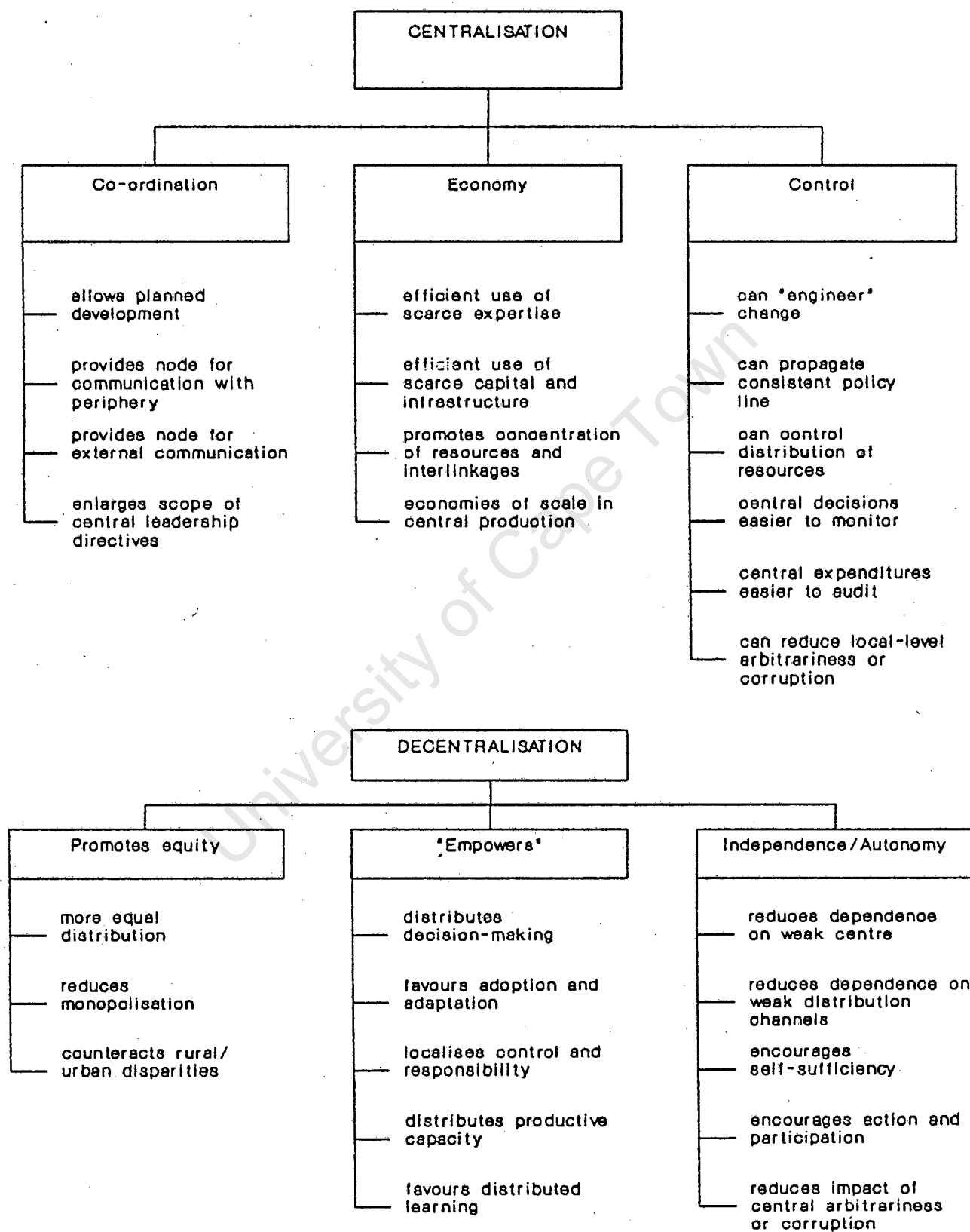
It could be added that state systems for mass schooling tend to show the same tension, between central planning and widely distributed "end-users" (teachers making use of central services, and finally pupils). While this is true generally, across school systems the degree of centralised control is variable and dynamic; within a particular system, it can be the subject of intense conflict.

A relevant example from such contested terrain was expressed by a South African scholar of education systems. In response to the idea that the South African Department of Education and Training might follow Bophuthatswana in introducing schools television, he suggested that any technology which increased centralisation within the D.E.T. system should be viewed with apprehension. Similarly, from counterparts in Bophuthatswana, several of the opinions recorded in earlier sections can be linked with conflict about appropriate degrees of centralisation.

In various ways, centralisation issues have also been prominent in debates about "appropriate technology". Notions of appropriate technology have moved through several shifts, from early focuses on suiting capital- or labour-intensive techniques to prevailing factor prices, through to later concerns with ecological compatibility (originating mainly as a first-world concern) or the management of international dependency relationships between underdeveloped and advanced economies in the course of technology and commodity transfer (mainly a third-world concern). The changes in conception of appropriate technology can be viewed as historically relative, for they can be associated with political and economic changes in the industrialised nations, technological advances, and with politico-economic experiences of development options and constraints in underdeveloped regions.

In most conceptions of appropriate technology, other than the most narrowly technical, the debate about centralisation versus decentralisation of productive capacity and lines of control has tended to go in favour of promoting decentralisation - both in application to the course of first-world industrial growth and to third-world development. There are certainly counter-arguments, however, and there have been a range of viewpoints and policy practices (China's dramatic reversals of policy providing clear examples in this regard). What is probably true is that there has been common ground in the varied debates in so far as they recognise strong interrelationships between the distribution of productive resources, the character of technology employed and socio-political configurations. This breadth of view is not always shared by agents of technical change and technology transfer. Hence centralisation/decentralisation issues are typically contested at a "policy" level.

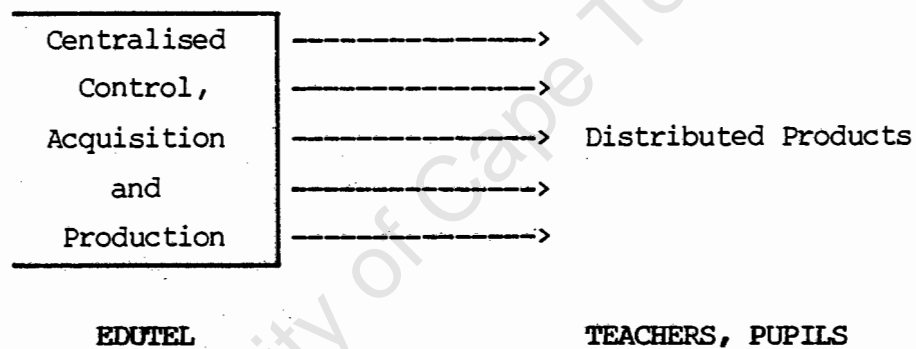
TABLE 10.1 Some Developmental Features of Centralisation and Decentralisation



As applied to an underdeveloped region such as Bophuthatswana, some of the salient arguments for decentralisation or centralisation are summarised in Table 10.1. They address issues of motivation, efficiency, power, political control and scarcity of resources. The fulcrum of the debate is scarcity of resources (human and material resources) for development, and the policy-level decision should be how to optimise the utilisation and further development of available resources.

In relation to the educational technology represented in the Edutel project, several of the arguments summarised in Table 10.1 can be associated with motivations for or objections against the schools television venture.

The broad characteristics of the project can be depicted as:



Objections to the project, referring issues discussed earlier to items in Table 10.1, include: insufficient involvement of teachers in decision-making, hindering acceptance and decentralised responsibility; over-reliance on a weak central organisation and weak distribution channels; lack of adaptability to local needs.

Motivations for the project included: a desire for more equal distribution of educational resources, partly to help counteract rural/urban disparities; "engineered" planned change; efficient use of central resources to compensate for weakness of regionally-distributed resources (human and material).

However, it could be maintained that the "centre" (the central Edutel organisation) has had weak production and delivery capacity, and hence weak penetration into the decentralised arena of classroom teaching. The unfortunate position, by this view, is that the attempt to

harness and efficiently employ scarce resources through centralised control has been less than successful due to insufficient human, financial and organisational resources at the centre. At the same time, potential advantages of decentralised development have not been achieved, partly because the method of project implementation did not promote this.

Focussing more narrowly now on the technology employed, are there features of the technology itself which helped "set" the terms of the project? The photovoltaic component will be discussed before considering the broader communications technology of educational television.

The photovoltaic component is essentially an "enabler" and does not inherently set the application for which it is used. Clearly photovoltaic generation could be used to power other electrical teaching aids, such as overhead slide projectors (more expensively), or other electronic aids such as computers. It is true that for reasons of cost, photovoltaic power is most attractive for light electrical loads, favouring electronic applications, which in turn can imply software dependence and hence dependence on central distribution sources. However, photovoltaic power supply in itself is attractive in developing areas largely because of its degree of independence from centralised sources.

Yet, as applied in the Edutel project, there have also been logistical and economic aspects which have promoted centralised decision-making in the installation of photovoltaic systems, and it is worth listing these:

<u>Centralised decisions</u>	<u>Reasons</u>
1. PV power supply for all relevant schools not connected to the grid. [even where schools were physically close to power lines]	Economy of standardisation, bulk supply, and systematic installation. [PV contractors could not be expected to take on responsibility for comparing costs and time for grid-connection, where a possibility]

2	PV power dedicated to TV/video load, not available for other purposes.	Expense of PV generating capacity, and in relation to this, the special adaptation of the TV and power-conditioning circuitry.
3	The use of (expensive) PV-adapted TV systems, even in grid-connected schools.	The logistics of standardisation especially with regard to maintenance.
4	Standard sizing of PV systems, irrespective of location.	Installation advantages of standardisation; lack of detailed local climatic information; dependence on overseas sizing technology.
5	The standard, seemingly excessive, specification load for which the PV systems were sized.	(i) Presumably a desire to install "full-capacity" systems from the outset, rather than use modularity benefits of PV modules (which would entail further installation costs at a later stage); (ii) Lack of advance knowledge of delivery potential of Edutel and acceptance by users.

Some of these central decisions, built into the contract with the supplying company, would have entailed cost penalties in particular instances, but often with the motive of achieving higher overall efficiency of supply, installation and maintenance. Some decisions (eg. point 5, perhaps point 2) could be argued to increase the cost:benefit ratio generally.

In the context of the broader discussion about centralisation/decentralisation, it can be pointed out that the "users" of the technology did not and perhaps were not in a position to take part in such decisions (although it is said that individual schools had the option of accepting or rejecting the package). Thus, while

photovoltaic technology is suited for decentralised applications, in this case central control predominated in the installation of photovoltaic systems.

Turning now to the communications technology, television broadcasting or mass videotape distribution are primarily media for unidirectional communication. Feedback is of course possible by other channels, but the technology differentially empowers information flow from sender to receivers. The same is true of other mass media, for example - within the educational context - text books or radio broadcasts (except that there have been sporadic uses elsewhere of two-way radio in rural education).

The essential characteristic of such media is their ability to repeat messages, in many locations or across time, and that is also their economic attraction. Educationally, the repetitive function has both strengths and weaknesses, depending on the content of messages and how they are used.

Assimilation and learning require interaction with information sources. Encouraging greater interaction is an aim of many pedagogical approaches, and is often considered an important factor in the choice of educational technology. In the Edutel schools technology, at a technical level, teacher interaction with video material is restricted to being able to switch on and off and to repeat sections of the video. The facility for recording broadcasts on videocassette brings this same flexibility of use to broadcast programmes. The scope for interaction with source material of course depends more importantly on the pedagogical design of the software - whether a programme is presented as a resource or trigger material, inviting participation, elucidation, critique, or whether it functions rather as autonomous stand-alone instruction. (This applies equally to text-books.) It may well be that, properly used, video programmes could offer greater scope for interactive participation in the classroom, for instance by providing stimuli to which both teacher and pupils can respond more freely than if the teacher were presenting a lesson unaided. Judging by collected opinions in earlier sections, however, it appears unlikely this has been the trend in Bophuthatswana classrooms, and more likely that the users have been essentially "receivers" of centrally disseminated messages.

One question here is the extent to which teachers could participate in the **production** of educational programmes. Edutel's intention was to train teachers to be script-writers in the production teams (implying career change, rather than opportunities for participation by practising teachers). The level of technical and professional skills required for both preparing and presenting good television programmes would tend to limit participation, although Michel and Thomas (1985:254) have reported effective participation by trainee teachers and university personnel in Haitian educational television. One educationist from Mmabatho suggested that educational radio has been more accessible for teachers. The demands on production and presentation skills are less, and because production is technically simpler and cheaper, there has been greater opportunity for teachers to contribute. It appears that radio broadcasts are being used most constructively in Bophuthatswana at primary school level.

The expense of producing television programmes must be counted the most important limiting factor, constraining scope for participation, scope for pedagogical experimentation, and, overall, the quantity of local production that is possible. In relation to this, the costs of production must also be justified in terms of potential "market size". Unless Edutel could export its products beyond the region - and this is certainly feasible, to a limited extent - does Bophuthatswana have a sufficiently large school audience to justify the expense of extensive local television productions? The limited allocations available from Broadcasting and Education budgets point to the difficulty, and enforce an unwanted degree of dependence on imported software (produced, of course, for considerably larger markets).

It could be argued that there would be a case for regional cooperation in producing educational software. At present, political differences and disparate educational systems are limiting factors, although there must also be areas of common interest, and good educational software in some subject areas could be widely acceptable. Such conjectures, however, return one to the question of whether educational television is an optimal medium for aiding education in the Southern African region, and bring back the dilemma that to run efficiently and cost-effectively, a schools television system presupposes centralised resources of considerable magnitude, needs to achieve wide coverage,

but for that requires decentralised acceptance by teachers and pupils, which can be imperilled by attempting a comprehensive service before the benefits have been established. Because of the nature of the medium, educational television with local content would be very expensive to "pilot" in underdeveloped regions, yet without proceeding through pilot stages has a reduced probability of success. Because of these factors, it is difficult to envisage other regions comparable to Bophuthatswana adopting similar educational television projects, or at least not wisely.

10.5.2 Self-sufficiency versus Dependency

Like the issue of centralisation/decentralisation, the issue of self-sufficiency versus dependency is also a prominent theme in debates about appropriate technology, and in development strategies more broadly considered.

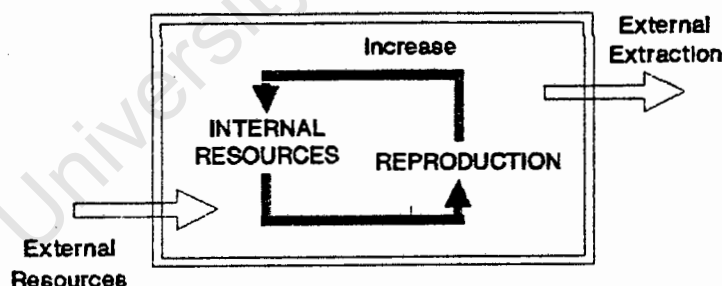
It is understandable that "self-sufficiency" should also often feature in national political pronouncements, especially in regions where there are perceived strategic reasons for avoiding interdependence, or where there has been a history of past (and perhaps continuing) political/economic domination.

In Bophuthatswana, "self-sufficiency" is a key theme in national political discourse, and extends into the "Popagano" philosophy of education. In this respect, Bophuthatswana does not differ from neighbouring independent states, such as Botswana. However, in common with other "national states" or "homelands" brought into being by the South African government, Bophuthatswana has a higher degree of continuing dependence on South Africa. Economically, this is illustrated by the high proportion of Bophuthatswanan wage earners who work, as migrants or commuters, in the South African economy. Politically, it is illustrated by the intervention of South African armed forces in 1988 to quell an attempted coup d'etat and restore the Bophuthatswana government to power. Consequently, "self-sufficiency" can be only pursued in a rather limited terrain, and the expressed fervour for it is complicated by powerful contradictory forces.

In any case, "self sufficiency" is an awkward concept to attempt to apply, in any complex society. There are two main problems. First,

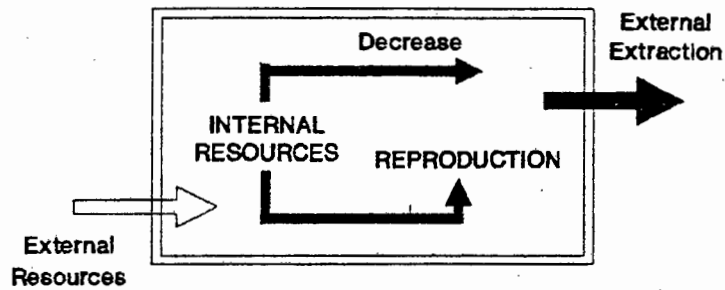
the concept implies some unit around which one can draw boundaries, and the practical implications will vary according to the unit or level of organisation being considered. For example, self-sufficiency at a national economic level is different from self-sufficiency in the economy of a rural community school. Similarly, for a national unit to be self-sufficient in energy resources there is no presumption that self-sufficiency obtains at every level, or that where it does (as in an isolated village) that this is advantageous. The second problem is that the term can obscure the diverse character of exchange relationships which are virtually inevitable both between societies, and within societies at every level, some of which can be synergistic, others antagonistic. It seems more useful to consider the "terms of exchange" in particular social, economic and political relationships. However, the concept of self-sufficiency still has a useful and more specific central thrust, if it is understood along the following lines: at a specified unit-level, sufficient access to internal resources (cognitive and material resources, and powers of social control) to allow the unit both to reproduce itself and to further increase its internal resources.

This need not exclude access to external resources, as schematically illustrated below, providing the above conditions are met.



In distinction to this, the notion of "dependency" focuses on social, economic and political interrelationships, specifically where the terms of exchange are adverse, thus hindering potential for autonomous development. In this sense, dependency is a concept associated with theories that view underdevelopment as an active process, caused in part by such adverse terms of exchange (schematised as [A] below). Dependency can also be used in a less theorised way, simply to indicate dependence on external assistance for internal survival and reproduction, as in [B].

[A]



[B]

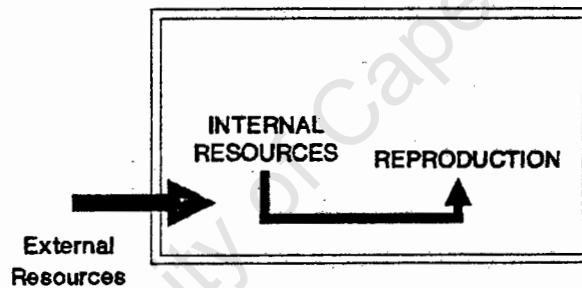


Table 10.2 attempts to set out some of the cognitive, material and social power resources which might be required to attain increased self-sufficiency at various levels in the school education process in Bophuthatswana. Clearly it does not provide a comprehensive picture, but helps to draw attention to areas of weakness, and to necessary interdependencies between different levels of organisation.

TABLE 10.2 Some Requirements for Increased Self-Sufficiency at Various Levels in the Educational System

	INTELLECTUAL/COGNITIVE RESOURCES	MATERIAL RESOURCES	POWER/ CONTROL
Pupil level	Acquiring learning skills Knowledge competence Self-esteem	Basic material needs Finance for fees, etc.	Ability to challenge their education Career mobility
Teacher level	Teacher competence Satisfactory social environment Self-esteem	Necessary material resources for teaching Satisfactory pay	Control over teaching process Control over educational content Classroom discipline
School level	Calibre and supply of teachers Attainment of pupils Congruence of school and community aspirations	Physical structures Finance for O & M Finance for development	Independence from adverse interference (eg. from tribal authorities) Constructive relationship with Department of Education
Education system level	Emancipation from "Bantu Education" Indigenous curriculum development Planning expertise Research and development Teacher training capacity Ability to produce and distribute educational materials	Ability to provide schools and equipment Ability to recruit and pay teachers Finance for development initiatives Finance for compulsory education	Freedom from or constructive relationship with government Ability to respond to challenge from teachers/pupils Ability to monitor schools effectively
Government or national level	Internal legitimacy Nationhood International recognition Sufficient technical expertise/capacity Sufficient organisational expertise Viability of national economy	Economic independence Infrastructure	Political independence Political power

Any materially-based perspective on development causalities would attribute a measure of primacy to the **central column** in Table 10.2. As would be expected in an economically underdeveloped region, Bophuthatswana experiences lack in almost every item at each level in this column. Critics of the political formation and national administration of Bophuthatswana would further identify weakness in the **bottom row** of the table, as a whole, and attribute causal consequence to these areas of weakness. In combination, the central column and bottom row mark out an **inverted T**, and what remains in the table marks out the principle terrain for reform aspirations in the educational system, subject to the base constraints of the inverted T.

It can be noted that attainment of "self-sufficiency" goals at one level can be dependent on other levels. Also, attainments at one level may be in conflict with or prejudicial to attainments at other levels. For example, the degree of self-determination which pupils or their parents could achieve over school education could be in conflict with teachers' control over the teaching process, educational content and classroom discipline. (As shown in South Africa, pupils' educational demands can extend as far as to challenge the political power of the state.)

To illustrate another aspect of conflicting interests, instances have been reported of rural teachers selling centrally distributed textbooks to pupils at inflated prices, refusing to allow them to purchase books from other sources, and refusing to register pupils who have not paid for these books in advance. Such strategies promote the material self-sufficiency of teachers at the expense of other groups, and can be traced to other causative weaknesses in the system.

Endemic scarcities and complex, often antagonistic, interrelationships are familiar characteristics of underdevelopment. A purpose of raising this framework is to address a narrower set of questions which relate to the educational technology used in the Edutel project. To what extent can this technology promote increased self-sufficiency and capacity for autonomous development? To what extent does it reflect and perhaps aggravate relations of dependency?

First, the educational technology of schools television will be considered, before focussing in on the photovoltaic power supply.

School pupils are the target of the school education process, unless one takes a broader view of the function of schooling in reproducing suitably educated and disciplined entrants into the adult society. The "Popagano" philosophy of education, as expressed in the report of the National Education Commission (Rep. Bophuthatswana, 1978), valued the attributes of self-sufficiency at both levels. School education should promote the capacity and powers of self-determination of school leavers; at the same time, the aim of achieving sufficient supply of well-educated and well-trained school leavers was viewed as one of the most vital steps towards achieving greater national self-sufficiency, reducing dependence on expatriates and foreign expertise. In the latter respect, inculcation of a distinctive national culture was included as a requirement of suitable education for promoting national self-sufficiency.

Typically, school pupils are dependent on their teachers to a large degree, and (as discussed earlier) a primary educational aim of introducing schools television was to diminish the negative aspects of dependence on an inadequate supply of suitably qualified teachers. To what degree this aim has been achieved is debatable, and not fully known. No evidence has been gathered that the autonomous learning of school pupils has been enhanced. Critical educationists, who have expressed doubts that school television has been effective, tend by contrast to see teachers as the agents in the system who need to achieve a greater measure of self-determination, and they do not regard the school television facilities as materially contributing towards this. Low levels of utilisation are attributed partly to the dependence of teachers upon central provision of software and supporting materials.

Dependency shows itself most clearly in the hardware/software split. The frequent unsuitability of imported software, and the difficulties in the way of producing local software have already been discussed. It appears that local production is often contracted out to basically South African producing companies. There have also been reports of private contracts being sought through under-the-counter offers of extra payment to government officials. Such irregularities, while not unexpected from some sections of the business world, would be less likely to occur if Edutel had the resources to operate autonomously.

Software dependency may be typical of transfers of modern electronic technology to underdeveloped regions. It could be thought of as a kind of "transparent" dependency, because on the surface, through hardware acquisition, it appears that the receiver nation has gained tools for its own use, promoting autonomous development. However, if the receiver nation is not in a position to produce the software, then both financially and perhaps culturally there is a continuing indebtedness to the more highly industrialised producer nations. In the case of educational television in Bophuthatswana, the dependence here has been evident. The software dependency includes a limitation on inculcating a "national culture" or, at least, transmitting locally selected values through the medium (as had been hoped). One consequence appears to be that local software production, including programmes classed as adult education, may have concentrated more than is optimal on national-symbolic matters, leaving the more strictly educational content in the hands of foreign production.

Concerns about software dependency have been strongly expressed by local educationists in relation to other electronic educational technology as well, notably computer assisted instruction. Large computer companies have solicited Bophuthatswanan educational authorities (as in some other South African "national states" or "homelands") and even offered considerable quantities of free hardware. In particular, American offered computer-based literacy technology has been criticised for pushing against the view that literacy should first be taught in the mother tongue of young children; for lack of local congruence; and for downline expenses even if initial pilot facilities are offered free.

A feature of dealings between government officials and representatives of powerful companies offering technology for development, in a context like Bophuthatswana, is an imbalance in expertise. The officials may lack the technical backup necessary to evaluate what is offered, and this problem is exacerbated if decisions are made by politicians without adequate consultation. This becomes a serious concern of educationists who worry that, even if motives are benign, decisions taken between state officials and powerful companies will effectively lead to "dumping" of expensive technology in schools; that the technological solution sold to high-level decision makers will not be a useful solution to needs at grassroots level.

There are broader dimensions of dependency which plague the educational system and in particular rural schooling in a region like Bophuthatswana. Urbanisation, industrialisation and the growth of central bureaucracy take place to a certain extent within the region, reducing the attraction of rural subsistence and pulling resources and people away from rural areas. Amongst other things, this dynamic reduces the supply of willing rural teachers, and relatively well-trained teachers are attracted into other jobs, especially during the honeymoon period of an expanding government bureaucracy. Urban employment opportunities however are not sufficient to absorb extensive migration from rural areas, which are therefore likely to remain sites of subsistence and family reproduction. There is a sense in which, to use the terminology of dependency theorists, rural areas become increasingly peripheralised relative to the urban centre/s, and the terms of exchange can become increasingly adverse as relatively fewer resources flow to rural areas, and as the countryside is depopulated of its most productive people. Rural areas then become a reproductive support system for the centre, and get little in return.

But in Bophuthatswana's case, the major demographic dynamic which sucks off the attainments of the schooling system arises from proximity to highly industrialised areas of South Africa, where employment prospects are relatively much greater. Thus Bophuthatswana as a whole can be viewed as a reproductive system for providing South African labour, and the irony appears that the resources which Bophuthatswana allocates to its education system largely bear fruit in the South African economy. This process is not total, but sufficient to establish a definite dependency cycle: within the context of Bophuthatswanan schools television, it is illustrated by the profits made by South African companies in supplying equipment or by undertaking contract software production, followed by the probability that if educational television were successful in raising the educational attainments of Bophuthatswanan school pupils, the gains would be transferred out of Bophuthatswana through migration of qualified school leavers to South Africa.

Turning now to the specific technology of photovoltaic power supply for schools television, there are a number of features of photovoltaic technology which bear on the issue of self-sufficiency versus dependency.

At a local level, photovoltaic power supply stands out as an autonomous source of electricity, with minimal dependence on infrastructure, no fuel requirements and very little maintenance. In these respects, photovoltaic generators provide a classic instance of a "self-sufficient" power supply, ideally suited to remote applications on earth or in space.

From a developmental perspective, however, there are more complex factors to consider. Some of these factors can be regarded as disadvantages of this particular technology transfer. The disadvantages will be outweighed if the "leverage" of the technology is high enough. Photovoltaic power is expensive, the modules are imported, and there are few beneficial multiplier effects in the acquisition of photovoltaic technology per se, but if photovoltaic power enables development initiatives of high value relative to the cost of the equipment, then the disadvantages are acceptable.

Some of the disadvantages can be listed as follows.

- 1 Photovoltaic generators, for underdeveloped regions, constitute a "package" technology. Some viewpoints on appropriate technology for developing areas stress that such technology should be readily understood, maintainable and adaptable by local people: this encourages their autonomous development. In the case of photovoltaic modules, the appropriateness consists rather in their resilience and the minimal intervention required from users.
- 2 The extensive research and development necessary for the production of photovoltaic modules has taken place in the advanced economies. There is virtually no transfer of this expertise and productive capacity to underdeveloped regions.
- 3 Expertise in designing and sizing photovoltaic-powered systems has also tended to concentrate in advanced economies, although

there is greater scope here for local development.

- 4 Since modules are imported, there are no socio-economic multipliers and there is no local employment generation in the production of modules. In the supply, installation and maintenance of systems there is limited employment generation, but labour requirements are small compared with capital expenses. Typically, underdeveloped regions would be dependent on foreign-based companies for design and supply functions.
- 5 Foreign exchange demands reduce the capacity of underdeveloped economies for autonomous development.

The above listed features fall within the concerns of "technological dependency" theorists, and illustrate respects in which the transfer of photovoltaic technology in itself does not contribute to the potential of an underdeveloped region to increase its productive capacity.

Further limitations include, of course, the expense of photovoltaic power. Although in remote areas photovoltaic supply may indeed be the cheapest feasible electricity source, over a period, the expense nonetheless calls for minimisation of electrical loads, and for the sake of efficiency this may imply dedication of the photovoltaic generator to a particular designed load (as in the present school television systems). Where this is the case, there can be further loss in potential "utilisation multipliers" - the potential that an electrical power supply, for instance, will spawn a variety of productive applications in a multiplicative way.

This issue connects with debates about rural electrification through grid extension, and contrasts the value of photovoltaic supply where there is no foreseeable possibility of grid supply with the possibility that stand-alone supplies like photovoltaic generators could be used as a substitute for grid extension, when the latter would be socially and economically preferable. If this were the case - and in the South African context, it would be most likely in peri-urban non-electrified areas - the "self-sufficiency" of a photovoltaic supply would be at the cost of scale economies and utilisation multipliers of central generation and grid supply.

Finally, a feature of photovoltaic technology is that the ratio of capital cost to running costs is high. This can be an advantage for sustained autonomy in underdeveloped locations where future income flows are uncertain. There is less likelihood of the equipment falling into disuse through lack of income (as with diesel gensets when there is no money for fuel or for repair). On the other hand, high initial costs call for satisfactory credit finance and where capital is scarce, represent competition for scarce investment resources. A further consequence of the high ratio of capital to running costs is that the electrical energy generated by a photovoltaic system must be fully utilised to minimise unit energy costs. The costs of not doing so will be discussed in the following section.

The possible disadvantages of photovoltaic technology raised above can of course be outweighed if the application, which photovoltaic power makes possible, has high developmental leverage. In the case of schools television, the photovoltaic component is a subsidiary component of the overall educational technology. The leverage - the ratio of product to inputs - can be considered in three stages.

(i) First, at a technical stage, the leverage is high, because energy-efficient applications equipment allows provision of a television/video service in schools for relatively low electrical power requirements. The photovoltaic proportion of overall system costs can be reduced.

(ii) Secondly, at the utilisation stage, the leverage of the technology would depend on the beneficial impact of the service on pupils and teachers, multiplied in some way by the number of people benefitting. Both aspects are difficult to quantify: the educational impact would be complex and qualitative, while lack of information about the numbers of people benefitting from schools television prevents any confident assessment. In principle, the leverage could be high, but in practice this may not be the case, for reasons discussed earlier.

(iii) Thirdly, there is the stage of broader development multipliers. Improved education is widely seen as a critical lever in an overall development path, raising the level of "human capital" in the population, which can have have multiplicative effects on capacity and productivity. Even if there is attrition, for example through urban drift and migration from the region, educational gains within the region must remain a priority for promoting internal autonomous development. With respect to schools television, this stage of leverage however is contingent on (ii). Utilisation is the crucial factor.

10.6 Photovoltaic Supply to Schools: Economic Assessment of Energy Costs

A full economic assessment of the costs of providing schools television in Bophuthatswana would require information not available for this study. Instead, a narrow economic assessment of the costs of electrical energy supply for off-grid schools is provided in this section.

A number of other local studies have explored the comparative costs of photovoltaic supply, for a variety of applications, with those of alternatives such as diesel generation (cf. Müller, 1987; Morris, 1988; Sinclair, 1989). Here, the focus will not be on making comparisons with alternatives, but rather on pointing out the strong relationship between utilisation levels and unit energy costs; and the sensitivity of energy costing to capital discount rates, and to assumptions about component lifetimes and project lifetime.

At the outset, it should be stated that in a particular application such as powering schools television, it is the service which should be costed and valued, rather than simply energy costs. For instance, through the use of energy-saving applications equipment, the use value of the electricity generated is increased. More broadly, if the service is of high value and energy consumption is low, then relatively high energy costs can more easily be justified.

However there is also purpose in calculating energy costs in isolation. On the one hand, the value of the service delivered is very difficult to evaluate economically. On the other, energy costs in isolation can more easily be extended to generalised applications. One aim of this section is to draw attention to factors which, in a range of developmental applications, would reduce the cost-effectiveness of photovoltaic generation.

The approach in calculating photovoltaic energy costs has been to add the initial costs of installed equipment to the net present value of future payments and receipts, discounted at selected rate/s of interest, and then to calculate the levelised annuity over the project lifetime which corresponds to this life-cycle cost and the same rate/s of interest. The levelised unit energy cost is obtained

by dividing these annual levelised energy costs by annual electricity consumption.

Several simplifying assumptions or estimates are made.

- 1 **Energy conversion sub-system.** The energy conversion sub-system is taken as the photovoltaic array and battery storage. This excludes the power-conditioning electronics (since in this application, that formed an integral part of the applications equipment). However, a cost margin is included for initial "balance of system" costs - array support, wiring, etc. - and for installation.
- 2 **System sizing.** It was argued in Chapter 9 that the installed battery capacity of systems in Bophuthatswana schools, as well as the nominal capacity of the array, were oversized for the intended application. To obtain more representative estimates of potential costs of photovoltaic power in this application, the costs are based on a more critical sizing, following the model predictions of Chapter 9. Array power is taken as 135 Wp and battery capacity is halved to 2.52 kWh (rated). With this sizing of components, it was predicted that the design load of 450 Wh/day could be supported with approximately 0.001 Loss of Power Probability. Photovoltaic module and battery costs are based on this recommended sizing.
- 3 **Utilisation.** Except where otherwise stated, it is assumed that the full design load of 450 Wh/day (corresponding to 70 hours' television and video use per week, or an electrical energy consumption of 164 kWh/year) is actually utilised. However, this is not a realistic assumption, so unit costs are also calculated as a function of utilisation levels.
- 4 **Component costs.** 1988 South African retail prices for Photowatt modules and Delco batteries have been used. Without quantity discount, these were: Photowatt modules R18/Wp, Delco batteries R205/kWh (rated capacity). Based on 1984 Photowatt information, a quantity discount of 15% has been applied for bulk purchase of modules. The same quantity discount has been applied to battery prices.

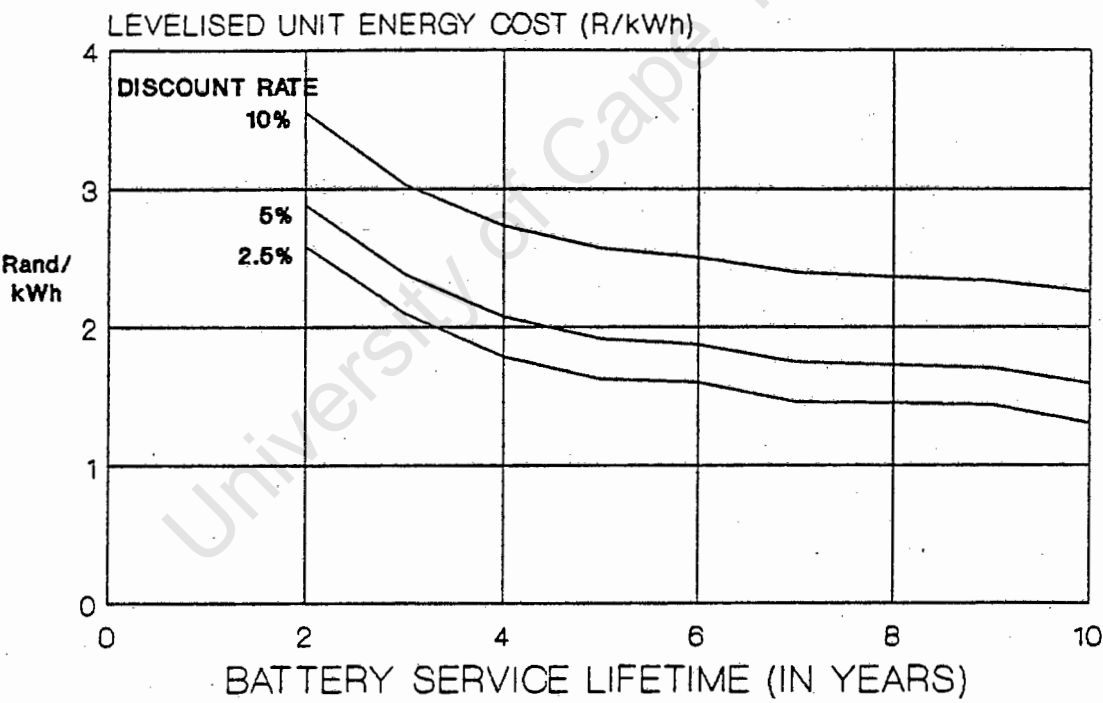
- 5 **B.O.S. and installation.** Balance of system costs and initial installation costs have been estimated as 15% of module and battery initial costs.
- 6 **Component lifetimes.** It has been assumed that the service lifetime of the array is at least 20 years. Battery service lifetime is estimated in the range 5 to 10 years. Battery lifetime would depend on a number of factors, principally utilisation patterns. Where not treated as a variable, battery lifetime has been assumed as 5 years.
- 7 **Project lifetime.** Except where otherwise stated, project lifetime has been taken as 20 years. This is the period used for calculating life-cycle costs and annuities.
- 8 **Replacement and salvage.** Unless otherwise stated, the photovoltaic modules are assumed to have no salvage value after twenty years and do not require replacement within the project lifetime. The cost of installing replacement batteries is assumed equal to the salvage cost of the expended batteries.
- 9 **Operation and maintenance.** Operation and maintenance costs are assumed to be zero (maintenance costs are attributed to the costs of maintaining the applications equipment).
- 10 **Escalation and inflation.** It is assumed there is no escalation in prices (ie. future battery costs are stable) and inflation is not considered (ie. calculations are in "real" terms, indexed to 1988 prices).
- 11 **Discount rate.** The real discount rate is taken to be in the range 2.5% to 10%. Where not treated as a variable, it is assumed to be 5%.
- 12 **Exchange rate.** Since the local prices of modules and Delco batteries are influenced by exchange rates, some costings have been converted to US dollars, using an average 1988 rand-dollar exchange rate of 1 rand = 0.44 US dollars.

Figure 10.1 depicts the annual levelised cost of consumed electrical energy for real discount rates varying between 2.5% and 10%. In this graph, battery service lifetime is also varied, up to a value of 10 years' service before replacement. Other assumptions are as noted above.

FIGURE 10.1 Annual levelised unit cost of consumed electrical energy, varying discount rate and battery service life.

PARAMETERS:

- Project Lifetime: 20 years
- Energy utilisation: 450 Wh/day (full design load)
- Array salvage value: 0 (after 20 years)



With a battery service lifetime of 10 years, it is seen that the levelised cost of utilised electrical energy would range from approximately R1.40/kWh (at a discount rate of 2.5%) to R2.25/kWh (at a discount rate of 10%). If battery service life is 5 years, the range would be R1.60/kWh to R2.60/kWh at these discount rates.

Corresponding unit energy costs per kWh in US dollars, at the 1988 exchange rate, would be:

		DISCOUNT RATE		
		2.5%	5%	10%
BATTERY LIFE	5 YEARS	\$0.70	\$0.84	\$1.14
BATTERY LIFE	10 YEARS	\$0.61	\$0.68	\$0.99

Given that initial costs constitute a relatively high proportion of the net present value of lifecycle costs of such a photovoltaic energy sub-system, levelised unit energy costs are also quite sensitive to project lifetime assumptions. It could be suggested that, in a specific application such as the present educational television project, it is unlikely that the project would survive for twenty years. Figure 10.2 depicts the relationship between unit energy costs and project lifetime, assuming now a fixed discount rate of 5% and a battery service life of 5 years.

In considering shorter periods for the project life (and corresponding periods for calculating life-cycle costs and annuities), the possible salvage value of the photovoltaic array at the end of the period is included in Figure 10.2.

If, at the end of the project, the array has negligible salvage value (for example, as a consequence of rapid technological advance in the interim) Figure 10.2 indicates that over a project lifetime of 10 years, levelised unit energy costs at full load consumption would be about R2.85/kWh as compared with R1.90/kWh for a project lifetime of 20 years.

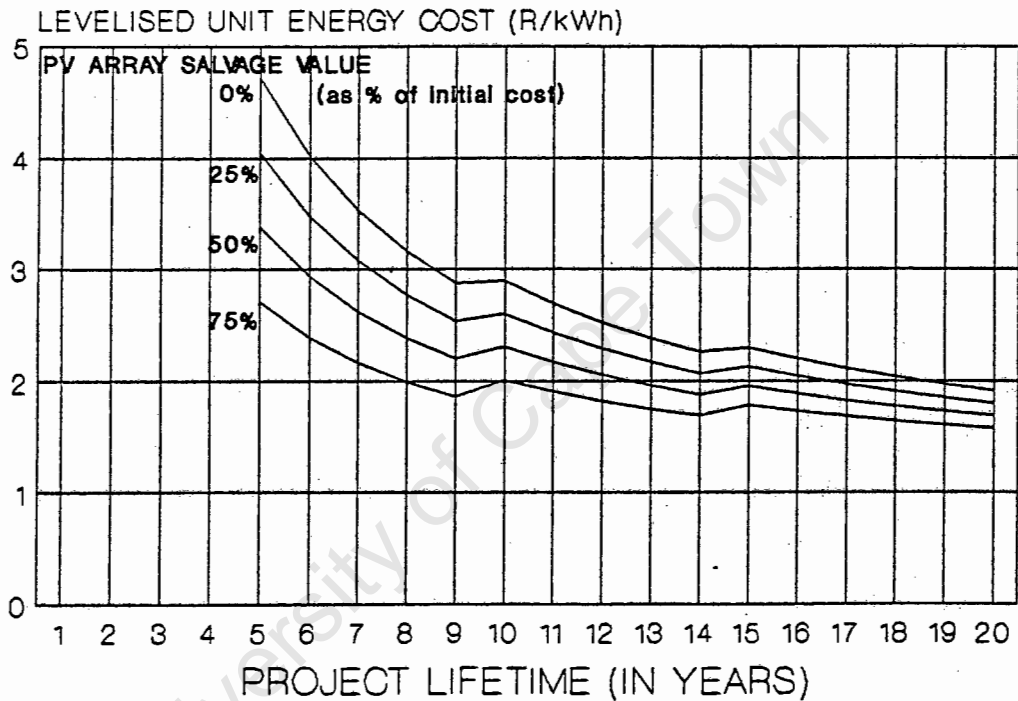
However, if the array has a salvage value of 50% of its initial value at the end of the project, the corresponding figure for a 10 year project lifetime would be in the region of R2.25/kWh.

(The kinks in the curves arise from battery replacement assumptions.)

FIGURE 10.2 Annual levelised unit cost of consumed electrical energy, varying project lifetime and array salvage value.

PARAMETERS:

Discount rate: 5 %
 Energy utilisation: 450 Wh/day (full design load)
 Battery service life: 5 years



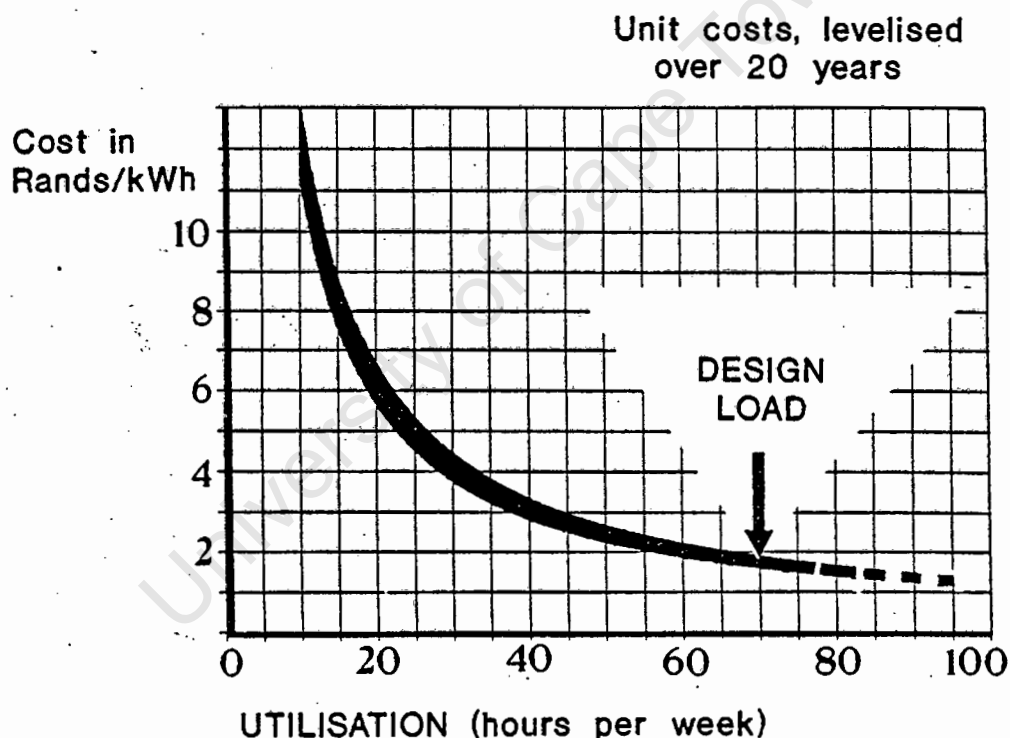
In practice, however, the levelised cost of consumed energy is likely to be determined most strongly by utilisation levels. All the costings above assume full utilisation of available electrical energy up to the design load of 450 Wh/day, or ten hours' use of the television and video each day of the year. As proposed in previous sections, this assumption is not realistic in the present context, and it is likely that actual energy utilisation is on average a small fraction of the design load.

Figure 10.3 illustrates the relationship between utilisation levels and unit energy costs, when other factors are held constant. (The width of the curve indicates a range in battery lifetime from 5 to 10 years.)

FIGURE 10.3 Annual levelised unit cost of consumed electrical energy, as a function of utilisation levels.

PARAMETERS:

Discount rate:	5 %
Project lifetime:	20 years
Battery service life:	5 - 10 years



The full design load corresponds to 70 hours' use per week. It is evident from Figure 10.3 that if average utilisation is only 20 hours per week (which, as an average throughout the year, is a quite conceivable level for schools making regular use of the facilities, and a likely overestimate for other schools) the levelised unit cost of consumed electricity would rise to about R6/kWh (or US\$2.64/kWh).

At a utilisation level of only 10 hours/week, unit costs would be in excess of R11/kWh. No other single factor has such a powerful bearing on unit energy costs.

The range of levelised unit energy costs obtained above, using varying assumptions for discount rates, battery lifetime, project life, array salvage value and utilisation levels, can be compared with similarly calculated cost estimates from other recent local studies.

Müller (1987) investigated the costs of stand-alone photovoltaic power for domestic electricity requirements in off-grid households in two locations in South Africa. In one (at Omdraaisvlei in the Karoo, latitude 30 degrees S., semi-arid climate) he estimated base case levelised unit costs as R1.49/kWh. At the other (Uitsig in the South Western Cape, latitude 34 degrees S., with mediterranean climate) estimated costs were R2.51/kWh. These estimates corresponded with the following assumptions: project life 20 years; real discount rate 4%; battery lifetime 3 years. The battery life expectancy here applied to cheaper SLI batteries; similar costs were estimated on the assumption of solar batteries with a lifetime of 7 years. These estimates assumed full utilisation of the design output of the systems.

From the present study, the cost estimates most comparable with Müller's assumptions are in the region of R1.70/kWh. This is of course a notional costing assuming (a) full utilisation of power up to the design load, and (b) a photovoltaic system more critically sized than those actually installed in Bophuthatswanan schools, in line with the indications of the sizing method in Chapter 9.

Morris (1988) monitored a number of photovoltaic and diesel genset installations in the Kruger National Park (latitude about 25 degrees S., sub-tropical lowveld climate) and obtained levelised unit costs of utilised photovoltaic energy in the range R3.93 to R10.35/kWh. The latter estimate was for an AC system where inverter efficiencies were very low, adding to the inefficiency costs of an oversized system. The load factors corresponding to the above figures were approximately 0.77 and 0.24 respectively. Costing assumptions included: discount rate 4%; project life 20 years; battery lifetime 10 years.

From the present study, estimates of actual unit costs of consumed energy in the Edutel installations, taking into account utilisation levels, could even exceed Morris's highest estimates (which were also largely attributable to overdesign or underutilisation).

The main purpose of the present economic assessment, however, rather than supplying comparative energy cost estimates, has been to draw attention to salient factors which have a bearing on cost-efficient design of stand-alone photovoltaic systems for applications in developing areas.

In the medium term, a continuing predicted decline in the cost of photovoltaic modules should add to the economic competitiveness of this power source, subject to local exchange rates. These factors are largely outside the control of local system designers.

For economical design, especially for non-crucial applications in developing areas, photovoltaic systems should be critically sized, preferably through use of a reliable Loss of Power Probability sizing method, in conjunction with valid local climatic data, to allow more accurate estimation of the economic tradeoffs between smaller system sizing and probability of occasional loss of power to load. Further progress is required to establish such reliable methods. Through adopting such an approach, and if present uncertainties and engineering margins can be reduced, there could be cost savings compared with prevalent sizing methods.

Critical sizing, of course, presumes accurate estimation of load energy demand, according to application, and in many applications this may constitute the largest area of uncertainty. Even where photovoltaic systems are powering technical loads, less subject to user intervention, accurate prediction of energy demand may be difficult (for instance, in refrigeration) while in applications where utilisation is largely determined by user preferences, energy demand can be even more difficult to predict. Large margins of error here could substantially outweigh any benefits from improved sizing techniques.

The Edutel example shows the danger, from an economic point of view, of over-generously specifying a design load, perhaps without adequate foresight into the likely development of the Edutel project, and perhaps without an appreciation of the cost penalties incurred by over-designing a photovoltaic system. Since the ratio of initial capital costs to running costs is high in the case of photovoltaic systems, underutilised generating capacity is essentially money wasted. The penalties are greater than would be the case with power systems where running costs are a higher proportion of total costs, such as diesel generation: spare capacity still represents an avoidable capital expenditure, but with diesel genset running costs (cf. Williams, 1986) typically greater than 50% of total lifecycle costs, the penalties of underutilisation are less severe.

There may be situations where accurate load prediction is less vital in photovoltaic system design. In a stand-alone setting, if there are readily substitutable loads, which are optional in nature but still have significant utility to the user, there can be greater scope for the user to maximise available electrical energy, thus reducing unit energy costs. At the other end of the scale, in crucial applications (such as vaccine refrigeration or repeater stations) where the costs of reliable power are small compared with the costs of loss of power, then safely over-sized systems may be justified. In hybrid systems, where photovoltaic power is a substitutable component of generation, or in grid-interactive systems, where in addition there can be effectively infinite storage for photovoltaic power, the precise sizing of the photovoltaic component will be less critical, since the costs of moving from the optimum substitution point will be less sharply defined and less severe.

But in stand-alone systems, without substitutable loads, the matching of photovoltaic supply to energy demand remains a difficult empirical question. If there is great uncertainty in predicting energy demand, it would seem advisable to make use of the modular characteristics of photovoltaic panels, sizing conservatively to begin with, and extending the array area if demand grows to exceed the installed generating capacity. Allied with this suggestion, it would seem advisable to make use of modules which are not excessive in unit size relative to the size of the expected load.

Finally, it should be pointed out again that in assessing the costs and benefits of technology used in the Edutel project, it is the value of the service which matters. Unit energy costs are relevant in assessing energy supply options, but if the value of the service is high, and energy requirements are low, even above-optimum unit energy costs can be acceptable. Another way of costing schools television in Bophuthatswanan schools is to observe that the photovoltaic systems provide reliable power for showing television and video programmes for up to 10 hours per day, and (through energy-efficient applications equipment) the levelised energy cost of providing for this service is a relatively modest R5 - R6 a week, more or less irrespective of utilisation level. In many respects, this is a more informative costing of the photovoltaic energy. However, the value of the service to users still depends on the facilities being utilised.

10.7 Summary

This section summarises some of the main points from the assessment of social, educational and economic aspects of Bophuthatswana's schools television project.

Advantages and disadvantages of photovoltaic power supply for this purpose were discussed, but it was stressed that the photovoltaic technology is only a minor contributing component in the project. Social, organisational and educational factors are pre-eminent in determining the success or failure of such a project.

Many received criticisms of the project were discussed in detail, against the background of Bophuthatswana's political and economic situation within South Africa. An overall assessment must be that the television and video facilities in schools are under-utilised, diminishing the potential benefits. Major reasons for difficulties in realising the potential value of the project, as suggested by interviewed observers and participants, included the following:

- 1 The scale of the project was too ambitious, in view of Bophuthatswana's limited financial, organisational and production resources. Other developing countries which have tried schools television with some success, such as Niger and Ivory Coast, proceeded much more slowly and started with considerably greater resources. By contrast, Edutel from the outset targetted all school standards, all middle and high schools, and all school subjects, for the educational television service.
- 2 It appears there may have been inadequate consultation with teachers before embarking on the project and inadequate response to feedback from teachers once the project was under way. The project has been characterised as a "top-down" and "technology-led" initiative, offering a package solution rather than a negotiated response to felt problems and needs.
- 3 It was claimed that political motivations and commercial interests played a dominant role in the decision to proceed with the project, and that to some extent this undermined the educational rationale, through premature central decision-making.

- 4 The nature of a mass-medium technology such as schools television/video places the distributed users of the service (teachers and pupils) in a position of dependence upon centralised organisation, production and distribution. It is suggested that central resources for Edutel's expansion were insufficient, in terms of person-power, organisation, production facilities, support facilities, and finance.
- 5 Considerable dependence on imported educational software has led to dissatisfaction with much of the software available to schools. Complaints were that many programmes were not readily comprehensible to local school pupils, lacking environmental congruence and posing language difficulties; that no clear distinction was made between instructional, educational and supplementary/enrichment programmes in acquiring software; and that teachers find it difficult to incorporate the available software in their syllabus teaching.
- 6 It has been difficult to meet requests for increased local production of software, because of scarcity of resources and production costs.
- 7 In view of the costs of delivering an appropriate schools television service, it has been questioned whether television was an appropriate choice of educational technology.
- 8 The implementation of the schools television project must be seen against other needs in the educational system (some of which educational television was intended to alleviate). There have been reports of community resentment over having been pressed to pay for the school television facilities, when other needs were seen as more immediate; low utilisation levels may add to the discouragement.

Chapter 11

TECHNICAL CONCLUSIONS AND RECOMMENDATIONS

This chapter reviews the main technical conclusions reached in the course of this study, and presents recommendations for photovoltaic system sizing approaches and for further related research.

First, conclusions specific to the photovoltaic systems for schools television in Bophuthatswana are summarised, before discussing aspects of more general applicability.

11.1 Installed Systems for Solar Powered Television and Video

The installed systems were judged to provide a reliable and appropriate technical solution to the problem of equipping off-grid schools with television and video facilities. The main threats to reliable operation appeared to be human abuse (damage to or theft of components) and lightning-induced component failures. The incidence of lightning damage did not appear to warrant the added expense of elaborate lightning protection. The modular design of the television and power control electronics provides a major benefit in allowing rapid onsite repair by relatively inexperienced maintenance staff. User maintenance requirements are minimal. The expected service life of the sealed lead-calcium batteries was estimated in the range 5 to 10 years but could well exceed this range under prevailing levels of usage. The service life of photovoltaic panels is commonly estimated to be in the region of 20 years, barring mechanical damage.

The energy-efficient design of the television receiver/monitor and the VCR allow provision of high quality full colour rendition at a fraction of the power requirement of equivalent domestic appliances. Solid state electronics allow efficient operation from the system 24V DC supply. Battery charging and undervoltage protection are tightly controlled by an integral energy management unit, operating at high transmission efficiency through pulse-width-modulated power control, with benefits for battery life expectancy and system efficiencies.

The sizing of the installed photovoltaic array and battery storage was assessed, and can be summarised under three sub-headings.

Generating and storage capacity in relation to design load

With two Photowatt PW-P 801 photovoltaic modules and 210 A-h rated battery storage at 24V, it was calculated that the installed systems could be expected reliably to meet the design load of 450 Wh/day under the full range of probable weather conditions. Calculations from the Loss of Power Probability model developed in Chapter 9 indicate that the installed battery capacity could be halved, while retaining an expected Loss of Power Probability of less than 0.001. It was noted that the surplus installed battery capacity, although unnecessary, could have the effect of extending battery life.

The local supplying company relied on sizing advice from the module manufacturers, and this was critically assessed. Originally the module manufacturers stipulated the use of two Photowatt PW-P 800 monocrystalline modules, rated at 82 Wp each. Calculations showed that an array power of 164 Wp would have been wastefully excessive, by a factor of between 20 - 30%.

The installed modules, however, were measured to have a power rating of approximately 67.5 Wp (converted as closely as possible to Standard Test Conditions) at the monitoring site. The corresponding array power of 135 Wp was judged well sized to attain a Loss of Power Probability of 0.001.

It is suggested that lower levels of expected power availability (eg. a long term Loss of Power Probability of 0.01) would be acceptable in non-crucial applications such as schools television, and preferable in terms of economy. This would permit a further reduction in array power of about 8%.

These calculations were based on ten years' hourly weather data from the Pretoria-Forum weather station, and included generous 15% margins for uncertainties in performance specifications and lifetime performance degradation of modules and batteries.

Matching of array output and load input characteristics

The installed Photowatt PW-P 801 modules appeared very well matched in their measured output characteristics to the system input loadline characteristics. This resulted from module optimum power voltages well suited to the battery charging voltage range under expected climatic and operating conditions. In addition, the low "fill factor" of these polycrystalline modules serves to reduce the power penalties of operation away from optimum power points on the array's output characteristic curves. Maximum expected deviation from optimum power, in energy demand conditions, was estimated at 6%.

With such good matching, it would not be worthwhile to make use of optimum power point tracking, unless cheap and highly reliable.

By contrast, the originally specified PW-P 800 modules, according to calculations based on the manufacturer's original specifications, would have been poorly matched, under expected local temperature conditions, having optimum power voltages excessively above system take-off voltages. Such modules would be suited to tropical or desert applications, or for use with an optimum power point tracker. If such modules had been employed in the present installations, maximum expectable losses due to operation away from optimum power points could at times reach 30%. This hypothetical examination illustrated the importance of matching array output characteristics to load input characteristics in photovoltaic system design.

System sizing and actual load energy demand

There is little doubt that the design load which was specified for school systems was excessively generous, allowing for up to 10 hours television use and 5 hours use of the VCR each day of the year. The potential benefits of critical system sizing and careful component matching will unfortunately be of little significance in situations where generating capacity is grossly underutilised. While actual load demand is difficult to predict in an application of this nature, since it depends both on user preferences and more broadly on the whole organisation and delivery of the educational television project, the costs of over-specifying a photovoltaic-powered system can be severe.

Lifecycle costing (following assumptions stated in Chapter 10) indicated that unit levelised energy costs for this application could be in the region of R1.50/kWh, for a well designed system, if actual load demand corresponded with the design load. Given the potential service value of television and video facilities in rural schools, their energy-efficiency, and the absence of competitive alternatives for off-grid electricity for light loads, such costs would be entirely acceptable. But through over-specification or underutilisation, unit costs in excess of R5 or R10/kWh are more likely, and less acceptable. (These unit costs would correspond to about eight and three hours' TV and video use per weekday, respectively.)

It is not realistic to hope for exact correspondence between actual load demand and design load in stand-alone photovoltaic systems with no load diversity, and where consumption depends on user behaviour. This is likely to remain the dominant factor in the economics of photovoltaic supply in such applications, and is a constraint on the benefits of critical technical design. However the margin of discrepancy between design load and actual energy demand could be reduced through realistic appraisal of probable utilisation levels, consultation where possible with users, and more conservative approaches in the design of photovoltaic systems, making use of the relatively scale-neutral characteristics of the technology which allow for modular expansion if load demand is demonstrated to exceed installed capacity.

In light of the generality of this problem in designing small stand-alone photovoltaic systems (for further local examples, see Müller, 1987; Morris, 1988; Eberhard and Sinclair, 1989) it is recommended that in parallel with ongoing technical research into sizing methods for photovoltaic systems, there could be efforts to develop and publicise user-oriented methodologies providing a guide for more accurate assessment of expectable load demand profiles.

Without conducting a representative survey of schools to obtain reliable utilisation data, it was not possible to provide accurate unit energy costs for powering schools television in Bophuthatswana, but it appears likely that they are an order of magnitude higher than optimum costs. This is largely a consequence of adopting an over-generous design load and of subsequent underutilisation.

11.2 Project Implementation and Technical Choice

Although this concluding chapter focusses on technical issues, and the discussion of social and educational aspects of the Edutel project in Chapter 10 will not be reviewed here, it is important to note the interaction between these broader dimensions of project implementation and the technical appropriateness of the installed systems. The photovoltaic power is dedicated to a particular service, and the value of that service depends on software, distribution, institutional and educational support, and utilisation. Levels of utilisation, which in turn are contingent on broad aspects of project implementation, have a direct bearing on the appropriateness of the technical design, and reflect on the appropriateness of the educational technology itself.

The experience of Edutel serves as a reminder that technological innovations seldom provide a "quick fix" for problems in underdevelopment. Technological initiatives take place within a context, and should not be expected to act as a primary agency of change. It can be observed that planners, technologists and suppliers are often not directly part of the context in which the technology is applied, and that wise and effective technological choice is promoted by well-informed participative decision making.

11.3 General Points For Local Photovoltaic System Design

A number of points emerged in the course of the monitoring study which could have implications for photovoltaic system design more generally. A brief synopsis follows, with recommendations (where appropriate) for further enquiry.

- 1 Local vendors are typically reliant on overseas manufacturers of photovoltaic equipment for system sizing expertise. Often, the assumptions built into such sizing methods are not available for local scrutiny (for instance, they may be embodied in proprietary software). However, it appears that critical scrutiny is warranted, since commercial suppliers may be basing their designs

on arbitrary decisions about "system autonomy" (days of battery storage), dubious solar radiation data, sizing methods which do not permit estimation of Loss of Power Probabilities, and commercially driven but otherwise indeterminate matching of system components, subject to the "lumpiness" of chosen photovoltaic modules and batteries. These criticisms may not hold in every instance. Manufacturers could instill greater confidence and assist comparability by providing more explicit information about the assumptions and methods used for sizing systems.

- 2 In view of the uncertainties and apparent limitations in commercially used sizing methods on the one hand, and the simplifying assumptions built into currently published Loss of Power Probability methodologies on the other, it appears worthwhile to develop a more sophisticated but practically useful LOPP sizing tool for the critical design of stand-alone photovoltaic systems, employing local historical weather data. Practical advantages of a reliable LOPP sizing methodology include the promise of reduced system costs and consequently greater affordability of photovoltaic supply for developing areas applications; better-informed assessment of the trade-offs between high system reliability and acceptable economies in system sizing; and enhanced ability to compare alternative energy supply options at comparable reliability levels.
- 3 It appears that peak power ratings of photovoltaic modules, from manufacturers' performance specifications, may not be sufficiently accurate, reliable or representative of array generating capacity in operating conditions. There is also doubt about the representative accuracy of $I=f(V)$ output characteristics routinely provided by manufacturers (present investigations at the Energy Research Institute indicate greatest discrepancies around the important "knee" of $I=f(V)$ curves). In general, the margin of latitude within which manufacturers specify module performance in Standard Test Conditions, eg. $\pm 12.5\%$, introduces from the outset an uncomfortably large margin of uncertainty for critical system design.

Specific questions for further enquiry are

- What is the extent of variation in output amongst modules from the same batch or of the same designation?
- By what magnitude should module output, specified under Standard Test Conditions, be derated for spectral variations in natural light, in local operating environments?
- By what magnitude should module output be derated for radiation received at higher incidence angles than in Standard Test Conditions?

These magnitudes need to be assessed to see whether deviations from manufacturers' performance specifications pose a significant threat to critical system sizing procedures. The model proposed in Chapter 9, based on predicted failure in adverse climatic conditions, could be particularly susceptible to such deviations from specified module performance.

- 4 Critical photovoltaic system design depends on optimum prediction of expected solar radiation received by the array. Long term historical weather station records appear the best data from which to make predictions. Recognising the intrinsic difficulties of insolation measurements, and the increasing call from solar technologies for accurate and continuous local data, the calibration of weather station instruments should be checked at regular intervals and mechanisms set in place to minimise data disruption from instrument malfunction. The implications of using data obtained from instruments with a broad spectral response for sizing photovoltaic arrays which have a selective spectral response need further assessment.
- 5 Using different extractions of solar radiation data from the same weather station (Pretoria-Forum) and different currently-used methods for calculating radiation received on a tilted surface from horizontal insolation records, discrepancies up to 12% were obtained in the present study. This points to the value of carefully screening raw weather station data in the course of statistical condensation, and of using the best known methods for

calculating tilt-plane insolation receipts. It appears that anisotropic methods are superior, and the so-called Perez method has performed well in validation tests. The main effect of using this method, in place of the isotropic methods commonly used in commercial programs, is that diffuse components of tilt-plane insolation are estimated higher. In some climatic regimes, this could lead to savings in critical system design.

- 6 It was noted earlier that the dominating factor in cost-efficient photovoltaic system design, in many applications in developing areas, will be the degree of match that can be obtained between energy demand profiles and system generating capacities. The point is generalisable to include seasonably variable or otherwise periodic demand profiles, and seasonal or shorter term variations in photovoltaic generation. Where demand profiles are contra-seasonal, or where there are occasional peak loads greater than battery storage capacity, average capacity factors are likely to be low, and it is unlikely that stand-alone photovoltaic systems will be an economic proposition. Since photovoltaic systems have relatively low running costs and high capital cost, economic operation requires high capacity factors. Besides careful research into probable demand profiles in the design of a stand-alone installation, there is a need for investigation of design strategies to minimise the penalties of design-demand mismatch. For small systems, these could include the encouragement of load diversity, and provision for greater discretionary consumer/user control over maximising the utility of available energy. For somewhat larger systems, or in applications with peaking loads, hybrid systems should be investigated to assess both the economic benefits and the conditions for optimising the contribution of each energy supply component.

11.4 Specific Proposals for Evaluating and Developing a Locally-Applicable Loss of Power Probability Sizing Method

The Loss of Power Probability model presented in Chapter 9, if validated, could provide the basis for an effective design tool for sizing photovoltaic systems with battery storage in local applications.

Potential advantages of the approach suggested, compared with other known LOPP methodologies, are that local historical weather data can be used (avoiding the inaccuracies resulting from over-generalisation of climatic assumptions in other methods reviewed); that although computer intensive work is needed to establish the required statistical solar radiation database, this can be done centrally, using batch mainframe processing, and the results readily incorporated in a PC-compatible sizing program; that the method takes into account, empirically, the seriality characteristics of local climates; that the specification of component performance parameters required for the model is restricted to a narrower range of critical operating conditions; that it does not assume array operation at optimum power points; and that the model provides a rational basis for selecting combinations of array power and battery storage to satisfy a required load and reliability level. General advantages of a LOPP sizing methodology compared with other sizing methods were outlined in Section 11.3 above.

The emphasis in the present study has been on putting forward a method for LOPP calculation, rather than on refining relationships within the model. The model was developed around the performance of a specific system, using data from one weather station. From here, the assumptions of the model need to be subjected to further critical scrutiny, tested for validity, and steps taken towards generalising its scope of application. Suggested steps are:

- 1 Seek critical assessment of the logic, assumptions and method of the model, through publication and/or direct contact with international workers in the field of LOPP sizing methodologies.
- 2 Test performance predictions of the model against a full photovoltaic simulation program. PVFORM, written by Menicucci

and Fernandez of Sandia National Laboratories, is an available simulation route. Although PVFORM does not simulate photovoltaic systems which do not have optimum power point tracking, it could be used to test a subset of model performance predictions. A more generalisable simulation program is under development at the ERI. It would be important to operate such simulation software on untreated solar radiation data over all available years, from several differing climates, rather than use data in a "Typical Meteorological Year" (TMY) form, since TMY data may not adequately preserve the serial characteristics on which the present model depends. This implies considerable computation and is a mainframe option (PVFORM can take several hours to process one year's data on a simple PC). For such simulation testing, there would be no need to restrict tests to South African data, if cleaner hourly solar radiation and temperature data over a longer timespan could be obtained elsewhere. An important consideration would be the method of handling bad or missing data to avoid misrepresenting runlength values, especially at low percentiles.

- 3 Analyse the levels of statistical uncertainty attached to predicting future solar radiation probabilities from historical weather records. Assuming no discernibly significant long-term trends in climate, available historical records can be considered as a sample from a population which includes the future. The best prediction of future probabilities should be provided by observed sample percentile levels. Empirically derived confidence intervals for the percentile estimates from the sample data can be obtained by a resampling technique, such as Efron's "Bootstrap" method (cf. Efron and Tibshirani, 1986), in preference to any parametric transformation approach. It would be useful, on this basis, to model confidence intervals of percentile estimates as a function of the sample size (ie. number of years' weather records) in order to assess minimum data requirements for statistically reasonable LOPP predictions. The confidence interval around very low percentile estimates will encompass higher percentile estimates, and investigation is needed to evaluate statistically reasonable lower LOPP limits according to data sample size and empirical distributions (these are likely to be climate-dependent). The analysis suggested would be computer intensive, and is a mainframe option.

- 4 Subject to the previous steps and tests, and any consequent modifications¹, evaluate the sizing predictions of the model more carefully in comparison with simpler commercial sizing methods, to assess the potential benefits, bearing in mind remaining margins of uncertainty in component performance characteristics and solar radiation data.
- 5 If justified by potential benefits for system design, investigate more detailed implications of following a run-length approach to system optimisation, for example the monthly distribution of critical runlengths, as a function of run-length, for typical local climates. This could have implications for selection of optimal tilt-angles and hence the subsequent processing of weather station data.
- 6 Consider any variations in model assumptions or in the statistical treatment of data required for sizing systems for intermittent and seasonally variable loads, and for hybrid applications of photovoltaic arrays. For example, in the latter case, much higher "Loss of Power Probabilities" for the photovoltaic component might be of interest, again with implications for subsequent processing of weather station data.
- 7 Screen, process and curve-fit solar radiation data from available local weather stations to obtain functions, for each site, of expected minimum plane-of-array insolation per day as a function of run-length, at selected probability levels, and selected angles of tilt.
- 8 Incorporate these functions in a menu-driven microcomputer program with user input for performance parameters of system components, refined code for generating LOPP predictions and array/battery substitution curves, and updatable data for economic optimisation. (In principle, sizing computations should take a minute or two at most on a PC.)

¹Discussions with Dr F Lasnier, of the Asian Institute of Technology, Bangkok, have already suggested that avoidance of any medium-term battery storage function may be a revisable assumption in the model, depending on the type of battery employed.

- 9 Continue with research, in consultation with manufacturers, to investigate performance characteristics of components, including those aspects of photovoltaic module performance referred to in Section 11.2, the charge and discharge efficiencies of commonly used batteries, and their cycle life, and the efficiencies of power-conditioning equipment, with the aim of reducing uncertainties and reducing design margins in photovoltaic system sizing.

It is anticipated that the steps suggested above would not constitute a comprehensive or fully adequate programme for further research. They are offered rather as a sketch, at this stage, of how the present research could be taken further, to contribute to improved sizing methods for photovoltaic systems in local applications.

Appendix A

REFERENCES

- Adkins G R
1982 "Instructional TV in developing countries." Media in Education and Development, 15: 120-123.
- AUDECAM
1975 "La television scolaire du Niger, 1964-1971." General Report. Paris: AUDECAM.
- Baldauf R B
1981 "Educational television, enculturation and acculturation: a study of change in American Samoa." International Review of Education, 27: 227-245.
- Bhatt B, P V Krishnamoorthy, R Marathey and M Bourgeois
1965 "Radio broadcasting serves rural development." Reports and Papers on Mass Communication, 40. Paris: UNESCO.
- Biggs W W
1984 "Radiation measurement." Li-200S Pyranometer Sensor Instruction Manual, Publication Number 8010-21R. Lincoln, Nebraska: LI-COR Corporation.
- Borchers M
1989 A decision-making tool for assessing grid electrification versus stand-alone power supply options for remote power users. Unpublished M.Sc.(Eng) thesis, Energy Research Institute, University of Cape Town.
- Borden C S, K Volkmer, E H Cochrane and A C Lawson
1984 Stand-alone flat-plate photovoltaic power systems: system sizing and life-cycle costing methodology for federal agencies. JPL Publications 84-37. Pasadena, CA.: Jet Propulsion Laboratories.
- Buresch M
1983 Photovoltaic energy systems: design and installation. New York: McGraw-Hill.
- Chapman R N
1986 "Design considerations for stand-alone photovoltaic systems." ASRE-126. Proc. of International Symposium on Solar and Renewable Energy, March 23-23 1986, Cairo.
- 1987 Sizing handbook for stand-alone photovoltaic/storage systems. Sandia Report, SAND87-1087. Albuquerque, NM.: Sandia National Laboratories.
- Chowdury B H and S Rahman
1987 "Comparative assessment of plane-of-array irradiance models." Solar Energy, 39 (5): 391-398.
- Coulson K L
1975 Solar and terrestrial radiation. New York: Academic Press.

- Cowan W D
1989 "Small photovoltaic systems for educational purposes." Proc. of Alternative Energy Supply Options for Developing Southern Africa Conf., Feb 2-3 1989, Johannesburg.
- CSIR
1971 Solar water heating in South Africa. Research Report No. 243. Pretoria: Council for Scientific and Industrial Research.
- De Clercq F
1984 Education and development in Bophuthatswana: potential and limitations. Research Monograph 3. Mmabatho: Institute of Education, University of Bophuthatswana.
- 1986 Conflicts over rural schooling: an historical case study of educational development in Taung. Research Monograph 7. Mmabatho: Institute of Education, University of Bophuthatswana.
- Eberhard A A
1989 A solar radiation data handbook for Southern Africa. Cape Town: Elan (in press).
- Eberhard A A, A A M Tegen and A T Williams
1988 A solar radiation data handbook for Southern Africa. ERI Report. Energy Research Institute, University of Cape Town.
- Eberhard A A and D J Sinclair
1989 "Photovoltaics for developing areas: lessons from demonstration projects." SAIEE Workshop on Alternative and Renewable Sources of Electrical Energy, 5 Sept 1989, Pretoria.
- Efron B and R Tibshirani
1986 "Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy." Statistical Science, 1 (1): 54-77.
- Flowers E C
1978 "Comparison of solar radiation sensors from various manufacturers". In 1878 Annual Report from NOAA to U.S. Department of Energy.
- Gana F G
1980 "Foreign films in Nigerian society." Educational Media International, 1980, 4: 14-15.
- Graaff J de V and M L Lawrence
1986 Rural parents and school enrolment patterns in two regions of Bophuthatswana. Research Monograph 6. Mmabatho: Institute of Education, University of Bophuthatswana.
- Harbison F
1973 "The Open University in the Third World". Educational Broadcasting International, 6 (4).

- Hawkrige D
1982 Organising educational broadcasting. London: Groom Helm.
- Holderness W L
1986 Upgrading primary education in the seventeen circuits, 1980-1985: a celebration of achievement. Occasional Publication 2. Mmabatho: Institute of Education, University of Bophuthatswana.
- Ingle H T
1973 "Behavioural objectives and the evaluation of educational reform in El Salvador." Educational Broadcasting International, 6 (2).

1974 Communication media and technology: a look at their role in non-formal education programs. Washington: Information Center on Instructional Technology, Academy for Educational Development.
- Klein S A and W Beckman
1987 "Loss-of-load probabilities for stand-alone photovoltaic systems." Solar Energy, 39 (6): 499-512.
- Lasnier F and T Gan Ang
1988 Solar photovoltaic handbook. Bangkok: Energy Technology Division, Asian Institute of Technology.
- Liu B Y H and R C Jordan
1960 "The interrelationship and characteristic distribution of direct, diffuse and total solar radiation." Solar Energy, 4 (3): 1-19.

1962 "Daily insolation of surfaces tilted towards the equator." Trans. ASHRAE, 526-541.
- Macomber H L and J B Ruzec
1981 Photovoltaic stand-alone systems. DOE/NASA/0195-1, NASA CR-165352 M206. Cleveland, Ohio.
- McAnany E G
1978 "Success or failure of communication technology in the third world: by what criteria shall we judge?" Educational Media International, 1978, 4: 16-23.
- Marchl H and E Brunswick
1977 "Educational television in developing countries." Educational Media International, 1977, 4: 9-13.
- Menicucci D F
1985 "PVFORM - a new approach to photovoltaic system performance modelling." Proc. of 18th IEEE Photovoltaics Specialists Conf., Oct 85, Las Vegas.

1986a The determination of optimum mounting configurations for flat plate photovoltaic modules based on a structured field experiment and simulated results from PVFORM, a photovoltaic system performance model. Sandia Report, SAND85-1251. Albuquerque, NM.: Sandia National Laboratories.

- 1986b "Photovoltaic array performance simulation models." Solar Cells, 18: 383-392.
- 1987 "Some applications of recent R&D experiences in the sizing of stand-alone photovoltaic power systems." ASME/JSME Sol. Eng. Conf., Honolulu, March 87.
- Menicucci D F and J P Fernandez
- 1984 "Verification of photovoltaic system modelling codes based on system experimental data." Proc. of 17th IEEE Photovoltaics Specialists Conf., May 1984, Kissimee Fa.
- 1985 User's manual for PVFORM: a photovoltaic system simulation program for stand-alone and grid-interactive applications." Sandia Report SAND85-0376. Albuquerque, NM.: Sandia National Laboratories.
- 1986 Estimates of available solar radiation and photovoltaic energy production for various tilted and tracking surfaces throughout the US based on PVFORM, a computerised performance model. Sandia Report, SAND85-2775. Albuquerque, NM.: Sandia National Laboratories.
- Michel C and R M Thomas
- 1985 "High quality, low-cost television for children of developing nations: a Haitian experience." International Journal for Educational Development, 1985, 5 (4): 249-257.
- Morris G J
- 1988 Performance evaluation of photovoltaic and diesel electricity generation applications in the Kruger National Park. Unpublished M.Sc.(Eng) thesis, Energy Research Institute, University of Cape Town.
- Müller D H
- 1987 The use of small photovoltaic systems for the electrification of off-grid homes. Unpublished M.Sc.(Eng) thesis, Energy Research Institute, University of Cape Town.
- Perez R R
- 1984 An anisotropic model of diffuse solar radiation with applications to an optimization of compound parabolic concentrators. DOE/#DEFG0577ET20182. U.S. Department of Energy.
- Perez R, R Stewart, C Arbogast, R Seals and J Scott
- 1986 "An anisotropic hourly diffuse radiation model for sloping surfaces: description, performance validation, site dependency evaluation." Solar Energy, 36 (6): 481-497.
- Perraton H
- 1981 "Radio broadcasting and public education in Africa." Educational Media International, 1979, 2: 4-10.
- Potts J
- 1979 "Educational media in developing countries". Educational Media International, 1979, 2: 25-27.

- Ratajczak A F
1985 Photovoltaics in remote locations: an experience summary. DOE/NASA/20485-20. Washington DC: NASA.
- Republic of Bophuthatswana
1973- Annual Reports, Department of Education. Mmabatho.
1978 "Education for Popagano." A Report of the National Education Commission. Mmabatho, August, 1978,
1978- National Assembly Debates. Mmabatho.
- Roodt M
1984 "Bop goes the easel! - educational television becomes a reality." Matlhasedi Education Bulletin, 3 (1): 30. Mmabatho: Institute of Education, University of Bophuthatswana.
- Rosenblum L
1982 Practical aspects of photovoltaic technology, applications and cost. NASA-CR-168025.
- Schramm W
1972 Quality in instructional television. Honolulu: University Press of Hawaii.
1977 Big media, little media. Beverly Hills: Sage.
- Schramm W and M T Betham
1981 Bold experiment: the story of educational television in American Samoa. Stanford: Stanford University Press.
- Sinclair D J
1989 A review of international and local developments in photovoltaic technology and economics for developing areas. Unpublished M.Sc.(Eng) thesis, Energy Research Institute, University of Cape Town.
- Valerien J
1980 "Education by television in the Ivory Coast." Educational Media International, 1980, 4: 11-15.
- Wang, Y-J
1987 The sizing of stand-alone photovoltaic systems. AIT Research Study, Asian Institute of Technology, Bangkok.
- Williams A T
1986 "Diesel power - the cost to beat in remote areas." Proc. of Renewable Energy Potential in Southern Africa Conf., 8-10 Sept 1986, Energy Research Institute, University of Cape Town.

Appendix B.1

Pyranometer Test Method

The Li-Cor silicon-cell pyranometer (model LI-200SZ-05, S/N PY7653) was tested for accuracy against two Kipp and Zonen thermopile solarimeters, in a variety of natural conditions.

Comparison of absolute calibration against South African Weather Bureau instruments was not possible, and the reference adopted for the tests was the mean inter-calibration of the two Kipp and Zonen (KZ) instruments. This entailed a 2% adjustment to the specified calibration of each KZ solarimeter. Using this adjustment, horizontal insolation measurements taken at the monitoring site with a KZ solarimeter were within 4% of measurements recorded for the same hours at the Pretoria-Forum weather station. A reasonable estimate of the uncertainty of the KZ calibration is $\pm 5\%$.

Output from the KZ instruments was measured by digital voltmeter, with expected inaccuracy $< \pm 1\%$. Output from the Li-Cor (LC) pyranometer was measured both by digital ammeter and by digital voltmeter readings across a calibrated 100 ohm shunt. Discrepancies between the latter measurements were less than 0.5%. Multimeter inaccuracy in the relevant measurement ranges should be $< \pm 1\%$.

For tests at the monitoring site, a KZ instrument was mounted on a tiltable platform adjacent to the array, to allow measurements for horizontal as well as plane of array insolation. The LC sensor was fixed in the plane of the array. Measurements were taken over two days at varying angles of incidence of the direct beam. Climatic conditions were steady, with clear July skies but a slight haze, and visibly discernible atmospheric pollution.

Further tests were conducted in the Karoo, in arid stable clear-sky conditions. The KZ and LC instruments were co-mounted on a tilting table, with facilities to measure the angle of tilt and the angle of incidence of the direct beam. Readings were taken at noon, to minimise effects of the sun's "motion" and to obtain an air mass (at mid-July noon elevation of the sun) of close to $AM=1.5$, which is used as a reference for photovoltaic module performance specification.

To investigate possible errors in KZ measurements due to tilt-mounting of the instrument (which could disturb convection in the dome), measurements from horizontal to vertical mounting positions were taken in close succession, and compared according to the cosine of corresponding incidence angles. Allowing for the diffuse component of irradiation (measured as 8% of global horizontal) and assuming isotropic distribution of diffuse irradiance (a reasonable assumption, given the small diffuse component) the deviations of tilt-mount readings from expectations thus calculated from global horizontal readings were typically around 1% and did not exceed 2%, which is within the accuracy of incidence angle measurements. It was concluded that errors due to operating the KZ instrument in a tilted position were not significant relative to other sources of discrepancy.

Pairs of readings for the LC and KZ instruments were recorded, in these stable sky conditions, for a range of angles of incidence of direct insolation, from zero to over 60 degrees, by tilting the table. These results appear in Figure 6.2 in the text.

The results for the monitoring site comparison (where different angles of incidence were associated with different elevations of the sun through the day) also appear in Figure 6.2.

Further tests were conducted in Cape Town, in clear but more humid mid-winter conditions, with the instruments mounted horizontally, at different times of day, and a consequent range of angles of incidence. The relationship between the angle of incidence and the deviation of LC measurements from KZ measurements was again linear, with a gradient approximately midway between the two relationships depicted in Figure 6.2.

Conclusions from these tests are reported in Sections 6.2.4 and 6.3 in the text.

Appendix B2

Method for Assessment of Shading of Monitored Array, by Month

A plan was made of the building surrounding the installed array, together with the heights above array height of its skyline. The orientation of the plan relative to solar north was recorded. By simple trigonometry, the elevation of the skyline relative to the array was calculated as a function of angle on the horizontal from true north. Calculations were performed in spreadsheet form.

The time of day, at different times of year, when the sun would first rise above or set below the skyline was found by calculating the sun's elevation as a function of hour angle from noon, julian day, and latitude. The following equations were used for the spreadsheet calculations:

Elevation of sun

$$@ASIN(@COS(\$LAT)*@COS(\$D50)*@COS(F\$47)+@SIN(\$LAT)*@SIN(\$D50))/\$DTOR$$

where cell references referred to

\$LAT: latitude of site
\$D50: declination vector (column)
F\$47: hourangle from noon vector (row)
\$DTOR: degrees to radians constant

and where the declination vector was

$$@ASIN(0.39795*@COS(0.98563*\$DTOR*(C50-173)))$$

where

C50: julian day-number vector

To evaluate the shading in each month, julian days for the mid-day of each month were used to table solar elevations as a function of hour angle for each month, and values were compared with skyline elevation angles of the building at the corresponding azimuth angles. Thus the "rising" and "setting" times of the sun on the array were found for the middle of each month (subject to the sun moving back of the array at late hours in summer months).

From rising and setting times, it was possible to evaluate the average monthly direct insolation lost to the array. South African Weather Bureau data for Pretoria-Forum weather station were used, to find the average horizontal insolation, for each month, for each hour of the day when the array would be shaded. For each month, these average hourly shaded components were totalled, and expressed as a percentage of total average daily horizontal insolation.

Calculation of Battery Lifetime

Formulae for estimating battery lifetime, using manufacturers' information for the batteries, and based on the depth of cycling of the batteries and their electrolyte temperature, are available from Lasnier and Can Ang (1988:116). They were used as follows:

CYCLE LIFE of a battery, when cycled to a set DEPTH OF DISCHARGE at temperature T, is given by:-

$$CL = (b - c * T) \exp(-a * DOD) \quad [1]$$

where CL: lifetime (in cycles)

T: battery temperature (degrees C.)

DOD: depth of discharge (unitless)

The parameters a, b and c can be derived from product information, if expected battery cycle lifetimes are provided for different depths of discharge and at varying temperatures

If so, then from three sets of combinations -

$$T_1 : DOD_1 : CL_1$$

$$T_1 : DOD_2 : CL_2$$

$$T_2 : DOD_3 : CL_3$$

- the parameters a, b and c can be derived :-

$$a = (\ln(CL_1/CL_2)) / (DOD_2 - DOD_1) \quad [2]$$

$$b = (T_2 * CL_1 * \exp(a * DOD_1) - T_1 * CL_2 * \exp(a * DOD_2)) / (T_2 - T_1) \quad [3]$$

$$c = (CL_1 * \exp(a * DOD_1) - CL_2 * \exp(a * DOD_2)) / (T_2 - T_1) \quad [4]$$

For variable cycles, the battery life is given by:-

$$1/L = \sum_{n=1}^{365} [1/CL(T_n, DOD_n)] \quad [5]$$

where L: battery lifetime (in years)

CL(T, DOD): cycle lifetime at temperature T and depth of discharge DOD

Unfortunately, the specified cycle lifetime of DELCO 2000 batteries was only available, from product information, at a single electrolyte temperature: so to estimate the expected lifetime of these batteries from the monitored data, battery temperature has been disregarded.

The grouped frequency distributions of observed depths of discharge, during the monitored months July, August and September, 1986, in conjunction with available product information, allows estimation of expected battery lifetime CORRESPONDING TO THE OBSERVED CYCLING REGIME. From monitoring data and product information:-

MAXIMUM DOD as fraction of rated capacity	RELATIVE FREQUENCY July-Sept 86	SPECIFIED CYCLE LIFE at this DOD
0,05	44%	4000
0,10	32%	2000
0,15	15%	1300
0,20	6%	850
0,25	3%	750

Adapting EQUATION [5] for frequency data, the expected battery lifetime if this regime continued would be approximated by:-

$$1/L = 365 * \sum_{i=1}^n \{f_i / CL(DOD_i)\} \quad [6]$$

where f_i is the relative frequency corresponding to depth of discharge category DOD_i , and where $CL(DOD_i)$ is the associated cycle life.

Thus,

$$1/L = 365 * \{0,44/4000 + 0,32/2000 + 0,15/1300 + 0,06/850 + 0,03/750\} \\ = 365 * 4,959 E-4$$

$$\text{and } L \approx 5,5 \text{ years}$$

It should be stressed that the observed cycling regime in these monitored months cannot be regarded as typical for all seasons. Insolation levels were low (especially in Sept.) and the controlled load consumption - at an average of 370 Wh/day - was almost certainly higher than could be expected in Bophutha-Tswanan schools - Tswanan schools; although below the design load of 425-450 Wh/day. The estimate of 5½ years for expected battery lifetime is therefore only an extrapolation from particular monitored conditions.

Appendix B4

Interface Design Parameters and Treatments

Measurement: POA Insolation
Signal source: Pyranometer
Range for variable: 0 - 1500 Watts/square metre
Signal range: 0 - 82 microamps
Waveform: Steady
Output range: 0 - 220 mV

Treatment: Voltage drop across 100 ohm (1%) resistor, then instrumentation differential amplifier circuit.

Calibration: Variable current source and digital ammeter.

Measurement: Ambient temperature
Signal source: IC zener transducer, LM335
Range for variable: -10 - +40 degrees C
Signal range: 2.632 - 3.132 V
Waveform: Steady
Output range: 0 - 2,2 V

Treatment: Power supply and adjustable calibration voltage to sensor. Input signal from sensor dropped across voltage divider, before differential amplification against calibrated reference voltage.

Calibration: Ice and boiling points to establish zeroing reference voltage, and slope, set with digital voltmeter. Checked against thermocouple.

Measurement: PV cell temperature
Signal source: IC zener transducer
Range for variable: -10 - +60 degrees C
Signal range: 2.632 - 3.332 V
Waveform: Steady
Output range: 0 - 2,2 V

Treatment: Power supply and adjustable calibration voltage to sensor. Input signal from sensor dropped across voltage divider, before differential amplification against calibrated reference voltage.

Calibration: Ice and boiling points to establish zeroing reference voltage, and slope, set with digital voltmeter. Checked against thermocouple.

Measurement: **PV array voltage**
Signal source: dV between Array positive and battery positive (interface ground). Added to battery voltage by calculation.
Range for variable: 0 - 50 V
Signal range: -30 - +20 V
Waveform: Ripple
Output range: 0 - 2,2 V

Treatment: After voltage divider, filter on input: 100 k + 2*100 uF back-to-back capacitance to ground. Differential amplification against buffered reference voltage to bring output signal always positive.

Calibration: Variable voltage source, digital voltmeter. Checked with varied waveforms against d.v.m.

Measurement: **Battery voltage**
Signal source: dV between battery positive (interface ground) and system earth, battery negative.
Range for variable: 22 - 30 V
Signal range: -30 - -22 V
Waveform: Steady
Output range: 0 - 2,2 V

Treatment: Voltage divider, then filter on input: 100k and 100uF to ground (unnecessary). Differential amplifier and inverter.

Calibration: Variable voltage source, digital voltmeter.

Measurement: **Battery current**
Signal source: dV across current shunt
Range for variable: -4 - +6 amps
Signal range: -33 - 50 mV
Waveform: Ripple
Output range: 0 - 2,2 V

Treatment: Filter on input: 100 k + 2*100 uF back to back capacitance to ground. Differential amplifier circuit with buffered offset to bring output always positive.

Calibration: Variable current source, digital ammeter.

Measurement: **Load current**
Signal source: dV across current shunt
Range for variable: 0 - 4 amps
Signal range: 0 - 33 mV
Waveform: Ripple
Output range: 0 - 2,2 V

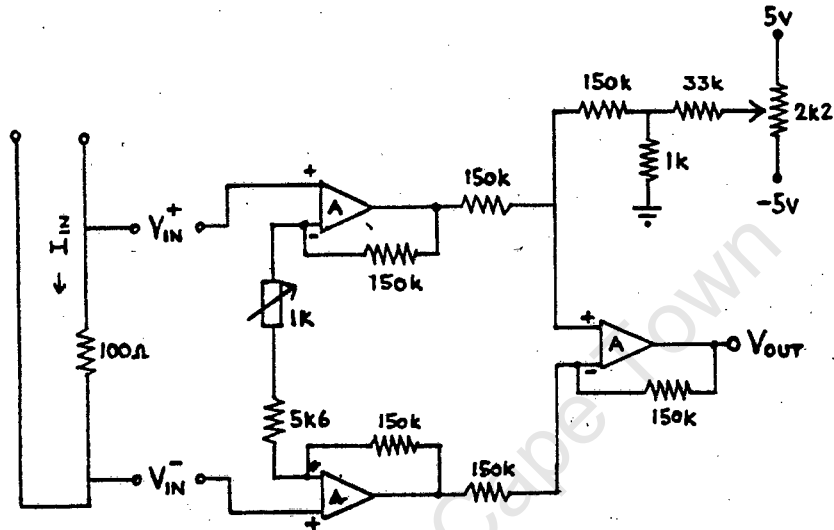
Treatment: Filter on inputs: 100 k + 100 uF capacitance to ground. Differential amplifier circuit.

Calibration: Variable current source, digital ammeter.

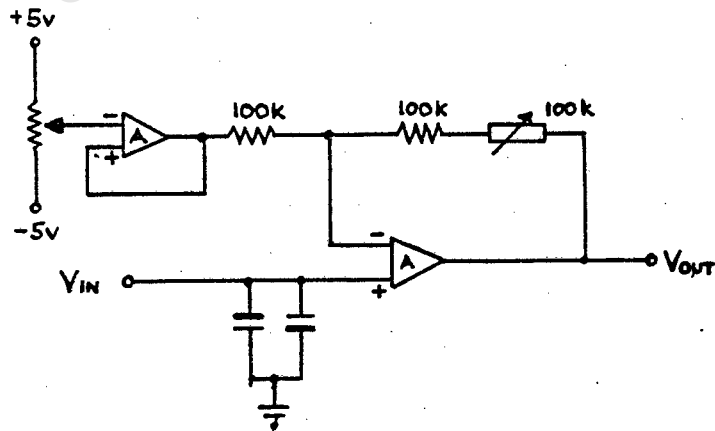
The active components used in these amplifying circuits were low consumption LM324 opamps, operating from a split ± 5 volt supply. For the voltage reference section of temperature measuring circuits, LM10's were used. The interface power supply, derived from dry cells, was switched on just before logging by a trigger signal from the data logger, in order to prolong battery life.

Circuit Diagrams for Signal Conditioning Interface

1 Solar radiation measurement

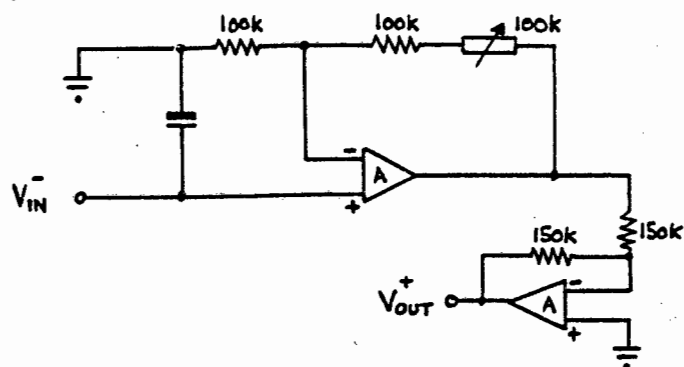


2 Voltage measurement with buffered offset

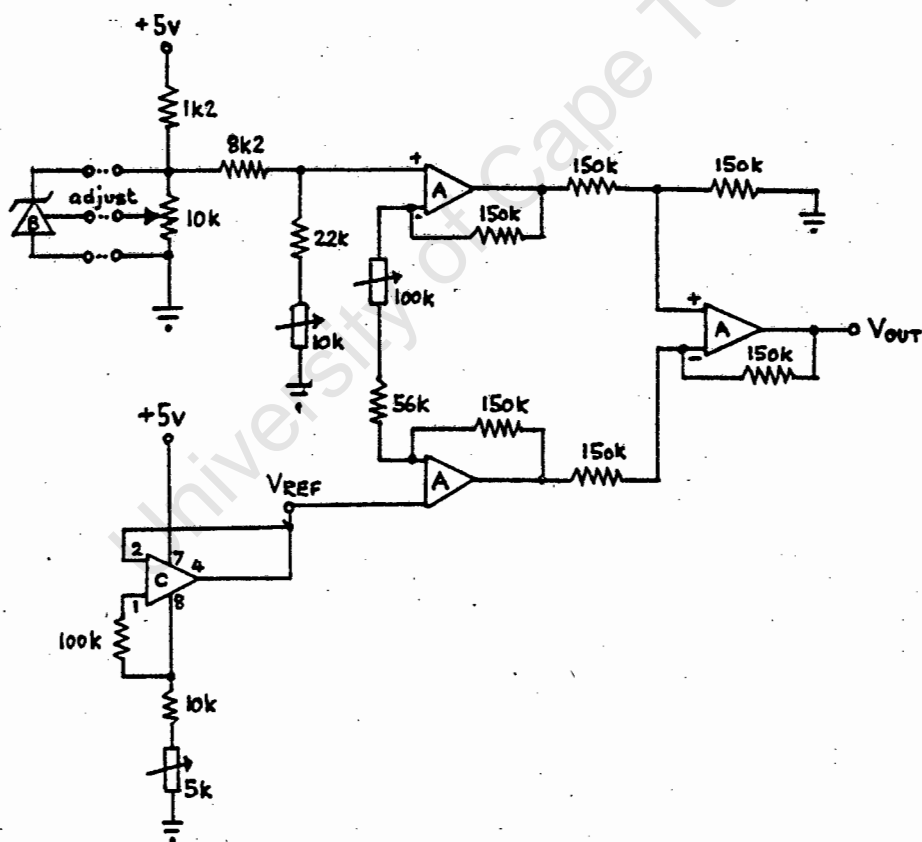


A: LM324
B: LM335
C: LM10

3 Negative voltage measurement with inversion

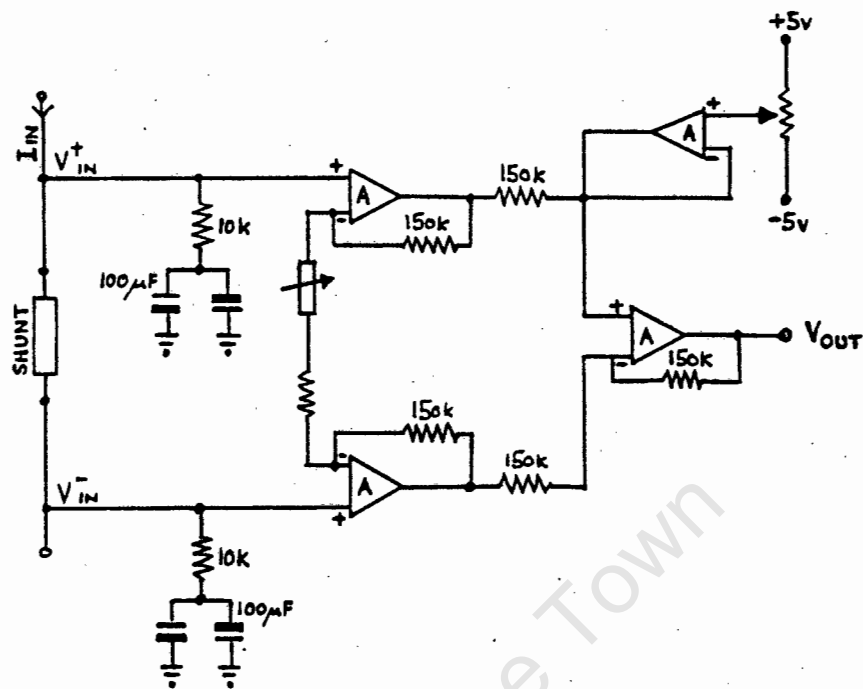


4 Temperature measurement (with Reference voltage)



A: LM324
 B: LM335
 C: LM10

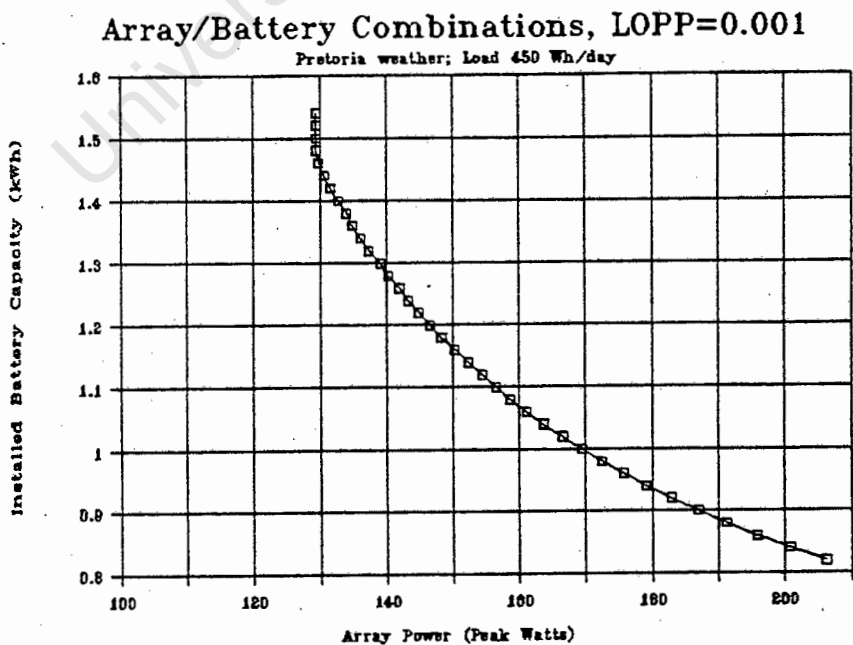
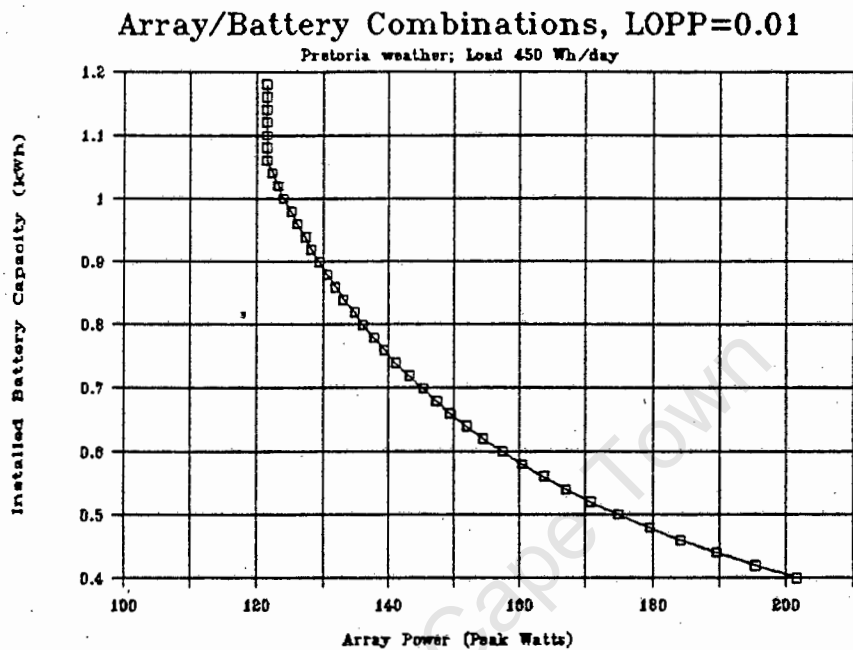
5 Current measurement, with buffered offset



- A: LM324
- B: LM335
- C: LM10

Appendix B6

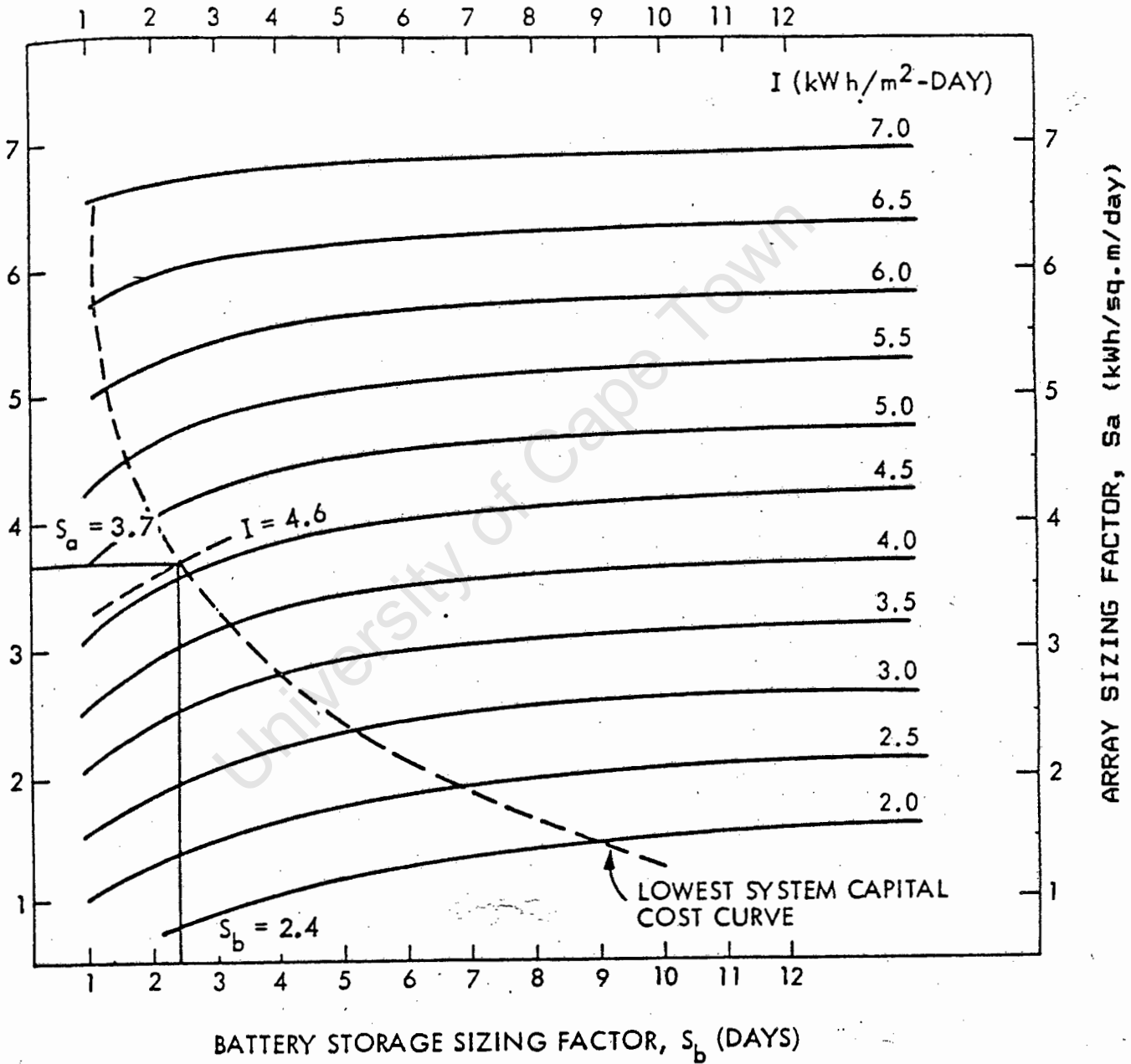
Array and Battery Combinations Predicted To Satisfy LOPP 0.01 and 0.001 in Pretoria Weather, Using PW-P 800 (monocrystalline) Modules.



Appendix B7

Sizing Nomogram Used in the Borden et al (1984) Loss of Energy Probability PV System Sizing Method.

For a design month LOEP of 0.1:



Source: Borden et al (1984, page 2-9)

Appendix B8

Assessing the long-term loss of power probability of the system sizing indicated by the Borden et al (1984) method, through comparison with critical run LOPP model predictions.

System Efficiencies and POA Insolation Requirements

For the Borden method sizing, average system efficiencies for the design month are required. On average, it was estimated that 50% of the load energy would pass through battery storage (battery energy efficiency 0.85 for this component) and all array-to-load energy would be subject to an average power-regulator efficiency of 0.95. Module conversion efficiency at 25 degrees C was taken as 0.063. Mean module operating temperature for the month was taken as 30 degrees C, and the temperature coefficient of module efficiency as -0.0028. Effective average insolation-to-load efficiency, including module efficiency and temperature correction, was 0.0547.

The critical conditions LOPP model needs efficiency estimates for adverse runs leading to system failure, rather than monthly average estimates, and this leads to slight differences in order to make as fair as possible a comparison. For these conditions, module operating temperature is taken as 25 degrees, and associated module conversion efficiency is 0.063, but a factor for deviation from optimum power points is included, 0.97. For critical runs, 60% of load energy is taken to be cycled through batteries (battery energy efficiency 0.85). Power regulator efficiency is unchanged at 0.95. The net path efficiency to load is therefore 0.053.

These efficiencies are employed in the critical run LOPP model as follows. The minimum required array output to sustain the design load of 450 Wh/day, over a run of N days, starting from fully charged batteries, is:

$$A = (450 / (0.95 * (0.6 * 0.85 + 0.4 * 1))) * (N - \text{AUTONOMY})$$

where AUTONOMY is the available battery capacity, for the purpose of this sizing comparison 1.3 days.

If a "battery capacity adjustment factor" (see Section 9.3.1) is included, this has the effect of limiting maximum state of charge of the batteries to 90% SOC. Given that the permitted depth of discharge considered in this example is 70%, this has the effect of derating AUTONOMY by 6/7 to 1.11 days battery storage.

Calculations proceed below with and without this battery capacity adjustment.

Minimum required array output per day, for run-length N, is simply

$$A / N \quad (\text{Wh/day})$$

For an array power of 106 Wp as indicated by the Borden method sizing, the corresponding POA insolation requirement is

$$(A / N) / (106 * 0.97) * 1000 \text{ Wh/sq.m/day}$$

where 0.97 represents the factor for optimum power deviations.

Long-term Loss of Power Probabilities

The critical run LOPP model estimates these from observed percentiles using, in this case, 10 years hourly solar radiation data for Pretoria-Forum weather station, converted to a tilt-plane of 30 degrees, and processed to provide the cumulative frequency distributions for runs of days from 1 to N.

The tables below show the minimum insolation requirements for sustained power to load, for the Borden method system sizing, and the corresponding relative frequency of POA insolation runs which are below this minimum requirement, derived from the data.

Since shorter runs are subsumed under longer runs, the predicted loss of power level for this sizing is provided by the maximum observed relative frequency of sub-minimal runs, ie. for the first case, using the model's battery capacity adjustment factor, the LOPP prediction is 0.034, while in the second case, where this factor is omitted, the prediction is 0.028.

	WITH BATTERY CORRECTION			LOSS OF POWER LEVELS
	Minimum Array Output Required (Wh)	Minimum Array Output Required (Wh/day)	Minimum POA Insolation Required (Wh/sq.m/day)	Percentage of Runs Below Required Insolation
Runlength: 1	0	0	0	0.0 %
2	463	232	2256	1.4 %
3	983	328	3194	2.8 %
4	1503	376	3663	3.3 %
5	2024	405	3945	3.4 %
6	2544	424	4132	3.4 %
7	3064	438	4266	3.4 %
8	3584	448	4367	3.4 %
9	4105	456	4445	3.3 %
10	4625	462	4508	3.2 %
11	5145	468	4559	3.1 %
12	5665	472	4601	2.9 %
13	6186	476	4638	2.8 %
14	6706	479	4668	2.6 %
15	7226	482	4695	2.4 %
16	7746	484	4719	2.2 %

WITHOUT BATTERY CORRECTION				LOSS OF POWER LEVELS
	Minimum Array Output Required (Wh)	Minimum Array Output Required (Wh/day)	Minimum POA Insolation Required (Wh/sq.m/day)	Percentage of Runs Below Required Insolation
Runlength: 1	0	0	0	0.0 %
2	364	182	1775	0.9 %
3	884	295	2873	1.8 %
4	1405	351	3423	2.4 %
5	1925	385	3752	2.7 %
6	2445	408	3972	2.7 %
7	2965	424	4129	2.8 %
8	3486	436	4247	2.8 %
9	4006	445	4338	2.6 %
10	4526	453	4411	2.7 %
11	5046	459	4471	2.7 %
12	5566	464	4521	2.4 %
13	6087	468	4563	2.2 %
14	6607	472	4600	2.0 %
15	7127	475	4631	1.7 %
16	7647	478	4659	1.5 %

Appendix C1

Program for Calculating Insolation on a Tilted Plane, Using an Isotropic Trigonometric Method

```

10 CLS
20 LOCATE 7
30 PRINT SPC(30)"SOLAR TILT"
40 PRINT SPC(30)"====="
50 PRINT:PRINT:PRINT:PRINT
60 PRINT "    Program modules for estimating solar irradiation"
70 PRINT "    received by a tilted surface, given insolation"
80 PRINT "    data for a horizontal surface"
90 LOCATE 20:PRINT "Bill Cowan, U.C.T.":PRINT "March 1986"
100 GOSUB 130:GOTO 190
110 '
120 '
130 LOCATE 23,10
140 PRINT "Press any key to continue ..."
150 A$=INKEY$:IF A$="" THEN 150
160 RETURN
170 '
180 '
190 CLS
200 LOCATE 5
210 PRINT "    Access:"
220 PRINT:PRINT "    Estimate global daily irradiation for tilted"
230 PRINT "    plane from daily means (or totals) of direct"
240 PRINT "    and diffuse horizontal irradiation"
250 PRINT "                                1"
260 PRINT:PRINT "    Estimate hourly or daily irradiation for "
270 PRINT "    tilted plane using HOURLY insolation data for"
280 PRINT "    direct and diffuse horizontal irradiation"
290 PRINT "                                2"
300 LOCATE 17
310 PRINT "                                Exit"
320 PRINT "
330 LOCATE 20
340 INPUT "Enter option number:",A
350 IF A=8 THEN END
360 '
370 '
380 'Defining functions and entering fixed parameters
390 CLS
400 DEF FNARCOS(X)=1.5708-ATN(X/SQR(1-X*X)) 'arc cos, with X in radians
410 PI=3.1416
420 DEF FNRAD(X)=X/180*PI 'to convert degrees to radians
430 IF NOTFIRST THEN 490
440 DIM RN(1),DRN(1),TIME(1),H(1),RT(1),DRT(1),GRT(1),CUMRT(1),CUMDRT(1),
    CUMGRT(1) '(dummy arrays, so they can be erased)
450 DIM STORE(12),VF(12)
460 NOTFIRST=1
470 '
480 '

```

8"

```

490 PRINT:PRINT:PRINT "Please enter the following fixed parameters
      for the site:--"
500 PRINT:PRINT:PRINT
510 PRINT "The latitude, in degrees South (positive for the Southern"
520 INPUT "hemisphere):",LAT
530 LATR=FNRAD(LAT)
540 PRINT:PRINT "The effective reflectivity of the horizontal
      surface around the"
550 INPUT "tilted collector (as a decimal fraction):",RHO
560 ON A GOSUB 600,880
570 GOTO 190 'return to main menu
580 '
590 '
600 REM SUBROUTINE FOR DAILY-MEANS DATA
610 GOSUB 4490 'to choose between daily means and daily totals
620 CLS:LOCATE 5
630 PRINT "      Estimating daily tilt-plane means from daily horizontal means."
640 PRINT:PRINT:PRINT:PRINT "You need to supply, for each day,":PRINT:PRINT
650 PRINT SPC(18) "-the daynumber (eg.Feb 15th=46)":PRINT
660 PRINT SPC(18) "-the ";B$;" direct and diffuse radiation"
670 PRINT SPC(18) " measured on a horizontal surface":PRINT:PRINT
680 PRINT"First, specify the tilt angle/s of the tilted collector":
      GOSUB 130 'pause
690 GOSUB 2590 'Entering tilt angle/s
700 CLS:LOCATE 10:PRINT"The data and results are not stored, in this module, so
710 INPUT "do you want a printed listing of data and results (Y/N)";LPF$
720 IF LPF$="n" OR LPF$="N" THEN 760
730 PRINT:PRINT "PRINTER READY?"
740 P$=INKEY$:IF P$="" THEN 740 ELSE IF P$="n" OR P$="N" THEN LPF$="N"
750 GOSUB 3170 'print heading
760 CLS:PRINT "DATA ENTRY":PRINT "=====":PRINT:PRINT
770 INPUT "Daynumber:      ",DN
780 INPUT "Direct:      ",MEANRN
790 INPUT "Diffuse:      ",MEANDRN
800 IF LPF$="y" OR LPF$="Y" THEN GOSUB 3260 'print data
810 GOSUB 2810 'calculations, and display results
820 PRINT:PRINT:INPUT "Do you want to continue (Y/N)";C$
830 IF C$="n" OR C$="N" THEN 850
840 GOTO 760
850 RETURN
860 '
870 '
880 REM SUBROUTINE FOR HOURLY INSOLATION DATA
890 GOSUB 950 'for data entry or retrieval
900 GOSUB 1760 'for calculations
910 GOSUB 3430 'to display and print results
920 RETURN
930 '
940 '
950 REM SUBROUTINE FOR ENTRY OR RETRIEVAL OF HOURLY INSOLATION DATA
960 CLS
970 PRINT "DATA ENTRY OR RETRIEVAL"
980 PRINT "Do you want to..."
990 PRINT "      Enter a new set of readings (1)"
1000 PRINT "      Use a previously written data file (2)"
1010 PRINT "      Enter new data to append to an existing file (3)"
1020 PRINT:INPUT "OPTION NUMBER:",OPl
1030 ON OPl GOTO 1050,1700,1100

```

```

1040 REM    NEW DATA OPTION
1050 PRINT:PRINT:PRINT "Data will be stored in a diskette data file."
1060 PRINT:LINE INPUT "Provide a new file name
                        (in the form B:filename.DAT)";DATAFILES$
1070 OPEN DATAFILES$ FOR OUTPUT AS #1
1080 GOTO 1110
1090 REM    APPEND NEW DATA TO EXISTING DATA FILE option
1100 PRINT:LINE INPUT "Give name of existing data file
                        (in the form B:filename.DAT): ";DATAFILES$:OPEN DATAFILES$ FOR APPEND AS #1
1110 CLS
1120 PRINT "Entering data for hourly readings, a day at a time:"
1130 PRINT "=====
1140 PRINT:PRINT:PRINT
1150 PRINT "First, enter the day-number, then enter hourly readings for that"
1160 PRINT "day (ie. the direct and diffuse radiation measurements for a "
1170 PRINT "horizontal collector, in Watts per meter-squared)."
1180 PRINT:PRINT "If measurements are not available for a
                        given time of day, enter"
1190 PRINT "zeros, and these will be treated as missing values."
1200 GOSUB 130 '(pause)
1210 CLS:LOCATE 5
1220 INPUT "Daynumber";DN:PRINT
1230 GOSUB 1570 'Returns the number of full daylight hours (NINT%),
                        the number of possible readings taken on the hour (NREAD),
                        the sunrise angle in radians (S)
1240 REM HOURLY MEASUREMENTS ENTRY
1250 ERASE RN,DRN,TIME 'Arrays for direct and diffuse readings, horizontal
1260 DIM RN(NREAD),DRN(NREAD),TIME(NREAD)
1270 PRINT "DIRECT","DIFFUSE"
1280 FOR HOUR = 0 TO NREAD-1
1290 TIME(HOUR)=12-NINT%/2 + HOUR
1300 PRINT TIME(HOUR)"h00:";
1310 PRINT ";;INPUT:"";RN(HOUR)
1320 PRINT ";;INPUT:"";DRN(HOUR)
1330 NEXT HOUR
1340 LOCATE 23,15:PRINT "WAIT"
1350 REM WRITING EACH DAY'S MEASUREMENTS TO DISK FILE
1360 PRINT #1,DN;DECL;S;NREAD;
1370 FOR HOUR = 0 TO NREAD-1
1380 PRINT #1, TIME(HOUR);RN(HOUR);DRN(HOUR);
1390 'Format of data file:
1400 '    DN: Day number
1410 '    DECL: Declination angle on this day, in radians
1420 '    S: Sunrise angle, in radians
1430 '    NREAD: Number of possible on-the-hour sets of readings
1440 'and then NREAD times the following:
1450 '        TIME: time of the readings (24h00 clock)
1460 '        RN: direct radiation on horizontal plane
1470 '        DRN: diffuse radiation on horizontal plane
1480 NEXT HOUR
1490 LOCATE 23,15:INPUT "CONTINUE (Y/N) ";C$
1500 IF C$="N" OR C$="n" THEN 1530
1510 GOTO 1210
1520 REM LOOP BACK FOR NEXT DAY'S READINGS
1530 CLOSE #1:OPEN DATAFILES$ FOR INPUT AS #1:RETURN 'for calculations
1540 '
1550 '
1560 REM SUBROUTINE FROM DAYNUMBER, SETTING..
1570 'Declination of sun's plane, in radians
1580 DECL=FNRAD(23.45)*SIN(FNRAD(360*(DN+101)/365))
1590 'Sunrise angle, in radians

```

```

1600 S=FNARCCOS(-TAN(DECL)*TAN(LATR))
1610 'Hours of light
1620 N=24*S/PI
1630 'Number of full clock hours in the day
1640 NINT%=2*INT(N/2)
1650 'Number of possible readings "on the hour"
1660 NREAD=NINT%+1
1670 RETURN
1680 '
1690 '
1700 REM   FOR TAKING DATA FROM AN EXISTING DATA FILE
1710 PRINT:PRINT
1720 LINE INPUT "Give name of data file (in the form B:filename.DAT)";DATAFILES$
1730 OPEN DATAFILES$ FOR INPUT AS #1:RETURN
1740 '
1750 '
1760 REM   PERFORMING CALCULATIONS FROM FILED DATA, AND FILING
        THE RESULTS IN A RESULTS FILE (Hourly data)
1770 RFILE$="B:Results.dat" 'sets up default results file
1780 CLS
1790 GOSUB 2590 'for entering tilt angle/s
1800 CLS:INPUT "Do you want to store your results in a
        specially named file (Y/N)";A$
1810 IF A$="N" OR A$="n" THEN 1830
1820 PRINT:LINE INPUT "Provide a new filename
        (in the form B:filename.DAT)";RFILE$
1830 OPEN RFILE$ FOR OUTPUT AS #2
1840 DIM MEANRT(1),MEANDRT(1),MEANGRT(1),TOTRT(1),TOTDRT(1),TOTGRT(1) 'Dummies
1850 REM   READ INPUT VARIABLES FROM DATA FILE
1860 IF EOF(1) THEN 2490
1870 INPUT #1, DN,DECL,S,NREAD
1880 CUMRN=0:CUMDRN=0:MISSING=0
1890 ERASE TIME,RN,DRN,H 'erase and redimension arrays
1900 DIM TIME(NREAD),RN(NREAD),DRN(NREAD),H(NREAD)
1910 CLS
1920 PRINT "Calculating for daynumber ";DN
1930 REM *****
1940 ERASE RT,DRT,GRT,CUMRT,CUMDRT,CUMGRT 'erase and dimension working arrays
1950 DIM RT(NREAD,NTILT),DRT(NREAD,NTILT),GRT(NREAD,NTILT),CUMRT(NTILT),
        CUMDRT(NTILT),CUMGRT(NTILT)
1960 FOR HOUR = 0 TO NREAD-1
1970 INPUT #1, TIME(HOUR),RN(HOUR),DRN(HOUR)
1980 H(HOUR)=(12-TIME(HOUR))*PI/12 'gives the hour angle of the sun in radians
1990 REM
2000 T=TMIN
2010 FOR TILT=1 TO NTILT
2020 TILTR=FNRAD(T) 'converts tilt angle to radians
2030 REM
2040 ' Direct radiation on tilted collector, at given hour and tilt angle:
2050 ' _____
2060 RT(HOUR,TILT)=RN(HOUR)*(SIN(DECL)*SIN(LATR-TILTR)+
        COS(DECL)*COS(LATR-TILTR)*ABS(COS(H(HOUR))))/
        (SIN(DECL)*SIN(LATR)+COS(DECL)*COS(LATR)*ABS(COS(H(HOUR))))
2070 ' Diffuse radiation on tilted collector, at given hour and tilt angle:
2080 ' _____
2090 GRN=RN(HOUR)+DRN(HOUR) '(global radiation on the horizontal plane)
2100 DRT(HOUR,TILT)=.5*(1+COS(TILTR))*DRN(HOUR)+.5*(1-COS(TILTR))*RHO*GRN
2110 ' Total radiation on tilted collector, at given hour and tilt angle:
2120 ' _____
2130 GRT(HOUR,TILT)=RT(HOUR,TILT)+DRT(HOUR,TILT)
2140 REM   Stoking accumulators:

```

```

2150 CUMRT(TILT)=CUMRT(TILT)+RT(HOUR,TILT)
2160 CUMDRT(TILT)=CUMDRT(TILT)+DRT(HOUR,TILT)
2170 CUMGRT(TILT)=CUMGRT(TILT)+GRT(HOUR,TILT)
2180 T=T+INC
2190 NEXT TILT
2200 REM *****
2210 CUMRN=CUMRN+RN(HOUR) 'counting up for horizontal direct mean
2220 CUMDRN=CUMDRN+DRN(HOUR) 'and diffuse mean
2230 NEXT HOUR
2240 REM *****
2250 MISSING=0
2260 GOSUB 2520 'for missing data treatment
2270 'Calculating means and totals for the day
2280 '-----
2290 ' (1) Horizontal measures:
2300 M=NREAD-MISSING '(valid number of non-zero measurements)
2310 MEANRN=CUMRN/M:MEANDRN=CUMDRN/M:MEANGRN=(CUMDRN+CUMRN)/M
2320 TOTRN=MEANRN*(NREAD):TOTDRN=MEANDRN*(NREAD):TOTGRN=MEANGRN*(NREAD)
2330 ' (these give approximate totals, leaving missing data out of
2340 ' means calculations)
2350 ERASE MEANRT,MEANDRT,MEANGRT,TOTRT,TOTDRT,TOTGRT
2360 DIM MEANRT(NTILT),MEANDRT(NTILT),MEANGRT(NTILT),
      TOTRT(NTILT),TOTDRT(NTILT),TOTGRT(NTILT)
2370 ' (2) Tilt calculations:
2380 FOR TILT=1 TO NTILT
2390 MEANRT(TILT)=CUMRT(TILT)/M
2400 MEANDRT(TILT)=CUMDRT(TILT)/M
2410 MEANGRT(TILT)=CUMGRT(TILT)/M
2420 TOTRT(TILT)=MEANRT(TILT)*(NREAD)
2430 TOTDRT(TILT)=MEANDRT(TILT)*(NREAD)
2440 TOTGRT(TILT)=MEANGRT(TILT)*(NREAD)
2450 NEXT TILT
2460 '
2470 GOSUB 3340 'Write day's results to results file
2480 GOTO 1860 'next day
2490 CLOSE #1:CLOSE #2: RETURN '(if end of data)
2500 '
2510 '
2520 REM Subroutine for missing values
2530 FOR HOUR = 0 TO NREAD-1
2540 IF RN(HOUR)=0 THEN MISSING=MISSING+1
2550 NEXT
2560 RETURN
2570 '
2580 '
2590 CLS: ' Subroutine for entering tilt angle/s
2600 PRINT "ENTERING THE ANGLE/S OF TILT for the TILTED COLLECTOR"
2610 PRINT "....."
2620 PRINT:PRINT " Do you want calculations for":PRINT
2630 PRINT " A single tilt angle (1)"
2640 PRINT " A range of tilt angles (2)"
2650 PRINT:INPUT "Enter option:",OPTILT
2660 PRINT:PRINT:PRINT "Enter the angle/s in degrees from
      the horizontal, positive for"
2670 PRINT "a Northwards tilt (in the Southern hemisphere)":PRINT:PRINT
2680 ON OPTILT GOTO 2690,2730
2690 PRINT:INPUT "TILT ANGLE";TANG
2700 TMIN=TANG:INC=0
2710 NTILT=1
2720 RETURN
2730 PRINT:INPUT "Enter minimum tilt angle:",TMIN

```

```

2740 INPUT "Enter maximum tilt angle:",TMAX
2750 PRINT:PRINT "With what size steps inbetween?"
2760 INPUT "    Size of increments, in degrees:",INC
2770 NTILT=INT((TMAX-TMIN)/INC)+1
2780 RETURN
2790 '
2800 '
2810 REM    SUBROUTINE FOR CALCULATING FROM DAILY MEANS (OR TOTALS)
2820 PRINT:PRINT"TILT-ANGLE",B$;" DIRECT",B$;" DIFFUSE",B$;" GLOBAL"
2830 IF LPF$="N" OR LPF$="n" THEN 2850
2840 LPRINT "TILT-ANGLE",B$;" DIRECT",B$;" DIFFUSE",B$;" GLOBAL"
2850 GOSUB 1560 'to get sun's declination and hours in the day
2860 T=TMIN
2870 FOR TILT=1 TO NTILT
2880 TILTR=FNRAD(T)
2890 COSACOUNT=0: COSBCOUNT=0: MEANRT=0: MEANDRT=0: MEANGRT=0
2900 ERASE H,TIME: DIM H(NREAD),TIME(NREAD)
2910 FOR HOUR=0 TO NREAD-1
2920 'Mean direct radiation on tilted plane, summing cosine ratios, weighted by
2930 'the radiation-loss factor, estimated hourly.
2940 TIME(HOUR)=12-NINT%/2+HOUR
2950 H(HOUR)=(12-TIME(HOUR))*PI/12 'gives hour angle of sun, in radians
2960 COSALPHA=SIN(DECL)*SIN(LATR)+COS(DECL)*COS(LATR)*COS(H(HOUR))
2970 ALPHA=FNARCCOS(COSALPHA)
2980 COSBETA=SIN(DECL)*SIN(LATR-TILTR)+COS(DECL)*COS(LATR-TILTR)*COS(H(HOUR))
2990 R=(LOG(91-ALPHA*180/PI))/4.5 'radiation loss factor at this hour angle
3000 COSACOUNT=COSACOUNT+R*COSALPHA 'Summing the weighted cosine ratios
3010 COSBCOUNT=COSBCOUNT+R*COSBETA
3020 NEXT HOUR
3030 MEANRT=MEANRN*COSBCOUNT/COSACOUNT
3040 'Mean diffuse radiation on tilted plane
3050 MEANGRN=MEANRN+MEANDRN
3060 MEANDRT = .5*(1+COS(TILTR))*MEANDRN+.5*(1-COS(TILTR))*RHO*MEANGRN
3070 'Mean global radiation on tilted plane:
3080 MEANGRT=MEANRT+MEANDRT
3090 PRINT T,MEANRT,MEANDRT,MEANGRT
3100 IF LPF$="n" OR LPF$="N" THEN 3120
3110 LPRINT T,MEANRT,MEANDRT,MEANGRT
3120 T=T+INC
3130 NEXT TILT
3140 RETURN
3150 '
3160 '
3170 'Subroutine for printer heading (daily means data)
3180 LPRINT "DAILY ";B$;"S, HORIZONTAL AND TILTED SURFACES"
3190 LPRINT "===== "
3200 LPRINT:LPRINT "Latitude of site: ";LAT; " degrees S."
3210 LPRINT "Surface reflectivity: ";RHO
3220 LPRINT " "
3230 LPRINT:RETURN
3240 '
3250 '
3260 'subroutine for printing data (daily means/totals)
3270 LPRINT:LPRINT "Daynumber ";DN
3280 LPRINT:LPRINT "HORIZONTAL DATA: ";B$;" DIRECT ";MEANRN;"
    ";B$;" DIFFUSE "; MEANDRN; " ";B$;" GLOBAL ";MEANRN+MEANDRN
3290 LPRINT "TILT CALCULATIONS:"
3300 RETURN
3310 '
3320 '

```



```

3330 ' Subroutine for filing calculated results from hourly calculations
      (output file is already open as #2)
3340 PRINT #2,DN;MEANRN;TOTRN;MEANDRN;TOTDRN;MEANGRN;TOTGRN;NTILT;
3350 T=TMIN
3360 FOR TILT = 1 TO NTILT
3370 PRINT #2,T;MEANRT(TILT);TOTRT(TILT);MEANDRT(TILT);
      TOTDRT(TILT);MEANGRT(TILT);TOTGRT(TILT);
3380 T=T+INC
3390 NEXT TILT
3400 RETURN
3410 '
3420 '
3430 'Subroutine for reading results file and displaying/printing results
3440 GOSUB 4190      'select print/display options
3450 OPEN RFILE$ FOR INPUT AS #2:CLS
3460 IF P THEN PRINT "ESTIMATIONS AT LATITUDE ";LAT;" degrees S.":PRINT "(with
      surface reflectivity ";RHO;")":PRINT
3470 IF L THEN LPRINT "ESTIMATIONS AT LATITUDE ";LAT;"
      degrees S.":LPRINT "(with
      surface reflectivity ";RHO;")":LPRINT
3480 ' read from results file DN,MEANRN,TOTRN,MEANDRN,
      TOTDRN,MEANGRN,TOTGRN,NTILT
3490 IF EOF(2) THEN CLOSE #2:RETURN
3500 INPUT #2,DN
3510 FOR V=1 TO 6:INPUT #2,STORE(V):NEXT
3520 INPUT #2,NTILT
3530 IF P THEN PRINT "Daynumber: ";DN
3540 IF L THEN LPRINT "Daynumber: ";DN
3550 GOSUB 3790      'headings for horizontal variables
3560 FOR V=1 TO 6
3570 IF VF(V)=0 THEN 3600      'Printing the selected horizontal
3580 IF P THEN PRINT STORE(V),      'variables
3590 IF L THEN LPRINT STORE(V),
3600 NEXT V
3610 PRINT: IF L THEN LPRINT
3620 GOSUB 3980      'headings for tilt variables
3630 FOR TILT = 1 TO NTILT
3640 INPUT #2,T
3650 IF L THEN LPRINT T,
3660 IF P THEN PRINT T,
3670 FOR V=7 TO 12
3680 INPUT #2, STORE(V)
3690 IF VF(V)=0 THEN 3720
3700 IF P THEN PRINT STORE(V),
3710 IF L THEN LPRINT STORE(V),
3720 NEXT V
3730 PRINT:IF L THEN LPRINT
3740 NEXT TILT
3750 IF P THEN GOSUB 130:CLS      'pause
3760 GOTO 3490      '(till end of results file)
3770 '
3780 '
3790 ' Subroutine for printing headings, hourly data, horizontal variables
3800 IF L THEN LPRINT "HORIZONTAL MEASUREMENTS"
3810 IF VF(1) AND L THEN LPRINT "MeanDir",
3820 IF VF(2) AND L THEN LPRINT "ToTDir",
3830 IF VF(3) AND L THEN LPRINT "MeanDif",
3840 IF VF(4) AND L THEN LPRINT "TotDif",
3850 IF VF(5) AND L THEN LPRINT "MeanGlob",
3860 IF VF(6) AND L THEN LPRINT "TotGlobl",
3870 IF P THEN PRINT "HORIZONTAL MEASUREMENTS"

```

```

3880 IF VF(1) AND P THEN PRINT "MeanDir",
3890 IF VF(2) AND P THEN PRINT "ToTDir",
3900 IF VF(3) AND P THEN PRINT "MeanDif",
3910 IF VF(4) AND P THEN PRINT "TotDif",
3920 IF VF(5) AND P THEN PRINT "MeanGlob",
3930 IF VF(6) AND P THEN PRINT "TotGlobl",
3940 PRINT:IF L THEN LPRINT
3950 RETURN
3960 '
3970 '
3980 ' Subroutine for printing headings, hourly data, tilt variables
3990 IF P THEN PRINT "TILT ESTIMATIONS"
4000 PRINT "Tilt",
4010 IF VF(7) AND P THEN PRINT "MeanDir",
4020 IF VF(8) AND P THEN PRINT "ToTDir",
4030 IF VF(9) AND P THEN PRINT "MeanDif",
4040 IF VF(10) AND P THEN PRINT "TotDif",
4050 IF VF(11) AND P THEN PRINT "MeanGlob",
4060 IF VF(12) AND P THEN PRINT "TotGlobl",
4070 IF L THEN LPRINT "TILT ESTIMATIONS"
4080 IF L THEN LPRINT "Tilt",
4090 IF VF(7) AND L THEN LPRINT "MeanDir",
4100 IF VF(8) AND L THEN LPRINT "ToTDir",
4110 IF VF(9) AND L THEN LPRINT "MeanDif",
4120 IF VF(10) AND L THEN LPRINT "TotDif",
4130 IF VF(11) AND L THEN LPRINT "MeanGlob",
4140 IF VF(12) AND L THEN LPRINT "TotGlobl",
4150 PRINT:IF L THEN LPRINT
4160 RETURN
4170 '
4180 '
4190 CLS:LOCATE 10
4200 PRINT " PRINTING
AND/OR DISPLAYING RESULTS":PRINT:PRINT:PRINT
4210 INPUT "Do you want a printed listing of results (Y/N)";LF$:PRINT
4220 INPUT "Do you want results displayed on the screen (Y/N)";PF$
4230 CLS:IF LF$="Y" OR LF$="y" THEN L=1 ELSE L=0
4240 IF PF$="Y" OR PF$="y" THEN P=1 ELSE P=0
4250 PRINT "SELECT THE VARIABLES YOU WANT DISPLAYED/PRINTED FOR EACH DAY"
4260 PRINT "Enter Y for inclusion, and N (or <RETURN>) for exclusion"
4270 LOCATE 5:PRINT "HORIZONTAL INSOLATION:"
4280 LOCATE 5,30:PRINT "TILT INSOLATION:":
4290 DIM X$(2),Y$(3)
4300 X$(1)="Mean ":X$(2)="Total "
4310 Y$(1)="direct":Y$(2)="diffuse":Y$(3)="global"
4320 LOCATE 7
4330 FOR I=1 TO 3:FOR J=1 TO 2
4340 PRINT X$(J)+Y$(I) TAB(30) X$(J)+Y$(I)
4350 NEXT J:NEXT I
4360 SET=0
4370 ROW=7:COL=15:V=1
4380 FOR I= 0 TO 1:FOR J=1 TO 6
4390 LOCATE ROW,COL
4400 INPUT INCLUDE$
4410 IF INCLUDE$= "y" OR INCLUDE$="Y" THEN VF(V)=1 ELSE VF(V)=0
4420 V=V+1:ROW=ROW+1
4430 NEXT J:ROW=7:COL=45:NEXT I
4440 IF P=0 THEN 4480
4450 LOCATE 22
4460 PRINT:PRINT "PRINTER READY?"
4470 P$=INKEY$:IF P$="" THEN 4470 ELSE IF P$="n" OR P$="N" THEN P=0

```

```
4480 RETURN
4490 '
4500 '
4510 'Subroutine for choosing daily means or daily totals
4520 '(The calculations are the same, only the headings are changed)
4530 CLS:LOCATE 5:PRINT "Do you want to use":PRINT
4540 PRINT SPC(10) "Daily means (1)":PRINT SPC(7) "or"
4550 PRINT SPC(10) "Daily totals (2)":PRINT
4560 INPUT "Enter option: ",QM
4570 IF QM=1 THEN B$="MEAN" ELSE IF QM=2 THEN B$="TOTAL" ELSE GOTO 4530
4580 RETURN
```

Appendix C2

Program for Calculating Tilt Plane Insolation, Using the Perez
Anisotropic Approach for the Diffuse Component. Code Adapted from
PVFORM (Menicucci and Fernandez, 1985).

```

10 REM          TILT PLANE INSOLATION USING PEREZ MODEL
20 REM          FOR DIFFUSE COMPONENT, FOLLOWING PVFORM CODE
30 REM
40 REM  Bill Cowan, 12.87
50 REM
60 REM  For original program annotation refer PVFORM,
70 REM          subroutines INSOL and DIFSE.
80 REM  -----
100 GOSUB 200 ' Initialise, dimension, read parameter data.
120 GOSUB 400 ' Solicit user input
130 IF MULTI THEN GOSUB 10000 'Option for multiple datasets
140 REM          Loop through available data (per day * 24 hours)
150 OPEN DTA$ FOR INPUT AS 1
155 OPEN OUTPT$ FOR OUTPUT AS 2
160 WHILE NOT EOF(1)
170     GOSUB 600 ' Read one day's data
180     GOSUB 1100 ' Perform calculations
190     GOSUB 3000 ' Output results
195 WEND
196 CLOSE 1,2
197 IF MULTI THEN GOTO 130 'Loop back if multiple datasets requested
198 END
199 REM  -----
200 REM          Subroutine from 200, to define functions
210 REM  -----
215 PI=3.141593
220 DEF FNASIN(X)=ATN(X/SQR(1-X*X)) 'where x in radians: ARC SINE
230 DEF FNACOS(X)=PI/2-ATN(X/SQR(1-X*X)) ' : ARC COS
240 REM
250 REM          Dimension arrays
255 DIM DTA$(1),OUTPT$(1) '(Dummy arrays for filename specs)
260 DIM HOR(24),HORDFS(24),DIRNRM(24),ITILT(24),F(6,8)
261 REM
262 REM          HOR      Global insolation on horizontal      W/sq.m
263 REM          HORDFS   Diffuse insolation on horizontal      W/sq.m
264 REM          DIRNRM   Direct normal insolation              W/sq.m
265 REM          ITILT    Calculated Plane of Array insolation   W/sq.m
266 REM          F        Data for Perez model parameters
267 REM
270 REM          Read data for Perez parameters:
271 FOR J=1 TO 8
272 FOR I=1 TO 6
273 READ F(I,J)
274 NEXT I
275 NEXT J
276 DATA -0.011, 0.748, -0.080, -0.048, 0.073, -0.024, -0.038, 1.115
277 DATA -0.109, -0.023, 0.106, -0.037, 0.166, 0.909, -0.179, 0.062
278 DATA -0.021, -0.050, 0.419, 0.646, -0.262, 0.140, -0.167, -0.042
279 DATA 0.710, 0.025, -0.290, 0.243, -0.511, -0.004, 0.857, -0.370
280 DATA -0.279, 0.267, -0.792, 0.076, 0.734, -0.073, -0.228, 0.231
281 DATA -1.180, 0.199, 0.421, -0.661, 0.097, 0.119, -2.125, 0.446

```

```

282 REM
300 RETURN
400 REM -----
401 REM          Subroutine from 120, to solicit user inputs
402 REM -----
403 REM
410 CLS
415 PRINT "PLANE OF ARRAY INSOLATION, FROM HOURLY WEATHER RECORDS"
416 PRINT
417 PRINT "Adapted from PVFORM Ver 3.2 by David Menicucci and James
418 PRINT "Fernandez of Sandia Labs, USA. Employs the Perez model for"
419 PRINT "calculating diffuse insolation component on tilted plane.
420 PRINT "This model contains empirical parameters (warning) and
421 PRINT "is intended to improve on isomorphic models of diffuse
422 PRINT "radiation.
423 PRINT
424 PRINT "The original PVFORM code requires as input Direct Normal Insolation
425 PRINT "and Global Horizontal Insolation (hourly records)
427 PRINT
428 PRINT "This adaptation requires as minimum input data:
429 PRINT "      Julian date of hourly records
430 PRINT "      Hourly global horizontal insolation      (W/sq.m)
431 PRINT "      Hourly diffuse insolation on horizontal (W/sq.m)
432 PRINT "(3 values per record and exactly 24 hourly records per day)
434 PRINT
435 PRINT "Output to file are
436 PRINT "      Julian date      Hour [option]
437 PRINT "      Calculated Plane of Array insolation,
          for given location and tilt.
438 PRINT
439 GOSUB 9000 'continue?
440 CLS
441 PRINT "Adaptation by Bill Cowan":PRINT "Department of Sociology"
442 PRINT "University of Cape Town
443 PRINT "Dec 1987
444 FOR I=1 TO 2700:NEXT
445 CLS
446 PRINT"Run once [1]   Run for multiple data sets [2]   Exit [9]":PRINT
447 INPUT "ENTER OPTION NUMBER: ",OPM
448 IF OPM=9 THEN END
449 IF OPM=2 THEN MULTI=1:RETURN
450 CLS:PRINT "Specify file containing input data
452 PRINT "(eg. B:INSOL85-87)
453 PRINT
454 LINE INPUT DTAS
455 PRINT:PRINT "Specify file for output
457 PRINT "(eg. B:POA)
458 PRINT
459 LINE INPUT OUTPT$
460 FOR I=1 TO 500:NEXT:CLS '- - - Also sub-entry point from 10045 - - -
461 PRINT "USER INPUTS":PRINT
462 PRINT "Enter the following:
463 PRINT "      LATITUDE (negative for southern hemisphere)
464 PRINT "      TILT OF ARRAY (degrees from horizontal)
465 PRINT "      AZIMUTH OF ARRAY (degrees W of North for S. hemisphere)
466 PRINT "      REFLECTIVITY OF SURROUNDS (eg 0.3 for grass)
467 PRINT
468 INPUT "Latitude:      ", TLAT
469 INPUT "Tilt:          ", TILT
470 INPUT "Azimuth:       ", TAZM
471 INPUT "Reflectivity ", REFL

```

```

472 PRINT:PRINT "What output do you want?"
473 PRINT:PRINT "    Hourly POA insolation    [1]"
474 PRINT "    Daily totals for POA    [2]"
475 PRINT:INPUT "Enter option:",OUTPUTFLAG
476 IF OUTPUTFLAG>2 OR OUTPUTFLAG<1 THEN 472
490 PRINT:PRINT:GOSUB 9000
491 REM
492 TILT=TILT*.017453 'convert tilt angle to radians
493 REM
495 RETURN
600 REM -----
610 REM Subroutine from 170 to read one day's data from data file
620 REM -----
630 FOR I=1 TO 24
635 IF EOF(1) THEN RETURN
636 REM *****Change to suit input data*****
640 INPUT# 1,YEAR, JLDATE,HOUR, GLOBAL.HORZ.INSOLATION,
        DIFFUSE.HORZ.INSOLATION,ZZ 'The last is a dummy
645 REM *****Change to suit input data*****
650 HOR(I) = GLOBAL.HORZ.INSOLATION
660 HORDFS(I) = DIFFUSE.HORZ.INSOLATION
665 NEXT
670 REM
680 REM Assumed: data file has these variables and 24 rods/day
690 RETURN
700 REM
1100 REM -----
1110 REM Subroutine from 180, INSOL + DFSE calculations
1120 REM -----
1130 DTOR=.0174533 'degrees to radians
1140 REM
1150 FOR I=1 TO 24
1160 IF HOR(I) > 0 THEN 1180
1170 ITILT(I)=0:GOTO 2245
1175 REM
1180 REM Hour angle and declination
1185 REM
1190 SOLTIME=I-.5
1200 IF SOLTIME <= 12 THEN HOURAN=(12-SOLTIME)*15 ELSE HOURAN=-(SOLTIME-12)*15
1210 ARG=.39795*COS(DTOR*.98563*(JLDATE-173))
1220 DEC=FNASIN(ARG)
1230 HOURAN=HOURAN*DTOR
1235 REM
1240 REM Elevation of sun
1250 REM
1260 ARG=COS(TLAT*DTOR)*COS(DEC)*COS(HOURAN)+SIN(TLAT*DTOR)*SIN(DEC)
1270 IF ARG > 1 THEN ARG=1 ELSE IF ARG < -1 THEN ARG = -1
1275 REM
1280 ELV=FNASIN(ARG) 'Sun's elevation
1285 REM
1290 REM Sun's azimuth
1300 REM
1310 ARG=COS(DEC)*SIN(HOURAN)/COS(ELV)
1320 IF ARG > 1 THEN ARG=1 ELSE IF ARG < -1 THEN ARG=-1
1330 AZTEMP=FNASIN(ARG)
1340 IF COS(HOURAN) > TAN(DEC)/TAN(TLAT*DTOR) THEN AZM=AZTEMP:GOTO 1420
1345 IF COS(HOURAN)=TAN(DEC)/TAN(TLAT*DTOR) THEN 1400
1346 REM cos(houran)<tan(etc.)
1350 IF AZTEMP < 0 THEN AZM=-PI-AZTEMP ELSE AZM=PI- AZTEMP:GOTO 1420
1400 IF HOURAN < 0 THEN AZM=-PI/2 ELSE AZM=PI/2
1420 REM

```

```

1430 CST=0
1440 DCM=0
1450 DH=0
1460 SE=SIN(ELV)
1470 CE=COS(ELV)
1480 SA= SIN(AZM)
1490 CA=COS(AZM)
1500 SB=SIN(TILT)
1510 CB=COS(TILT)
1520 TT=PI/2-ELV
1530 CT=COS(TT)
1531 REM
1532 REM *****
1533 REM      Here is a patch, changing PVFORM code to allow for
1534 REM      different input data, ie. for Global and Diffuse Insolation
1535 REM      on horizontal rather than Direct Normal and Global Horizontal
1536 REM
1537 DH=HORDFS(I) 'from data input DIFFUSE ON HORIZONTAL
1538 REM      Original: DH=HOR(I)-(SE*DIRNRM(I))
1539 REM
1540 IF SE < .01 THEN DIRNRM(I)=0:GOTO 1544
1541 REM      To avoid zero division or inaccuracy below:
1542 HORDIRECT=HOR(I)-DH
1543 DIRNRM(I)=HORDIRECT/SE 'dividing by sine of the elevation
1544 REM *****
1545 REM
1550 DIR=DIRNRM(I)*3.6
1560 REM      Convert Watts to kJ/h for next model
1570 DH=DH*3.6
1580 REM
1590 REM      Going into Perez model for fixed tilt array
1600 REM
1610 AAT=(SB*CE*COS(AZM-TAZM*DTOR)+CB*SE) 'Cosine of incidence angle
1620 CST=AAT
1630 TA=FNACOS(CST) 'Incidence angle
1640 S=TILT 'Tilt angle
1650 REM
1660 REM      DH      diffuse on horizontal (kJ/hr)
1670 REM      DIR      direct normal radiation
1680 REM      T      solar zenith angle
1690 REM      TA      solar incidence on tilting plane (KJ/hr)
1700 REM      DCM      calculated diffuse on tilted plane
1710 REM      S      slope angle
1720 REM      CST      cosine(TA)
1730 REM      CT      cos(T)
1740 REM      F(6,8) data matrix for Perez parameters
1750 REM      F(LY,1)-f(LY,3)= Parameter F1 )
1760 REM      F(LY,4)-f(LY,6)= Parameter F2 ) [doesn't fit later eqns]
1770 REM
1780 REM      Parameters EPSILON and DELTA:
1785 IF DH<=0 THEN DH=1 'avoid division by zero from data inaccuracies
1790 EPS1=(DIR+DH)/DH
1800 CSS=COS(S)
1810 DELTA=(DH/CT)/4921
1820 REM
1830 ALP=25*PI/180 ' half angle of circumsolar region
1840 REM
1850 IF EPS1 <= 1.056 THEN LY=1: GOTO 1950
1860 IF EPS1 < 1.253 THEN LY=2: GOTO 1950
1870 IF EPS1 < 1.586 THEN LY=3: GOTO 1950
1880 IF EPS1 < 2.134 THEN LY=4: GOTO 1950

```

```

1890 IF EPS1 < 3.23 THEN LY=5:GOTO 1950
1900 IF EPS1 < 5.98 THEN LY=6:GOTO 1950
1910 IF EPS1 < 10.08 THEN LY=7:GOTO 1950
1940 LY=8
1950 F1=F(1,LY)+F(2,LY)*DELTA+F(3,LY)*T
1960 F2=F(4,LY)+F(5,LY)*DELTA+F(6,LY)*T
1970 REM
1980 SAL=2*(1-COS(ALP))
1990 TB=PI/2-ALP
2000 TC=PI/2+ALP
2010 CS=(1+CSS)/2
2020 REM
2030 IF T <= TB THEN XH=CT:YH=1:GOTO 2060
2040 YH=(PI/2-T+ALP)/(2*ALP)
2050 XH=YH*SIN(YH*ALP)
2060 REM
2070 IF TA <= TB THEN XC=YH*CST:GOTO 2100
2080 IF TA<=TC THEN YC=(PI/2-TA+ALP)/(2*ALP):XC=YH*YC*SIN(YC*ALP):GOTO 2100
2090 XC=0
2100 REM
2110 AA=SAL*XC
2120 CC=SAL*XH
2130 DCM=DH*(CS*(1-F1)+F1*(AA/CC)+F2*SIN(S))
2140 REM
2150 REM          End of Perez model for diffuse component
2160 REM
2170 DCM=DCM/3.6 'Convert back to Watts
2180 REM
2190 DIRFOR=CST*DIRNRM(I)
2200 IF DIRFOR < 0 THEN DIRFOR=0 ' Check for sun behind collector
2210 REM
2220 REFLCM=.5*(1-COS(TILT))*REFL*HOR(I) ' Reflected component
2230 REM
2240 ITILT(I)=DIRFOR+DCM+REFLCM
2245 NEXT I
2250 RETURN
2260 REM
3000 REM -----
3010 REM          Subroutines from 190, to write results to file
3020 REM -----
3025 ON OUTPUTFLAG GOTO 3040,3110
3026 REM
3030 REM          Hourly data option
3035 REM -----
3040 PRINT,PRINT "Day no. " JLDATE
3050 FOR I=1 TO 24
3055 PRINT I;
3060 PRINT# 2, JLDATE, I, ITILT(I)
3070 NEXT
3080 RETURN
3090 REM
3100 REM          Daily totals option
3105 REM -----
3110 DAYTOT=0
3120 FOR I=1 TO 24
3130 DAYTOT=DAYTOT+ITILT(I)
3140 NEXT I
3150 PRINT "Day No. " JLDATE,DAYTOT
3160 PRINT# 2, JLDATE,DAYTOT
3170 RETURN
8990 REM -----

```



```

8991 REM          Screen pause
8992 REM _____
9000 PRINT "          Press any key to continue
9005 Z$=INKEY$
9010 WHILE Z$=""
9020 GOTO 9005
9030 WEND
9040 RETURN
9050 REM _____
10000 REM _____
10010 REM Subroutine from 130, to name and later read multiple files
10020 REM _____
10030 PASSES=PASSES+1
10040 IF PASSES>1 THEN 10270 'Omit following, except on first entry.
10045 GOSUB 460 '      Nips off last part of Sub 400 for user parameters
10050 CLS:PRINT "Enter names of files for input and output.
10060 PRINT "Suitable input format is assumed. If in doubt check Line 640
10070 PRINT "in program listing, and modify if necessary.": PRINT
10080 PRINT "First enter number of datafiles to be processed as a batch:"
10090 INPUT "NFILES= ",NFILES
10100 ERASE DTA$,OUTPT$:DIM DTA$(NFILES),OUTPT$(NFILES)
10110 CLS:PRINT "Please give a unique output file for each datafile to
10120 PRINT "be processed.":PRINT
10130 FOR I=1 TO NFILES
10140   PRINT "Set "I
10150   LINE INPUT "Hourly data filename: ";DTA$(I)
10160   LINE INPUT "Output filename: ";OUTPT$(I)
10170 NEXT I
10180 CLS
10190 FOR I=1 TO NFILES
10200   PRINT DTA$(I)," ",OUTPT$(I)
10210 NEXT I
10220 PRINT:INPUT "OK (Y/N)";CN$
10230 IF CN$ <> "Y" AND CN$ <> "y" THEN 10050 'loop back for new entry
10240 REM
10250 REM          Read filenames and open files
10260 REM
10270 IF PASSES>NFILES THEN END 'Last data file has been finished
10280 DTA$=DTA$(PASSES):OUTPT$=OUTPT$(PASSES)
10290 RETURN

```

Appendix C3

Program for Screening and Reformatting Solar Radiation Data From South African Weather Bureau Tape.

```

10 REM      Program to read data from S.A. Weather Bureau Tapes,
20 REM      transferred to PC disk, for GLOBAL and DIFFUSE radiation
30 REM      recorded on a horizontal surface (hourly records).
40 REM
50 REM      This data is recorded per year, per month, per hour, and
60 REM      then for each hour there are up to 31 values, for the days
70 REM      of the month.
80 REM
90 REM      This program outputs to PC file the following variables in
100 REM     their HOURLY sequence, with 24 records per day:
110 REM
120 REM          YEAR          19XX
130 REM          JULIAN        XXX      Julian date
140 REM          TIME          XX       on 24 hr clock
150 REM          GLOBAL        XXXX     Mean W/sq.m per hour
160 REM          DIFFUSE       XXXX     Mean W/sq.m per hour
170 REM
180 REM      In addition, there can be added to these records an
190 REM      estimated prediction of AMBIENT TEMPERATURE (for use in
200 REM      PV simulation models), derived from the data for
210 REM      global radiation, and from further required data for the
220 REM      average mean and maximum temperatures for each month at
230 REM      the location; giving
240 REM
250 REM          AMBIENT        XX       Degrees C.
260 REM
270 REM
280 REM
290 REM
300 REM      Bill Cowan, Department of Sociology, UCT
310 REM      Dec 1987
320 REM
330 REM
340 REM
350 REM
360 REM
370 REM
380 REM
390 REM
400 GOSUB 1000 'User input, specify and open files.
410 GOSUB 2000 'Dimension arrays and initialise
415 REM      Loop through all SAWB data, check for matching between
416 REM      file records and read into monthly arrays
417 WHILE NOT EOF(1): WHILE NOT EOF(2)
420 FOR HOUR=1 TO 24
430 GOSUB 8000 'Read data for this month and hour, thru 24 hrs, into array
435 NEXT HOUR
436 GOSUB 11010 'Check for error/missing codes and take appropriate
437 REM      steps
440 IF AMBIENTFLAG > 0 THEN GOSUB 9000 'Estimate and add AMBIENT
450 GOSUB 10000 'Write hourly sequence to file
460 IF JULIAN < 40 THEN GOSUB 12000 'Check in time whether a leap year
470 WEND: PRINT: PRINT "EOF on #2":END
480 WEND: PRINT: PRINT "EOF on #1":END
490 REM
500 REM
510 REM
520 REM
530 REM
540 REM
550 REM
560 REM
570 REM
580 REM
590 REM
600 REM
610 REM
620 REM
630 REM
640 REM
650 REM
660 REM
670 REM
680 REM
690 REM
700 REM
710 REM
720 REM
730 REM
740 REM
750 REM
760 REM
770 REM
780 REM
790 REM
800 REM
810 REM
820 REM
830 REM
840 REM
850 REM
860 REM
870 REM
880 REM
890 REM
900 REM
910 REM
920 REM
930 REM
940 REM
950 REM
960 REM
970 REM
980 REM
990 REM
1000 REM      Subroutine: User specifications, from 400
1010 REM
1020 REM
1030 REM
1040 REM
1050 REM
1060 REM
1070 REM
1080 REM
1090 REM
1100 REM
1110 REM
1120 REM
1130 REM
1140 REM
1150 REM
1160 REM
1170 REM
1180 REM
1190 REM
1200 REM
1210 REM
1220 REM
1230 REM
1240 REM
1250 REM
1260 REM
1270 REM
1280 REM
1290 REM
1300 REM
1310 REM
1320 REM
1330 REM
1340 REM
1350 REM
1360 REM
1370 REM
1380 REM
1390 REM
1400 REM
1410 REM
1420 REM
1430 REM
1440 REM
1450 REM
1460 REM
1470 REM
1480 REM
1490 REM
1500 REM
1510 CLS:PRINT "SPECIFY FILE FOR GLOBAL INSOLATION DATA"
1520 PRINT "(eg. C:DIR.70)"
1530 INPUT " ",F1$

```

```

1540 PRINT
1550 PRINT "SPECIFY FILE FOR DIFFUSE RADIATION DATA":PRINT
1560 INPUT "      ",F2$
1570 PRINT
1580 PRINT "SPECIFY FILE FOR OUTPUT":PRINT
1590 INPUT "      ",F3$
1600 OPEN F1$ FOR INPUT AS 1
1610 OPEN F2$ FOR INPUT AS 2
1620 OPEN F3$ FOR OUTPUT AS 3
1999 RETURN
2000 REM
2010 REM      Subroutine from 410, to initialise and dimension arrays
2020 REM
2030 DIM GLOBAL(31,24)
2040 DIM DIFFUSE(31,24)
2050 DIM AMBIENT(31,24)
2055 DIM WRITEFLAG(1),REPS(1) 'Dummy arrays for later dimensioning
2060 DIM DAYSIN(12) 'days in month
2070 DIM JULIANFIRST(12) 'the Julian day preceding each month
2071 REM
2072 REM      Set number of days in each month of the year
2073 REM
2080 FOR MONTH = 1 TO 12
2090     READ DAYSIN(MONTH)
2100 NEXT MONTH
2110 DATA 31,28,31,30,31,30,31,31,30,31,30,31
2111 REM
2112 REM      Set Julian cutpoints (adjustments made later for
2113 REM      leap years, after reading YEAR value in data)
2114 REM
2120 J=0
2130 FOR MONTH = 1 TO 12
2140     JULIANFIRST(MONTH)=J
2150     J=J+DAYSIN(MONTH)
2160 NEXT MONTH
2999 RETURN
8000 REM
8001 REM      Subroutine from nnn to read data from two files,
8010 REM      check record identifications for match, and read
8020 REM      the <= 31 monthly values into arrays
8030 REM
8040 LINE INPUT #1,LINE1$
8050 LINE INPUT #1,LINE2$
8060 LINE INPUT #1,LINE3$
8070 LINE INPUT #2, LINE11$
8080 LINE INPUT #2, LINE21$
8090 LINE INPUT #2, LINE31$
8100 REM      Check Station ID and Year and Month are the same
8110 REM      for each input record.
8120 IF LEFT$(LINE1$,16) <> LEFT$(LINE11$,16) THEN 13000
8130 MONTH=VAL(MID$(LINE1$,15,2))
8140 YEAR=VAL(MID$(LINE1$,11,4))
8150 TIME=VAL(MID$(LINE1$,17,2))
8160 TIME1=VAL(MID$(LINE11$,17,2))
8165 REM      Check the hour-code is compatible
8170 IF TIME+24 <> TIME1 THEN 13100
8171 REM      Check the data time = the output hour
8172 IF TIME <> HOUR THEN 13200
8180 REM      Read lines 2 and 3 in fields
8185 REM
8190 REM      Read second record

```

```

8200 FOR X=1 TO 15
8210   STARTPOS=6*X-5
8220   DAY=X
8230   GLOBAL(DAY,HOUR)=10*VAL(MID$(LINE2$,STARTPOS,6))
8240   DIFFUSE(DAY,HOUR)=10*VAL(MID$(LINE21$,STARTPOS,6))
8250 REM       (The "10*" converts decaWatts to Watts/sq.m)
8260 NEXT X
8270 REM       Read third record
8280 FOR X=1 TO 16
8290   STARTPOS=6*X-5
8300   DAY=15+X
8305 IF DAY>DAYSIN(MONTH) THEN 8330 'Don't read if past end of month
8310   GLOBAL(DAY,HOUR)=10*VAL(MID$(LINE3$,STARTPOS,6))
8320   DIFFUSE(DAY,HOUR)=10*VAL(MID$(LINE31$,STARTPOS,6))
8330 NEXT X
8350 REM
8999 RETURN
10000 REM
10010 REM       Subroutine from 450, writing data to file in hourly
10020 REM       sequence
10030 REM
10035 FOR DAY = 1 TO 31
10036 IF DAY > DAYSIN(MONTH) THEN 10070 'Don't write past end of that month
10037 JULIAN=JULIANFIRST(MONTH) + DAY
10040 FOR HOUR=1 TO 24
10050 PRINT# 3, USING "####. ";YEAR, JULIAN, HOUR, GLOBAL(DAY,HOUR),
      DIFFUSE(DAY,HOUR),AMBIENT(DAY,HOUR)
10060 NEXT HOUR
10065 PRINT "Day number "JULIAN, YEAR
10070 NEXT DAY
10080 RETURN
11000 REM
11010 REM       Subroutine from 436, to handle error codes in data
11020 REM
11030 REM       In data, zero readings (night) are coded -7777 while
11040 REM       error readings are coded -9999. These values become
11050 REM       -77770 and -99990 after "conversion" to W/sq.m
11060 REM
11070 REM       The -77770's are now recoded to zero. When -99990's
11080 REM       are encountered, an attempt is made to interpolate
11090 REM       replacement values. If this fails, the subroutine
11100 REM       returns a WRITEFLAG set to skip writing of that day's
11110 REM       data. The cumulative total of days thus skipped is
11120 REM       displayed on the screen, along with each day's tally
11130 REM       for successfully interpolated datapoints.
11140 REM
11142 ERASE WRITEFLAG,REPS 'Erase before redimensioning
11145 DIM WRITEFLAG(31),REPS(31) 'Set flags/counters to zero
11160 FOR DAY=1 TO DAYSIN(MONTH): FOR HOUR=1 TO 24
11170 G=GLOBAL(DAY,HOUR): D=DIFFUSE(DAY,HOUR)
11180 REM       Test for -77770
11190 IF G+77770!<1 THEN GLOBAL(DAY,HOUR)=0:GOTO 11580 'continue for diffuse
11200 REM       Test for -99990
11210 IF NOT(G+99990!<1) THEN 11580 'continue for diffuse
11220 REM       ***ERROR. If error at night, ignore and set to zero:
11230 IF HOUR<4 OR HOUR>20 THEN GLOBAL(DAY,HOUR)=0:GOTO 11580 'Continue
11240 REM       Otherwise assess extent of damage on that day:
11250 ERRORSG=0: ERRORSD=0
11260 FOR H=4 TO 20
11270   IF GLOBAL(DAY,H)+99990!<1 THEN ERRORSG=ERRORSG+1
11280   IF DIFFUSE(DAY,H)+99990!<1 THEN ERRORSD=ERRORSD+1

```

```

11290 NEXT H
11300 IF ERRORSG>4 OR ERRORSD>4 THEN 11305 'Too much uncertainty
11301 GOSUB 11310 'Attempt monthly means replacement
11302 IF WRITEFLAG(DAY)=1 THEN 11810 'Skip to next day's data
11303 REPS(DAY)=REPS(DAY)+1 'count number of replacements
11304 GOTO 11800 'to next hour
11305 REM Replacement not attempted: skip day
11306 WRITEFLAG(DAY)=1: GOTO 11810 'next day
11309 REM
11310 REM If sufficient valid records in month, replace with mean
11320 REM monthly values for that hour
11321 REM
11330 NTEMP=0:SUMTEMPG=0:SUMTEMPD=0
11340 FOR M=1 TO DAYSIN(MONTH)
11350 GTEMP=GLOBAL(M,HOUR)
11360 IF GTEMP<=0 THEN 11420
11370 DTEMP=DIFFUSE(M,HOUR)
11380 IF DTEMP<=0 THEN 11420
11390 SUMTEMPG=SUMTEMPG+GTEMP
11400 SUMTEMPD=SUMTEMPD+DTEMP
11410 NTEMP=NTEMP+1
11420 NEXT M
11425 REM
11430 IF NTEMP<DAYSIN(MONTH)-5 THEN WRITEFLAG(DAY)=1 'too few valid pairs
11440 GLOBAL(DAY,HOUR)=SUMTEMPG/NTEMP
11450 DIFFUSE(DAY,HOUR)=SUMTEMPD/NTEMP
11460 RETURN
11461 REM
11570 REM Now do the same for DIFFUSE readings
11575 REM
11580 REM Test for -77770
11585 REM
11590 IF D+77770!<1 THEN DIFFUSE(DAY,HOUR)=0: GOTO 11800 'next hour
11600 REM Test for -99990
11610 IF NOT(D+99990!<1) THEN 11800 'next hour
11620 REM ****ERROR. If error at night, ignore and set to zero:
11630 IF HOUR<4 OR HOUR>20 THEN DIFFUSE(DAY,HOUR)=0:GOTO 11800 'next hour
11640 REM Otherwise, assess extent of damage on that day:
11650 ERRORSG=0: ERRORSD=0
11660 FOR H=4 TO 20
11670 IF GLOBAL(DAY,H)+99990!<1 THEN ERRORSG=ERRORSG+1
11680 IF DIFFUSE(DAY,H)+99990!<1 THEN ERRORSD=ERRORSD+1
11690 NEXT H
11700 IF ERRORSG>4 OR ERRORSD>4 THEN 11705 'Too much uncertainty
11701 GOSUB 11310 'Attempt monthly means replacement
11702 IF WRITEFLAG(DAY)=1 THEN 11810 'skip to next day's data
11703 REPS(DAY)=REPS(DAY)+1
11704 GOTO 11800 'next hour
11705 REM Replacement not attempted: skip day
11706 WRITEFLAG(DAY)=1: GOTO 11810 'next day
11707 REM
11800 NEXT HOUR
11806 IF REPS(DAY)=0 THEN 11810
11807 PRINT "Day ",JULIAN, REPS(DAY), " replaced values."
11810 IF WRITEFLAG(DAY)=1 THEN COUNTSKIP=1+COUNTSKIP:PRINT "Skips " COUNTSKIP
11830 NEXT DAY
11999 RETURN
12000 REM
12010 REM Subroutine from 460 to adjust for leap years
12020 REM
12030 IF (YEAR MOD 4)>0 THEN 12999

```

```

12040 DAYSIN(2)=29
12050 FOR MONTH=3 TO 12
12060   JULIANFIRST(MONTH)=JULIANFIRST(MONTH)+1
12070 NEXT MONTH
12999 RETURN
13000 REM
13010 REM      Subroutine from 8120.  Files don't match
13020 MISMATCH=MISMATCH+1
13030 PRINT "Mismatch between global and diffuse files   #" MISMATCH
13040 RETURN
13100 REM
13110 REM      Subroutine from 8170.  Hour codes don't match
13120 MISMATCH=MISMATCH+1
13130 PRINT "Mismatch in hour codes between input files   #" MISMATCH
13140 RETURN
13200 REM
13210 REM      Subroutine from 8172.  Hour codes <> loop HOUR
13220 MISMATCH=MISMATCH+1
13230 PRINT "Mismatch between data hour code and program loop #" MISMATCH
13240 RETURN

```

Appendix C4

Excerpt from BMDP Runstream for Cumulative Frequencies and Percentiles
for Average Daily POA Insolation, Over Runs of Days

USING PROGRAM BMDP2D - DETAILED DATA DESCRIPTION

Input data: 10 years' daily records, containing julian date and
total daily plane of array insolation (converted for 30 degrees
tilt)

```
/PROB TITLE= 'DATA SUMMARY DAILY FORUM POA 19666-1975 AT TILT=30'.  
/INPUT VAR=2. FORMAT=FREE.  
/VAR NAMES= JULIAN, POA, RUN1, RUN2, .... RUN19, RUN20.  
ADD = 20.  
RETAIN.  
/TRANS  
  if (POA gt 100 and POA lt 10500) then (  
    RUN20=(RUN19*19 + POA)/20.  
    RUN19=(RUN18*18 + POA)/19.  
    .  
    .  
    .  
    RUN2 =(RUN1 + POA)/2.  
    RUN1 =POA.  
  ).  
  if (KASE lt 20) then USE = -1. [omit first nineteen]  
/COUNT ROUND=(3)20*20.  
/END.
```

Appendix C5

Code for Obtaining Convergence Between POA Insolation Supply and
System Energy Demand, for Given LOPP Levels, By Varying Array Size and
Battery Capacity.

```

10 REM                                     LOPP CALCULATIONS FOR MONITORED PV SYSTEM
20 REM
30 REM Bill Cowan, Department of Sociology, University of Cape Town 1/88
40 REM
50 REM      Adapt for optimisation required.
60 REM
70 REM      Eqns for avg daily POA, Pretoria, by runlength N:
80 REM      _____
90 REM      for Probability 0.01
100 REM      P=30-64,2527*n+1230/n+1975.748*log(n)
110 REM      for Probability 0.005
120 REM      P=-1170-87.4139*n+2173.5/n+2468.285*log(n)
130 REM      for Probability 0.001
140 REM      All in Wh/sq.m/day
150 REM      P=-2134-87.4106*n+2589.4/n+2692.507*log(n)
160 REM      All in Wh/sq.m/day
170 REM      on 30 degree tilt-plane
180 REM      _____
190 REM
200 REM      Eqn for avg POA Energy Demand, by run length N:
210 REM      _____
220 REM      PD=((n-c*.86/L)*L/(a*.053))/n
230 REM      where   C: installed battery capacity   (Wh)
240 REM               L: avg daily load               (Wh/day)
250 REM               A: array area                   (sq.m)
260 REM               N: length of deficit run        (days)
270 REM      _____
280 REM
290 CLS: PRINT "Press CTL-BREAK to interrupt":PRINT:PRINT
300 INPUT "Results file";F$:OPEN F$ FOR OUTPUT AS #1
310 REM
320 L=450                                'Set Load
330 CMIN= 400 : CMAX = 3000              'Set range for battery capacity
340 AMIN= 1.3 : AMAX = 3                  'Set range for array area
350 CSTEP= 20 : ASTEP = .005             'Set amounts for increments
360 REM      _____
370 REM
380 GOSUB 780 'Find first convergence
390 REM      Having found first convergence, step up battery capacity
400 REM      and decrease array size to find minimum array size for any
410 REM      length of run
420 REM
430 FOR C= CMIN TO CMAX STEP CSTEP
440     FOR ALOOP = AMAX TO AMIN STEP -ASTEP
450         A=AFIRST
460 REM      _____
470 REM      Length-of-dayrun loop to find next convergence
480 REM      _____
490 NNEXT=NFIRST
500 FOR I = 1 TO 45 STEP .2
510 N=NNEXT

```



```

520 IF N > 30 THEN N=30 'force early asymptote for expected POA
530 FOUND=0
540 REM
550 REM          Select desired probability by toggling apostrophe:
560 REM
570 'P=30-64.2527*N+1230/N+1975.748*LOG(N)      'probability 0.01
580 P=-2134-87.4106*N+2589.4/N+2692.507*LOG(N) 'probability 0.001
590 N=NNEXT      'reset N for energy demand function
600 PD=((N-C*.86/L)*L/(A*.053))/N
610 IF PD >= P THEN FOUND=1: GOTO 670
620 NNEXT=NNEXT+.2
630 NEXT I
640 REM -----
650 AFIRST=AFIRST-ASTEP      'Return to ALOOP with decrement
660 NEXT ALOOP
670 IF FOUND THEN PRINT #1,A;C;N:PRINT A,C,N
680 IF ALAST AND A AND (ALAST-A)/A < .0001 THEN ASYMCNT=1+ASYMCNT
690 IF ASYMCNT > 5 THEN PRINT "Array asymptote reached":GOTO 730
700 ALAST=A
710 AFIRST=A:NFIRST=N      'Return to CLOOP with last values
720 NEXT C
730 CLOSE 1
740 END
750 REM -----
760 REM Subroutine from 380 for first convergence
770 REM -----
780 C=CMIN:FOUND=0
790 FOR A=AMAX TO AMIN STEP -.01
800 FOR N=1 TO 5
810 REM
820 REM          Toggle apostrophe for desired probability level
830 REM
840 'p=30-64.2527*N+1230/N+1975.748*LOG(N)      'probability 0.01
850 P=-2134-87.4106*N+2589.4/N+2692.507*LOG(N) 'probability 0.001
860 PD=((N-C*.86/L)*L/(A*.053))/N
870 IF PD >= P THEN FOUND = 1: GOTO 920
880 NEXT N
890 NEXT A
900 PRINT "First convergence not found.  Decrease minimum battery capacity.
910 STOP
920 IF A<AMAX THEN 960
930 PRINT "First convergence not found.  Increase max array area."
940 PRINT "Or increase minimum battery capacity.
950 STOP
960 AFIRST=A+.01
970 NFIRST=N-1      'Set these values for prior to convergence
980 PRINT "First convergence:  Array area "AFIRST"
990 PRINT "                  in dayrun length "N
1000 RETURN

```

Appendix D1

Questioning the assumption that distribution of daily insolation is independent of locality or type of climate as employed in Chapman's (1987) Loss of Load Probability sizing methodology.

This assumption draws on a subsidiary observation by Liu and Jordan (1960), in a paper primarily directed to other purposes. It has been adopted as an attractive simplifying possibility by a number of writers aiming for generalisation of expected insolation incomes, without regard to local climate, as a step towards simplified photovoltaic system sizing.

Liu and Jordan's observation may be valid, but the evidence cited in the paper does not appear conclusive, although the statistical presentations are in a visually persuasive form.

The section of the paper referred to is where the authors (1960:10-12) investigate the cumulative frequency distributions, by month, of the observed "clearness index" for groups of disparate weather stations. The clearness index is defined as the ratio of daily total radiation measured on a horizontal surface to the extraterrestrial calculated daily insolation on a horizontal surface.

In presenting the comparisons, for groups of three selected "typical" weather stations at a time, the authors arrange the data so that for each comparison, the mean clearness index for each station-month is approximately the same. This has the effect of bringing 50 percentile values for each compared station-month into a narrow band, reflecting (a) the technique used for selecting station-months for comparison, and (b) the fairly consistent relationship between mean and median clearness indices for the station-months thus selected.

It is felt that the apparent "closeness" of the cumulative frequency curves presented in this way could mislead through visual inspection (and no statistical measures for distributional identity were provided by the authors in this paper).

For example, one set of curves shows the cumulative frequency distributions for San Antonio (June), Newport (September) and Blue Hill, Ma (July). All these station-months have an average clearness index of about 0.5. This set of curves could therefore be regarded as the most representative of likely clearness indices, with respect to a wide variety of weather stations. Other sets presented for the comparison are at average clearness indices of 0.3 and 0.7 which (as shown in Table 2, p13) are distributionally infrequent.

For San Antonio, Newport and Blue Hill, the selected months show clearness indices which are very close at the 50 percentile, and nearly identical at the 60 percentile, and although the curves snake around this convergence point, the visual impression is one of great similarity. However, this is a characteristic of cumulative frequency distributions. If the data were portrayed in the form of a non-cumulative frequency distribution, the disparities would be more visually evident.

For example, at the 20 percentile level, Newport has a clearness index of 0.26 while Blue Hill shows a value of 0.36 - higher by almost 40%. This shows the higher probability of cloud, etc., in adverse insolation conditions, at one station in comparison with the other,

even when the selected months for the compared stations have been selected for near-equality of clearness index means.

Since Loss of Load Probabilities in photovoltaic system sizing are particularly sensitive to the distribution of adverse insolation conditions (low percentile values), such disparities could be expected to have a significant impact.

(This is irrespective of the question of differences in the persistence of weather, amongst sites.)

The statistical presentation in Liu and Jordan (1960) does not permit definite conclusions about whether such disparities at lower percentiles are systematic; but equally does not seem to warrant the inference that variations in daily insolation distributions - especially at lower percentiles - are independent of climate and locality.